SECTION ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS

AN EXPLORATIVE STUDY ON THEIR POTENTIAL FOR ARCHITECTURE

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SUMMARY

Glass buildings seem to be as popular as ever (Louter, 2011) and glass shapes the appearance of contemporary architecture unlike any other building material (Wurm, 2007). Moreover, the demand for glass buildings is rising (Eskilson, 2018). As designers look to make the buildings as transparent as possible, the ambition is to execute structural elements out of glass too. Glass has always been perceived as luxurious and through history has been associated with knowledge, modernity, quality engineering and technological progression. Additionally, glass architecture has always been a signifier of public identity (Eskilson, 2018). These characteristics are still true for modern glass buildings, which is part of people's fascination with them.

In the foreseeable future, to be able to keep captivating people the 'marvels' for the average urban viewer should be greater and kept fresh. This is why more variety should be added to the architectural expression while the current characteristics of glass elements should be kept or even enhanced. Another reason for adding new elements to the toolkit is to simultaeniously keep up with building requirements like safety and sustainability. Combined this is why the toolkit for architectural glass needs to be expanded upon to be able to keep up with future building requirements and expectations.

A structural element would be a promising addition to the current toolkit because of the already great variety of non-structural elements and the ambition to make more structures transparent. A section-active structural glass element would be a promising addition to the current toolkit because these structural elements are implemented especially often and there is a lack of variety here specifically. To design this section active structural glass element from extruded glass would be promising because the extrusion process allows for complex geometry beneficial to the aesthetic experience and also the structural performance. Another benefit of this process would be that the borosilicate glass used for this is much more fire resistant than the glass used for structural fins (O'Regan, 2015). The research question thus is: what is the potential of section-active extruded glass structural elements for architectural design?

To answer this question a design vocabulary is set out in three different design aspects: system, section, and connection. After designing principle solutions the best option is chosen through assessments. The assessment of all parts of the design at all stages will be done following the same criteria. For the criteria a wide perspective was chosen that includes the entire cycle of the element's lifetime: safety, structural performance, building sequence, sustainability, costs, and aesthetics. After assessments, it is decided on a system comprising of individual post-tensioned segments of elliptical shaped glass section with steel cast connections, bolted together on site. The system is designed as modular, re-usable and recyclable. This draft design is dimensioned through hand calculations and numerical simulations in finite element analysis software.

To evaluate the potential of the dimensioned system for implementation in architecture, it is compared to the glass fin which is its only direct competitor. In order to offer a fair comparison the same façade is designed with both systems.

The conclusion of this comparison is that the designed system has a promising potential for architectural implementation with regards to structural performance, safety, building sequence, sustainability, and aesthetics. Obviously additional physical testing is needed to affirm estimations and more research has to be done should it be developed to a market-ready product. The exact costs are unclear too as no equipment exists at this point to produce the extruded glass segments in the required dimensions. The tooling costs will be high but the material costs are low, making it especially viable when mass-produced as products with standard dimensions. Summarizing the comparison the first indications and explorations necessitate to think positively towards the possibilities of such an extruded system for architecture.

keywords: structural glass, glass structures, extruded glass, glass architecture, section active glass systems, glass beams, tubular glass

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ACKNOWLEDGEMENTS

This project concludes my education at the Delft University of Technology. It was a fantastic time for me in which I learned about building technology and many things else alike. I could not have done this alone. A huge thank you goes to everybody that supported me, questioned me and inspired me. I'd like to thank the following people especially:

Ate Snijder not only for sharing his great knowledge in structural mechanics, but also for his patience, curious attitude and inspiring thought-processes. Thank you for giving me the freedom to shape this project to meet my personal learning goals. It was an absolute pleasure having you as my first mentor.

Marcel Bilow not only for sharing his spectacular wide knowledge of products and their manufacturing processes, but also for his ability to teach complex problems through great stories that stick with you and translating complex considerations to down-to-earth solutions. Thank you so much for being my second mentor.

James O'Callaghan not only for sharing his great knowledge of architectural glass in practice, but also for his ability to zoom out and asking the right question in every situation. Thank you very much for your involvement in this project, it benefitted greatly from your perspective.

I'd also like to thank SCHOTT for providing us with samples for testing and showing us their factory. Special thanks to Klaas Roelfsema, Kerstin Kohl and Markus Ollig. Thank you for hospitality and sharing your stories and craftsmanship with us.

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TABLE OF CONTENTS

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INTRODUCTION

This graduation thesis is an explorative research in the field of structural design and product design, for architecture.

The demand for glass architecture is rising (Eskilson, 2018). To keep up with this rise in demand and the expectations that come with this in terms of user experience and building requirements, like safety and sustainability, the toolkit for architectural glass needs to be updated continuously.

This thesis aims to design a meaningful addition to this toolkit by exploring the potential of section active extruded glass structural elements for architectural design.

In a wider perspective this project relates to Delft University of Technology's Glass & Transparency Research Group and the chairs of Structural Design & Mechanics and Architectural Glass. A number of structural glass projects have already been executed and many others are being worked on, each increasing in complexity. Examples of this are the glass bridge (Snijder et al, 2018) and glass swing (Snijder et al, 2019). This thesis positions itself as an extension of this line. Where all previous projects were using vector active structural glass elements, this project complements those and tries to broaden the horizon by exploring the possibilities for section active structural glass elements.

This thesis also positions itself alongside the graduation thesis of Steven Engels. His thesis expands upon the knowledge of vector active tubular glass structures. Some research data and general thoughts could be shared and exchanged.

This thesis is generally conducted through researching by design. Conclusions for this research are drawn by methodically comparing different design alternatives. An example is the system comparison in the section 'Draft design'. Design facilitates my research in this case. However also some input/starting parameters are needed for the designs and here you could argue that the thesis is conducted through designing by research. An example of this is the compressive strength test. This research facilitates my design.

This thesis was partly made possible by our collaboration with glass manufacturing company SCHOTT. They are interested in expanding their market and looking into new applications for their products. This has been beneficial to this thesis as they could support us with samples for testing, giving us a tour through the factory, and kindly answering our questions about the production process and its possibilities.

The results are to a good extent applicable in practice. However the result of the thesis is not a market-ready product. It's rather a set of ideas valued on potential. This research will serve as a possible inspiration for further research and product development for others as well as myself.

The project does contribute to sustainable development as the design is a modular and re-usable façade system. Regardless of whether the designed system will be implemented in any shape or size, the design-thinking could still contribute to more sustainable designs of any kind in the future. If this design would be widely architecturally implemented it would not directly have a huge impact with regards to sustainability. This is because if you look at the building practice in general only a small percent of buildings will use the designed elements. However, since the type of buildings this system would be used in is public and often exemplary, the sustainable approach could then stimulate other designers of the built environment to more sustainable designs, increasing its impact.

The aim for the socio-cultural and ethical impact of this thesis is to further develop a contemporary and upcoming architectural language which is enjoyed world-wide as it's featured in one-of-a-kind designs of mostly public buildings which are for everyone to experience.

In a wider social context glass buildings are perceived as barer/representation of the digital age. It's an ultramodern aesthetical language. This language needs to be updated and variety needs to be added to keep the experience special and to keep improving. It helps society portray the zeitgeist if you will.

When splitting the project in people, planet, profit/prosperity, it aims to do the following:

- People: it aims to add positive experience value for users of buildings where the designed element would be used.
- Planet: glass is a very sustainable material and it aims for the system to be modular and re-usable.
- Profit/prosperity: It aims to inspire good products which can then be produced for actual designs.

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TERMINOLOGY AND DEFINITIONS

This section is designed to very briefly discuss ambigous terms or terms not widely used in structural design.

Structural glass:
Like many seemingly straightforward terms in the architectural lexicon, the words “structural glass” can mean a variety of things depending on the context and the time period (Eskilson, 2018). In this document, structural glass refers to glass elements that are designed to transmit loads and are part of the primary of secondary structural systems in the built environment.

Primary, secondary, and tertiary elements:
The Primary structure comprises all those parts required to carry all the forces acting on a building including its own weight. Failure of the primary structure is associated with collapse of the entire building. A number of secondary structures are integrated into or attached to the primary structure. Failure of one of these only results in local collapse, the structure as a whole remains stable. Tertiary structures are all constructions which are part of the secondary structures and whose stability is not critical to the stability of those secondary structures, e.g. a window within a façade element (Balkow et al., 2007).

Structure categorization:
In his book ‘Tragsysteme’, Heino Engel categorizes structures. In this work, his terminology will be used to define/discuss structures. The most important categories for this work are:

FORM-ACTIVE:
Non-rigid, flexible matter, shaped in a certain way and secured by fixed ends, can support itself and span space. Examples: cable structures, tent structures, arch structures.

VECTOR-ACTIVE:
Short, solid, straight-line elements, i. e. lineal members are structural components that because of their small section in comparison to their length can transmit only forces in direction of their length, i. e. normal stresses. Examples: flat trusses, space trusses.

SECTION-ACTIVE:
Section-active elements are elements that cannot only transmit forces in direction of their length, but also act in bending, i. e. deflection of the middle axis. Examples: beams, rigid frames, slab structures.

SURFACE-ACTIVE:
Structural continuity of the elements in two axes, i. e. surface resistance against compressive, tensile, and shear stresses. Examples: plate structures, folded plate structures, shell structures (Engel, 1997).

METHODOLOGY

Note: due the covid-19 crisis, the university and its labs were closed a couple weeks before the P3 and remained closed for the rest of the academic year. This is why not all tests are executed as planned. To still continue the storyline of this thesis, the chapters are still in their respective places explaining the function of the test in that point of time. Where the test reports would be are now research proposals. The research proposals can be found in the appendices and would need to be executed to take over certain estimations in this report and to confirm the numerical findings.

General outline

The overarching quest of this graduation thesis is to try to expand in a meaningful way upon the current vocabulary/toolkit of architectural glass elements.

I To be able to do this, first the perception and meaning of glass should be understood. What message does glass convey? How is it seen by society and designers? In this first chapter, these questions will be answered in a historical context first, leading up to how glass is perceived now and taking a quick look into the role of architectural glass in the future. After understanding the meaning of glass through the eyes of society and designers, the significance of all elements in the current glass toolkit can be understood.

II This toolkit is compiled from literature and current designs. To be able to further evaluate the current toolkit, the following parameters are taken into account: number of alternatives for an element, its structural level (primary, secondary, and tertiary), structural category (form active, vector active, section active, surface active) and production processes. From this analysis, a promising addition will be defined and categorized.

III This categorization will form the input for the design process along with design context needs to be formulated which can test the potential for architecture best: a façade system.

During the design process, three main methods of working will be alternated between and combined: analytical, numerical and experimental analysis. The following keywords fit with each method.

- Analytical: qualifying forces, sketches, quick physical models, estimations of performances
- Numerical: quantifying forces, dimensioning, fine-tuning
- Experimental: physical testing, validation of numerical models, confirmation of expected performances

IV The first design choices are made based on analytical methods of working. First principally different solutions are set against each other and options with the most potential will be developed further. This is done for systems, sections and connections. Together these design choices form the draft design.

V Then material properties are researched through experimental analysis. Compressive and tensile strength will be tested so they can be used later as input for other design processes.

In the meanwhile, the preliminary design will be physically tested and modelled in finite element software. The physical test will be leading in validating the numerical model of not only the preliminary design, but also give confidence in models of the draft design.

VI/VII After having acquired the first validation of the numerical models, the draft design is then dimensioned and a new round of physical testing can commence, again validating the numerical model and also delivering real-world proof of the design.

VIII Before the final comparison, a way of producing, assembling and installing the system is designed.

IX/X To assist the assessment, the designed element is implemented in an architectural context and rendered for impressions and the same façade is designed with its direct competitor in order to give a fair comparison.

XI Then the design is assessed for the last time and compared to currently already existing section active structural glass systems determining the answer to the main question.

Performance criteria

The assessment of all parts of the design at all stages will be done following the same criteria. For the criteria a wide perspective was chosen that includes the entire cycle of the element's lifetime: production, construction, in-use period, and afterlife. From each criteria, relevant sub-criteria are chosen for each step in the design process to be able to judge the elements more accurately.

The criteria are:
- Safety
- Structural performance
- Building sequence
- Sustainability
- Costs
- Aesthetics

In assessments, sustainability is often not given its own category as it should be incorporated in all other criteria and treated as an integrated part of all phases of the design.

Potential rubric
In the final assessment, the designed system is compared to its main competitor using the chosen criteria. If it likely matches the performance of the current best section active structural glass system then the architectural potential is found to be high since the existing system is already very widely implemented. If it likely exceeds the performance of the current best system then the architectural potential is found to be very high. If the designed system likely subceeds the current best system, the found potential decreases as the difference in performance increases.

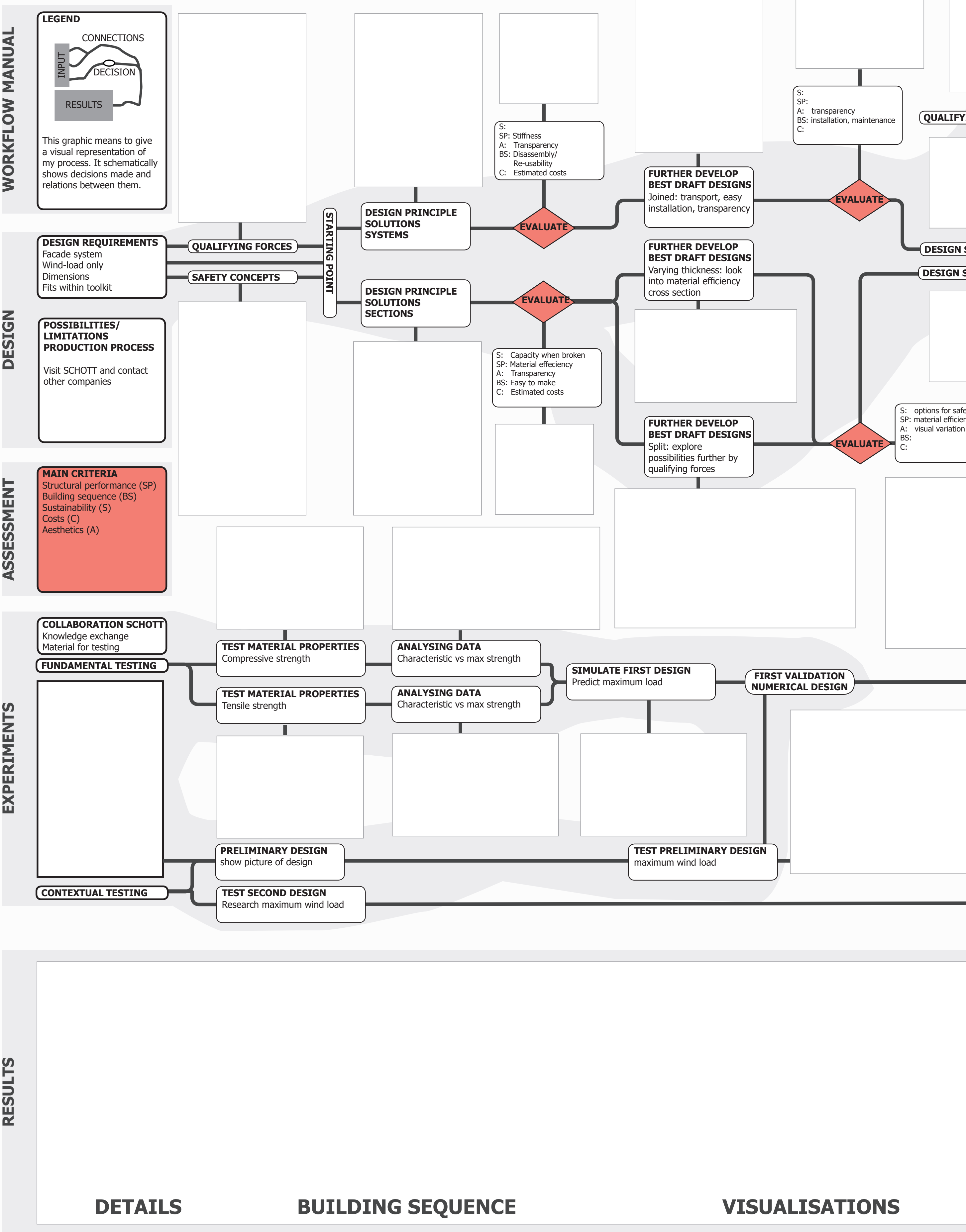
Workflow
In the workflow graphic the entire process is planned, laid out and documented. Step by step it shows the process and the influence of all design decisions on the end result. It can be found in figure 1.

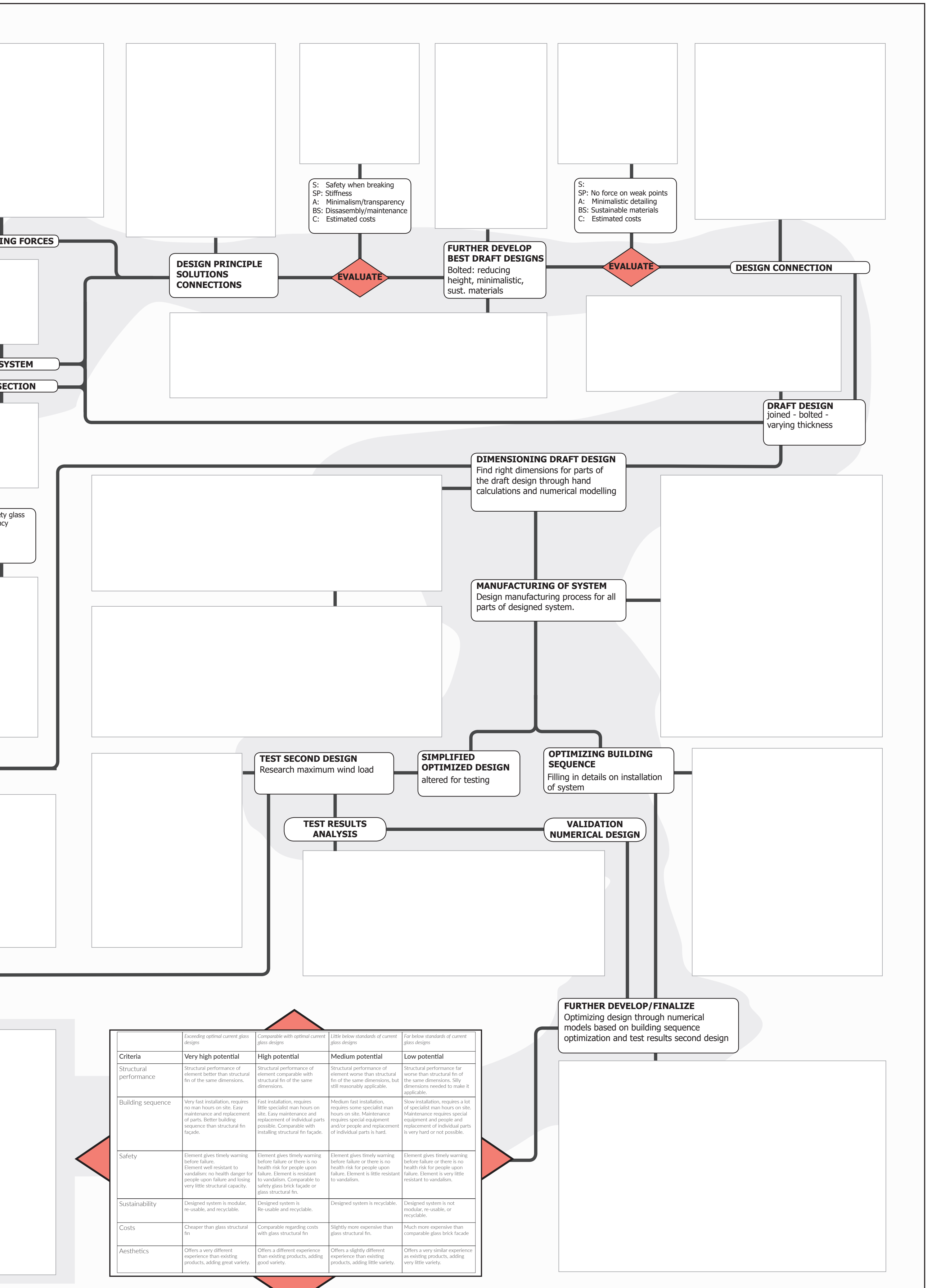
	Exceeding optimal current glass designs	*Comparable with optimal current glass designs*	*Little below standards of current glass designs*	*Far below standards of current glass designs*
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
Structural performance	Structural performance of element better than structural fin of the same dimensions.	Structural performance of element comparable with structural fin of the same dimensions.	Structural performance of element worse than structural fin of the same dimensions, but still reasonably applicable.	Structural performance far worse than structural fin of the same dimensions. Silly dimensions needed to make it applicable.
Building sequence	Very fast installation, requires no man hours on site. Easy maintenance and replacement of parts. Better building sequence than structural fin façade.	Fast installation, requires little specialist man hours on site. Easy maintenance and replacement of individual parts possible. Comparable with installing structural fin façade.	Medium fast installation, requires some specialist man hours on site. Maintenance requires special equipment and/or people and replacement of individual parts is hard.	Slow installation, requires a lot of specialist man hours on site. Maintenance requires special equipment and people and replacement of individual parts is very hard or not possible.
Safety	Element gives timely warning before failure. Element well resistant to vandalism: no health danger for people upon failure and losing very little structural capacity.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is resistant to vandalism. Comparable to safety glass brick façade or glass structural fin.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is little resistant to vandalism.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is very little resistant to vandalism.
Sustainability	Designed system is modular, re-usable, and recyclable.	Designed system is Re-usable and recyclable.	Designed system is recyclable.	Designed system is not modular, re-usable, or recyclable.
Costs	Cheaper than glass structural fin	Comparable regarding costs with glass structural fin	Slightly more expensive than glass structural fin.	Much more expensive than comparable glass brick façade
Aesthetics	Offers a very different experience than existing products, adding great variety.	Offers a different experience than existing products, adding good variety.	Offers a slightly different experience than existing products, adding little variety.	Offers a very similar experience as existing products, adding very little variety.

Table 1: the potential rubric as designed to assist answering the research question

WORKFLOW THESIS

WHAT IS THE POTENTIAL OF SECTION ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS FOR ARCHITECTURE?





	Exceeding optimal current glass designs	*Comparable with optimal current glass designs*	*Little below standards of current glass designs*	*Far below standards of current glass designs*
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
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Figure 1: the empty workflow as designed to aid the design process

I: PREFACE

Brief interpretation of the perception of architectural glass historically

This history begins at the modern times of the early industrial age. Before this, glass was rare, although the first usage -or discovery if you will- of glass was an estimated four thousand years earlier (Patterson et al., 2011). It was very precious and would be used for jewels amongst other things. As with so many other materials vital to modern architecture, the technological history of glass begins with a series of breakthroughs that shifted glass manufacture away from its artisanal roots into the urban world of mass production (Eskilson, 2018). Overall, the emphasis of glass manufacture [for architecture] was always to make it cheaper, clearer, and larger (Eskilson, 2018).

In the early industrial age, glass served architecture mainly as a utilitarian product: to enclose windows from the elements and admit light while preserving a view outside (Eskilson, 2018). It was not cheap, also because governments were looking to raise revenue via consumption trough taxes on 'luxury goods'. This resulted in the fact that glass and windows became one of the most overt symbols of personal wealth. An example of this is Hardwick Hall (Eskilson, 2018).

However perhaps even more than the windows of a manor house, the all-encompassing glass skins of nineteenth-century greenhouses stunned viewers with their display of wealth and cultivated learning (Eskilson, 2018). Then, Crystal Palace was constructed. The sheer size of the structure in Hyde Park repositioned glass that had started as a signifier of private wealth into a signifier of public, national identity (Eskilson, 2018).

However, few saw the crystal palace as representative of architecture per se in the 1860's. Rather it was a novelty, a stunt. In this way, the elaborate windows of this showroom functioned more as a huge billboard than as an element of architecture (Eskilson, 2018). Also throughout the nineteenth century, large glass windows do not seem to be identified as part of any given architectural style. As can be seen in the department stores, arcades and shops at the time: glass functioned as a utilitarian element appropriate for any and all types of architecture but was itself implying filling the void created by the design of the window opening (Eskilson, 2018).

The Crystal Palace was a monument to consumption, the first of its kind. A place where the combined mythologies of consumerism first appeared in concentrated form. Along these lines, the Crystal Palace also stands as a formative example of that other great monument to nineteenth-century consumption, the department store (Eskilson, 2018). Later for any shop able to afford a glass frontage there was the additional advantage of shutting out the filthy, bustling city streets while allowing for display and the entrance of natural light. In this manner, glass in the eighteenth century served a major function in the gradual class-based stratification of shopping, signaling affluence (Eskilson, 2018).

In the meanwhile British public health reformers in the 1800s had begun making the connection between epidemics – typhus and cholera most prominently - and an overall lack of sanitation. Architectural glass comes into the picture of promoting public health through the same type of ambiguous science that had created the so-called miasma theory; part conjecture, part self-evident common sense, but not a lot of empirical data. First and foremost, glass looks clean (Eskilson, 2018).

In the same way glass was also used for incubators for the thermal support of premature infants in 1890. Glass provided confidence to parents that the system was clean and technologically advanced.

In the same train of thought, the notion that basement spaces were disease-ridden was standard fare. The desire to banish these unhealthy fogs with natural light was one of the impetuses of glass vault-lighting, one of the earliest examples of structural glass. Variously called deck lights, sidewalk lights, or pavement lights, these elements consisted of rows of translucent glass set into a framework of either iron or concrete, usually as part of a sidewalk; this at a time when many commercial basements extended under the adjoining footway. Aside from their health-promoting function, vault lights also made economical use of daylight at a time before inexpensive electricity and lightbulbs would transform the illumination industry (Eskilson, 2018).

This also goes for Chicago construction in the late 1800's where daylight ruled construction. Here, as the first high-rises were constructed, gas lighting had very low candlepower, was messy and often dangerous. Arc lights were hard to handle and also burned hot and dangerous. One of the essential

Figure 2: when glass first was discovered, it was used for jewels[1]

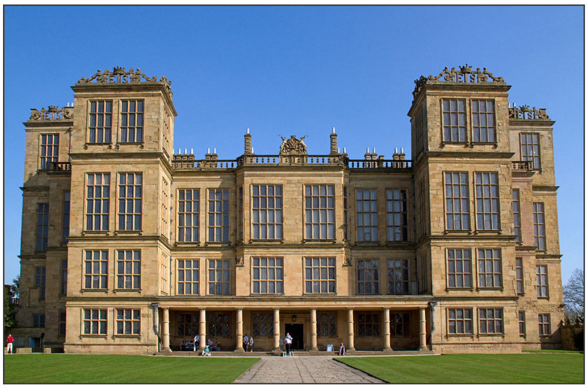


Figure 3: Hardwick Hall, with its many windows a symbol of personal wealth[2]

Figure 4: A traditional greenhouse, stunning viewers with its display of wealth and cultivated learning[3]

Figure 5: the Chrystal Palace, shifting the perspective from private to public wealth[4]

Figure 6: shops that were able to afford a glass frontage could keep the filthy streets outside while still displaying their goods[5]

Figure 7: the Reliance building with a characteristic Chicago window, optimized for letting in daylight[6]

Figure 8: the curtain wall started the international style of corporate buildings[7]

Figure 9: the entrance of the Van Gogh museum in Amsterdam signals local public identity[8]

components of modern architecture at that time was the windows that served as a gateway for natural light and ventilation. Only later they were superseded by electric lighting in the early 1900s and air-conditioning in the 1930s (Eskilson, 2018).

In the early years of the twentieth century, no conceptual issue quite consumed the practice of architecture like the present and future possibilities of glass technology (Eskilson, 2018).

At a symposium in June of 1887 which was focused on the architectural potential of new materials, Daniel H. Burnham mentioned the potential of structural glass. He pointed out that glass is inexpensive and has excellent compressive strength, and therefore would be a suitable structural replacement for stone, terracotta, and even plaster. It is clear from the record of the meeting that this vision was largely met with skepticism (Eskilson, 2018).

At the time there were two main streams when it came to glass in architecture – functionalism and expressionism - both valued glass as a promising technology with an almost limitless potential to upend traditional forms. Glass during this era gradually proved its ability to thrive as both skin and structure, forging new types of form and meaning that resonate through to the present (Eskilson, 2018).

Functionalists:

Architects wrote in the 1920s of how the transparent glass wall could open up a view of the inner structure, but the true triumph of the curtain wall arises in the 1950s when the field of glass comes to the fore and effaces its innards on behalf of a glittering surface. The nexus of power that made Gropius' Bauhaus curtain so significant was its newly apparent relationship to the glamorous mid-century towers that arose in major American cities, especially New York where they become the ultimate signifiers of American capitalism. In the 1950s, the iconography of the modern corporation shifts dramatically, from one that embraced static monumentality to a new desire to project efficiency through the lightness and flexibility of the recently christened International Style. If the glass box skyscraper retained any element of expressionist magic, it was through its night-time illumination (Eskilson, 2018).

In terms of glass itself, the use of tempered, or toughened glass – either drawn or plate – became a standard practice. The invention of tempered glass, whereby through either chemical or thermal processes the material is made five or even ten times stronger than conventional annealed glass, was extremely important to the rise of the mass curtain wall. The fact that tempered glass breaks into relatively blunt edged pebbles was a huge advantage, as the fear of shards of annealed glass raining down on passer-by was a real one (Eskilson, 2018).

There was one last key link in the technological change that would make the glass curtain wall ultimately triumphant: the invention of the float glass process by Pilkington Brothers during the 1950's. While the basic idea – pouring molten glass not on to a casting table but rather onto a liquid metal substrate – had been experimented with for decades, Pilkington managed to solve a number of chemical and engineering challenges that had prevented the technology from becoming commercially viable (Eskilson, 2018).

Expressionists:

The modernists were the new expressionists after the gothic period. These other protagonists of the modern spirit saw the "liberated wall" as a possibility of bringing "light, air and openings" to the masses of urban workers dwelling in extremely densely populated, dark and unhealthy living quarters (Eskilson, 2018, Behling et al., 1999). The idea of being able to take down the barrier between inside and outside fascinated architects. The translucence and dematerialization of the physical body into an ephemeral form were goals which contemporary artists had already pursued in their avant-garde photography (Behling et al., 1999).

Brief interpretation of the perception of glass in current times

The usage of glass went from literal jewels to a building material for jewels of the built environment. It invariably produces surprises and generates a great variety of unexpected effects which even the experienced designer will only partly anticipate. It is the sense of wonder by which architects and engineers are inspired to use glass (Nijsse, 2003).

Buildings that have glass as the main design element still signal affluence. An example is the overwhelming glass experience of a contemporary Apple store (Eskilson, 2018). One could argue that the class-based stratification of shopping has in this way carried through to the twenty-first century.

What also still holds true is that glass buildings are a signifier of public identity and even national identity to some degree. Oftentimes this identity is more local than it was in the past, nowadays it's often the identity of a city or even a single entity like a museum. An example of this would be the entrance of the Van Gogh Museum in Amsterdam. It is more a signifier of the identity of the museum than national identity or even the cities identity.

Glass buildings seem to be as popular as ever (Louter, 2011) and it shapes the appearance of contemporary architecture unlike any other building material (Wurm, 2007). Glass has perhaps found its greatest architectural role as a harbinger of advanced digital culture. A new development that supports architectural glass and stimulated research into making structures of glass is that of new adhesives that allow for effective glass-to-glass bonds.

The current glass building designs mostly continue on modernist beliefs/concepts of blending inside and outside and the more daring designs are still seen as 'stunts'. A change here is that the architectural narrative is shifting from designers to engineers (Eskilson, 2018). To make a glass design requires more engineering than a 'regular' design as there is no hiding in this particular aesthetic language. Every building component and even detail is very visible and can ruin the transparent experience. This also could be why it is particularly interesting to many engineers. It is a great challenge to meet the structural and aesthetic requirements in highly thought out and one-of-a-kind designs.

And to still stun people, something special is needed indeed. Corporate atria, hospitals, museums, schools, malls, airports: nowadays, glass façades may be literally transparent but they are also largely invisible in the public's imagination; it requires a glass enclosure that is exceedingly captivating to grab the attention of the average urban viewer (Eskilson, 2018). This is also a reason why the development of the glass architectural toolbox cannot stop for this architectural language to remain successful and interesting.

Another big theme of current times is sustainability. It has recently grown exponentially in importance (Eskilson, 2018) and while glass in itself could be a very sustainable material and glass buildings form only a very small percentage of all buildings, special attention should be paid to not be wasteful.

Figure 10: a contemporary Apple store on 5th Avenue in New York[9]

Figure 11: Crystal Houses in Amsterdam[10]

Brief estimation of future developments in architectural glass

In the foreseeable future, to be able to keep captivating people and keep up with the building requirements, variety should be added to the aesthetic language and the engineering 'marvels' should be bigger while the current characteristics of glass should be kept or enhanced. This could mean making new, more or bigger structures out of glass, but also making them even more transparent in the members and connections. In any case the toolkit needs to be kept up to date to keep the modern affluence. And while the jewels need to be prettier, sustainability will be a theme that is only going to grow stronger.

Problem statement

The toolkit for architectural glass needs to be expanded upon to be able to keep up with future building requirements and expectations.

II: CURRENT TOOLKIT

After understanding the perception of glass, the significance of the current toolkit can be understood. This current toolkit is compiled by combining and going through types of glasses, production processes, glass products, treatments, coatings and interlayers. After the current toolkit has been compiled, a meaningful addition can be defined.

GLASS TYPES

Table 2 shows the most occurring glass types with their common uses in architecture and some key characteristics. The costs of each type is also globally defined. Many variations on these main types exist since the exact composition of glass can be varied upon practically endlessly.

Name type of glass	Description	Common uses
Soda-lime glass (or commercial glass)	• Least expensive and most common glass. Applications range from blown glass packaging to windowpanes. • Made up of silica sand (up to 75%), soda ash, lime (calcium oxide) and other additives. • It's a 'soft' glass that is relatively easy to mould and fabricate. It softens at around 400-500 C and so is economical for mass production. However, this also means that soda-lime glass is prone to shatter at high temperatures or in response to sudden changes in temperature. Costs: Low	Windowpanes (float glass), auto- motive windows, mirrors, packaging
Lead alkali glass: • lead glass • crystal glass	• Due to the lead content these glasses have a higher refractive index than other types. Increased refraction produces a clearer and more lustrous glass. • Lead alkali glass is silica based, but the lime is replaced by lead and the soda replaced with potash. If it has less than 25% lead it is known as crystal glass and when there is more than 25% lead it is known as lead glass. Over prolonged periods the lead content can leach, so this glass is not suitable for storing liquids and foods. • It is even 'softer' than soda-lime glass. • Cutting enhances the sparkle of the glass and as such is used in the production of decorative tableware, ornaments and jewelry. • Lead content makes it suitable for certain radiation shielding applications (more than 50% lead). Costs: Moderate to high	Vases, ornaments, jewelry, awards, prisms, lenses, radiation shielding
Borosilicate glass (or DURAN©, Simax, Pyrex)	• Primarily used for its resistance to high temperatures and thermal shock. • It contains up to 15% boric oxide and small amounts of other alkalis. • It is 'harder' and more durable than soda lime and lead alkali glass. • Borosilicate glass has a higher impact resistance. • It has low levels of thermal expansion and is resistant to thermal shock. • Its softening point is relatively high at 800-850 C. This makes it more difficult to mould and fabricate, but means that it can be used for high temperature applications. • It is more resistant to acids than soda lime glass and has moderate resistance to alkalis. Costs: Moderate to high	Ovenware, coffee pots, scientific glassware, sculpture, ornaments and complex profiles
High performance glasses: • glass ceramic • aluminosilicate glass • quartz glass	• These glasses have high working temperatures; they are relatively difficult to fabricate, but have superior resistance to heat and thermal shock. • High performance, high costs. • Glass ceramics are so called because they are shaped like glass in a molten state but heat-treated to give a high level of crystallinity, similar to ceramics. The resulting material is harder, more durable and resistant to rapid temperature change. • Aluminosilicate glass contains higher levels of aluminum oxide than other lower cost glasses. It is similar to borosilicate glass, but has improved resistance to chemicals, high temperatures and thermal shock. • Quart glass, also known as fused quartz and silica glass, is made up of almost pure silica (silicon dioxide). It has exceptional resistance to high temperatures, thermal shock and most chemicals. Costs: high to very high	Stove and fireplace doors, cooker tops, light covers for industrial applications.

Table 2: Most occurring glass types with their common uses and some key characteristics (Thompson, 2007)

PRODUCTION PROCESSES

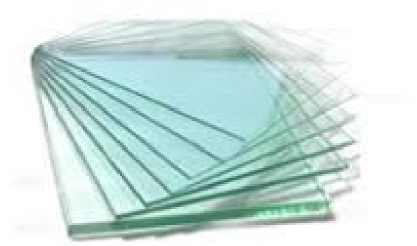
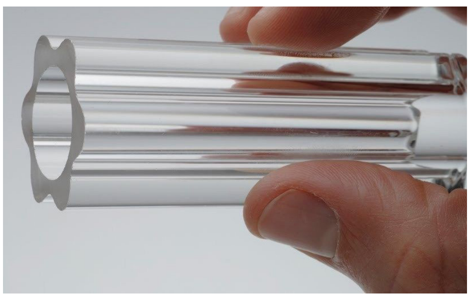
Table 3 shows the most commonly occurring production processes with a brief description and their common uses. Naturally, not all production processes have wide applications in architecture.

Name process	Description	Common uses
Casting	Molten glass is poured into a mould.	Decorative items, solid items • glass bricks • sculptures
Blowing (blow and blow)	Glass is injected into a mould and blown into a general shape. After transferring to a second mould, it is further blown into shape.	Narrow-neck containers • no particular uses in architecture • bottles
Blowing (press and blow)	Similar to blow and blow, but here in the first mould it's pressed into shape instead of blown.	Wide-mouth containers • no particular uses in architecture • bowls
Floating	Glass 'floats' from the melting tank through a separate float bath (liquid tin).	Panes • windows • fins
Drawing (by machine)	Glass rolls out of melting tank through rollers. Rollers give the glass its pattern.	Panes • windows
Pressing	Pressed glass (or pattern glass) is glass made using a plunger to press molten glass into a mould.	Decorative items • bowls
Rolling	Similar to float glass, but rolled out of the melting tank by two rollers.	Panes • windows
Extruding (direct)	The billet is compressed within the container and forced by the punch to flow through the die aperture. The cross section of the extruded product is determined by the shape of this aperture. During this process punch and extruded rod move in the same direction (Roeder, 1970)	Special chemical properties (unconventional): • Glasses with a steep viscosity-temperature curve (or short glasses). Their rather narrow temperature range for working is very inconvenient for shaping. • Glasses with a strong tendency to devitrify (become opaque amongst other things) • High melting glasses. Suitable for conventional glasses too if rods or tubes with other than circular cross sections are to be produced. Due to the comparatively low working temperature, surface tension does not have much effect; the products therefore have sharp edges and are very accurate in shape.
Extruding (inverted)	The hollow punch supporting the die in front is pressed against the billet, and the extruded rod inside the punch moves opposite to it.	

Table 3: Most common production processes with a brief description and common uses (Balkow et al., 2007, Thompson, 2007)

GLASS PRODUCTS

Table 4 shows the most occurring glass products with a brief description of the product, common uses and pictures for reference. A product in this sense is referring to the outcome of a production process and not bound yet by a specific geometry or dimensions.

Name product	Description product	Common uses	Picture(s)
Cast glass	• Not very common in architecture, but can be used for making brick-like blocks. • Attention needs to be paid to the solidifying time and process of the element as this can have a large impact on planning and material properties.	Blocks, bricks	 *Figure 12: Cast glass*[11]
Float glass	• Most widely used type of glass. Thicknesses from 2 to 19 mm. • Maximum ribbon sizes of 3.2x6.0m. Can be coloured during the manufacturing process. • When lower amounts of Fe2O3, it is possible to reduce or even virtually eliminate the natural green tint of float glass (low-iron or clear-white glass).	Standard windows, façade elements	 *Figure 13: Float glass*[12]
Drawn sheet glass	• Drawn sheet glass and float glass have the same chemical composition as well as the same general physical properties. However, drawn sheet glass exhibits slight waves and "batter" in the surface perpendicular to the direction of drawing. • Thicknesses from 2 to 12 mm.	Windows, older style windows	 *Figure 14: Drawn sheet glass*[13]
Patterned (or rolled) glass	• The liquid glass melt, like an overflowing bath, is fed between one or more pairs of rollers to give it a characteristic surface texture as required. Therefore, the glass can be given two smooth surfaces, one smooth and one textured surface or two textured sides depending on the design of the roller or table surfaces. • Rolled glasses are translucent, they cannot reproduce the transparency of float or drawn sheet.	Privacy windows	 *Figure 15: Patterned (or rolled) glass*[14]
Extruded glass	• Extruded glass profiles are typically borosilicate glass, because soda lime is 'softer' and prone to breaking during processing. • Determined by the equipment, the extruded profiles could be of complex geometry and in large dimensions. Currently existing equipment cannot produce these large elements as it has no applications that demand such dimensions yet.	Privacy windows	 *Figure 16: Extruded glass*[15]

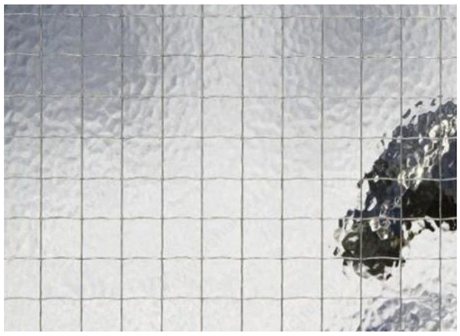
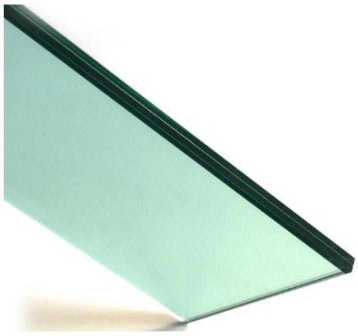
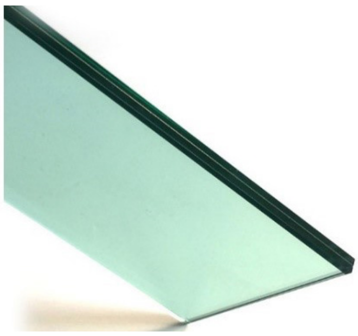
Name product	Description product	Common uses	Picture(s)
Glass ceramics	• Glass ceramics are produced just like float, drawn sheet or rolled glass. They can be coloured by adding further substances. The fracture pattern of glass ceramics is basically the same as that of float glass.	Not commonly used in architecture	 *Figure 17: Glass ceramics*[16]
Polished wire glass	• Clear soda-lime-silica glass whose surfaces have been polished and made parallel. Glass is produced by casting and then polished. A spot-welded wire mesh is inserted during the manufacture. It's not a safety glass and possesses no safety properties. It is mainly used for aesthetic reasons, as a fragment-bonding glass for roof glazing or sometimes as fire-resistant glass.	Workshop windows, privacy windows	 *Figure 18: Wire glass*[17]
Channel shaped glass	• Profiled glass element with textured surfaces which are produced by casting. Used for single skin or double skin (inner) walls. • The elements are produced U-shaped and then fitted together to form a wall.	Inner walls, façades	 *Figure 19: channel shaped glass*[18]
Laminated glass	• Element consisting of panes and intermediate layers. The laminating can make the glass stronger or stiffer or it can be used to make the element better insulating.	Windows, façades	 *Figure 20: Laminated glass*[19]
Laminated safety glass	• At least two panes and one intermediate layer. It is considered a safety glass because fragments are held together upon fracture.	Structural fins, balustrades	 *Figure 21: Laminated safety glass*[20]

Table 4: Most common products of glasses for architecture with a brief description and common uses. (Balkow et al., 2007)

TREATMENTS AND COATINGS

A treatment or coating is a finishing process to add a new quality to the material or enhance existing properties. Table 5 shows the most common coatings and table 6 shows the most common interlayers for architecture with a brief description and common uses. Remark: some products, treatments and/or coatings can be combined to what is known commercially as:

- Anti-vandal glass: Rock throw resistant
- Anti-intruder glass: Prevent openings larger than 400x400mm with an axe
- Bullet resistant glass: No penetration and no glass splinters
- Explosion resistant glass: Laminated safety glass
- Alarm glass: Silver wires placed within the make-up of the laminated safety glass
- Heated glass: Conductive coating to the surface or placing a fine wire within the makeup of the laminated safety glass
- Insulating glass: At least two separate panes kept apart by spacers

Name coating	Description	Common uses
Online coating	Method of coating. Spread over the upper surface while it is still hot during the production of float glass. Metal oxide.	Solar control
Offline coating: magnetron sputtering	Method of coating. Acceleration of free electrons in an electric field which then collide with gas molecules. Finished product can usually only be left outside for a limited period.	Low-emissivity coatings
Offline coating: Evaporation	Not really used anymore.	-
Offline coating: Sol-gel process	Glass is dipped in a liquid.	Solar control
Enamelling	Applying a coloured ceramic layer to the glass surface and then baking it into the glass. It's mostly used for decorative purposes, not often in architecture.	Adding colours
Acid etching	Patterns and pictures can be etched into the surface by masking certain areas.	Matt finish
Sand blasting	The element gets blasted by tiny sand particles at high speeds.	Matt finish
Edge works	Normal cut edge; simplest and used wherever the edge of the glass is placed in a frame and there is no danger of being injured by the sharp edge. Other types can be achieved by grinding and polishing.	-

Table 5: Most common coatings for architecture with a brief description and common uses (Balkow et al., 2007)

Name treatment	Description	Common uses
Bending	Flat panes reheated and bent. Watch for tolerances.	Façades, art
Thermally toughened safety glass (or toughened/tempered safety glass)	Reheated and cooled quickly. It creates additional compressive stresses in the surfaces which makes the glass stronger. Bending strength increases, likewise the thermal fatigue resistance. Can accommodate higher tensile forces due to the pre-stress. When breaks than into numerous small pieces whose edges are generally blunt. Cannot be worked (drilled etc.) afterwards.	When failing of the element would likely cause injuries through large pieces of falling glass.
Heat strengthened glass	Higher bending strength and better thermal fatigue, but no a safety glass (toughened glass is). Different fracture pattern. Also cannot be drilled etc. into afterwards.	Oftentimes used as structurally better inner layer(s) of laminated element with sacrificial layers on both sides.
Chemically strengthened glass	Chemical pre-stressing by ionic exchange. Glass is immersed in a hot molten salt. Can be cut afterwards, but loses its strengthening in the new edge.	Similar to heat strengthened glass, but structurally even better.

Table 6: Most common treatments for architecture with a brief description and common uses (Balkow et al., 2007)

INTERLAYERS

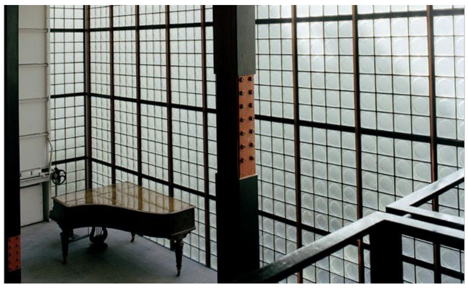
Table 7 shows the most common interlayers used in architecture with their application process, their structural behaviour and safety aspects. These interlayers are applicable to laminated glasses especially. An example of this in the final toolkit is the structural glass fin, which comprises of at least two layers of glass. Since interlayers are not as frequently occurring in the current toolkit, the interlayers are generalised to the extend in which the information still suffices for compiling the current toolkit, but keeping it concise.

Name interlayer	Application process	Structural behaviour	Safety
Sheet laminating, main types: • PVB (poly vinyl butyral) • EVA (ethyl vinyl acetate) • ionoplast	PVB is the most common sheet interlayer material. The sheets of glass are assembled with an extruded sheet of interlayer between them. The 'sandwich' is then passed through an oven that heats it to approximately 70°C, from which it passes between rollers that squeeze out any excess air and form the initial bond. The laminate then moves to an autoclave where it is heated to approximately 140°C under a pressure of about 800kN/m2 in a vacuum bag.	Generally, for the PVB and resin interlayer materials, short-term out of plane loads can be resisted by both laminates acting compositely. Due to creep in the interlayer elements with long-term out of plane loads are generally considered to act non-compositely, with the loads being shared by each laminate in proportion to their relative stiffness. Laminated glass panels with an ionoplast interlayer exhibit some composite action even during long-term loading conditions, although their strength is diminished somewhat. This is due to the stiffness of the ionoplast interlayer decreasing over time.	If one or both layers of glass in a laminated panel break, the broken pieces of glass will generally remain bonded to the interlayer.
Resins laminating, main types: • Acrylic • PET (polyester) • TUP (thermoplastic polyurethane)	The sheets of glass are brought together and held a certain distance apart by double-sided tape around their perimeter. Resin is then poured between the two sheets. When all the air has been displaced, the open edge is sealed and the laminate stored horizontally while the resin cures and solidifies. Curing is via a chemical reaction or ultra violet light. Size is limited by the ability of the fabricator or by the size of the panes available.	Generally, for the PVB and resin interlayer materials, short-term out of plane loads can be resisted by both laminates acting compositely. Due to creep in the interlayer long-term out of place loads are generally considered to act non-compositely, with the loads being shared by each laminate in proportion to their relative stiffness.	If one or both layers of glass in a laminated panel break, the broken pieces of glass will generally remain bonded to the interlayer. Intumescent resin interlayers react to heat in such a way that during a fire they turn into foam. This change not only resists the passage of fire but also reduces the conduction and the radiation of heat through the glass. This protects people who may need to pass it on their way out of the building.

Table 7: Most common interlayers used in architecture with a brief description of the application process, structural behaviour and safety (O'Regan et al., 2015)

CURRENT TOOLKIT

Table 7 shows the most elements of the current architectural glass toolkit with a brief description of the element, common uses and a reference image. After analysing the current toolkit, a meaningful addition will be defined.

Name element	Common structural use	Description	Common uses	Picture(s)
Glass pane	Tertiary	Float glass which can be laminated or insulated too. It is most likely toughened when the panel is large and has a coating for solar control but it can be seen in all kinds of sizes and is very versatile regarding treatments and coatings too.	Façade panels, roof panels, windows	 *Figure 22: Apple Store, Hangzhou*[21]
Bent glass pane	Tertiary	This is float glass which is then hot bent. When the glass cools, the glass remains in its hot shape. This is obviously more expensive than normal float glass. Used for artistic effects or to play with people's experience of the view inside out or outside in. Harder to laminate, but a solar coating can usually be expected.	Façades, sculptures	 *Figure 23: Cloud Pavilion, Shanghai*[22]
Cold bent glass	Tertiary	This is very thin glass. It's so thin it's flexible. This is why it can be bent cold. This cheaper way of shaping glass is promising for all kinds of designs. Indoor climate can be a challenge though.	Furniture, sculptures, quadruple glazing	 *Figure 24: Design for look-out point*[23]
Glass blocks (non-structural)	Tertiary	These glass blocks, either hollow or solid, are positioned in a frame which carries the load. The blocks are often not transparent and have a matt or patterned finished.	Façade systems (not transparent)	 *Figure 25: Maison de Verre, Paris*[24]
Polished wired glass	Tertiary	Polished wire glass is sometimes considered old-fashioned but is integrated in new designs too. The wavy panels make for an interesting effect. The glass is not used for façades in general.	Workshop windows	 *Figure 26: Project Unknown, Location Unknown*[25]

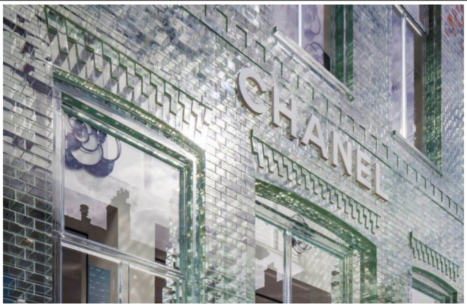
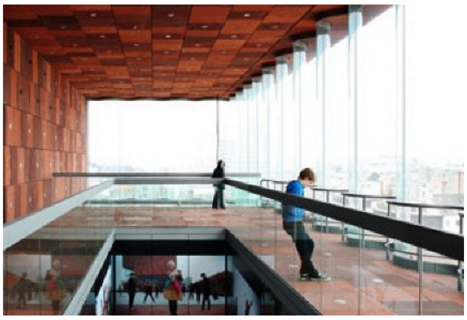
Channel shaped glass	Tertiary	Channel shaped glass elements are stacked together to form façades or inner walls. Inner walls are more common than façades though.	Façades, inner walls	 *Figure 27: Fort York Visitor Centre, Toronto[26]*
Post-tensioned truss	[experimental] Secondary, vector active	These extruded glass elements are not applied widely at all yet. They are used in the Tower Place's design in London. The glass conveys the compression forces while the steel inside helps with conveying the tension.	Trusses	 *Figure 28: Tower Place, London[27]*
Glass blocks (structural)	Secondary, section active	These cast glass blocks can resemble a transparent brick wall, but the bricks themselves are limited in size and expensive to produce.	Brick-like blocks, ornaments	 *Figure 29: Crystal houses, Amsterdam[28]*
Glass Fin	Secondary, section active	These laminated float glass elements. They usually consist of two or three layers and may have sacrificial layers imbedded. This is the most used structural glass element.	Façade columns, beams	 *Figure 30: Apple Store, New York[29]*
Bent Glass Pane	Secondary, surface active	These laminated float glass elements. They usually consist of two or three layers and may have sacrificial layers imbedded. This is the most used structural glass element.	Façades, sculptures	 *Figure 31: Museum aan de Stroom, Antwerp[30]*

Table 7: Most common elements of the current architectural glass toolkit with a brief description of the element and common uses

WHAT WOULD BE A VALUABLE ADDITION TO THIS TOOLKIT?

Structural glass

From the current toolkit it can be concluded that there is a far greater variety of non-structural (or tertiary) elements than secondary or primary structural elements. However to be able to keep captivating the average urban viewer's attention, glass architecture needs to be as transparent as possible, likely meaning that more and more structures need to be executed in glass. A structural (secondary or primary) element would thus be a great addition to the current toolkit.

Elements in the primary order of structural importance in big buildings are very rare because of safety issues, mostly concerning failure due to vandalism or immediate failure without warning. The scaling of secondary elements and installing these elements into the primary structure will be left for further research. In theory they fulfil the same purpose, which is the conveying of loads. This why in this research an emphasis will be put on the difference between tertiary and secondary/primary elements.

Section active

Currently there is not a great variation in structural systems, especially when looking at designing traditional structures existing of flat surfaces supported by beams, which is one of the most conventional ways of architectural glass design. The structural glass fins are usually chosen over their brick counterpart for their simple and transparent look and conveying the elegancy and minimalism better. Furthermore, they are much cheaper and easier to produce and install. This is also the reason why many glass designs look similar. Another section-active structural glass element would thus be a great addition to the current toolkit.

Extruded glass

In current architectural design, there are almost no products which are made from extruded glass. From this production method, although possibly more expensive than the float glass production method, geometry with complex sections can be produced. Apart from aesthetically pleasing this can be put to structural uses too, creating columns or beams with a great material efficiency and geometrical stability. A section-active extruded glass structural element could thus be a great addition to the current toolkit. Another benefit of this process would be that the borosilicate glass used for this is much more fire resistant than the glass used for structural fins for example (O'Regan et al., 2015), improving the general safety.

Research question

In order to test how promising the defined element really is, the following research question was formulated: what is the potential of section-active extruded glass structural elements for architectural design?

Existing section active systems and their strengths and weaknesses

The glass structural fin system can be considered the oldest structural glass façade system type. (Pilkington et al., 2011) Certainly this structural form has been more widely applied than any other, perhaps because it has been transformed by companies like Pilkington into packaged product systems, available from a single source, with an extended warranty. Today however, it is easy to piece together a glass fin system by buying glass locally or regionally and ordering hardware from a catalogue. Glass fin façades are topologically equivalent to a mullion system. The glass typically acts as a vertical mullion on the vertical glass grid, resisting lateral loads. The systems are most often suspended but can also be base-loaded. The glass cladding is typically suspended, with the dead load carried by an overhead building structure (Pilkington et al., 2011).

The glass structural bricks are relatively new and only rarely used. This is because of obvious heightened costs, their slow installation on site and their aesthetic which only serves particular designs. However this aesthetic is truly special and also the main selling point for this system. Future developments could make this system more popular when the building sequence is improved.

THE PRELIMINARY DESIGN

Before continuing to the actual designing of the defined addition, the preliminary design will be discussed. The preliminary design forms a point of inspiration for this graduation thesis. It is a continuation of the following glass projects:

- Glass bridge (Snijder et al, 2018) vector active struts
- Glass swing (Snijder et al, 2019) vector active post-tensioned bundles of glass rods

This project however explores glass in bending. The preliminary design is a first thought product by Ate Snijder. This will not be an ideal design but rather a source of further ideas, to set a benchmark and give insight into how such an element could behave structurally

The design consists of a glass ellipse-like shape with on the inside two steel rods in two separate glass circular tubes. The element is post-tensioned through the steel rods and clamped together by steel plates. To avoid peak stresses in the glass from touching the metal, POM plates serve as an interlayer and are used to introduce the forces like was successfully achieved in precedents. The element is meant to be loaded on the connections instead of with a Q-load. The glass ellipse is designed to convey the shear force and most of the moment. The glass rods are there for helping convey the moment and to add surface for conveying of normal forces.

Figure 32: exploded view of the preliminary design, length of the glass segments is shortened for this image

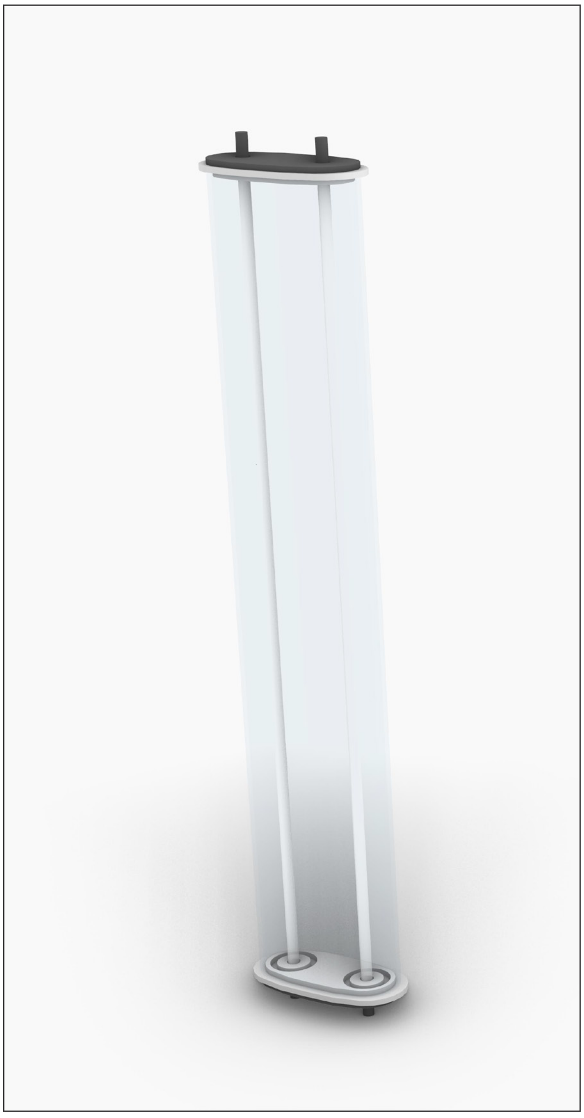


Figure 33: impression of the assembled preliminary design

III: DESIGN CONTEXT

Because of the limited time span, one representative system will be designed to test the potential of a wider set of systems and elements that are similar in structural requirements.

FAÇADE SYSTEM

The designed system will be a façade system. This is not only deemed as the best option because it is the most common section active system in the architectural design language of structural glass but it is also an example of a beam that is designed to withstand out of plane forces especially. If the designed system can be a good façade system, it undeniably has potential.

To truly focus on being section-active, the design will not carry dead load of the building above, but merely its own weight and the wind load. A perhaps post-tensioning of the system might be added to that. This also means that the façade must carry its own weight or be suspended from the roof or levels above.

The designed element will be subjected to in-plane loads and lateral loads. Similarly it is also taken into account that wind cannot only push, but can also create a pulling force. This pulling force is often the governing load-case for structural fins as they have an unrestrained edge prone to buckling.

Dimensions glass elements

For the starting point of this design, it is assumed the façade has glass panels that require connections to the structural column at set lengths. Probably a way of connecting the (likely) tubular elements together needs to be designed because of logistical impracticalities/ impossibilities that will occur when designing for one-piece full-length columns. Creating a re-usable and modular systems also has serious sustainability benefits.

Safety concepts

One of the major criteria to pay attention to for implementing structural glass designs is safety. As glass is brittle it can break suddenly when exposed to extreme loading, peak stresses or acts of vandalism.

It is assumed that peak stresses can be prevented by good design but acts of vandalism cannot which means that effectively any glass element can break at any time during its in-use period. However, it is also assumed that only one element can be vandalized at a time and the vandal generally can be stopped after breaking one element.

To assess safety risks in the design, the risk table (table 8) is used as guidance. This table is designed as a simplified version of the risk assessment method in the current Dutch building code for glass in buildings (NEN 2608, 2014). Risk is chance that something happens times the consequences when it happens. A score of 10 or above is considered as unacceptable. However, risk should be decreased whenever and wherever possible. The risk table will be used throughout the design process.

To avoid high scores on the risk table, it should be highly improbable that large pieces of glass fall on people in the event of failure. Also, the building should not collapse if an element fails. Lastly, other building components like façade panels should also not be able to cause injury falling on bystanders. The analysis sequence in figures 35, 36, and 37 sketch principal solutions.

To further illustrate this with the risk table: shards of glass falling down from acts of vandalism could kill people, which is not acceptable even if it happens only once in the lifetime of the building. This is why either it should be prevented that shards of glass come falling down or when falling down it should never fall on people. The first can be achieved by using safety glass, which shatters in very small pieces. These pieces could potentially still hurt someone, but this is acceptable when it happens with very low frequency. The second solution can be achieved only if people are not allowed near the glass part or in intermediate screen is placed between people and the glass part.

There are two main solutions to avoid building collapse. The first one is residual strength, this means that although an element is attacked, it will in all cases remain structurally capable of carrying sufficient loads. The second solution is a second load path, which means that surrounding structural elements can carry extra loads for when a column fails.

There are also two main solutions to avoid façade panels falling. The first one is to attach façade panels to multiple structural elements in such a way that not all are necessary for its stability. The second one is to let the façade be self-supported.

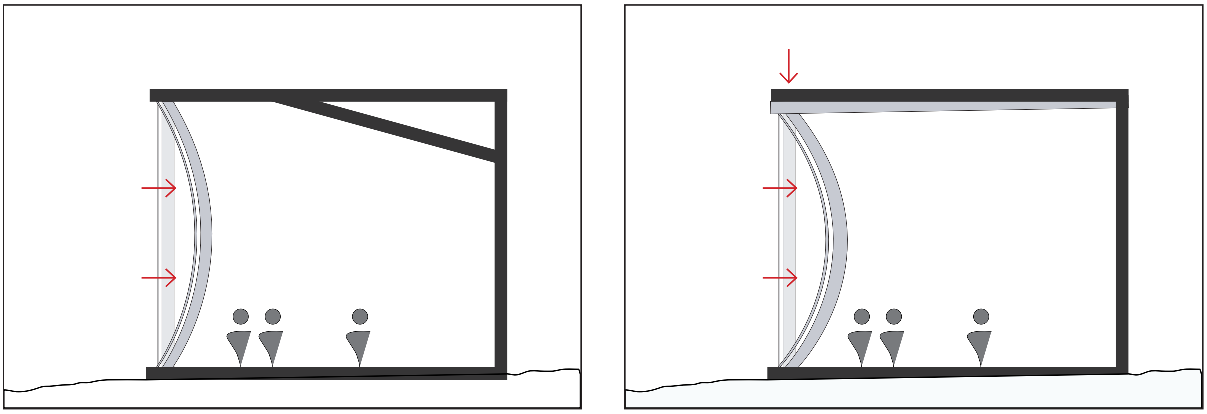


Figure 34: the global deformation of a façade system carrying just wind load and of a façade also carrying dead load from a roof structure or floors above

				Risk Impact				
				Insignificant	Minor	Moderate	Major	Severe
				Stub a toe	Hurt	Broken bones	Death	Multiple deaths
				1	3	5	10	15
Frequency	Very High	Daily	5	5	15	25	50	75
	High	Weekly	4	4	12	20	40	60
	Moderate	Monthly	3	3	9	15	30	45
	Low	Yearly	2	2	6	10	20	30
	Very Low	Once	1	1	3	5	10	15

Table 8: the risk table, multiplying the consequences by the frequency

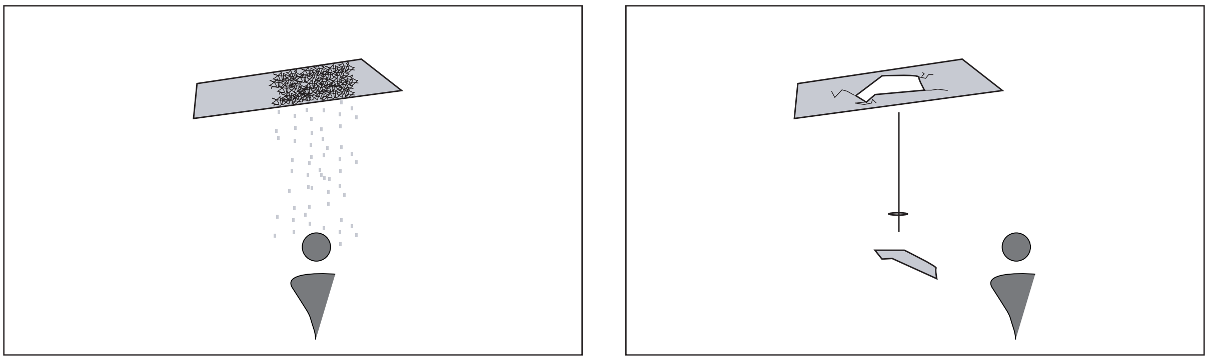


Figure 35: two safety concepts to avoid people getting hurt, the first one being installing safety glass so no large shards can come falling down (left) and the second one being keeping people away from risk areas (right)

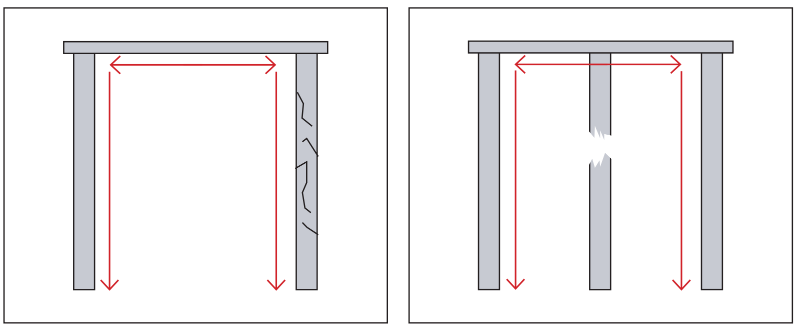


Figure 36: two safety concepts to prevent building collapse, the first one being residual strength (left) and the second one being having a second load path (right)

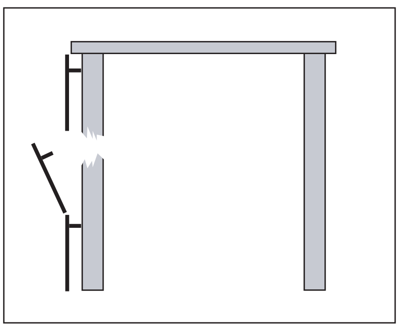


Figure 17: when a façade column is vandalized, the façade should remain in place

IV: DRAFT DESIGN

To come to a draft design, three design choices are made consecutively. First a system is designed, largely determining structural behaviour, the connection and greatly influencing the section. Then the section is designed, also largely influencing the connection. Then the connection is designed, facilitating the earlier design choices. Each design choice has their own respective chapter all largely with the same structure. First the forces acting on the component to be designed are qualified. This gives an insight in which loads to account for and they help shape the component. Then relevant sub criteria are formulated before designing principle solutions. These principle solutions are then assessed against the formulated sub criteria and a favourite is chosen to further develop.

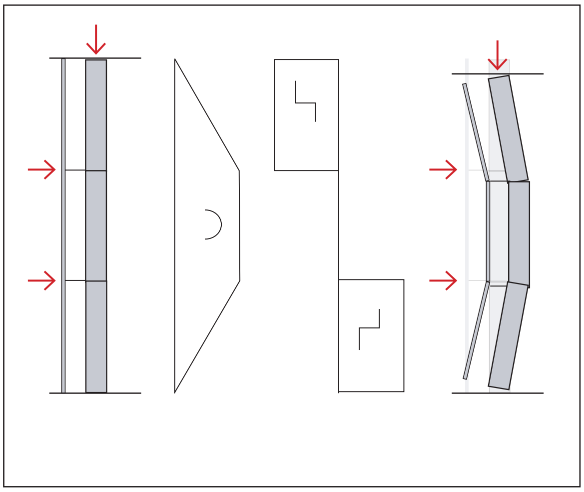


Figure 38: schematic overview of forces acting on the façade system, including global deformation

SYSTEMS

Qualifying forces

In figure 38 the forces which act on the system are drawn schematically. The wind load which is a Qload on the façade, is converted to point loads on the column. This is required since it is very difficult to have a continuous load on a tubular glass element. It's hard to design a proper transfer of forces between façade panels and a bent parallel surface without causing peak stresses or aesthetically unpleasant solutions regarding transparency. So since the force is easiest conveyed not in the ellipse, the connections are the most logical points for transferring these forces.

For fins it is easier to work with Qloads since it is a flat element perpendicular to the façade panels. However, in this case it could also be a non-optimal solution since light cannot enter the fin from all sides, losing transparency.

These point loads result in moment and also in a shear force. This can be seen in the diagrams and more detailed schematic drawings of figure 39. In these detailed drawings it is also portrayed how tension in the glass can be minimized through compressing the element. This could be from self-weight, but it can also be from post-tensioning. One can imagine a situation where the post-tensioning is equal to the expected tension and as a result the element would only be loaded in compression. This can have serious benefits as glass has a low characteristic tensile strength. Through unavoidable very small cracks in the surface the element gets pulled apart and can fail instantly.

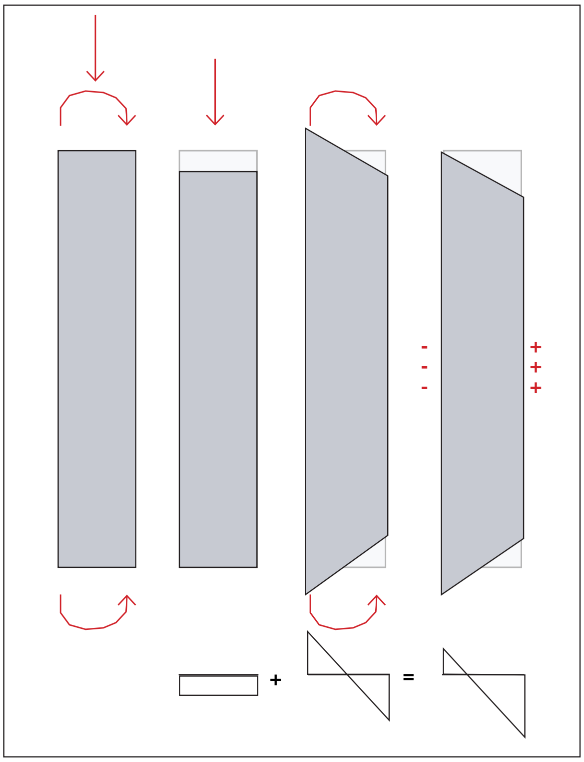


Figure 39: schematic overview of forces acting on the glass segments, including tension diagram

In the latter stages of the design, minimal eccentricity needs to be taken into account. Due to imperfections in the installation of the system and rare load cases the system will be subjected to forces other than perpendicular ones.

Performance criteria for designed element

- Safety: consequences of vandalism
- Structural performance: efficient use of surface area and materials
- Aesthetics: transparency
- Building sequence: assembly/disassembly
- Costs: estimated costs

Principle solutions

Laminated

The laminated system consists of segments that are glued together alternatively with half steps by adhesives. This creates one stiff element without any visible connections. It has to be prefabricated and transported in one piece. Disassembly will not be possible because of the adhesive. This could be the most transparent option, the option with the most minimalistic detailing. It is comparable with how a structural glass fin functions.

Joined

The joined alternative consists of standard length units pre-fabricated in a factory where they are also tensioned. Once on site a number of them are dry-assembled together by a mechanical connection. There is no escaping making a visible detail here, but in the case of a façade system the element needs to be attached to the actual façade panels anyhow every now and then.

Stringed

Delivered in standard lengths, the elements are tensioned as a whole on the site, which then makes them a stiff whole. It might be difficult to tension them properly making it not easy to install. It is not as easy to repair as the bolted version or as minimalistic as the laminated version. It finds a middle ground though between the other variants and has a bit of all qualities.

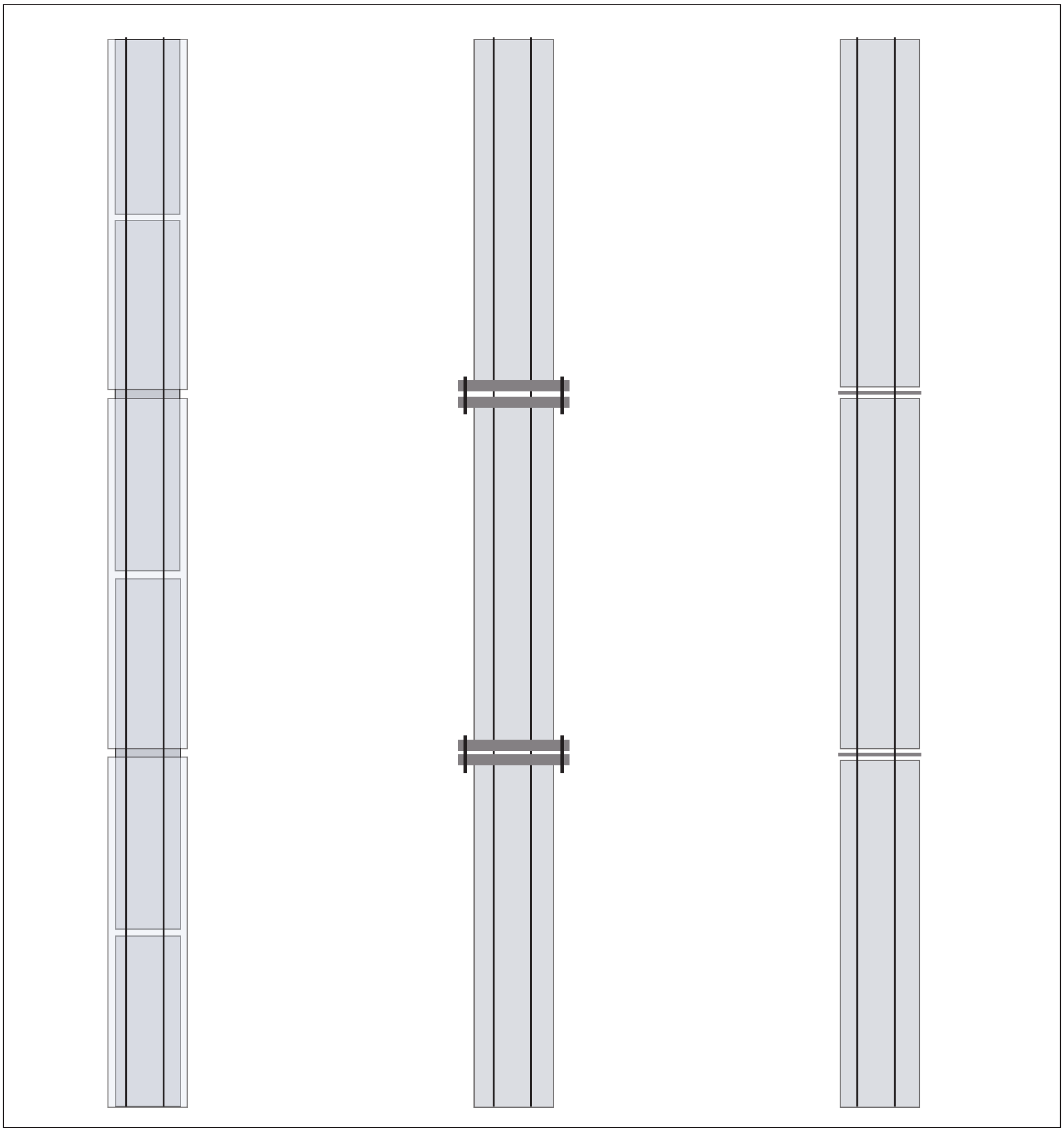


Figure 40: schematic drawings of system principle solutions

System	Description	Safety: Consequences of vandalism	Structural performance: Stiffness	Aesthetics: Transparency	Building sequence: Disassembly/ re-usability	Costs: Estimated costs	Remarks
Laminated	Has to be prefabricated and transported in one piece. Disassembly not possible because of the adhesive. Could be very transparent and achieved with very minimalistic detailing. Because of layering of the section, it could be well-resistant against vandalism but has to then be replaced as a whole.	++	+++	+++	0	+++	The in-ability to disassemble this system might be too big of a price to pay for maximum transparency. This maximum transparency could be compromised anyway because mountings for the façade panels need to be attached.
Joined	Fabricated in the factory in standard length units. These are tensioned apart from seperately. Easy assembly on the site. Dry assembled. More detailing in sight. Individual segments not too resistant against vandalism but parts can be replaced individually and steel cables/rods can keep system in place.	++	++	+	+++	+	This is the system easiest to assemble, repair and recycle. The price to pay for this is less minimalistic detailing. This could be compensated by stating the façade should be attached to the system anyway and lengths of the elements can still differ.
Stringed	Delivered in standard lengths, the elements are tensioned on the site, which makes them a stiff whole. It's not as easy to install and repair as the bolted and not as minimalistic as the laminated, but has a bit of both qualities. Individual segments not too resistant against vandalism and system could be then very unstable, causing failure of other segments too. Cables/rods can keep system in place.	+	+	++	+	++	This system is the in-between. The main difference between this and the bolted system is that here the entire system is post-tensioned, while in the bolt system each element is post-tensioned separately.

Table 9: assessment of system principal solutions

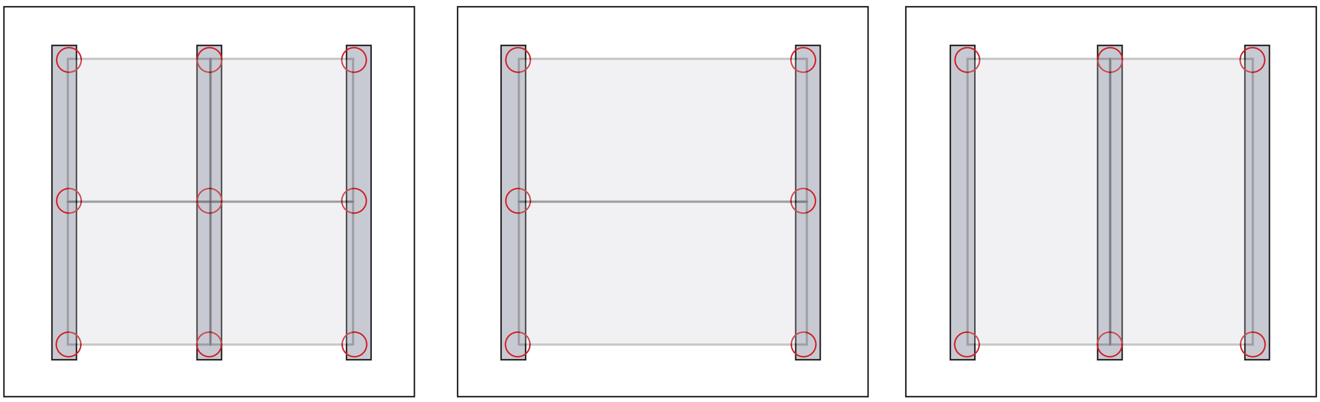


Figure 41: exploration of panel configuration and needed connection points with square (left), horizontal (middle), and vertical (right)

Favourite(s):
The joined system is chosen to be the favourite. It seems to have a lot of potential in the building sequence and on a sustainability level. It is not too sensitive to factory tolerances like the laminated system and in quick physical models has a far better stiffness than the stringed alternative. This joined system requires careful detailing though.

Points of attentions for further development:
- Aesthetics: panel configuration, criteria for connection
- Building Sequence: panel configuration, transportation, easy installation

FURTHER DEVELOPMENT
In the further development stage, the design is coloured in by formulating requirements and boundary conditions.

Panel configuration:
In figure 41, the implications of the panel configuration for the building sequence and aesthetics is explored.

Square panels are easiest to handle logistically because of their smaller size, but require most connections. Horizontal panels require the same amount of connections vertically as the square panels but the columns can be further apart. Vertical panels require the same amount of connections horizontally as the square panels but less vertical connections are required.

Transportation:
The maximum dimensions of load on a truck in the Netherlands is:
- Length: 12 m
- Width: 2.6 m
- Height: 4 m

Glass façade panels are often transported on A-frames. corners protected by wood or another soft material. Foam and cardboard is put between glass elements to prevent damaging. Foils may be applied to prevent from further scratching. This system could lend itself well for also transporting the glass segments.

Installation
Pieces are assembled in the factory and post-tensioned already in conditioned circumstances to avoid dust and moisture reducing the transparency of the glass from the inside. All that's left on the site is to mechanically join the elements

The system has to be easy for maintenance. One should be able to check the amount of post-tensioning on a regular basis and adjusted easily in case needed.

The connections need to be as minimalistic as possible in relation to the glass to keep up the aesthetic of the glass toolkit. This regards the 'height' of the connection as well as the amount of visible parts/seams.

Lastly, the connection needs to be ready for disassembly.

CONCLUSIONS
The transparency is increased by choosing panel layout considerately, but minimalistic detailing is going to determine greatly the success of the design regarding transparency. However, structural performance must not be lost sight of. This will be resolved in the section 'Connections' and in the dimensioning process.

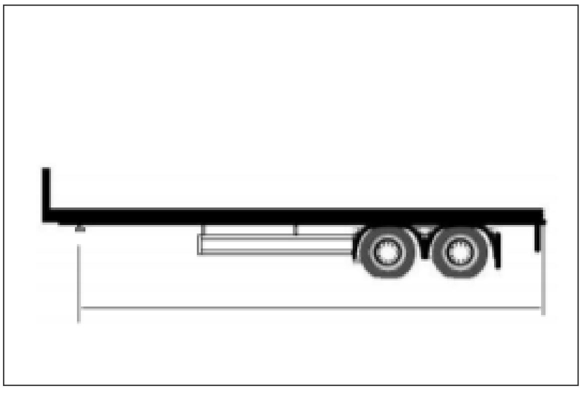


Figure 42: the maximum load size on trucks in the Netherlands is Length: 12 m, Width: 2.6m, Height: 4m[31]

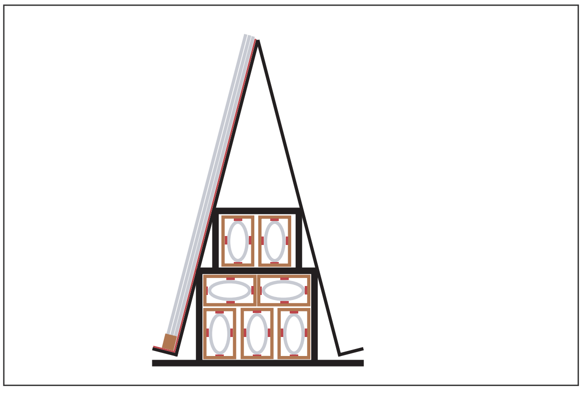


Figure 43: glass façades are often transported on A-frames, this system would lend itself well for transporting column segments

SECTIONS

For the sections the forces are not qualified again separately as the same forces working on the system are working on the section.

Performance criteria for designed element

- Safety: structural capacity when broken
- Structural performance: material efficiency
- Aesthetics: transparency
- Building sequence: production simplicity
- Costs: estimated costs
- Sustainability: re-usability

Principle solutions

On a general note, the principal solutions drawn up here are derived from ellipses. This is because this shape makes great use of the tubular possibilities of the extrusion process and offers geometric stability. It does not mean that the final section will also need to be elliptical.

Laminated section

In this variant, there are multiple ellipses laminated together. The joined ellipse conveys shear forces and is also coupling the moment. The laminating of the ellipses makes for more stiffness and a bigger surface area. When vandalized, the inner ellipse could remain intact and so the cross-section could preserve some structural integrity.

Varying thickness section

With a greater second moment of area than a regular ellipse, this section has a greater material efficiency and is arguably profiting from the new possibilities of the extrusion production process most. When just consisting out of one element, this option is very transparent, but preserves no structural integrity when attacked since it has just one layer.

Section with inner tubes

This is one of the cheaper solutions. This is a glass ellipse with glass tubes inserted in the ellipse to get more surface area and create a stiffer profile. The tubes are placed as far out of the centre as possible. This section has most of the material in the right places for less of the cost than the varying thickness ellipse.

Split forces section

This section is based upon splitting the forces to be conveyed, having specialized elements for the moment and the shear force. In figure 45 a split section is drawn that can convey shear despite the split but each halve can be compressed separately. When dry assembled, almost no tension can occur in the glass, leaving the tension for the steel rod, which would mean this section could have the greatest material efficiency. To clarify: the steel rods don't need much post-tension in the glass in this variant because there can only be little tension in the element.

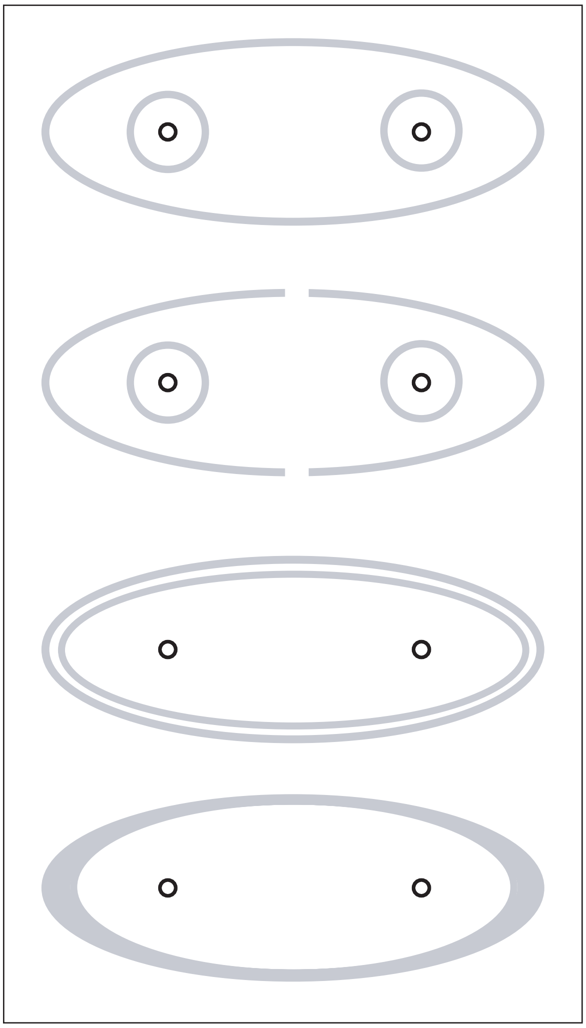
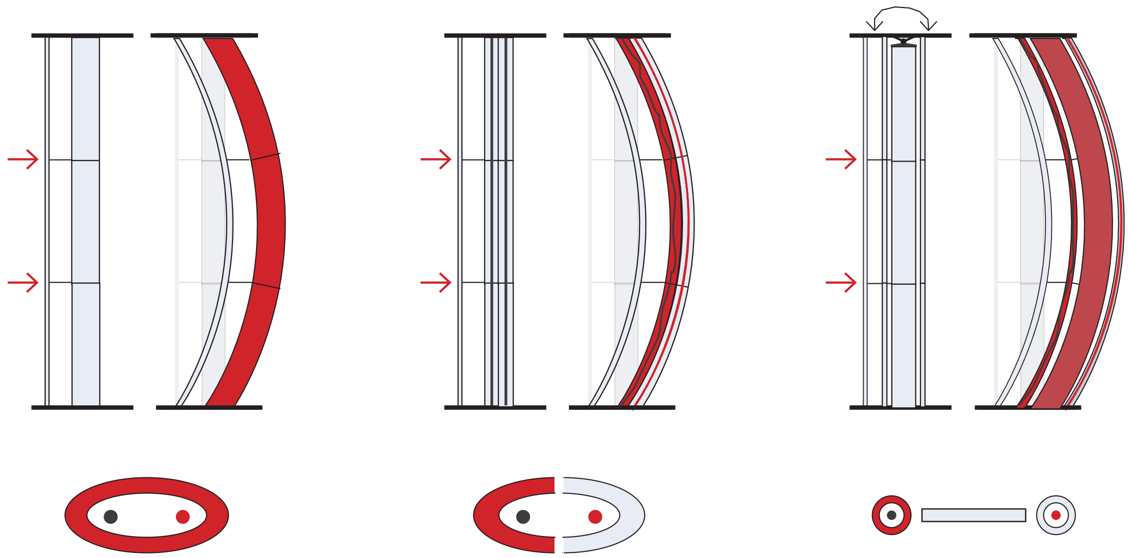


Figure 44: schematic drawings of section principle solutions

It does not need to be an ellipse either. To save costs or pursue other aesthetics this could also be some other shape. Additionally, other systems could be imagined where the forces are split. Schematic drawings qualifying forces can be found in figure 45 to explore this idea further.

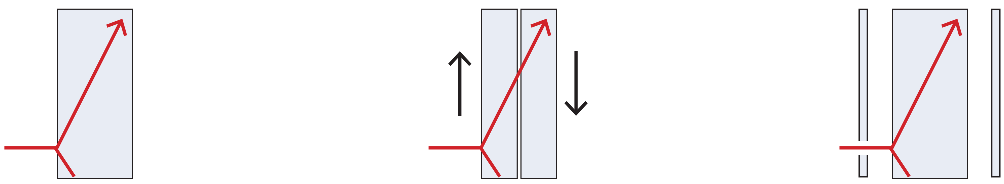


The entire section is working here to convey the moment. A major disadvantage of this is that half of the section is conveying tension and glass doesn't hold up that well in tension. This can be avoided by not loading it eccentric. This can be done by splitting the ellipse.

Compression only half, glass takes all forces of moment, cable tension releases

Tension only half, glass takes no forces of moment because cable tension increases

The same principle as for the split section is true here. But in this section the forces are split up even more as the middle part cannot convey any forces of the moment because of the rotation connection on top.



Shear force is conveyed through the section as it would through any section and material. The amount of material parallel to the direction of the shear force is very important for the stress in the material.

Shear force is conveyed through both halves. Connection has to allow for this passing on of forces. However, elements must also be able to slide over one another.

Shear force in this section is not conveyed by the outer tubes, just by the main section. This main section is clamped on one end of the column and connected with rotational freedom on the other. This allows it to still convey shear.

Figure 45: exploration of 'split forces section'

Favourite(s):

The varying thickness ellipse seems like the best solution overall. It takes great advantage of the possibilities especially for bending and 'signature look' of the production process. However, the split ellipse is worth investigating further too because this could have the most structural potential. This idea will be saved for further research.

Points of attentions for further development:

- Safety: options for safety glass
- Structural Performance: material efficiency, exploring section shapes
- Aesthetics: visual variation to the toolkit

FURTHER DEVELOPMENT

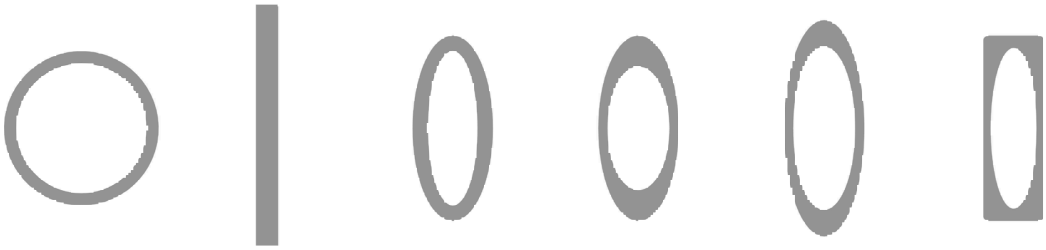
In the further development stage for the section, different dimensions, shapes and proportions are explored in their structural potential. This can be found in figure 46 and table 11.

CONCLUSIONS

From this it can be concluded that Ellipse 2 is the favourite. Adding variation is the main goal of this quest and this is why this criteria is leading. The structural performance of the ellipse is comparable with the fin given it could have similar material properties, which validates it plenty. The definitive dimensions will have to be fine-tuned later by numerical models.

		Safety	**Structural performance**	**Aesthetics**	**Building sequence**	**Costs**	
		Capacity when broken	Material efficiency	Transparency	Easy to produce	Estimated costs	
System	**Description**						**Remarks**
Ellipse + tubes	With the tubes placed all the way to the side, this section has most of the material at the right places for less of the cost than the varying thickness ellipse.	+	++	++	+++	+	This section could be the easiest to produce of all cross sections. It's an in between option with a balance of qualities.
Split section	This section is based upon a split ellipse that can convey shear despite the split but can be compressed separately. When dry assembled, no tension can occur in the glass, leaving the tension for the steel rod. Which would mean this section could have the greatest material efficiency.	++	+++	++	+	++	This section only works when detailed correctly and can be considered most experimental of all. When working, it could have the greatest material efficiency.
Varying thickness section	With a greater second moment than a regular ellipse, this section has a greater material efficiency. When just consisting out of one element, this option is very transparent, but preserves no structural integrity when attacked.	0	+++	+++	++	++	This section improves upon the laminated ellipse in regards of material efficiency and evens it in transparency. However, when consisting of just one element, this means that when vandalized, no structural integrity remains.
Laminated section	Ellipse conveys shear forces and is also coupling the moment. Multiple ellipses (probably two) laminated together for more stiffness and bigger surface area. When attacked, the inner ellipse could remain intact and so preserve some structural integrity.	++	++	+++	0	+	This section fits best with the laminated system and shares its benefits and problems. It's an all-in move. It likely requires special transport and careful installation. Making it is extraordinary difficult due to tolerances.

Table 10: assessment of section principal solutions



	Circle - reference	Fin - reference	Ellipse 1 - as by SCHOTT	Ellipse 2 - optimized	Ellipse 3 - bigger bounding box	Rounded square tube
H [mm]:	250	400	300	300	350	300
B [mm]:	250	36	130	130	130	100
A [mm^2]:	1.45 $*10^4$	1.44 $*10^4$	1.49 $*10^4$	1.49 $*10^4$	1.50 $*10^4$	1.48 $*10^4$
I [mm^4]:	1.0 $*10^8$	1.9 $*10^8$	1.1 $*10^8$	1.3 $*10^8$	1.8 $*10^8$	1.6 $*10^8$

Figure 46: assessment of section further development solutions, all sections are approximately given the same surface area

		Structural performance	**Aesthetics**	**Aesthetics**	**Costs**	
		Material efficiency	Adding variation to current toolkit	Size bounding box	Estimated costs	
System	**Description**					**Remarks**
Circle - reference	A circular cross section	++	++	+++	+	
Fin - reference	A square solid cross section	+++	++	+	++	
Ellipse 1 as produced by SCHOTT	This ellipse is produced in the same proportions by SCHOTT, it has been blown up a little to match the target surface area.	+++	+++	++	++	This ellipse is not varying in thickness. In a way this is also a reference.
Ellipse 2 'optimized'	This ellipse is optimized by making it thicker on the ends and more slender towards the middle.	++	+++	0	+	This ellipse performs just as good as the fin in conveying the moment, the shear forces are a little higher. It adds as much visual variation as the first ellipse as it does not look significantly different.
Ellipse 3 'bigger bounding box	This ellipse is optimized in a similar way to ellipse 2 but is allowed a greater bounding box.	+++	+++	++	++	This ellipse performs better because of it having more distance between the material and the centre of the section. This costs from an aesthetic point of view.
Rounded square	This ellipse is closer to a square then an ellipse, but has rounded corners.	++	+++	0	+	This ellipse is best structurally because it has most material furthest away from the centre of the section. However, it does not add the greatest variation visually because already many flat/orthogonal elements already exist in the toolkit.

Table 11: assessment of section further development solutions

Connections

With the system and the section decided, now the connection will be designed facilitating the earlier decisions and matching the perceived characteristics of glass systems.

When designing the connection, likely an intermediate layer will be needed between the glass and the material of the connection itself. This is needed to introduce forces properly. Another way of introducing loads in the glass is through connections not on the edges of the glass. However for this a glue connection is needed or holes need to be drilled in the glass. The first option is not desired because of production tolerances of the ellipse creating a surface which is not too suitable for a glue bonding. The second option is not desired because drilling holes for point connections is very complex because of the elliptical section.

Qualifying forces

To later be able to assess the principal solutions on their structural potential, the forces working on the connections are explored. Requirements will be given for all connections.

Connections to main structure

To reduce the buckling length, which is one of the normative parameters for slender façade profiles, it is desirable that the element is clamped at both ends. This means it is restricted in all rotations and all translations. To ensure such a connection, it is preferred that the element has a couple of fixed points distributed along the edges of the element. It should be avoided having connections just in the centre as it could result in allowing rotations in z-axis or even other directions.

Connections internal parts

The individual elements within the system should be restricted in all translations and rotations as well with regards to each other. This enables them to transmit loads and rotations in order to avoid buckling, remaining stable and stiff.

Connections to façade

Regarding the connections to the façade, more degrees of freedom are allowed. The translation does not need to be restricted in the vertical axis as the façade should carry its own weight. It also doesn't need to be restricted in the width direction of the façade panels for rotation as the façade panel connections on all corners of the panel will establish that anyhow.

In figure 48 the moment, normal forces and shear forces are drawn from two directions on three principally different connection solutions:

- horizontal surface connection
- vertical point connection
- horizontal point connection

Performance criteria for designed element

- Safety:
- Structural performance: stiffness
- Aesthetics: minimalistic
- Building sequence: quick/easy to assemble
- Costs: estimated costs
- Sustainability: de-mountability

Principle solutions

Screwed

This variation involves screwing the elements together like a cap to a bottle, except the cap is another bottle. This has real benefits in building sequence, but since the screwing mechanism has to be circular, this is not ideal for an elliptical section.

Bolted

This variation could be considered most basic and it is friendly regarding building sequence. However the risk is that too much force is conveyed through too few bolts. This has to be avoided. Also the bolts have to be hidden for a minimalistic aesthetic.

Glued/welded

In this variation the elements are stuck together with a very large surface area. This has obvious structural advantages, but the building sequence aspects are cut short as gluing takes a long time and welding on site and this close to the glass is impractical, expensive and is detrimental for disassembly.

Click-system

In this variation the two parts click together. It

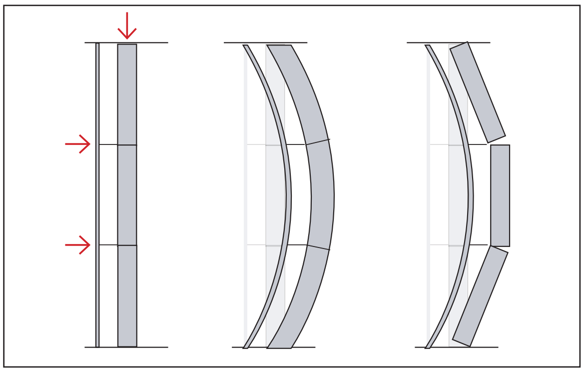


Figure 47: showing deformation of façade system with connections restraining rotation (left) and connections not restraining rotations (right)

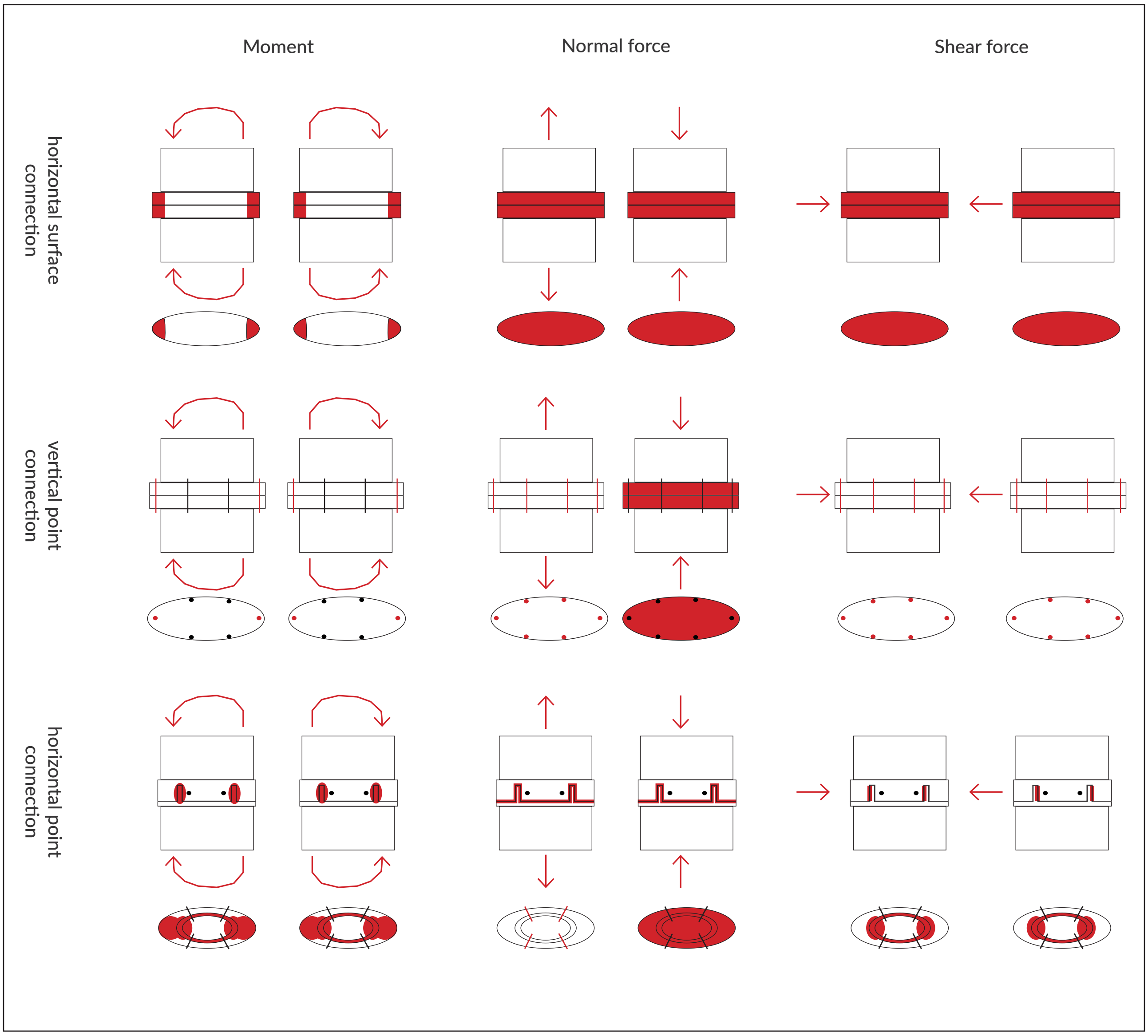


Figure 48: qualifying forces on the connection through exploring three main different types of connections and highlighting the load-conveying geometry

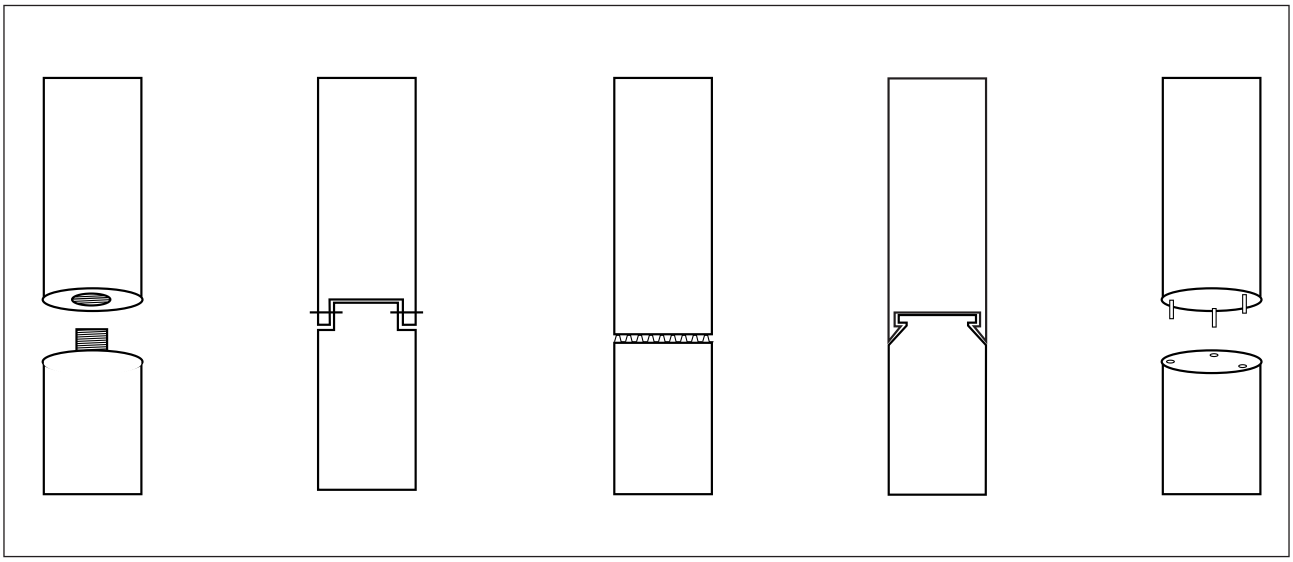


Figure 49: schematic drawings of connection principle solutions

System	Description	Safety	Structural performance	Aesthetics	Building sequence	Costs	Sustainability	Remarks
			Stiffness	Minimalistic	Quick/easy to assemble	Estimated costs	De-mountable	
Screwed	Two elements screwed together.		+	++	+++	+	+++	This variant is strong regarding building sequence and aesthetics but not as stiff as some other variants.
Bolted	Two elements bolted together.		++	++	++	++	+++	This variant scores good overall. It has no weak points if the connection can be hidden and it stands out on sustainability.
Click-system	Two elements clicked together.		+	+++	+++	++	++	This variant installs very quickly but has to pay for it in structural performance.
Welded/ glued	Two elements stuck to each other.		+++	+++	+	++	+	This variant is very strong structurally but lacks in building sequence and sustainability.
Interlocking	Two elements geometrically interlocking.		+	+	+++	++	+++	This variant lacks structural performance and due to needed height is not as minimalistic.

Table 12: assessment of connection principal solutions

could be very minimalistic, but the structural performance could not be as good as other variants.

Interlocking

This variation is based upon interlocking the two elements. This can be really seamless but it may require more height so it may not be as minimalistic after all.

Favourite(s):

The bolted variant is chosen to be the favourite. It performs best overall and so has no weak points. The requirement for success of this variant is keeping the detailing minimalistic. This is what will be focused on in the further development.

Points of attention for further development:

- Structural Performance: avoiding too much force on weak points
- Aesthetics: minimalistic detailing: reducing height connections, no connection parts in sight, highly engineered look
- Sustainability: sustainable materials used, connection lasts as long as the glass

Further development

In figures 50 to 54, the design of the connection is explored. Special attention is paid to reducing the height of the connection and keeping the connection minimalistic. In figure 52 the design is drawn in section and exploded view.

Conclusion

With the design features of the further development stage in place the connection has taken shape. It's ready now for the numerical analysis. To increase the potential or architectural design, this system needs to be compatible with many different façade connections like for example spider connections. This is why for this design a generic bolt-receiving connection to the façade has been chosen.

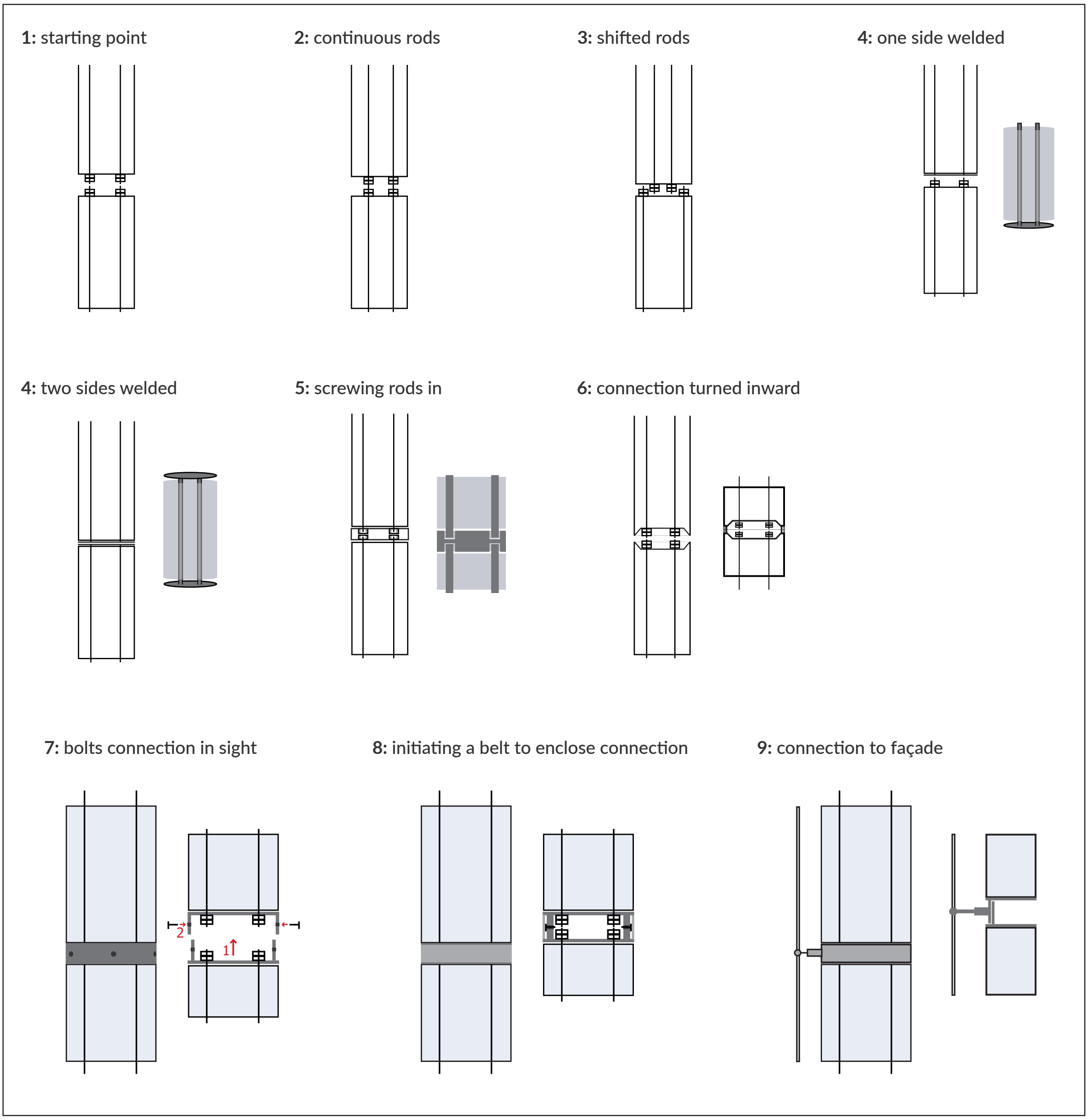


Figure 50: further development of the connection, exploration of reducing the connection height

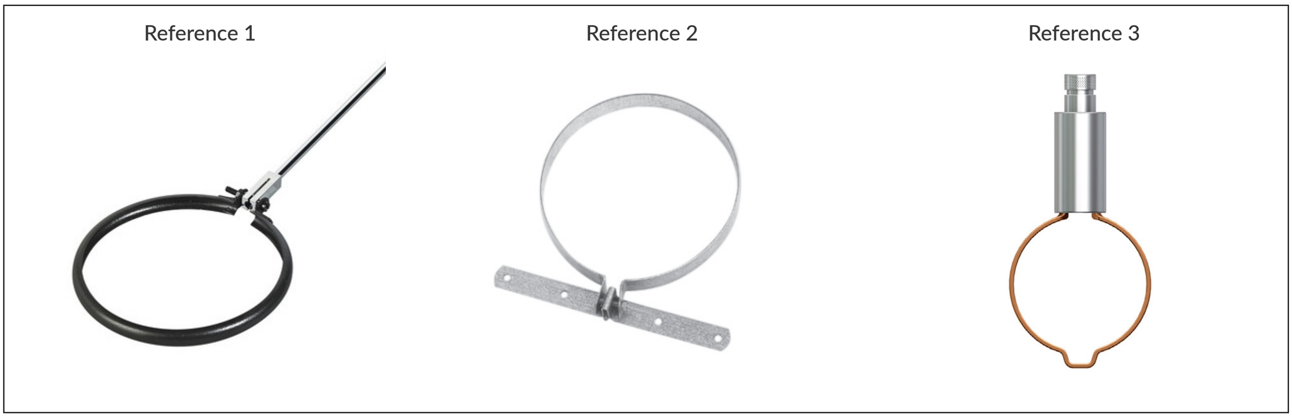


Figure 51: references for the belt[32] [33] [34]

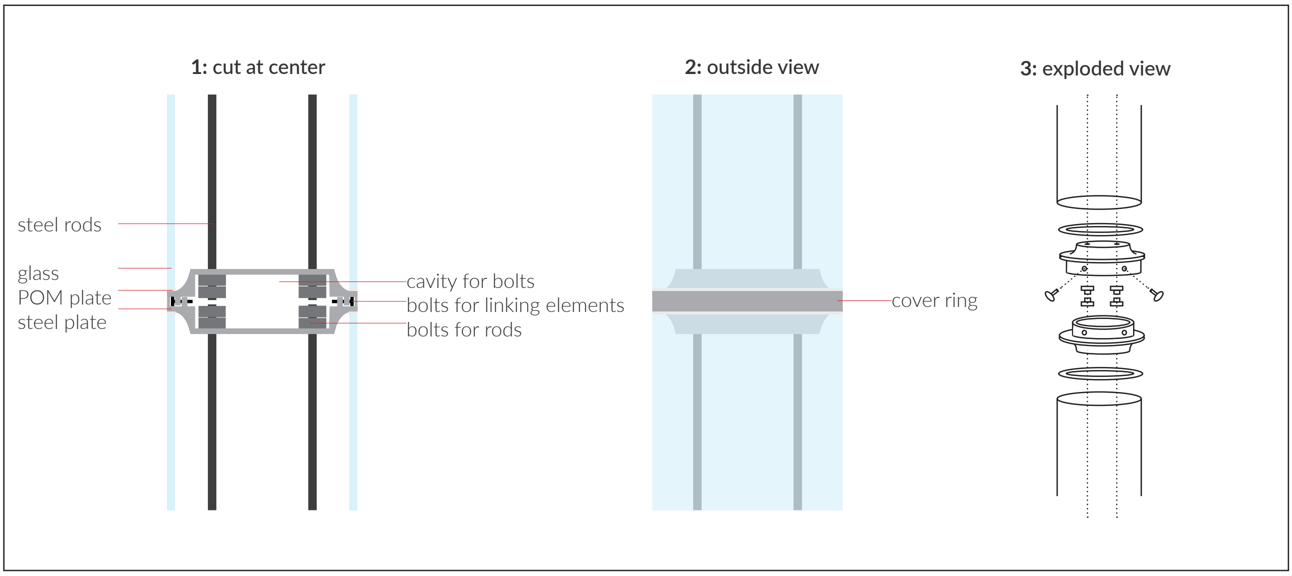


Figure 52: schematic drawings of connection principle solutions

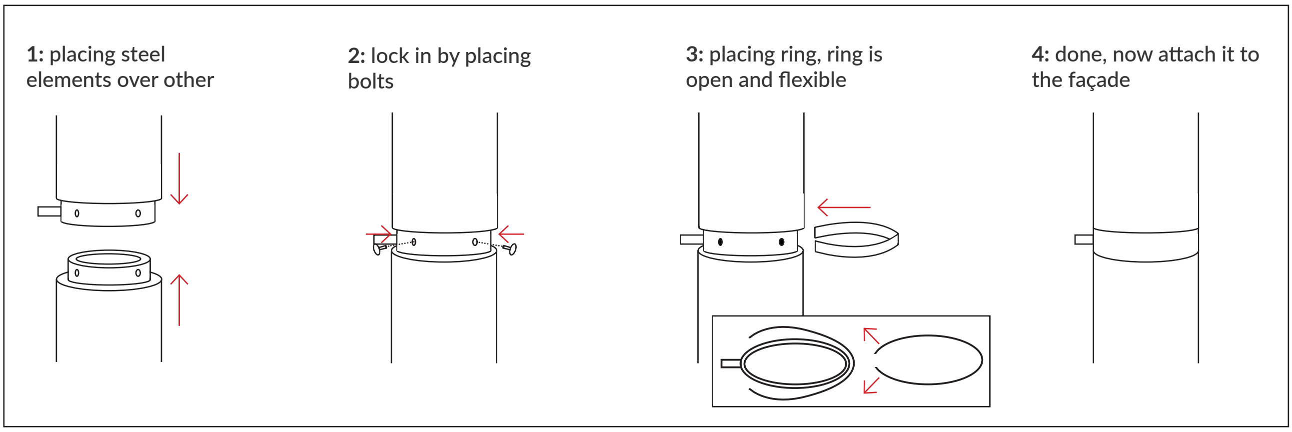


Figure 53: early sketch of installation sequence

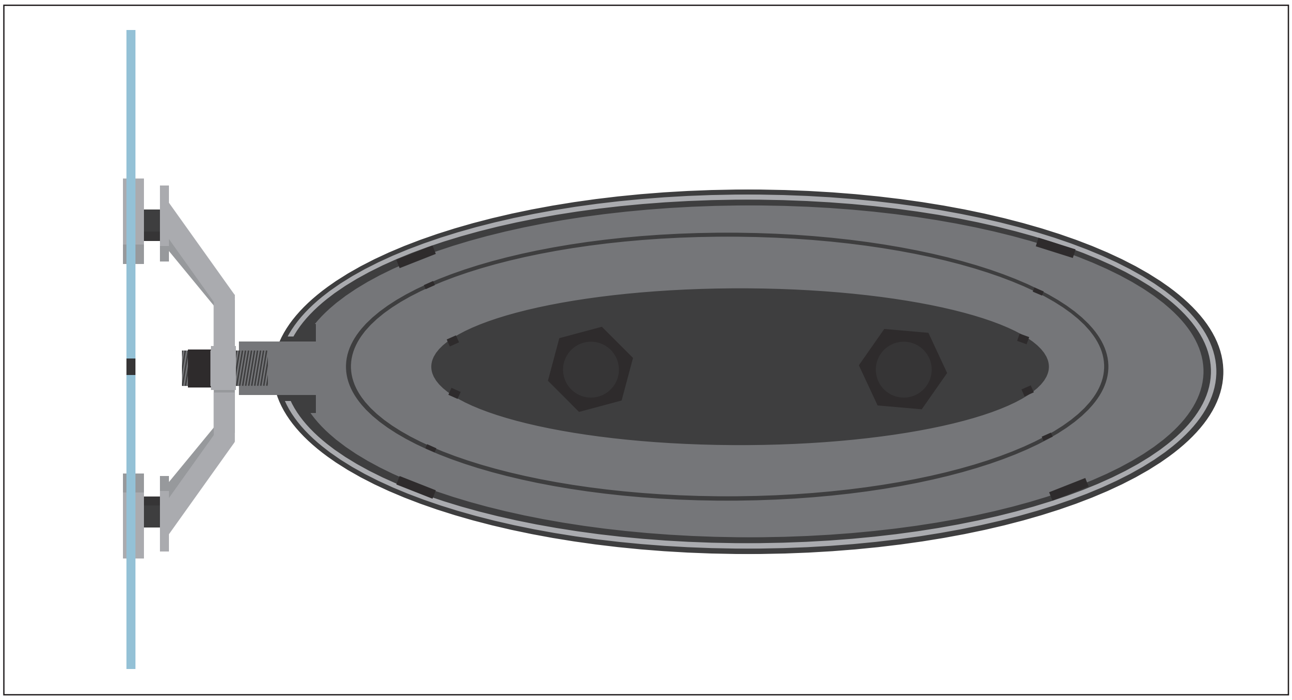


Figure 54: schematic cross section of assembled connection

Draft design outcome

The end result of this draft design stage is visualized in figure 55. It is decided on a joined system, the improved ellipse section, and a bolted connection. It should be noted that the design has no real dimensions yet, which is why the visualisation is only indicative of the final product, not an accurate representation.

This design could perform excellent with regards to sustainability and building sequence especially, but should also perform well on all other criteria.

Figure 55: early impression of the draft design (undimensioned)

V: PHYSICAL TESTING

Physical testing is a large part of the experimental analysis. It is used in this thesis to acquire needed data that is not already out there. Of course this concerns any data related to the performance of the design, but also material properties. Structural behaviour of glass products vary per production technique, finishes applied, introducing of forces and geometry. This is why it is important to establish certain characteristics of extruded glass products used for this design. Physical testing is thus used in the following three ways:

- To be able to design a structural system, certain material properties need to be known. In this case the two most important material properties are compressive strength and tensile strength.
- To help simulate and optimize the design, the numerical models need to be validated by real-world data.
- The final design needs to be tested as if it were already implemented in a building to deliver final proof of the structural performance.

Note: due the covid-19 crisis, the university and its labs were closed a couple weeks for the P3 and remained closed for the rest of the academic year. This is why not all tests are executed as planned. To still continue the storyline of this thesis, the chapters are still in their respective places explaining the function of the test in that point of time. Where those test reports would be are now research proposals. The research proposals can be found in the appendices and would need to be executed to take over certain estimations in this report and to confirm the numerical findings.

Fundamental and contextual testing

Two principally different methods of testing are considered. In fundamental testing, samples will be tested in the simplest form to test the material properties as well as the consistency of the samples.

In contextual testing, the designed system is tested in its entirety to see how all elements work together. This gives information on the quality of the design and the real-world performance. Both methods are crucial to come to the right conclusions.

This is how the two methods will be applied to help answer the main question of this thesis:

Fundamental:
- to research material properties through sample-testing: compressive strength and tensile strength

Contextual:
- to validate the numerical models by data comparison: force at failure, failure behaviour, deflection
- proof the physical working of the design through simulation of the structural performances: force at failure, failure behaviour, deflection

Validity of experiments

To reach a reliable extent of statistical validity, as many samples as reasonably are available are tested. When testing individual samples the minimum needed for a reliable outcome is set at

Figure 56: the Toni-bank used for the compressive tests

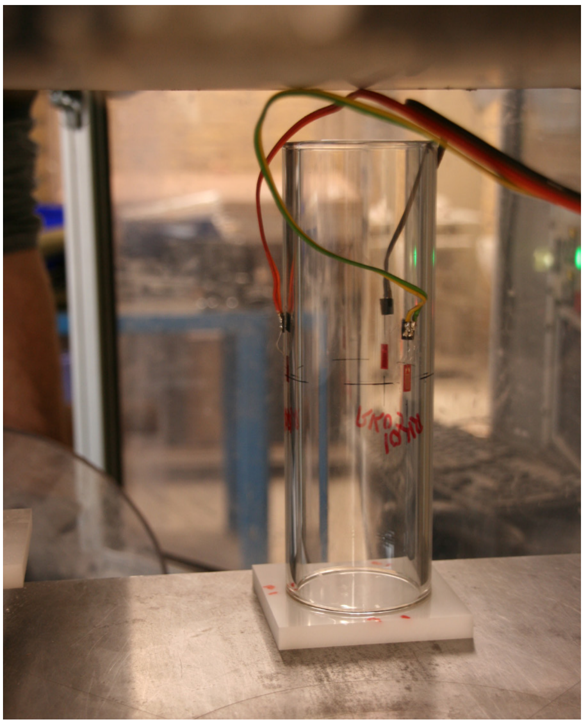


Figure 57: a non-hardened (DURAN©) test sample equipped with strain gauges standing on a POM-plate

ten. This is important as it is expected that the found material characteristics could vary and fluctuate.

Fundamental testing

This chapter comprises of the two tests needed for testing material properties to be used as input for the designs.

Test 1: Compressive strength

See appendix A for the entire report.

In the compressive strength test, circular extruded glass samples of different dimensions were squashed in a Toni bank. Part of the samples were hardened while most of them were not. The research questions were answered as follows:

"What is the average maximum compressive stress the glass samples can be subjected to without showing defects?

For not-hardened glass this value would be approximately 35 N/mm². For hardened glass this value would be approximately 74 N/mm².

What is the average maximum compressive stress to which the samples can be subjected to without failing?

For not-hardened glass this value would be dependent on the section. It is implied that the thicker the profile, the lower the maximum compressive strength. During this experiment it ranged from: 65 N/mm² for the 9mm thickness samples to 85 N/mm² for the 5mm thickness samples. For hardened glass this value would be approximately 96 N/mm².

			compressive force at first crack [kN]	compressive stress at first crack [N/mm²]	z-distribution	maximum compressive force [kN]	maximum compressive stress [N/mm²]	z-distribution
group name	**9mm**	STRG	134	36,2	0,0867	214,8	58,0	0,0370
surface area	3704 mm²	3.1	136	36,7	0,0792	220,4	59,5	0,0473
OD	70 mm	8.1	110	29,7	0,0569	271,3	73,2	0,0227
WT	9 mm	9.1	101	27,3	0,0237	228,2	61,6	0,0596
		11.1	147	39,7	0,0341	272,8	73,6	0,0205
samples	17 #	12.1	109	29,4	0,0526	266,6	72,0	0,0303
Avg first crack	33,9 N/mm²	13.1	59	15,9	0,0000	218,0	58,9	0,0430
SD	3,9 N/mm²	17.1	140	37,8	0,0624	256,9	69,3	0,0479
Avg max	64,5 N/mm²	18.1	117	31,6	0,0858	235,5	63,6	0,0661
SD	6,0 N/mm²	19.1	118	31,9	0,0892	228,5	61,7	0,0600
		20.1	135	36,4	0,0831	256,0	69,1	0,0494
		21.1	33	8,9	0,0000	225,1	60,8	0,0551
		34.2	135	36,4	0,0831	221,8	59,9	0,0498
		38.3	52	14,0	0,0000	271,7	73,4	0,0220
		40.3	9	2,4	0,0000	212,9	57,5	0,0337
		41.4	52	14,0	0,0000	210,6	56,8	0,0296
		42.4	29	7,8	0,0000	248,5	67,1	0,0607
group name	**5mm**	STRG	81	38,2	0,1710	166,0	78,3	0,0320
surface area	2121 mm²	24.1				165,4	78,0	0,0312
OD	70 mm	26.2	75	35,4	0,1710	155,3	73,2	0,0181
WT	5 mm	27.2	41	19,3	0,0000	208,0	98,1	0,0169
		30.2	8	3,8	0,0000	127,4	60,1	0,0010
samples	6 #	31.3	43	20,3	0,0000	197,3	93,0	0,0307
Avg first crack	36,8 N/mm²	33.3				194,9	91,9	0,0337
SD	1,4 N/mm²							
Avg max	85,4 N/mm²							
SD	9,3 N/mm²							
group name	**hardened**	D03	324	87,8	0,0176	350,0	94,8	0,0558
surface area	3691 mm²	D04	329	89,1	0,0160	386,5	104,7	0,0258
OD	120 mm	D08	364	98,6	0,0064	364,2	98,7	0,0521
WT	5 mm	D10	250	67,7	0,0253	357,1	96,8	0,0559
		D11	255	69,1	0,0263	364,0	98,6	0,0522
samples	10 #	D15	230	62,3	0,0199	291,1	78,9	0,0032
Avg first crack	74,0 N/mm²	D16	202	54,7	0,0112	346,5	93,9	0,0543
SD	14,3 N/mm²	D17	260	70,4	0,0270	370,1	100,3	0,0464
Avg max	95,8 N/mm²	D19	312	84,5	0,0213	379,3	102,8	0,0349
SD	7,1 N/mm²	D20	206	55,8	0,0124	329,0	89,1	0,0359

Table 13: overview of data obtained with in orange questionable data and in red discarded data

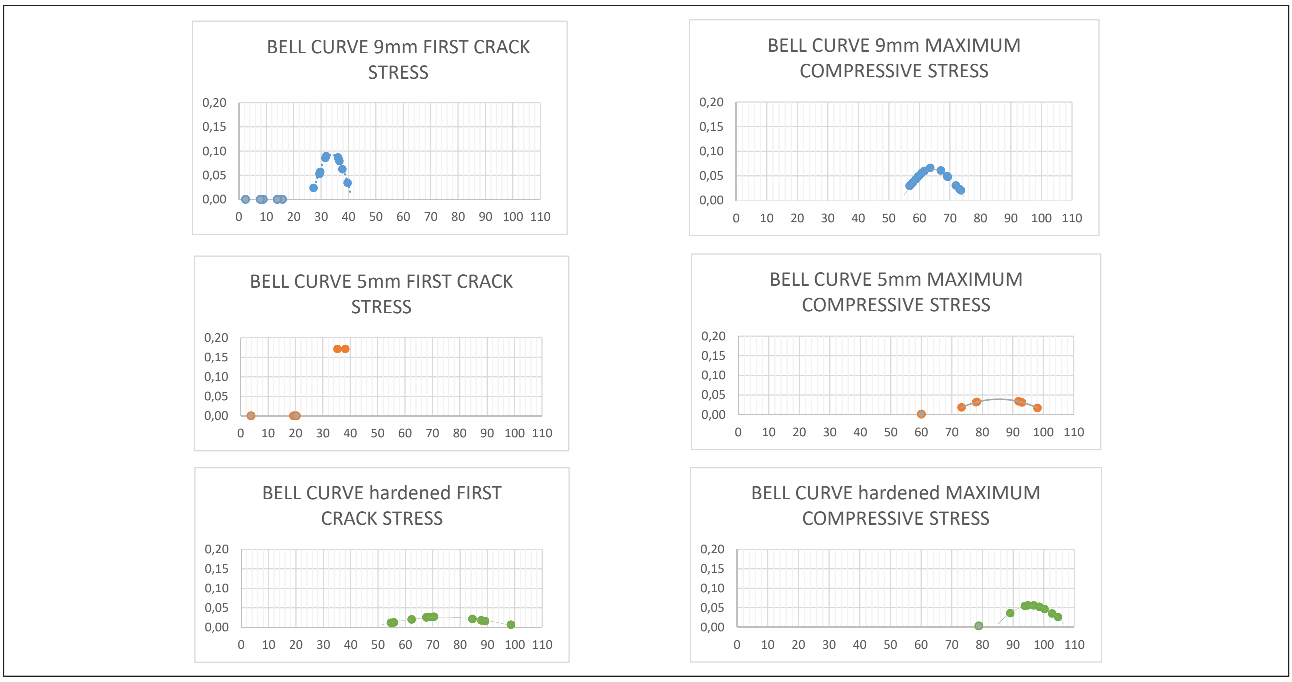


Figure 58: bell curves for all test groups, displaying the consistency of the samples

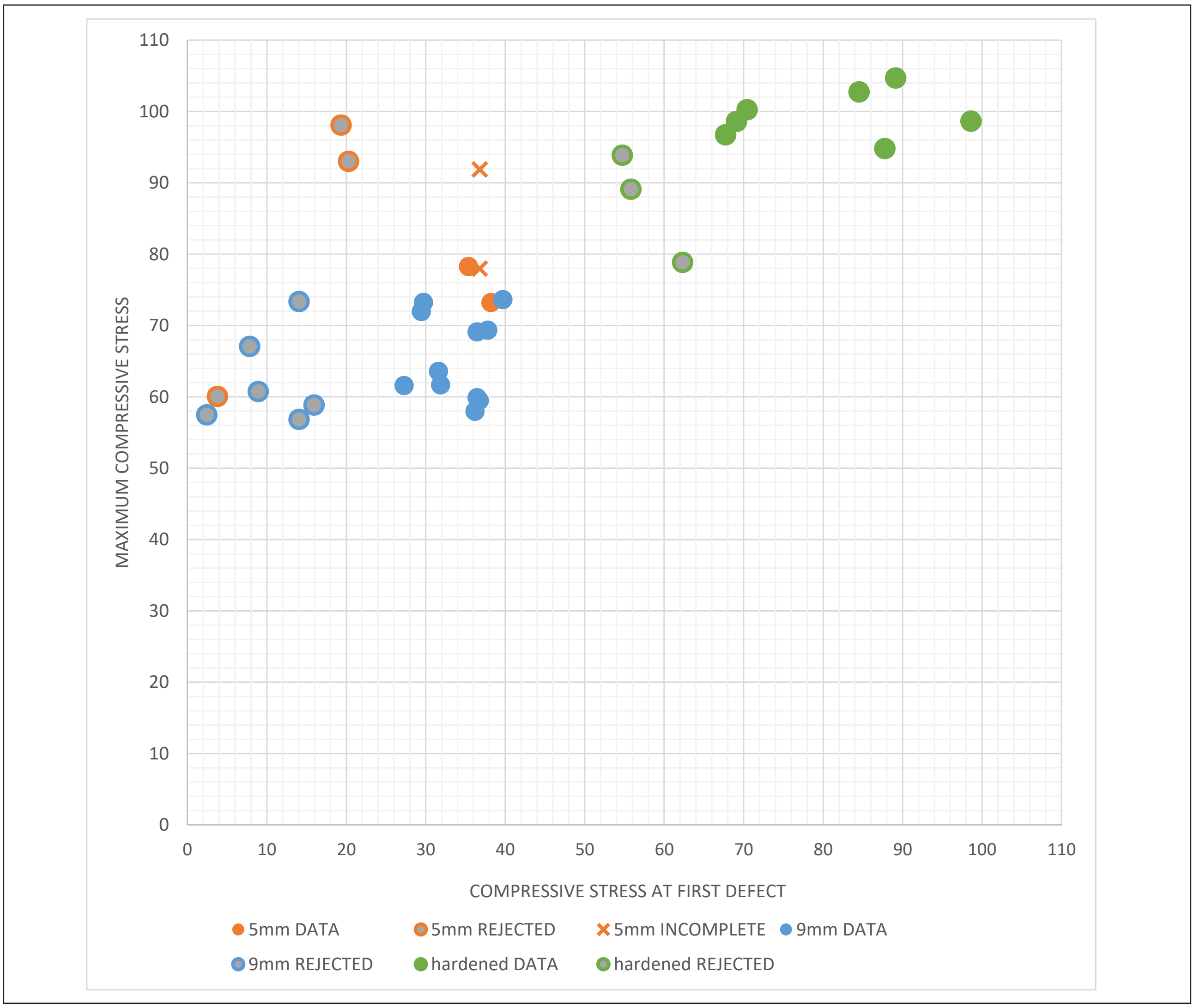


Figure 59: overview of data obtained visualized

How does observed sample quality relate to test performance?
It seemed sometimes relevant. It could cause peak stresses in which cases the glass failed under relatively small loads. It didn't matter always though, some of the samples with observed 'bad quality' outperformed the flawless ones. Table 13 shows all data including data that was rejected. On many occasions, this data of rejected samples were also samples of perceived very bad quality in which the flaws led to immediate peak stresses (marked in red). On other occasions, the sample of the rejected data had only minor flaws and the inferior quality could less obviously be predicted.

How do the performances of the hardened samples relate to the non-hardened samples?
The hardened samples performed more consistent and had approximately twice the strength at showing first defect.

Were the forces induced equally?
It can be concluded that for most samples the forces were induced equally. When testing product properties this is more than sufficient as when used in practice, it will also likely not be loaded perfectly. Some elements failed very quickly which can only be attributed to peak stresses. This could have to do with the force introduction, but also with imperfections in the profile.

How does the glass fail and why?
It usually cracks from top to bottom multiple times shortly after one another. Then one of the smaller newly created sections buckles."

Continuing in this thesis it is decided to use hardened glass for its far superior compressive strength. Of course hardened glass was already preferred over non-hardened glass because of the safe breaking behaviour. It is interesting that the glass has some structural reserve after showing first defect. This means that it is likely to give a timely warning before failure. For further calculations a value of 60 N/mm^2 for the compressive strength is used. This is one standard deviation below the average. This quality should be able to be achieved for all samples.

The quality of samples could even be well enhanced probably when there were to be a better quality control of the samples with their structural purpose in mind. This would exclude samples with flaws or imperfections on the edges of the glass and perhaps they could even be subjected to a brief compressive test in the factory to check for unforeseen behaviour.

Test 2: Tensile strength
See appendix B for research proposal.

The tensile strength serves as an input parameter for the needed dimensions of the glass segments in the dimensioning process. It also determines how much the glass needs to be post-tensioned.

Continuing in this thesis a value of 7 N/mm^2 is assumed for the tensile strength. It is taken from a glass laboratory and manufacturer in the United Kingdom which tested the strength of regular borosilicate glass (Scientific Glass Laboratories, 2020).

Contextual testing part I

After establishing the compressive and tensile strength, the preliminary design would then be tested to understand the structural behaviour better before determining the needed dimensions for the draft design.

Test 1: Test Preliminary design
See appendix C for research proposal.

The preliminary design would be tested to get a first validation of numerical models before the dimensioning of the draft design. The results would show in which way the models are incorrect and if the results should be adjusted one way or another.

When this were completed, it would then assure the numerical models give accurate predictions and would make the design of the structural performance of the new system easier.

Continuing in this thesis the project has proceeded without a first validation. This means that numerical results may be inaccurate with respect to the real world performances.

VI: DIMENSIONING DRAFT DESIGN

In this chapter the draft design will be dimensioned. The draft design is designed by qualifying forces, meaning that for its structural performance loads are named and described but not yet given quantity. This will happen in this chapter and this initiates the proper dimensioning for the elements. In the question: 'what is the architectural potential for section active extruded glass structural elements?' the dimensioning determines not only the structural performance but also largely the aesthetics. Both these elements are paramount for understanding the architectural potential.

The goal of the following calculations and simulations is to give the draft design the dimensions globally needed for a sufficient structural performance in a chosen architectural situation. The following parts of the system are dimensioned here: glass section, steel rods, steel connection. The POM plates are excluded because the combination of the glass and their dimension has been tested in the compressive tests, resulting in the compressive strength calculated with. Additionally, non-structural parts will not be dimensioned here.

As stated in 'Design Context', the chosen architectural situation is a façade system as this the most common section active structural glass system in architecture. This design context will now be dimensioned too. To be able to say the designed element bears potential, a façade of at least six meters high needs to be able to be executed out of the new system. This is grand enough for a double height façade of a regular building or façade for a large pavilion. Whether the designed system has potential for larger structures will be determined by the dimensions the system needs for the 6m high façade. If the glass and connection don't require too large dimensions, it can likely be scaled up without losing too much aesthetic value. This will be left for further research.

After stating general parameters and discussing general concerns, hand calculations will be made to serve as estimations and a starting point for the numerical process. The numerical process will be used to further dimension the more complex geometry and to make calculations for the displacement of the entire system.

GENERAL PARAMETERS

The used material parameters can be in table 14. The Young's modulus of borosilicate glass ranges from 48-70 GPa depending on exact type of borosilicate glass and the Poisson's ratio ranges from 0.20-0.23 (Granta Design Limited, 2019). For this calculation common values have been chosen for these parameters.

The used design parameters can be found in table 15. For the distance between the columns, a common distance for architecture is chosen.

PERFORMANCE EVALUATION

For this calculation it is chosen to work with ULS (ultimate limit state) and SLS (serviceability limit state). ULS is a method of evaluation in which is checked whether an element will break due to stress levels exceeding allowable amounts. SLS is a method of evaluation in which is checked whether an element will deform too much or not.

ULS will be used for separate parts of the system and parts of connection where applicable. SLS will be used for the deformations of the system as a whole. For this calculation the rotational stiffness of the connection needs to be calculated. This will serve as input for springs with which lines representing the glass sections will be connected to each other in a global model.

SAFETY FACTORS

The following calculations will be executed without safety factors, but with a load of 4.5 kN/m^2. This is a very high load. To illustrate: the wind-load along the North Sea coast in the Netherlands at 100m height is 2.38 kN/m^2 (VKG, 2007). It could be imagined that the safety factors cut the chosen allowable load to about the same values. The exact values of the safety factors are not important for this design as the goal is the testing of the potential. Exact placing and other context dependable factors will determine exact load and load factors. When the structure can withstand a load of 4.5 kN/m^2 on the façade it means it has potential and can be scaled, stretched and twisted to suit specific needs.

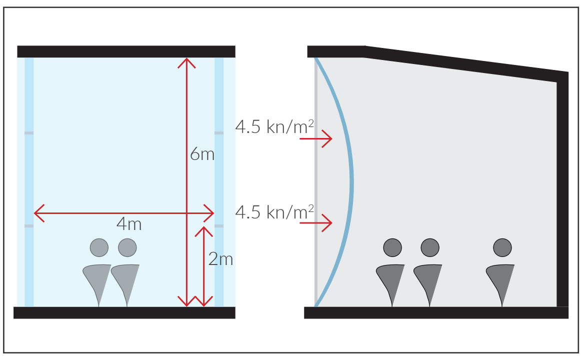


Figure 60: design context dimensioned

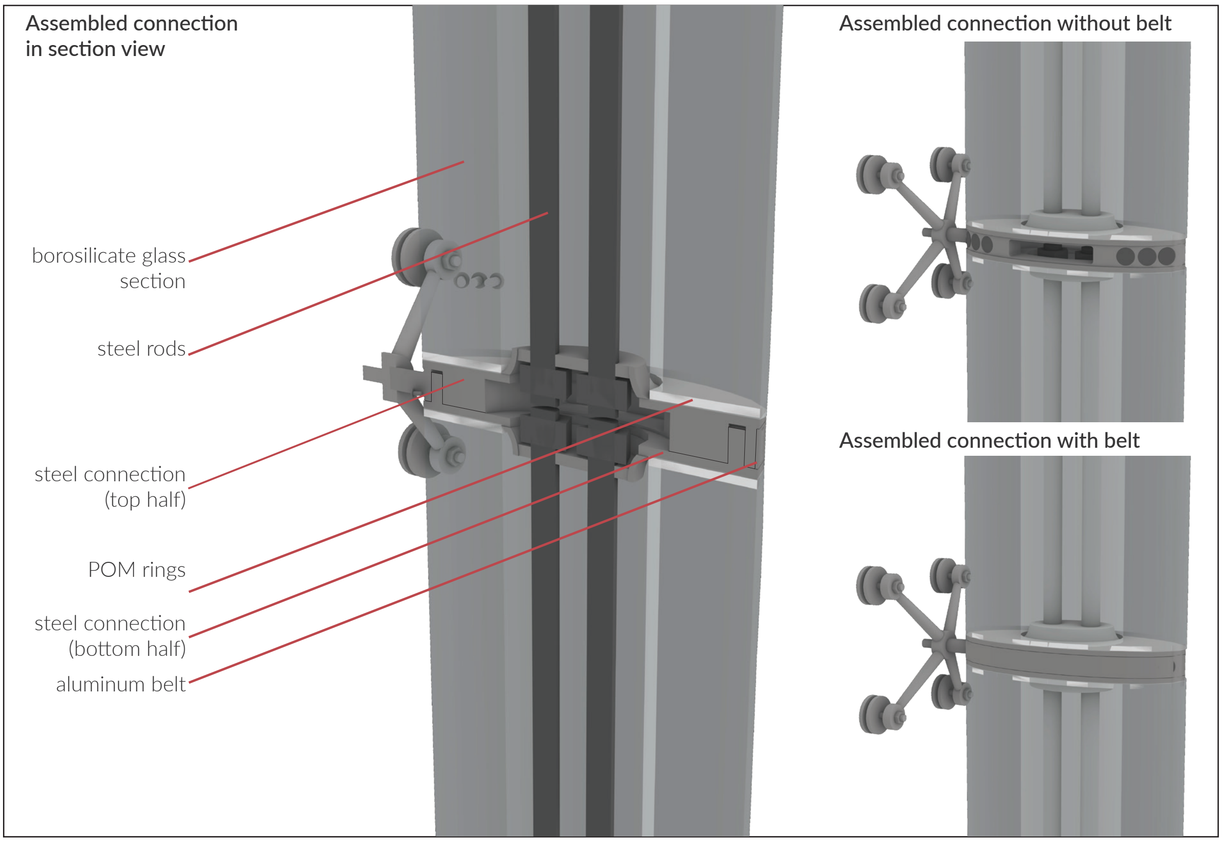
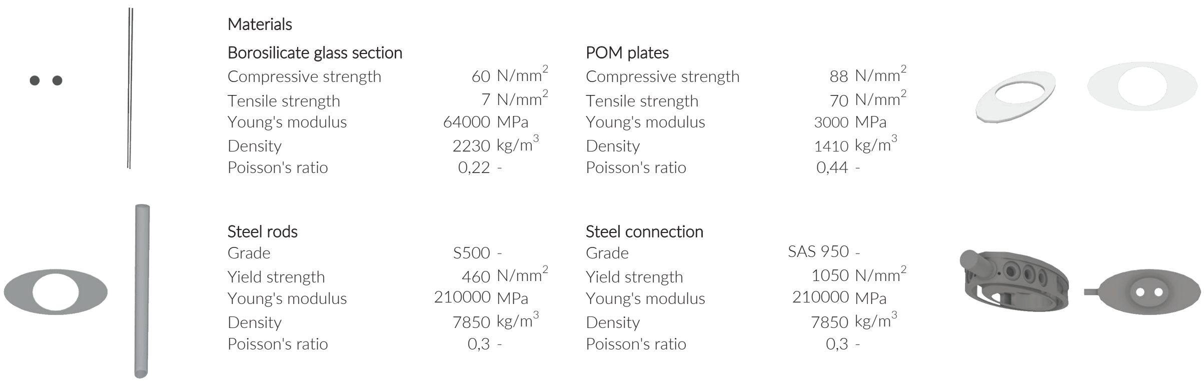


Figure 61: three views of the draft design illustrating all parts, this design has not been dimensioned yet



Materials

Borosilicate glass section		POM plates	
Compressive strength	60 N/mm^2	Compressive strength	88 N/mm^2
Tensile strength	7 N/mm^2	Tensile strength	70 N/mm^2
Young's modulus	64000 MPa	Young's modulus	3000 MPa
Density	2230 kg/m^3	Density	1410 kg/m^3
Poisson's ratio	0,22 -	Poisson's ratio	0,44 -

Steel rods		Steel connection	
Grade	S500 -	Grade	SAS 950 -
Yield strength	460 N/mm^2	Yield strength	1050 N/mm^2
Young's modulus	210000 MPa	Young's modulus	210000 MPa
Density	7850 kg/m^3	Density	7850 kg/m^3
Poisson's ratio	0,3 -	Poisson's ratio	0,3 -

Table 14: material input parameters, colour of POM can vary

Overall parameters

Facade	
Height facade	6,00 m
location connections	2,00 m
Distance between columns	4,00 m
load	4,50 kN/m2
Max area per connection	8 m2
Max load per connection	36 kN/m2

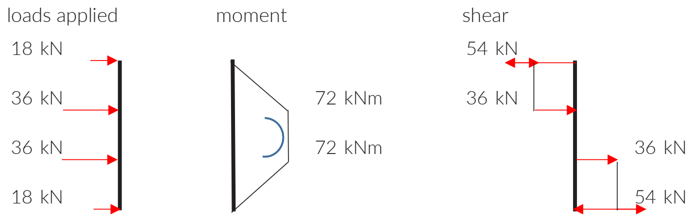


Table 15: design context input parameters

For the SLS the load is commonly taken much lower than for the ULS. This is because safety factors don't have to be taken into account for the calculation of the deformation. However, as later will be discovered, the ULS will be the normative method. The SLS is within acceptable ranges even with the same high load as the ULS. However it has to be noted that the total deformation of the system would in reality be smaller.

Safety concept

Residual strength vs second load path

For this design, the residual strength concept has not been chosen because a situation needs to be taken into account where an element is destroyed in such a fashion that structurally speaking it doesn't exist anymore. This holds specifically true in case of this design with no sacrificial layer(s) of glass.

The chosen concept is that of second load paths. However, it's not by adding extra structural members but by making use of the extra capacity each element already has. During the compression test it was shown that the glass sections can handle more than they are used for. The designed with value is a standard deviation from the value at first defect, but glass is actually able to withstand a greater load than that. The glass actually has an approximate 30% reserve. Additionally, safety factors are reduced when an element is vandalized. The chance that an element is vandalized in the most extreme load condition (storm that occurs once in the lifetime of a building) is so small that a reduction in the load may be calculated with.

When an element is vandalized and the load of 4.5 kN/mm^2 is decreased to even 3.5 kN/mm^2 the reserve of 30% is enough for neighbouring column to take the extra loads from the missing column in compression. In tension, it is not confirmed if there is a similar reserve in strength after first defect, but following the logic of the glass not failing because it reaches the strength threshold but because of a local peak stress after which the remaining material has enough capacity still to convey even more force then before, this could be assumed. If this is not the case, the steel rods would take over the extra tensile forces and keep the system and façade in place for a safe evacuation. It has to be kept in mind that it is highly unlikely that a segment is vandalized in the most extreme load condition it is designed for.

This chosen method could have financial consequences as instead of just one section, multiple sections may need to be replaced upon failure of one because they are pushed over their first defect threshold. However, the chance that vandalism occurs is so small that it is probably worth this risk and oftentimes this concept will likely even save on costs by not having to place extra elements. However, even more important is that it is a safe concept and people will be able to exit the building without danger after which repairs can occur. Additionally it has the visual benefit of not having more columns then needed, contributing to the minimalism.

Safety upon complete failure

Because of the system being executed in safety glass, it cannot harm bystanders. Also the steel rods keeps the system and façade in place at all times. This will be confirmed by later calculations.

Model building

For this purpose, the method of having several local detailed models and one global simple model has been chosen over building a global detailed model. A global detailed model would be overly complex and would not lead to a significantly better performance evaluation for the desired accuracy of this explorative study. The local detailed models and the simple global model will be discussed below.

Order of dimensioning

Analytical (ULS):

1. Given the general parameters, a single continuous glass column is assumed. Because the maximum tensile and compressive stress of the glass is known, the maximum allowable moment can be calculated. From this we can calculate the needed second moment of inertia (second moment of area) of the profile. From this parameter, a profile is designed to match it.
2. The radius of the rods can be determined by looking at the maximum stress in the glass. This stress needs to be corrected by adding extra compression to make sure the maximum tensile stress is not surpassed. The force needed to create this extra compression in the glass together with the allowable stress of the steel gives the radius of the rods.
3. The stress in the rods gives a hint at the needed structural performance of the cap of the connection. This is roughly calculated by hand.

Not all parameters could be estimated through hand calculations. Where not possible or where results of hand calculations would be too inaccurate, a value is estimated by intuition.

When all these steps are successfully completed the parameters to start the simulations are acquired.

Numerical (ULS):

1. The designed section is modelled as a continuous tube over the entire height of the façade and the displacement and stress is checked. The displacement is checked to get an idea of the total deformation of the entire system, which is expected to be somewhat similar.
2. The cap of the connection is modelled with the bolts attached to check the stress levels and the displacement of the cap.
3. The connection is simulated under the moment to test the stress in the connection and the bolts.
4. The connection at the base and top are checked.

When all steps are successfully completed the needed dimensions of the system to pass the ULS are found.

Global model (SLS):

1. The rotational stiffness of the connection is simulated in a detailed small model. This can be used as input for the simple global model.
2. In the global model the glass elements are modelled as 2D lines with the second moment of area and young's modulus as input. The connections are modelled as springs with the rotational stiffness that is found in step 1. The total deformation is found by subjecting the system to the global forces found in the general parameters.

When all steps are successfully completed the system has passed the SLS.

Analytical 1: Section

In figure 64 the calculation for the needed second moment of area is given and in figure 65 the dimensions chosen for the glass section. The needed stress correction by the rods is also calculated in figure 62.

A minimum dimension of the inner ellipse of the glass section is given by the space needed for the rods and bolts since the bolt's tension needs to be able to be adjusted.

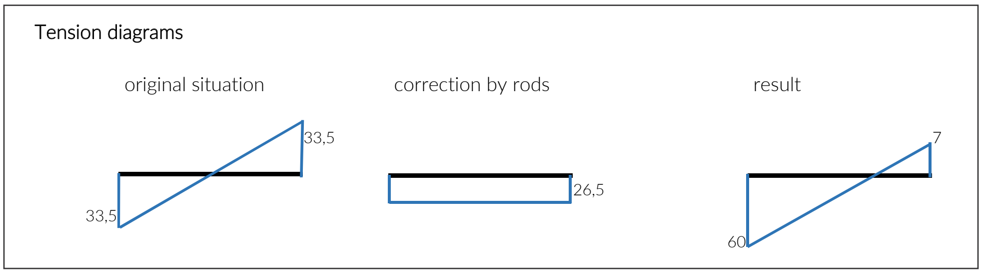


Figure 62: tension diagrams of glass with the maximum allowable compression and tension as starting point, finding the tension correction needed by the rods

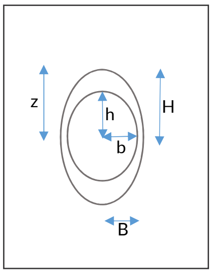


Figure 63: parameters glass profile

Finding second moment of area needed for glass section

$$\sigma_{max} = zM/I_{needed}$$

with

σ_{max}	maximum stress in glass because of wind load
z	maximum distance from center profile
M	moment due to wind load
I_{needed}	second moment of area

$$I_{needed} = 4.51 * 10^8 \ mm^4$$

Figure 64: calculation for finding the second moment of area needed for the glass section

Designing the glass section

$$I_{profile} = \left[\frac{\pi}{4} H^3 B\right] - \left[\frac{\pi}{4} h^3 b\right]$$

with chosen dimensions

h	155 mm
b	80 mm
H	210 mm
B	100 mm

$$I_{profile} = 4.93 * 10^8 \ mm^4$$

Figure 65: calculation for designing the glass section

Analytical 2: Rods

Below the calculation for radius of the rods is given. A scenario could be imagined where there would be one steel rod instead of two. In this case the choice for one steel rod was made because of the additional stability at total failure of the glass and the ability to post tension the glass more equally. However arguments could be made that one rod would aesthetically be more pleasing.

Finding the needed surface area per steel rod

$$N = \frac{F}{2 * A_{needed\ per\ rod}}$$

with
N allowable tensile stress steel rods
A surface area needed per steel rod

and

$$F = \sigma_{needed\ for\ correction\ glass} * A_{surface\ area\ glass\ section}$$

$$A_{needed\ per\ rod} = 340.93\ mm^2$$

Finding the needed radius per steel rod

$$r_{needed\ per\ rod} = \sqrt{\frac{A_{needed\ per\ rod}}{\pi}}$$

with
r radius needed per steel rod
A surface area needed per steel rod

$$r_{needed\ per\ rod} = 10.4\ mm$$

$$r_{rods} = 11.0\ mm$$

Figure 66: calculation for needed

Analytical 3: the cap

In figure 67 the calculation for the thickness of the cap is given. This calculation serves as an estimation. To grasp the range the actual thickness will be in, the thickness is first calculated as if there were simple point loads on a simply supported beam and secondly as a moment on a fully supported plate. The actual dimensions will be simulated later.

Numerical 1: Section

This model confirms the expected stress in the glass section found through hand calculations. It is a modelled as a single structural solid with point loads at the places the connections would be.

Simplifications:

- Peak stresses occur where the point loads are placed upon the glass. This would not be the case in the real situation.
- The glass is not post-tensioned in this example, which is also not needed as this calculation serves to confirm the expected stress induced by the moment.

Numerical 2: connection cap

The hand calculations for the needed thickness of the cap are not that accurate and also lacking parameters needed to build the geometry. This is why a broader study is done to compare the efficiency of multiple design options. To give the cap structural integrity, two different ways are imagined: adding thickness to existing geometry and adding extra supporting material. A combination of these methods is used to make sure it passes the ULS.

The two selected parameters are explored using a Python script. The script allows for very fast model making and assessing. Three design options

Estimating the needed thickness of the connection cap

$$\sigma_{max} = zM/I_{needed}$$

with
σ_{max} maximum allowable stress in cap
z maximum distance from center cap: ½h

and

$$I_{needed} = \frac{1}{12}bh^3$$

with
h height (thickness) cap
b width cap

and
M moment due to rods pulling on the cap with two ways of approaching it:

$$M_{plate\ (simplified)} = \alpha F \qquad M_{beam} = F\ \frac{L}{3}$$

with
α correction factor based on proportions cap
F point load of rods on the cap

F point loads of rods on the cap
L length of cap

Both are calculated to estimate a range the actual height needed will be in since it's in-between a plate and a beam

When combining the formulas

$$\sigma_{max} = \frac{1}{2}h\ \frac{\alpha P}{\frac{1}{12}bh^3} \qquad \sigma_{max} = \frac{1}{2}h\ \frac{F\frac{L}{3}}{\frac{1}{12}bh^3}$$

$$h_{plate} = 7.0\ mm \qquad h_{beam} = 45\ mm$$

$$7.0\ mm < h_{actual\ needed} < 45\ mm$$

Figure 67: estimation of the needed thickness of the cap

Model name:	Section with load
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometrystructural:	Imported, structural solids
Material(s):	Borosilicate glass
Load(s):	Point loads
Supports:	T1 T2 T3

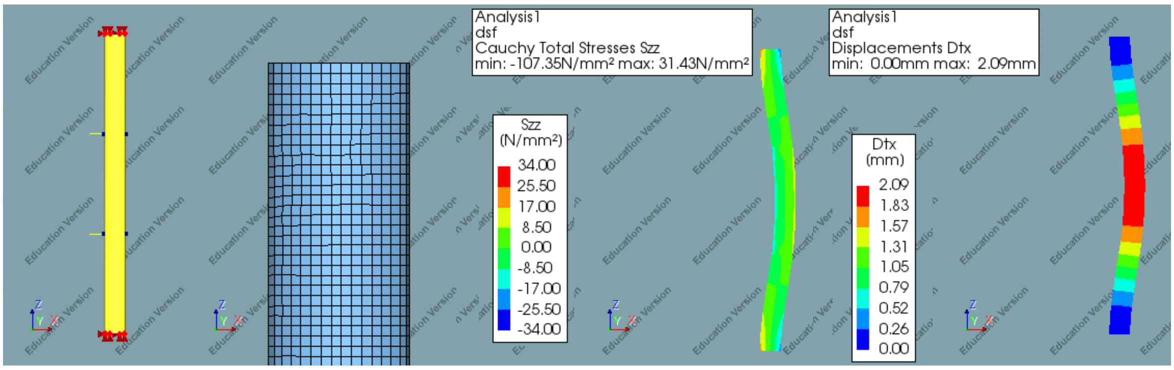


Figure 68: simulation glass section with stress caused by moment

are derived from the two imagined ways of adding structurally integrity. These are:

- Option 1: cap thickness: 10mm, 20mm, 30mm, 40mm
- Option 2: side wall thickness 10mm, 20mm
- Extra supporting material: no, yes (slanted side wall + extra middle wall)

To clarify these options, please see figure 69. With the Python script, all possible combinations of options could be analysed.

The models for checking the structural integrity of the caps against the force projected onto them by the rods consist of solid geometry extracted from a 3D model. The loads are the forces found in the previous section and they are projected upwards along the Z-axis. As normative results the principal stresses are shown as this is more complex geometry and biggest stresses might not align along prescribed vectors.

The SLS will not be calculated for this element as the deformation of the cap is not significant. Steel has too high of a young's modulus to deform significantly over such a small length.

Simplifications:

- The models are a slight simplification of the ultimate design. This was chosen because of modelling complications due to the Python script. Slightly simplified models could be produced much faster and the impact of certain alterations could be discovered far more quickly. No significant accuracy was lost.
- It has not been taken into account that the nuts could loosen by the force of the rods. In reality this is a situation that should be avoided by the design. In the design it's countered by having two nuts but this mechanism could also take the shape of lock-nuts or similar systems.

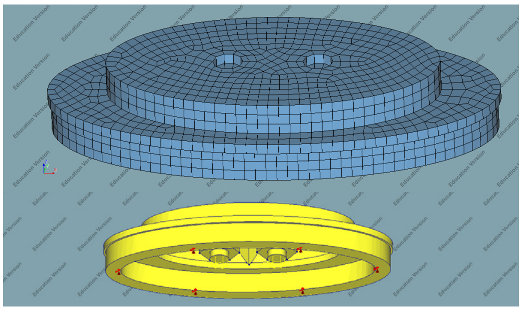
Remarks model series

- The thinner models show a lot of peak stresses. The results are not very accurate but it is clear that the stress in the material is too high. In later models these peak stresses resolve to just a few points.

In the table 16 and corresponding graph in figure 70 the results of the exploration are displayed. The S1 and S3 are displayed as they are most extreme. Given Mohr's circle for a 3D element, the S2 will always give values in-between S1 and S3.

The stresses in the table are the found maximum stresses at standard points in the model. This excludes weird pinches in one single node where the stress due to the meshing is absurdly high and also makes the models more comparable. These points are chosen by biggest stresses from the models with most material. Models with less material might also have big stresses elsewhere. To fully display the stresses in the models, the Python script included saving multiple screenshots. These are shown in figure 69 too. All stresses, tension and compression, are expressed in positive numbers to make the table and graphs especially more readable.

Model name: Cap with loads by rods
[cap thickness]_[side wall thickness_[extra material]
Default Mesher type: Hexa/Quad
Default Mesher order: Quadratic Linear Interpolation
Geometry: Imported, structural solids
Material(s): Steel Connection
Load(s): Area loads
Supports: T1 T2 T3



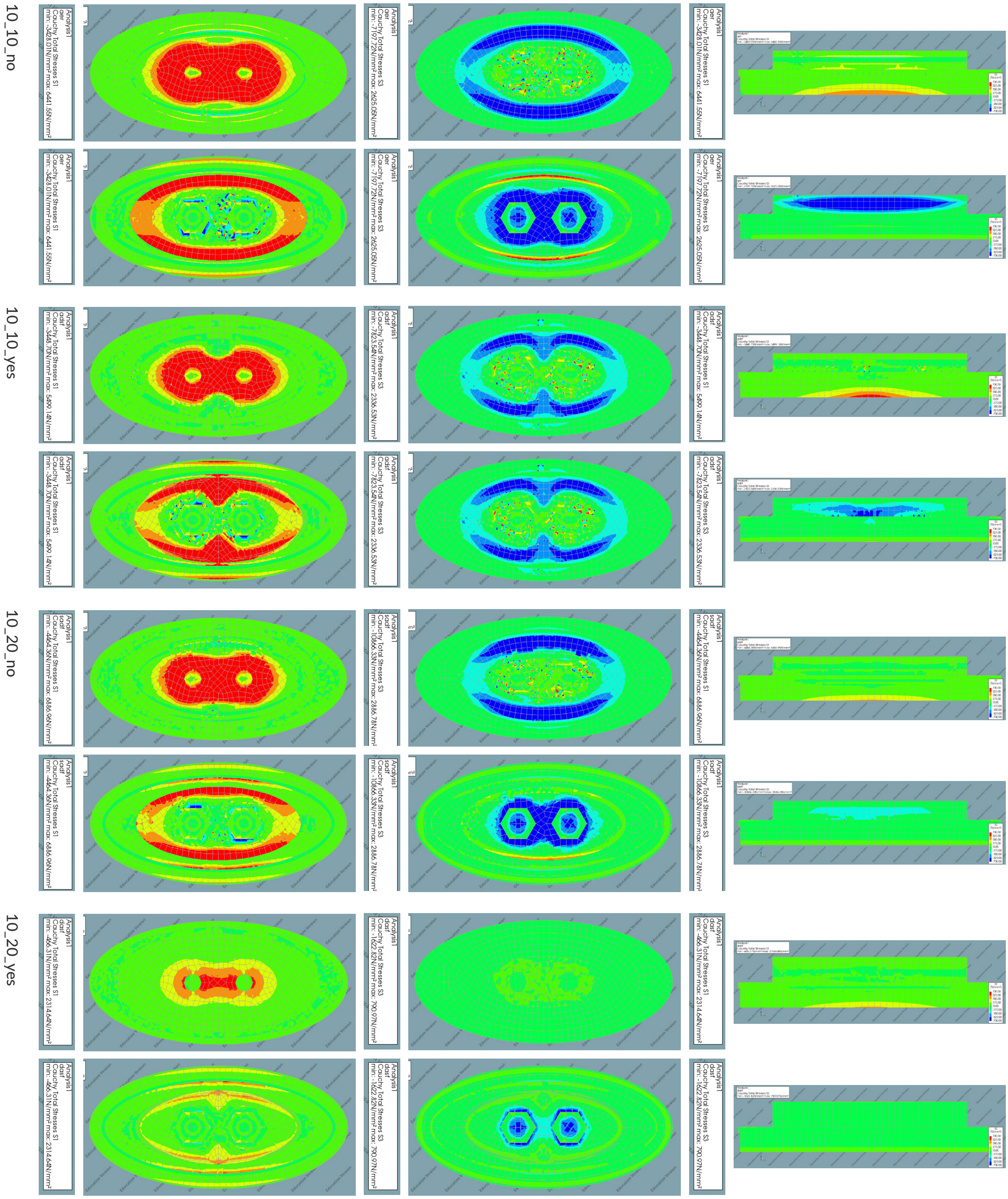


Figure 69: exploration of principal stresses for all combinations of design options (page 1/4)

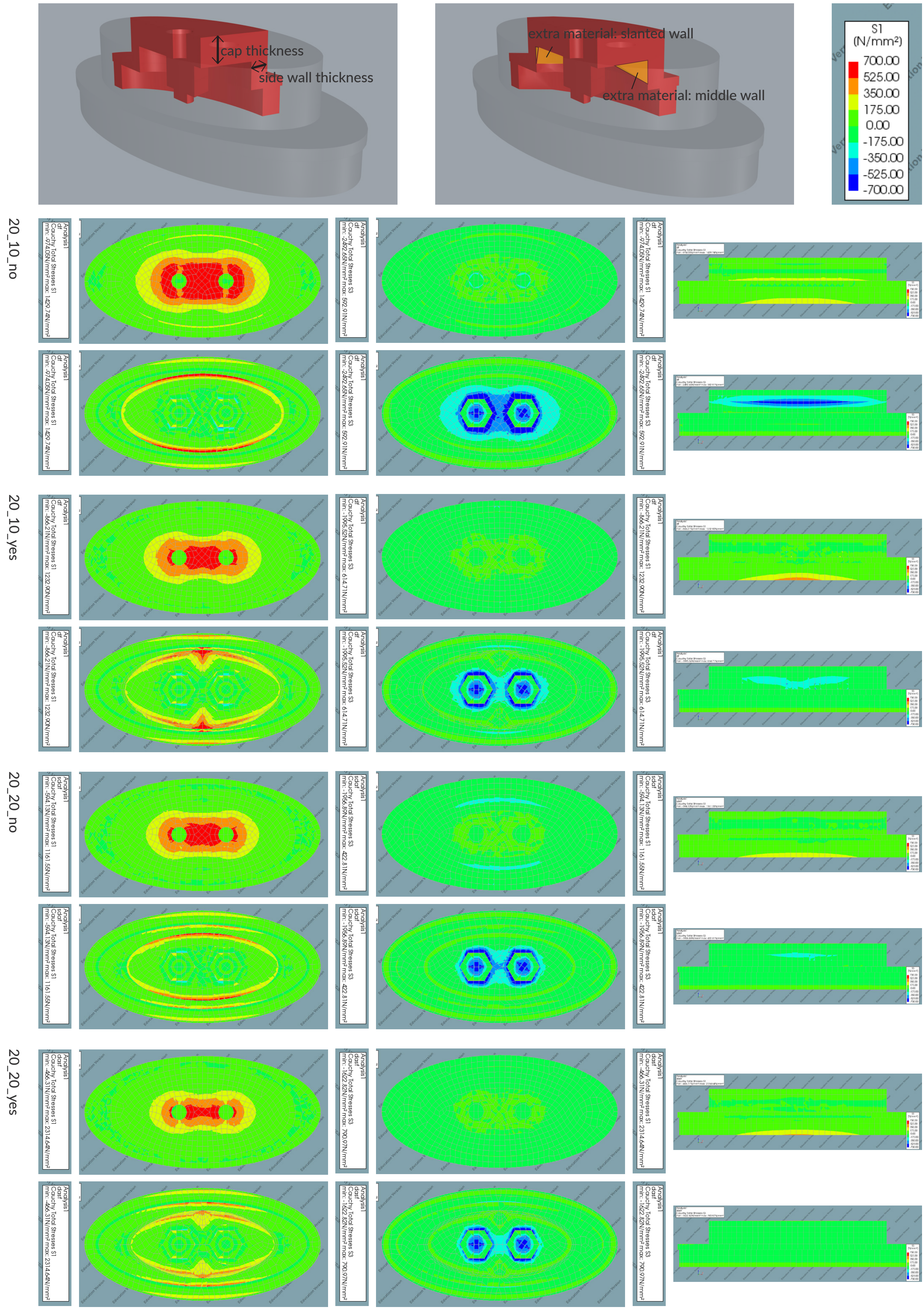
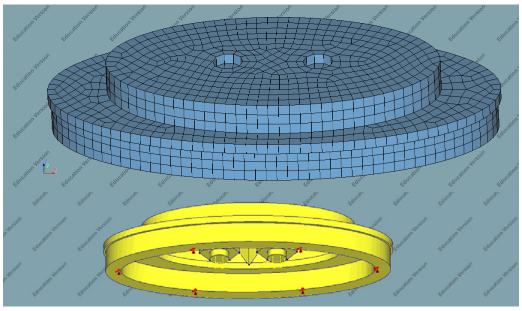


Figure 69: exploration of principal stresses for all combinations of design options (page 2/4)

Model name:	Cap with loads by rods
[cap thickness]_[side wall thickness_[extra material]	
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry:	Imported, structural solids
Material(s):	Steel Connection
Load(s):	Area loads
Supports:	T1 T2 T3



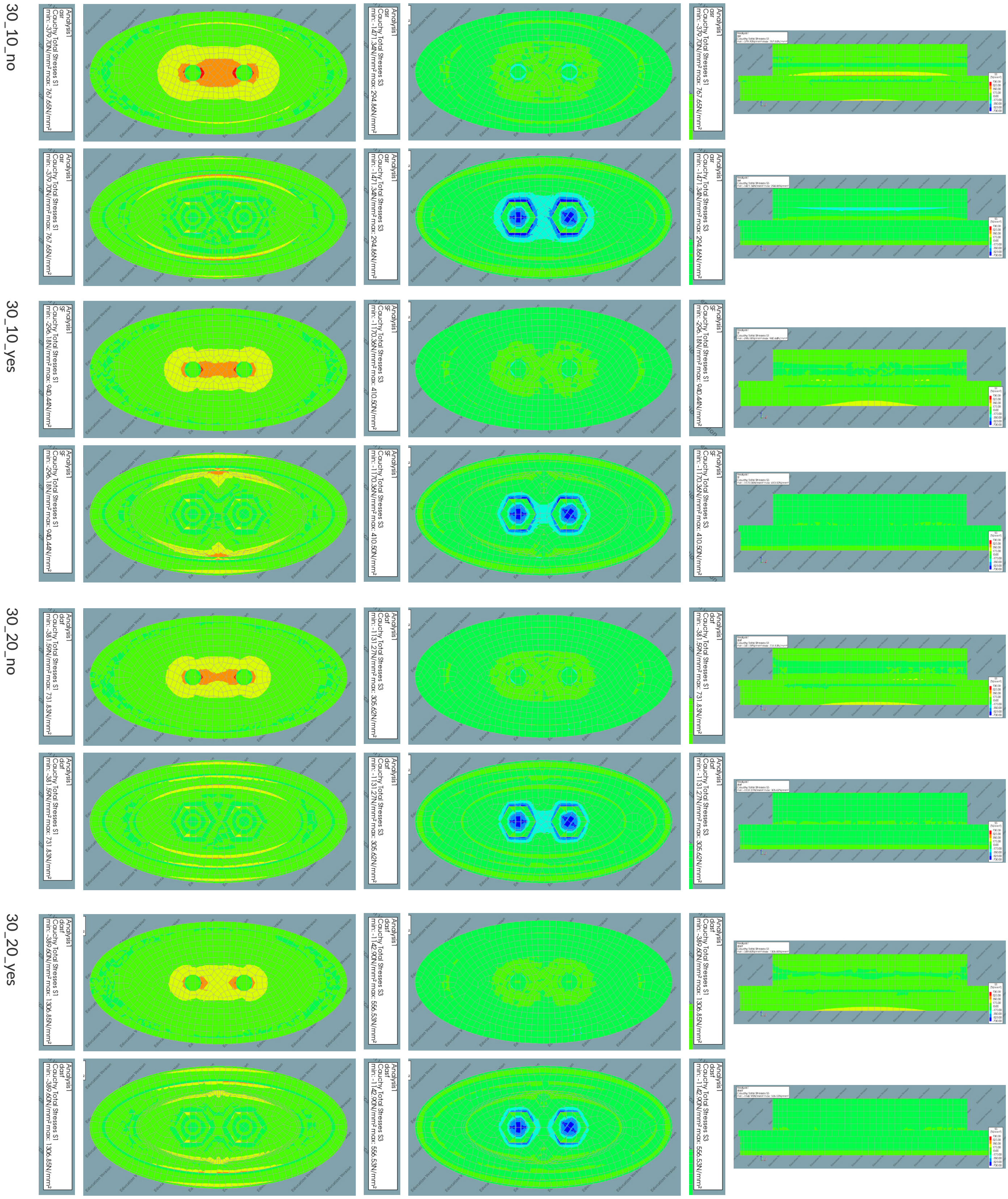


Figure 69: exploration of principal stresses for all combinations of design options (page 3/4)

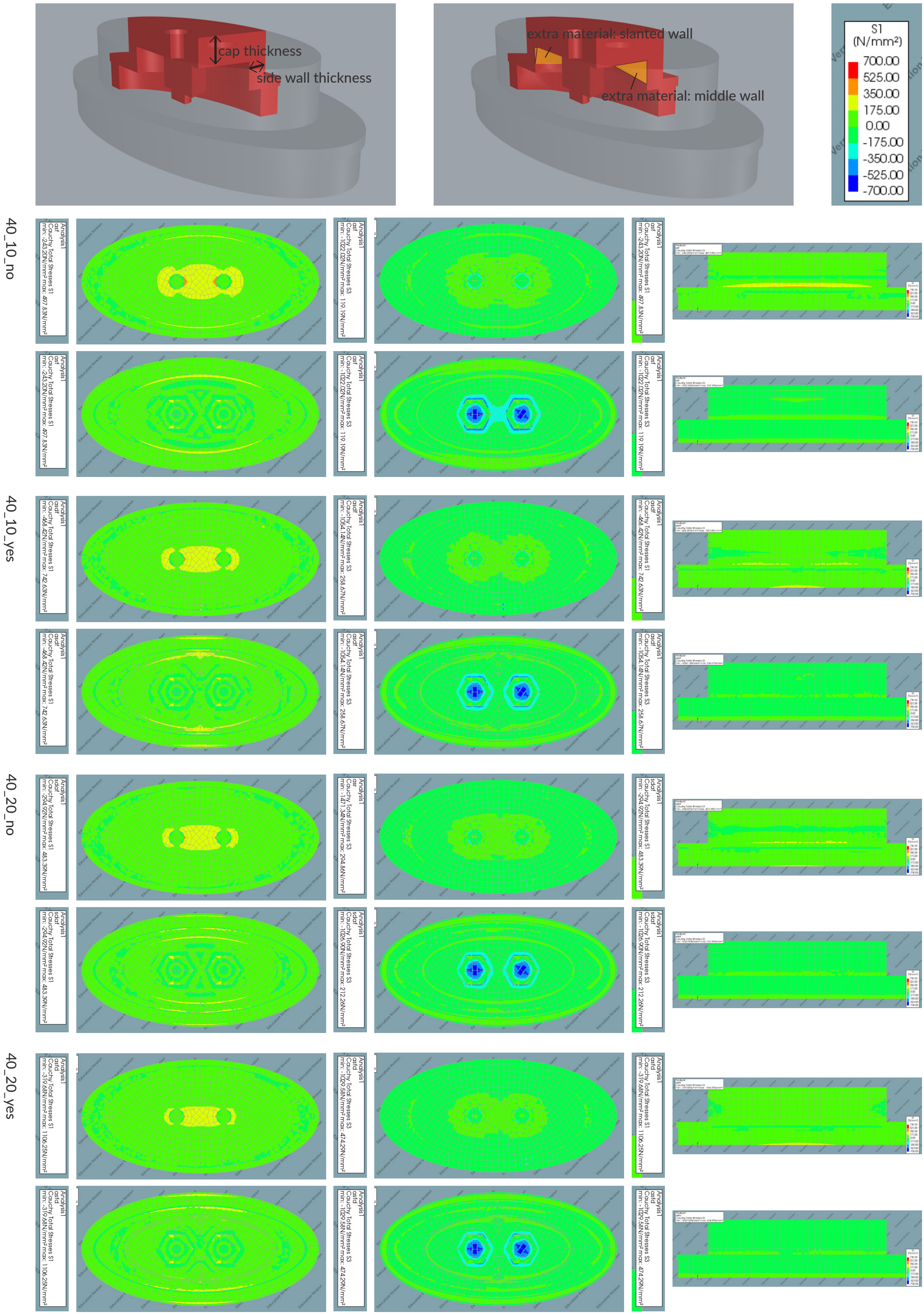


Figure 69: exploration of principal stresses for all combinations of design options (page 4/4)

Model #	Name	Cap thickness	Side wall thickness	Extra material		S1 S1 min	S1 max	S3 S3 max	S3 min
1	10_10_no	10	10	no	10_10_no	325	1250	3	1760
2	10_10_yes	10	10	yes	10_10_yes	290	1000	23	1150
3	10_20_no	10	20	no	10_20_no	380	930	11	1160
4	10_20_yes	10	20	yes	10_20_yes	260	860	47	1030
5	20_10_no	20	10	no	20_10_no	140	820	20	790
6	20_10_yes	20	10	yes	20_10_yes	60	655	10	410
7	20_20_no	20	20	no	20_20_no	130	660	3	550
8	20_20_yes	20	20	yes	20_20_yes	80	583	6	480
9	30_10_no	30	10	no	30_10_no	55	505	2	430
10	30_10_yes	30	10	yes	30_10_yes	35	410	5	260
11	30_20_no	30	20	no	30_20_no	43	420	2	325
12	30_20_yes	30	20	yes	30_20_yes	33	353	3	217
13	40_10_no	40	10	no	40_10_no	44	325	2	293
14	40_10_yes	40	10	yes	40_10_yes	28	283	2	247
15	40_20_no	40	20	no	40_20_no	33	276	3	221
16	40_20_yes	40	20	yes	40_20_yes	40	253	2	237

Table 16: maximum found principal stresses, both tension and compression are displayed as positive values, values in red are considered not allowable; model colours correspond with figure 70

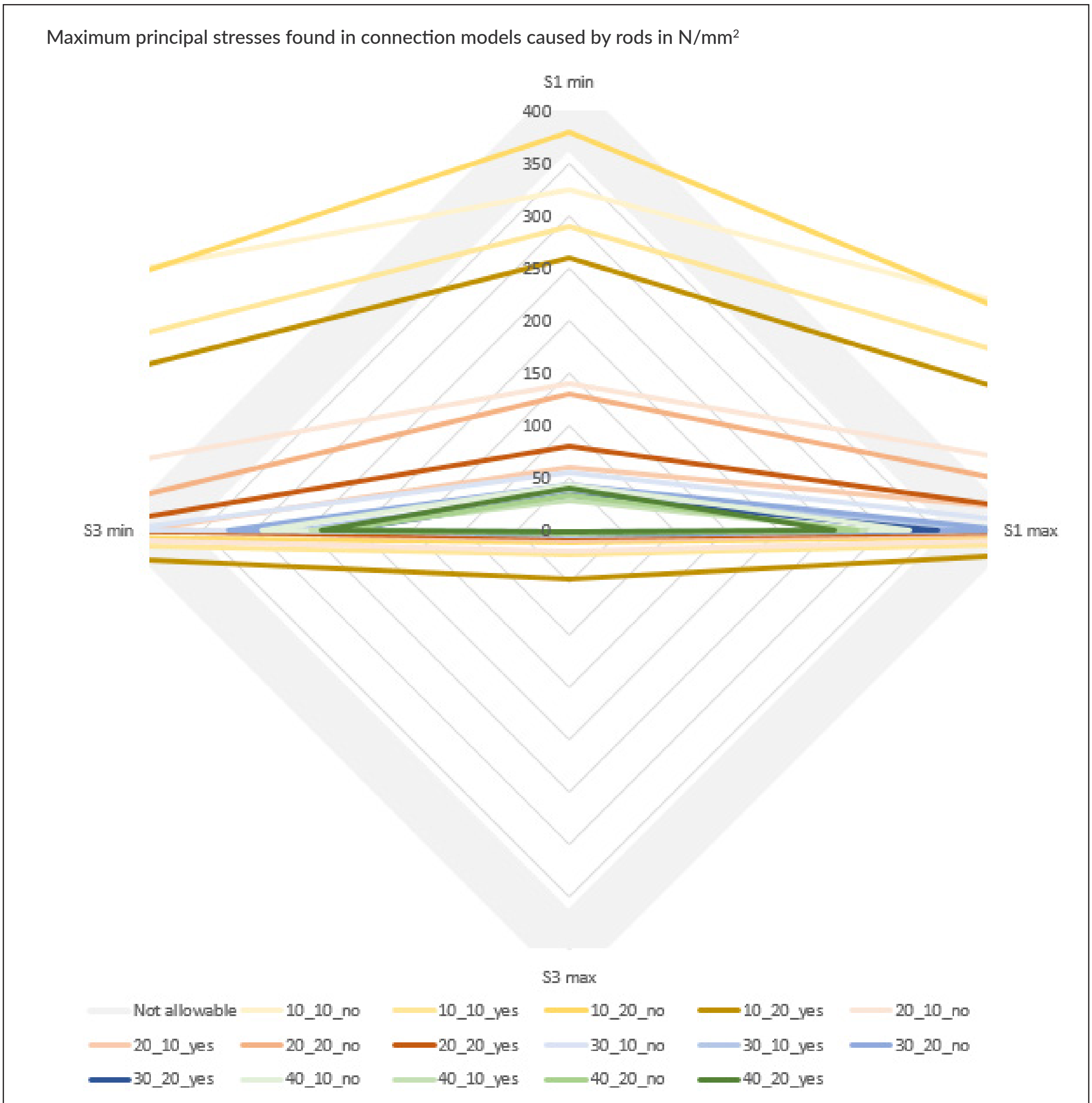


Figure 70: visual representation of found maximum principal stresses

From this study it can be concluded that a connection with a cap thickness of 30mm, a side wall thickness of 20mm and with extra supporting material seems the most favourable option. It is the first model that does not exceed the tolerable stress amount given by the material parameters.

Of course also a higher grade of stell could have been chosen to reduce geometry size, but this result already shows it is possible to make such a connection work, which fulfils the purpose of this thesis.

Numerical 3: Connection

The geometry for this model is extracted from a 3D model and exported as an IGES file. Because the particular software did not have the needed degree of freedom for subjecting structural solids to moments, the moment is created by area loads which is also still clearly visible in the results.

Simplifications:

- The moment is created by projecting area loads onto the faces of the connection. In reality the forces would be more evenly distributed. It has been chosen to project the load on the centre of each end of the profile to ensure that the stress in reality would be slightly smaller.
- The POM rings are not modelled here because they would not effect this particular situation in reality. This is because the POM just passes through the same normal forces and the POM will not change the distribution of those forces.
- The bottom face of the wall acts as a completely stiff support.
- The actual caps of the connection are not modelled here as a simplification. This is a way to simplify the simulation without losing significant additional accuracy.

From the analysing of a first design it became clear that far more material was needed as the stress on the walls and the bolts is too high. The connection was still hollow up to that point, of which there is no need for except for trivial weight and material savings. In a new model the stress is reduced to low values through adding more material. Stress peaks in the new design are created by the type of loading. In reality it would be more evenly distributed and so it passes this test.

Model name:	Connection for stress
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometrystructural:	Imported, structural solids
Material(s):	Connection steel
Load(s):	Area loads
Supports:	T1 T2 T3

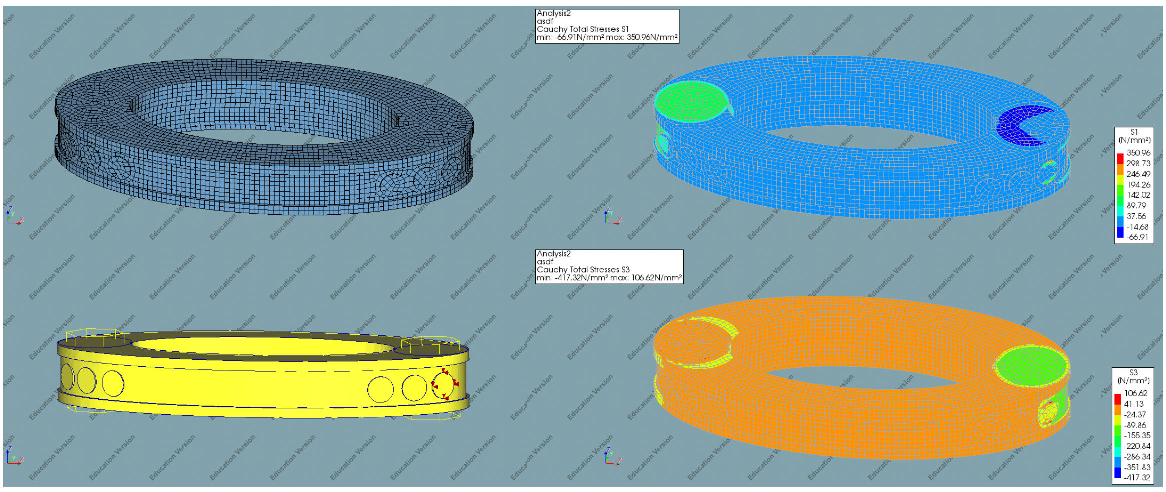


Figure 71: visual representation of found maximum principal stresses

Numerical 4: Base connection and top connection

The base and top connection haven't been subjected to in-depth analysis because of the following reasons:

- The base and top connection has the same amount of material as regular connections in the same places or more. This means it would pass the test if the forces were the same.
- The stress on the cap given by the rods is identical to the other connections, especially due to the model set-up chosen. In reality the stresses would be slightly but insignificantly different.
- The shear forces through the base connection is halve of that of other connections. This has been made visible in the general parameters section. When taking this into account, this connection will automatically perform better in that regard than the other (already simulated) connection.
- There is (almost) no moment on this connection. This has also been made visible in the general parameters section.
- The execution of these connections is not critical to the potential of the entire system. Similar connections have been designed before and there would always be a way to make them work and they could also be hidden from view if desired.

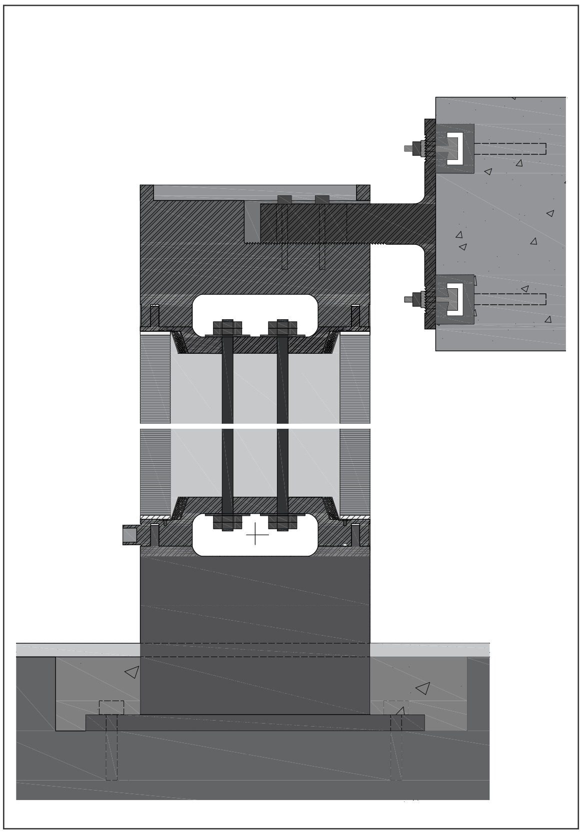


Figure 72: visual representation of found maximum principal stresses

Global model 1: rotational stiffness connection

The geometry for this model is extracted from a 3D model and exported as an IGES file. Because the particular analysis software used did not have the needed degree of freedom for subjecting structural solids to moments, the moment is created by to area loads which is also still clearly visible in the results.

Simplifications:

- The moment is created by projecting area loads onto the faces of the connection. In reality the forces would be more evenly distributed. It has been chosen to project the load on the outer ends of the profile to ensure that the rotation in reality would be slightly smaller.
- The caps are not exported for this calculation because of modelling complications. This simpler version of reality should be slightly less stiff and thus have a bigger rotation.
- It is assumed that the bolts form a perfectly stiff connection between the two halves of the connection. In reality there will be very little room and it will be slightly less stiff than found here.

The rotation is calculated by taking the translation along the Z-axis at both ends of the profile. Between the found points a straight line is drawn. Then, the 'normal' line is drawn and the angle between the normal line and the new line is calculated. After it has been converted to radians the rotational stiffness can be calculated. The found rotational stiffness is very high and thus the connection is very stiff. This is expected because the connection is small in height and very solid which means it cannot deform much. Most deformation is caused by the POM layers.

Model name:	Connection for rotation
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry:	Imported, structural solids
Material(s):	POM, Connection steel
Load(s):	Area loads
Supports:	T1 T2 T3

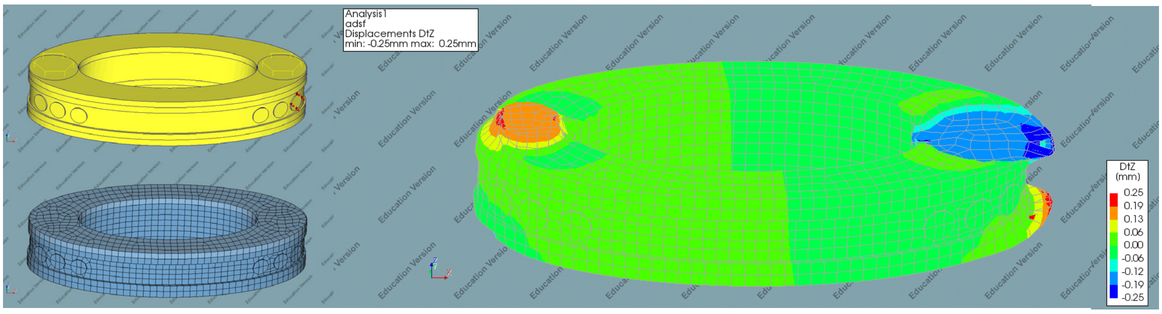


Figure 73: simulation of displacement connection for calculating rotational stiffness

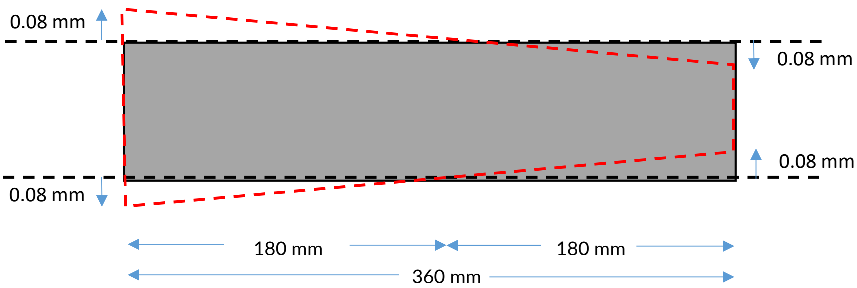


Figure 74: diagram for calculating rotation connection

Calculating the rotation on one side

$$\tan\alpha = \frac{O}{A}$$

with

α rotation

O Opposite side length

A Near side length

$$\alpha = 4.44 * 10^{-4}\ radians$$

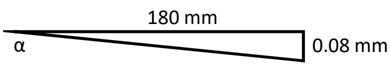


Figure 75: calculation rotation on one side of the connection

Finding rotational stiffness

The rotation needs to be doubled because it happens on both sides

$$k = \frac{\alpha_{total}}{M}$$

with

k rotational stiffness of connection

α_{total} total rotation of connection

M moment on connection

$$k = 1.23 * 10^{-8}\ radians/Nm$$

Figure 76: calculation rotational stiffness connection

Global model 2: total deformation

The global 2D model comprises of three line segments which represent the glass members. The line segments are connected by:

- Rotational springs for conveying the rotations around the Z-axis.
- Hinges for conveying the translations between the members.

The cross section is converted to a simple rectangle with the same second moment of inertia. The loads are directly taken from the general parameters. The glass members are clamped at both ends of the system for all translations and rotations according to the actual design.

Figure 77 shows the found displacement in the Y-direction of the system.

Simplifications:

- The system would be standing upright. This means that weight of the members is working in-plane instead of out-of-plane. The actual translation would thus be a little smaller.
- The connections are not assigned dimensions. This means that the system would in actuality be slightly longer. The actual translation would thus be a little larger.
- The connections are not assigned weight. This means that the system would in actuality be a little heavier. The actual translation would thus be a little bigger.

Global model 3: total deformation after failure

This calculation serves as a prediction of what happens to the system when all glass segments would fail or would be vandalized. This is important since the façade should not break entirely or worse: be a potential cause of harm.

Simplifications:

- The connections are assumed to be of the same elasticity than the cable and are not modelled here. In reality the deformation would be slightly less since the connection is stiffer than the rods and these small sections don't deform that much.
- In the geometrically non-linear analysis executed here, the load is added in small steps. Due to software difficulties the total load is slightly higher than intended as can be checked in the support reactions.
- The model doesn't account for the façade panels lending resistance against the system translating. In reality they most like would. It depends on the context. If the panels are mounted with a hinging connection it would not alter the results of this test, but if the panels are mounted with a springing connection or even fixed they would alter the results by giving resistance and lessening the deformation or break entirely and not alter the results or alter the results in an unforeseen way.
- In the simulation it is assumed that all glass segments disappeared. In reality this would be a very rare situation. It is more likely that one element is vandalized or even two. One or two would thus still be in place and the deflection would be smaller than calculated here.
- In reality the chance that an element is vandalized under the most extreme loading condition is very small. This is why the deflection would often be (much) smaller than the extruded results.
- The calculation shows that under the extreme load of 4.5kN/m^2 the system has a maximum horizontal translation of approximately 310mm. This then means that the façade should be designed in such a way that it can withstand it safely or even without damaging. In any case it shows that the façade columns will stay in place safely and still offer resistance against deflection.

Other scenarios for failing

In compression the extruded borosilicate glass seems to have a tested structural reserve after first defect. meaning that when cracked it is still able to withstand forces. Because of pending experiment results it is not sure whether in tension it has a similar reserve.

The structural reserve (in tension too) is based on the assumption that the material did not fail because it met the maximum stress threshold, but because it was loaded non-optimal with regards to introducing of the loads or imperfections in the sample. This means that although it has failed locally, the rest of the sample has enough working material left to convey the forces. However there is also a chance that this doesn't work in tension because the defects could to be critical for the geometrical stability of the entire sample.

The three scenarios for failure that this ensues can be found in figure 79.

Model name:	Global model for displacement
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry:	2D lines and vertexes
Material(s):	Glass, Rotational spring
Load(s):	Point loads
Supports:	T1 T2 T3 R1 R2 R3

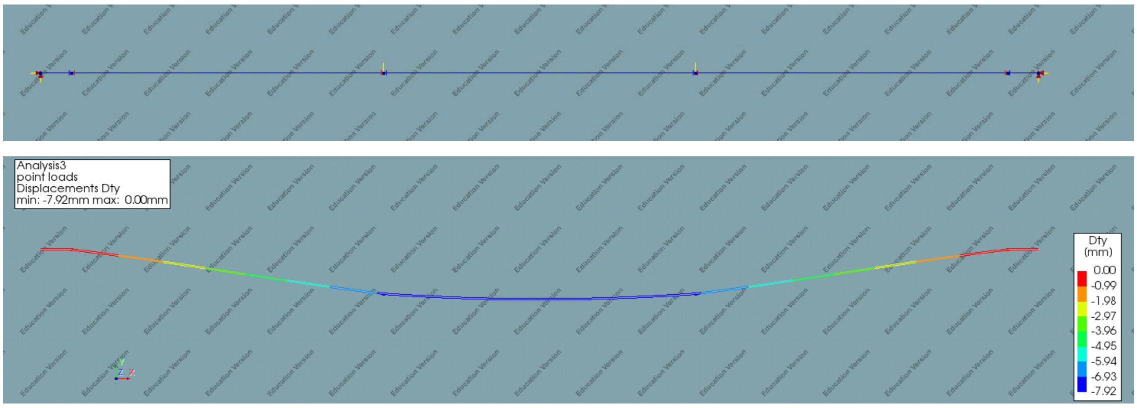


Figure 77: simulation displacement global model

Model name:	Cable model for displacement
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry:	3D Class II beams as lines
Material(s):	Steel rods
Load(s):	Point loads
Supports:	T1 T2 T3 (extra stability support T2)

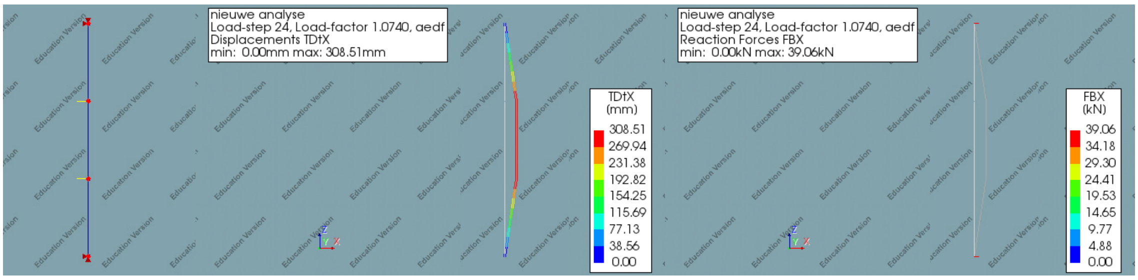


Figure 78: simulation displacement upon total failure

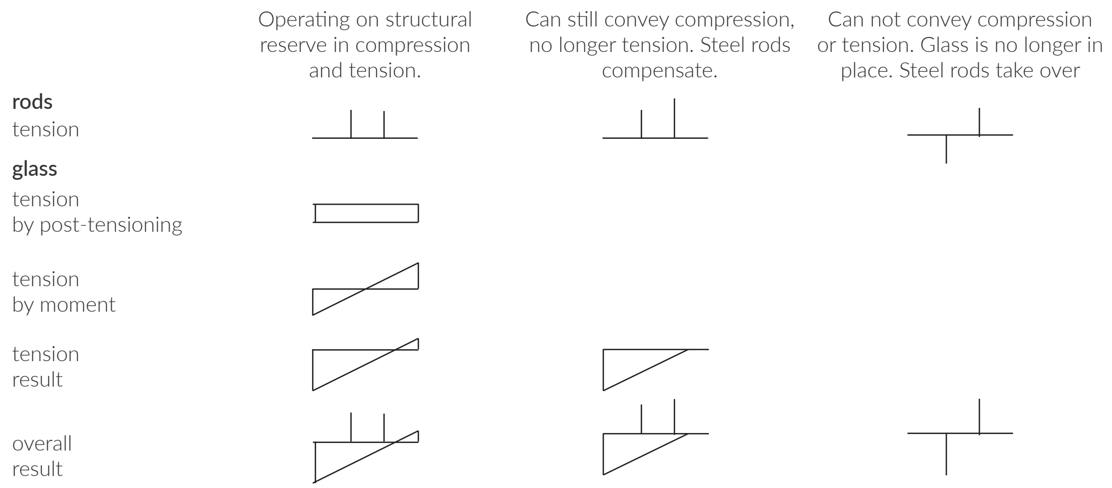


Figure 79: scenario's for failing after first defect

Overview results

In the overview shown below it is clear that with the given dimensions the designed system passes ULS and SLS.

Remarks:

- The needed cap thickness falls in the expected range as estimated through hand calculations.
- The calculated translation of the global model is the result of simulating just the glass section over the entire height of the façade, not including the connections. This shows the influence of the connections on the total translation. The allowable deformation is taken as 1/300th of its length.

Part	Parameter	Calculated/ estimated dimension		Calculated stress [N/mm2]	Simulated dimension		Simulated (max) stress [N/mm2]		Allowable stress [N/mm2]
ULS									
Glass	Isection	4,93E+08	mm4	31	3,16E+08	mm4	31	<	33
Rods	Radius steel rods	15	mm	506	-----		-----	<	550
Connection	Cap thickness	7-45	mm	350	30	mm	-----		-----
	Side wall thickness	-----	mm	-----	20	mm	-----		-----
	total				-		353	<	355
SLS									
Part	Parameter	Calculated/ estimated dimension		Calculated deformation [mm]	Simulated dimension		Total deformation [mm]		Allowed deformation [mm]
Connection	Rotational stiffness connection	-----	Nm/radian	-----	3,01E+07	Nm/radian	-		-
Total system	Translation global model	-----		2,09	-----		7,9	<	20
	Translation vandalized system	-----					308		-----

Table 17: overview of the results of the dimensioning process

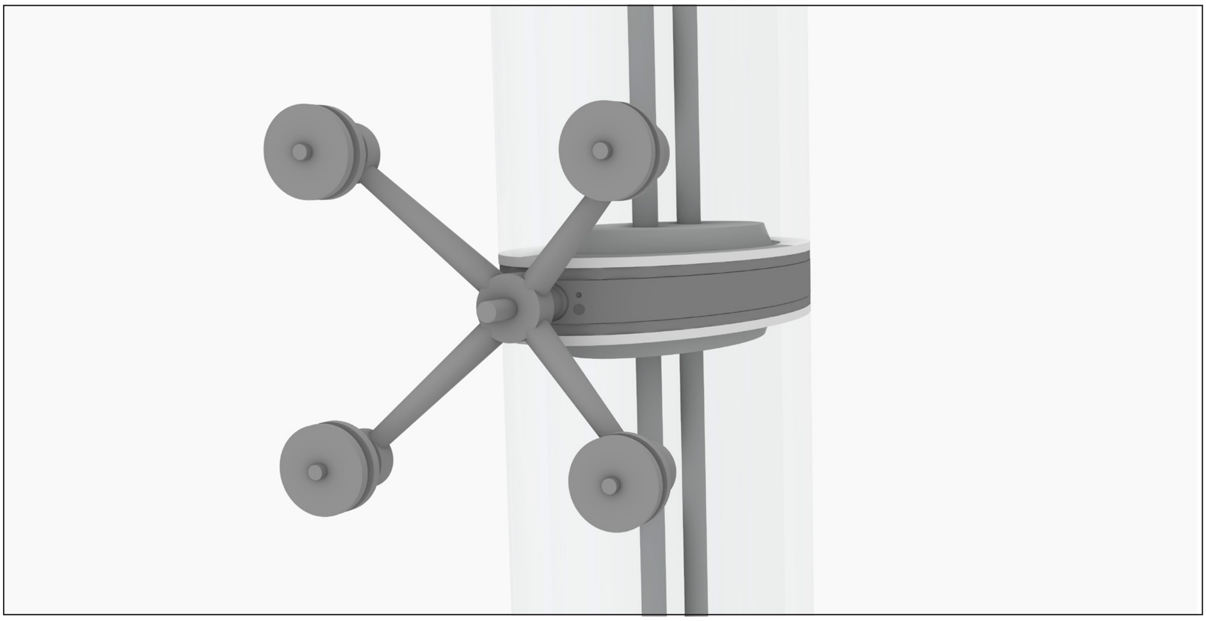


Figure 80: visualisation of the outcome of the dimensioning process

VII: CONTEXTUAL TESTING PART II

Now that the design has been dimensioned its performances should be confirmed before moving onto the building sequence and ultimately the final comparison.

Test 2: Test First design

See appendix D for research proposal.
The dimensioned design would be tested to get a validation of the numerical models that have been made and would also proof the structural performance it is calculated to have. Afterwards one last round of optimization could be commenced before calling the design finished.

For this test the set-up of the preliminary design could be re-used.

Continuing in this thesis the project has proceeded without this validation. This means that numerical results may be inaccurate with respect to the real world performances.

VIII: BUILDING SEQUENCE

In this chapter, the production, assembly, installation, inspection and maintenance of the dimensioned system is designed consecutively.

Production of segments of system

Since the focus of this thesis is not how to produce the connections, especially since other suitable connections could also be envisioned, not much time will be spent weighing alternatives for production. The designed connection serves as an example of what would be possible and how it could work and in a similar line of thought this chapter will serve as an example of how it could be produced.

The aim for the connection is to look minimalistic, polished and well-engineered. It has to fit the modern, special and luxurious affluence of glass architecture.

A segment of the designed system comprises of the following parts:

- Borosilicate glass section
- Steel rods
- Steel connection
- Desiccant holder
- POM rings
- Aluminium belt

Of each part the production will be discussed briefly.

Borosilicate glass section
The glass section is extruded through the process as described in 'Current Toolkit: Production Processes'. If this system were to be produced, it would be beneficial to have a number of standard dimensions in which the system is produced. This is customary for a lot of products for the built environment. Because making an aperture is expensive, the few standard dimensions would help reduce the costs as well as help the system to be more modular.

Steel rods
The steel rods can be rolled or extruded and afterwards screw thread can be created at both ends. No special attention will be paid to this part as this is standard procedure and the product has many applications in day-to-day life.

The steel connection
Casting the steel connection
The connection is cast in two parts obviously as a half is attached later to each end of the glass sections. For the casting process, several production techniques have been considered.
Sand casting and investment casting are both suitable processes. Sand casting is cheaper but due to its poor surface finish it requires more finishing later. It also has more limitations in geometry (Thompson, 2007).

Investment casting is slower and more expensive, but the quality of produced parts is very high and complex shapes with high integrity are possible. This process is also used for a lot of spider connection systems (Thompson, 2007).

Continuing it is imagined that the connection will be cast but lacks the exact precision needed and surface treatment is also required. In the case of investment casting the same treatments are needed but with less intensity.

Finishing the steel connection
In a casting process the creation of sharp edges are not really possible. This is why the element is casted with a little more material where sharp edges need to be. Later it can then be milled, grinded or polished to the desired geometry. The finishing techniques are described here in order of application and visualised in figure 83.

1: Milling
By milling the edges are sharpened. It is needed where a perfect fit with another part is needed. This is mainly where the belt needs to be placed and where the wall of the bottom half slides in the top half of the connection. Another use for milling is for making sure the bolt heads are sunken into the wall so it doesn't obstruct the belt.

2: Drilling
Because the casting process does not create perfect round holes, these are re-drilled to ensure a perfect fit for the bolt.

3: Polishing
All visible parts of the connection are polished to meet the aspired look. Also all parts are polished which are not milled or grinded but which do connect closely with another part to make sure the fit is perfect.

4: Grinding
To make sure the upper end of the connection is perfectly flat where it meets the other half in order to make the connection as stiff as possible, it needs to be grinded on a belt.

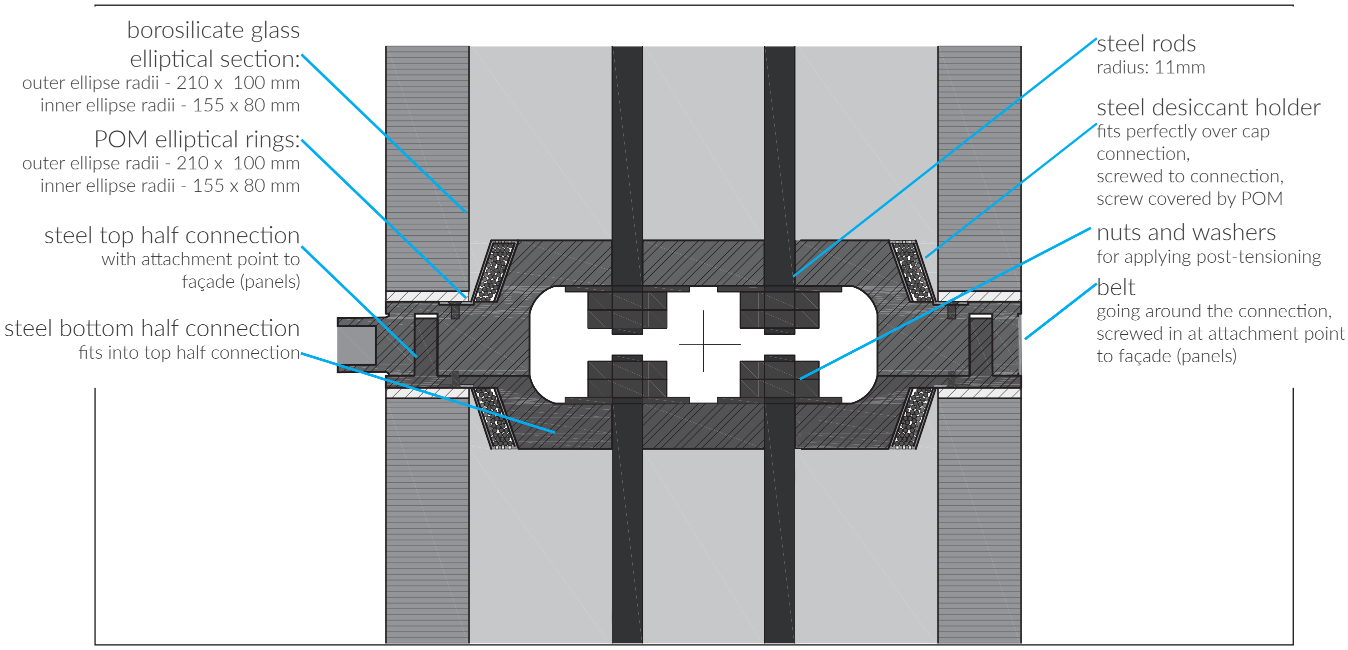


Figure 81: connection detail drawing 1:5

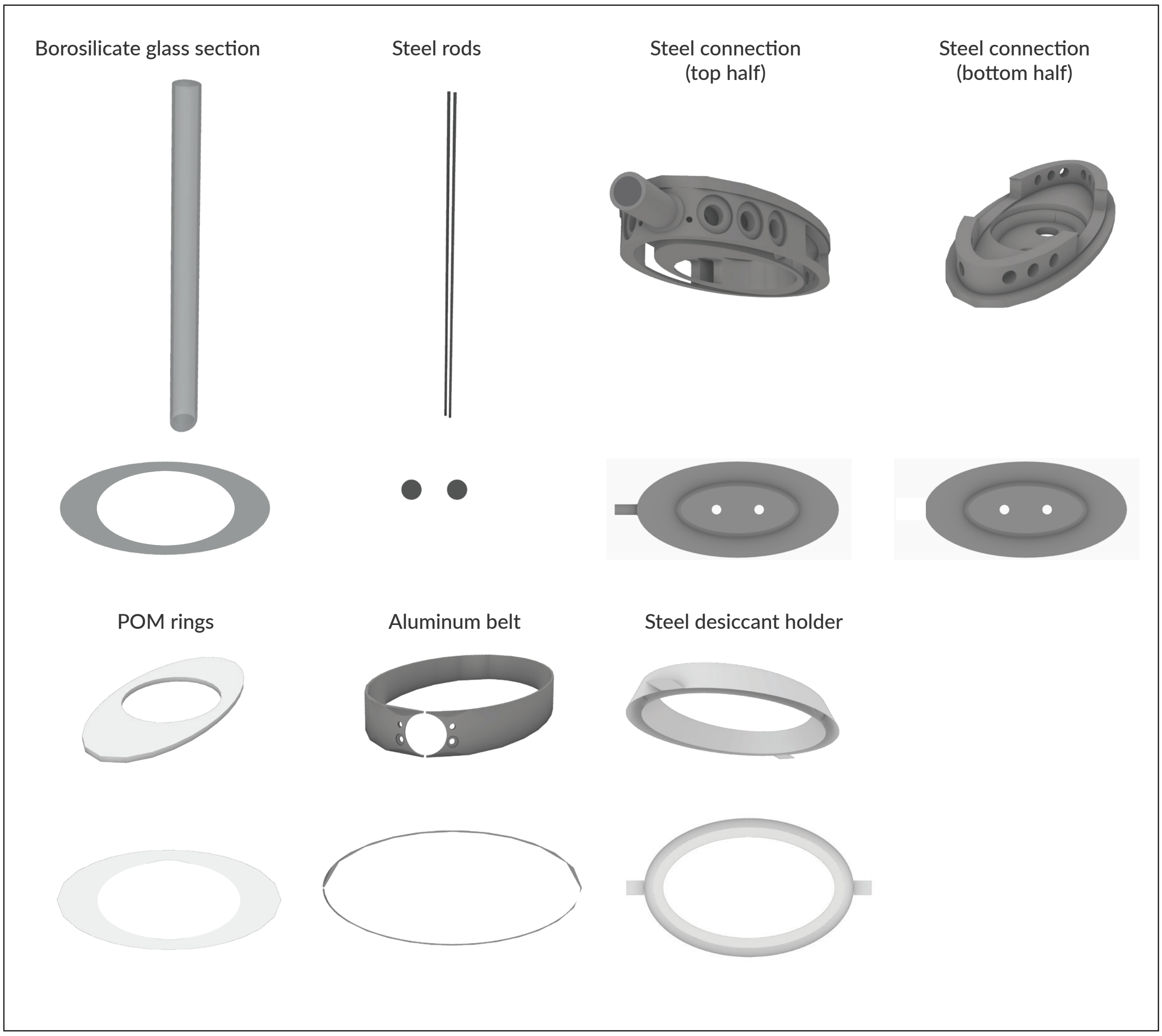


Figure 82: overview of all parts

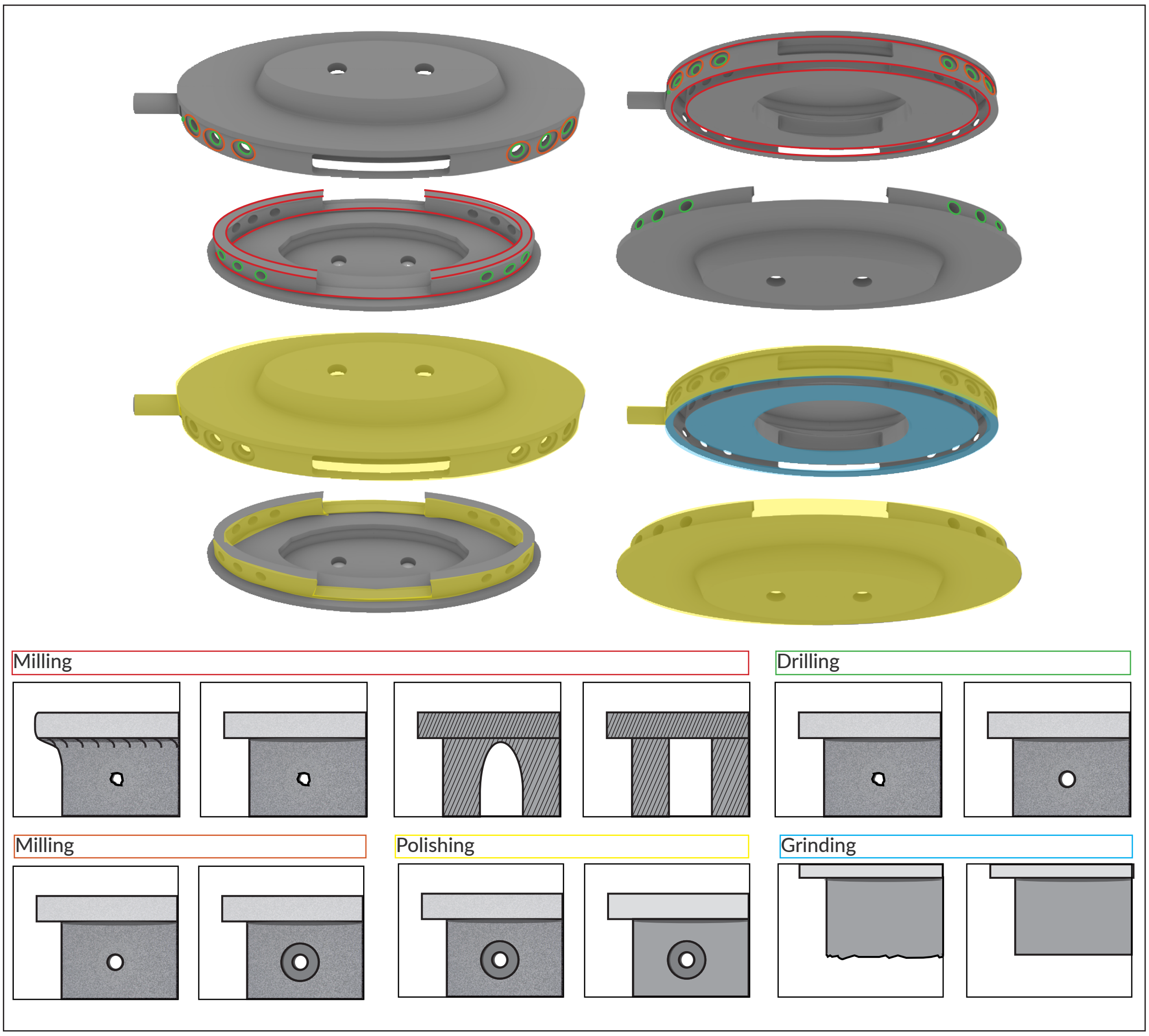


Figure 83: finishing techniques suggested for the connection

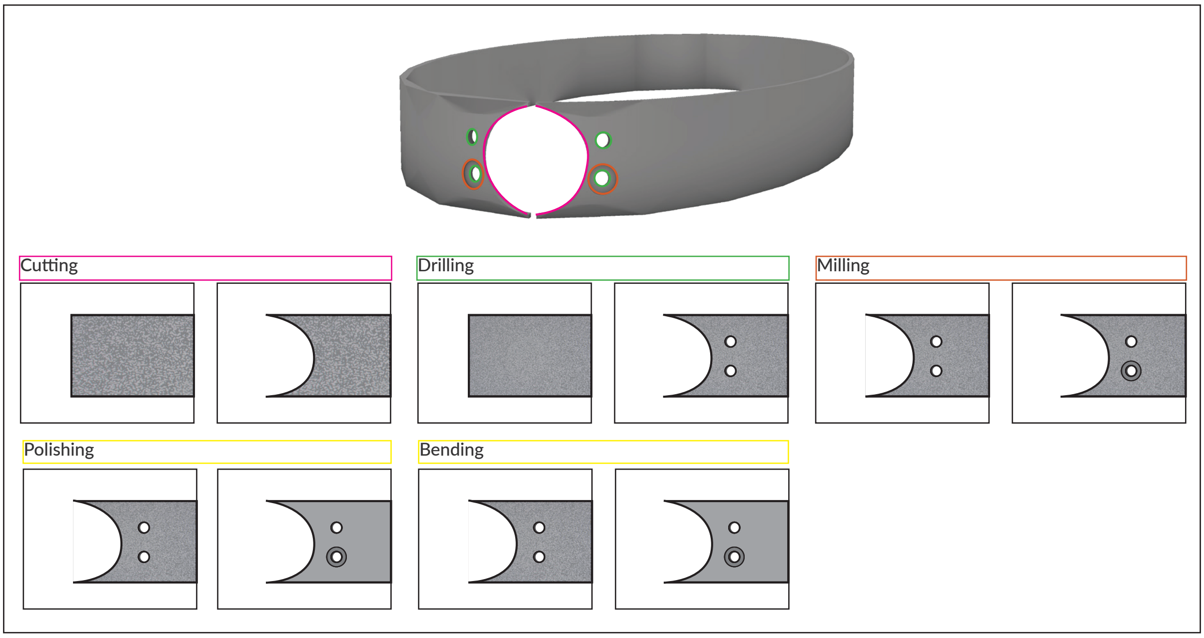


Figure 84: finishing techniques suggested for the belt

Belt

The belt is made of an elastic metal like an aluminium strip for example of about 3 millimetres thick. This is how it could be produced.

1. The strip is cut in order to fit around the connection to the spider system later.
2. Two holes are drilled in each end. One of them is for screwing the belt to the connection and some material around the hole is milled away to let the screw sink in. The other is there to aid attaching the belt to the connection. Grabbing onto these holes with a plier, the ends of the belt can be pinched together, aligning the second pair of holes with the holes in the connection.
3. The belt is then bent into shape and polished.

Desiccant holder

The desiccant holder is a part not discussed earlier but which is very necessary. Like in windows, cavities in glass can fog up over time, making the glass element look milky i.e. become less transparent. This happens when water somehow gets in and condensates. This has to be prevented, which in windows is done by placing desiccants in the window frame. The same technique is applied here. The desiccant holder could be is a cast metal part shaped to fit exactly around the cap of the connections. It is produced in similar fashion of the connection itself. The top plate is perforated in order for the desiccants to be in contact with the air inside the glass. It could also be made of gauze. During assembly, the desiccant holder is filled and screwed onto the connection. The screw sinks in the connection and the POM ring falls over it.

POM rings

POM (polyoxymethylene) is a high performance plastic and can be cut precisely by a laser cutter. Since this already has many applications in day to day life its production will not be discussed further.

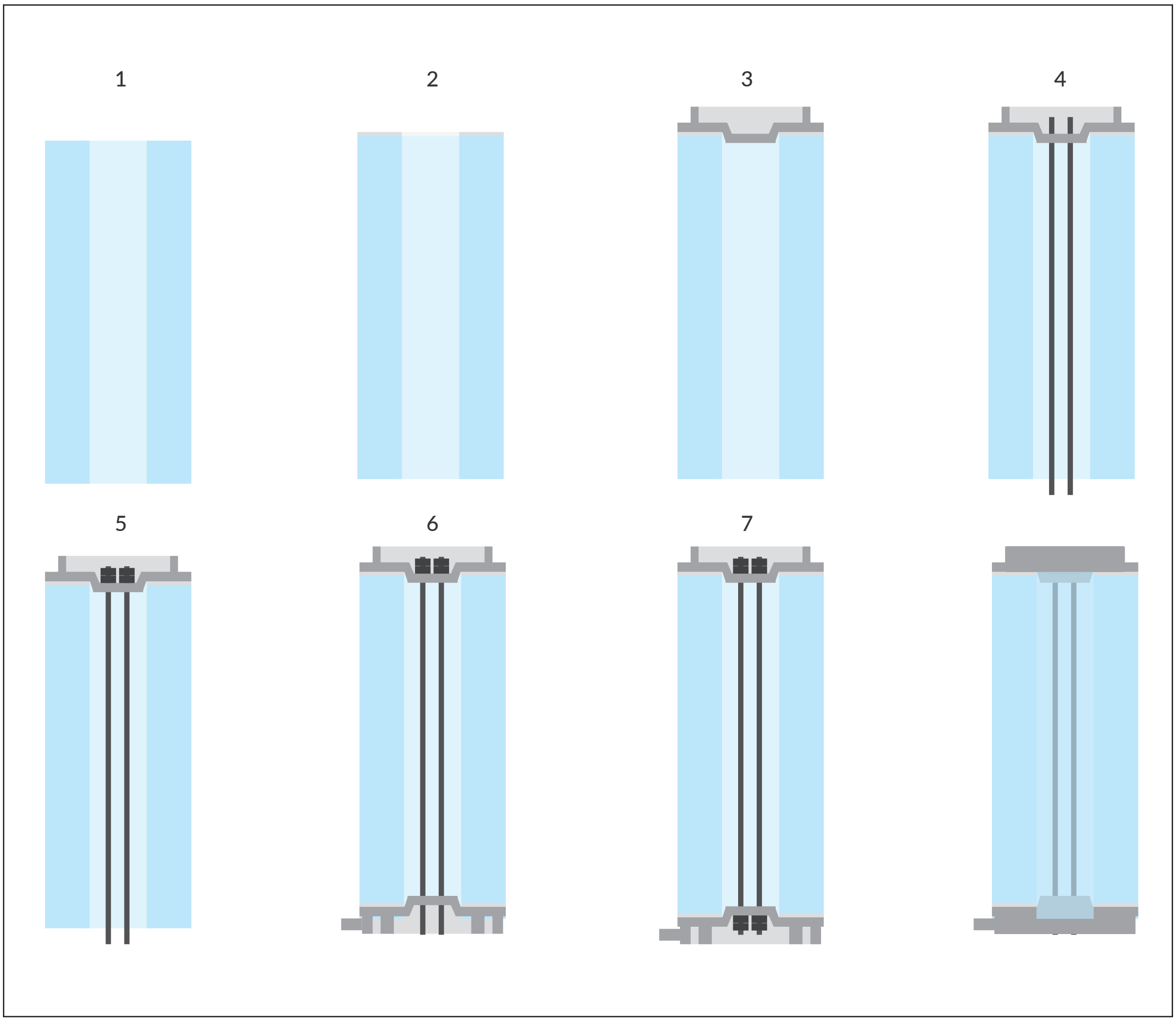


Figure 85: assembly of segment in section view

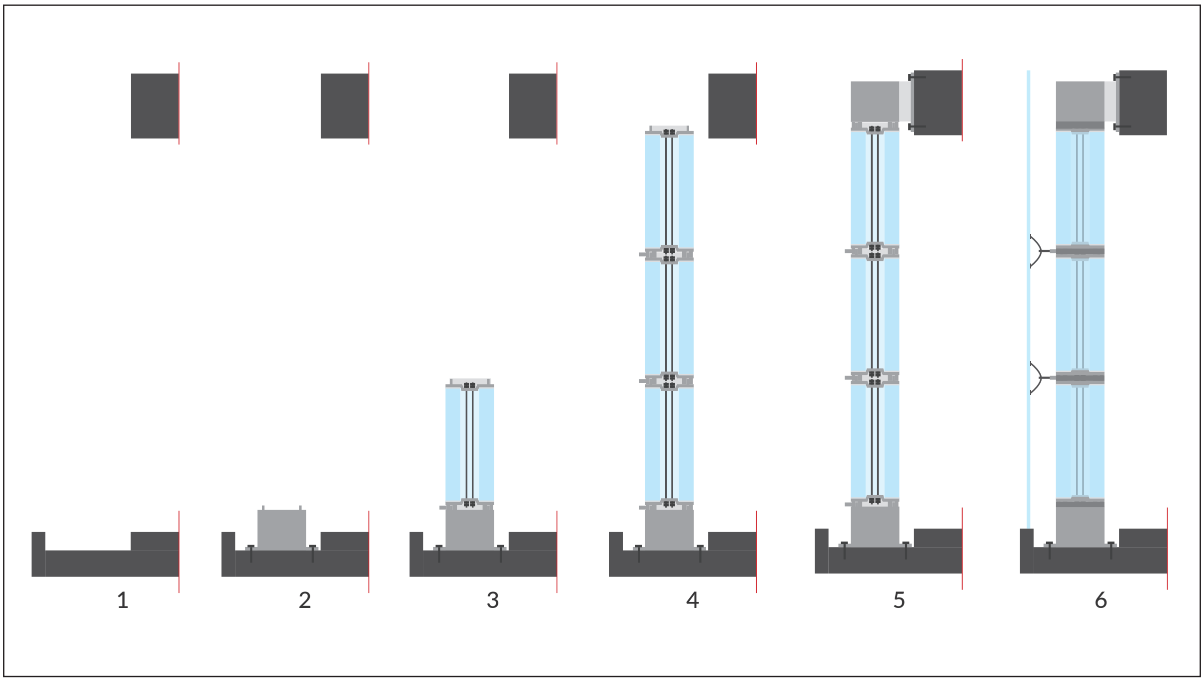


Figure 86: installation of system in section view

Assembly of segments of system

In the image series in figure 85, the assembly process of one segment is explained. This needs to happen under controlled circumstances where no dust and moisture can reduce the transparency by entering the hollow core.

1. The glass section is the starting point for the assembly process.
2. A POM ring is put on one end of the glass.
3. The connection, on which the filled desiccant holder has already been mounted, is then laid on the POM ring.
4. The rods are placed inside the glass section by sliding them through the holes in the connection.
5. The rods are secured on one end by placing the nuts inside the connection.
6. Then a POM ring and the other half of the connection is placed on the other side of the glass section. The rods slide through the holes in this connection too. This half of the connection has the attachment point for the façade connection too.
7. The rods are secured within this connection too. They are then post-tensioned by twisting the nuts tighter and tighter often alternating between the two and making sure the rods doesn't twist to prevent torsion. To do this, a torque wrench would be used.

Installation of designed system

In the image series in figure 86, the installation process of a façade system is explained. Special attention is paid to adjusting for construction intolerances.

1. The starting point is the floor where the system will be mounted on and the beam the system will be attached to. The floor has to be perfectly level for this which can be expected.
2. The base connection is bolted to the concrete of the floor. Later the cavity in the floor can be filled with concrete or covered with a lid or top floor.
3. The first segment is installed by lifting it in place and simply bolting it on.
4. This is repeated for all other segments the system comprises of.
5. The top connection is placed on the top segment.
6. The top connection is bolted to the beam and aligned perfectly with the beam already in place. How this can be achieved is shown in figure 90. The connection allows for translations in three directions before securing it.
7. Once the system is installed successfully, the belts can be placed over the connections. This is done by pinching the ends together through the top holes and using the bottom holes to screw the belt in place.
8. Now the system is ready for the glass panels and spider connections to be placed.

Maintenance and inspection

Inspection of glass structures typically consists of checking the connections and the glass itself. Connections often are weak points in a construction which is why special attention should be paid here. The steel parts can also be checked for corrosion, breakages and loose elements (O'Regan et al, 2015). It should also be checked whether the POM is degrading any way.

Also some months after installation, the post-tensioning level of the glass and the nuts inside the connection should be checked. This can be done by removing the belts of all segments and looking inside the connections to see if the bolts still align and offer the same resistance by working with the torque wrench again.

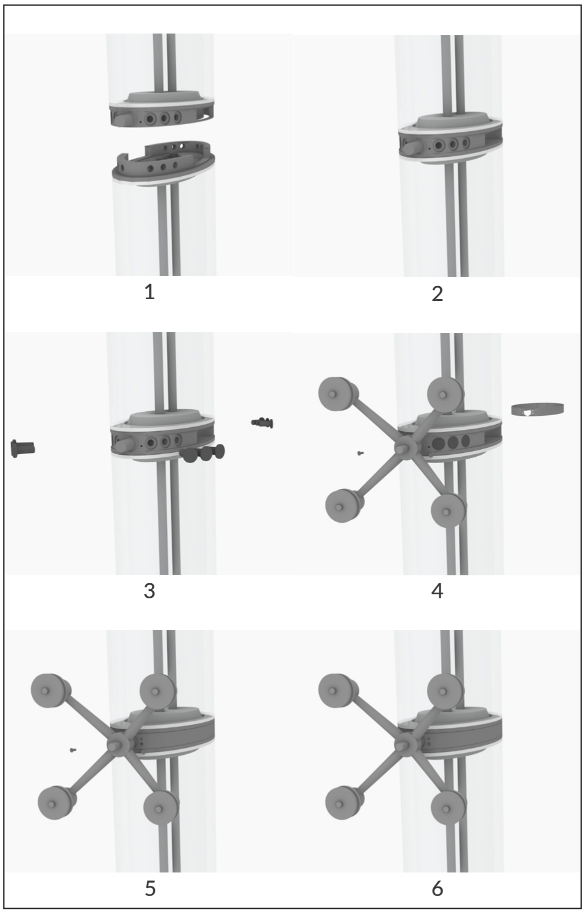


Figure 87: sequence of drawing displaying connecting two segments

1:5 Detail connection

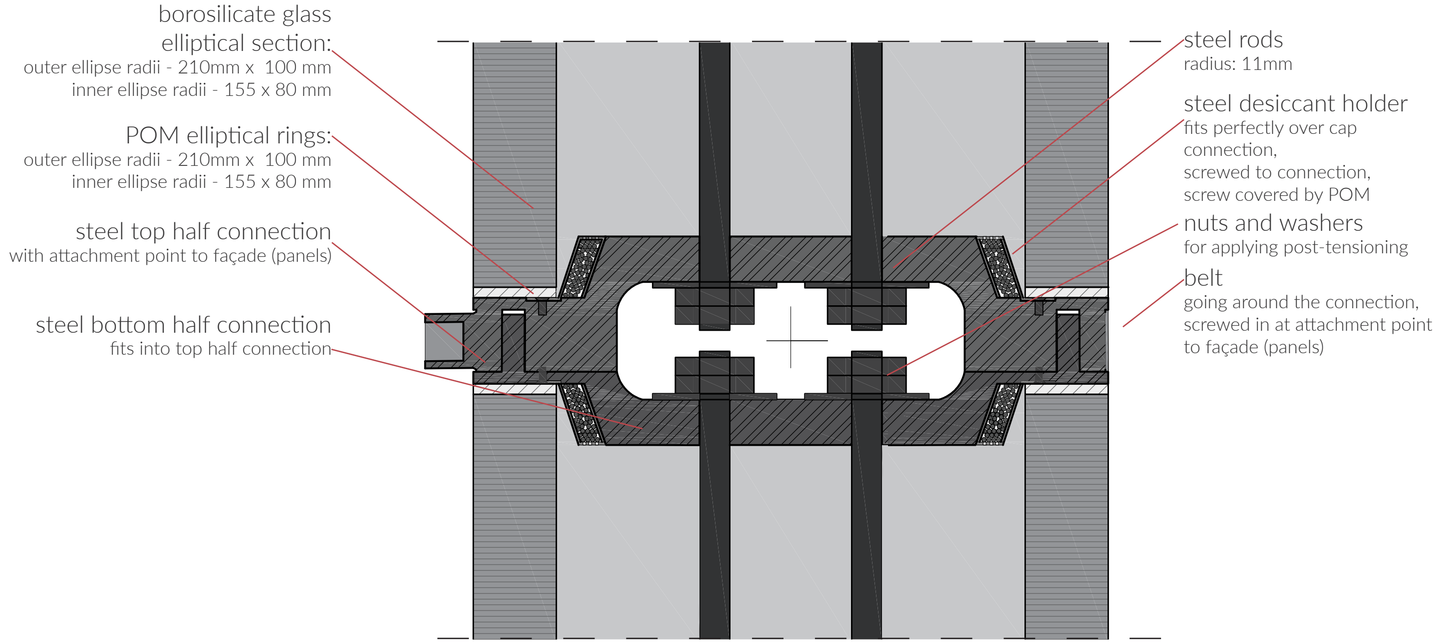


Figure 88: detail drawing of connection between segments

1:5 Detail base connection

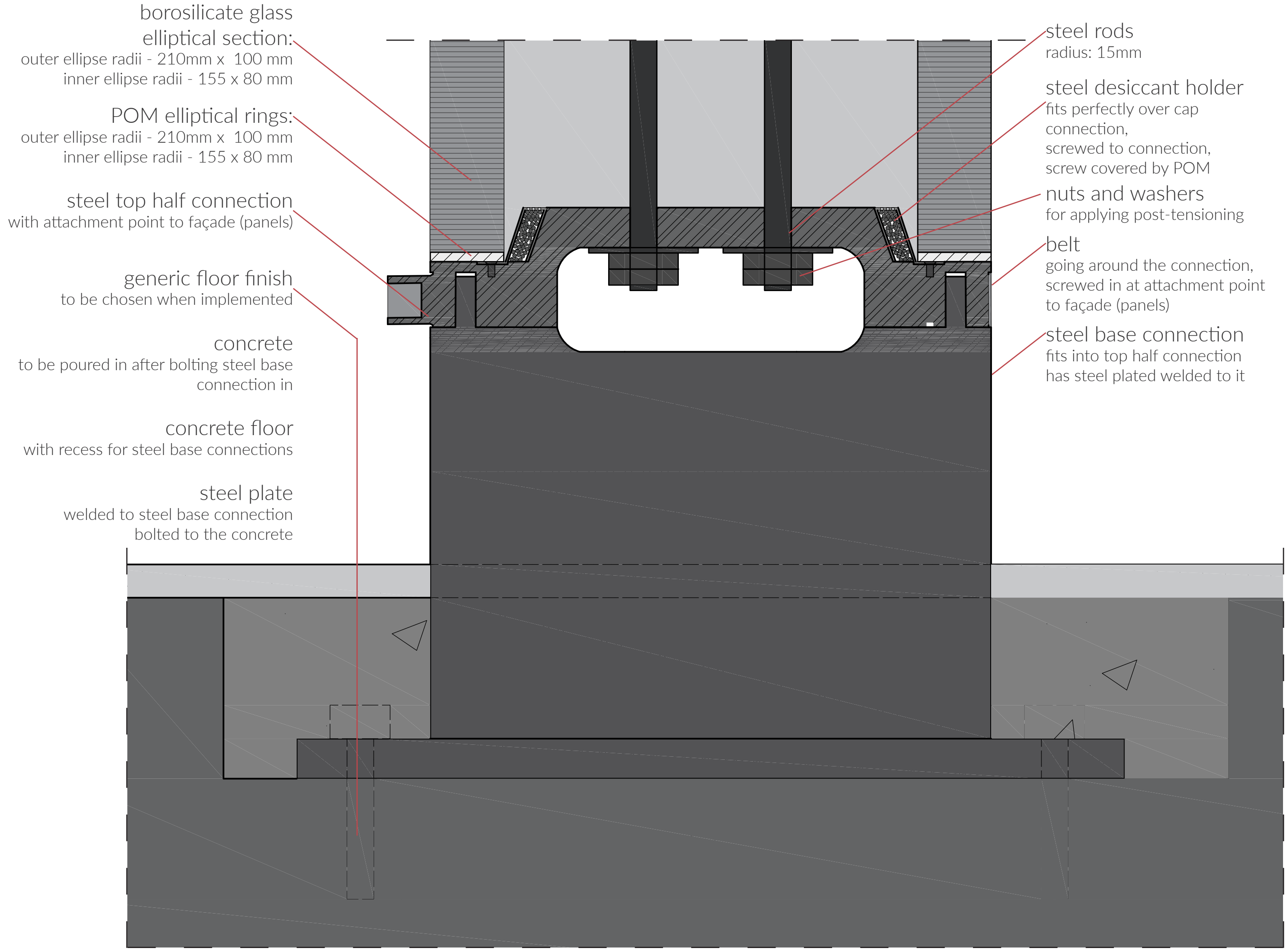
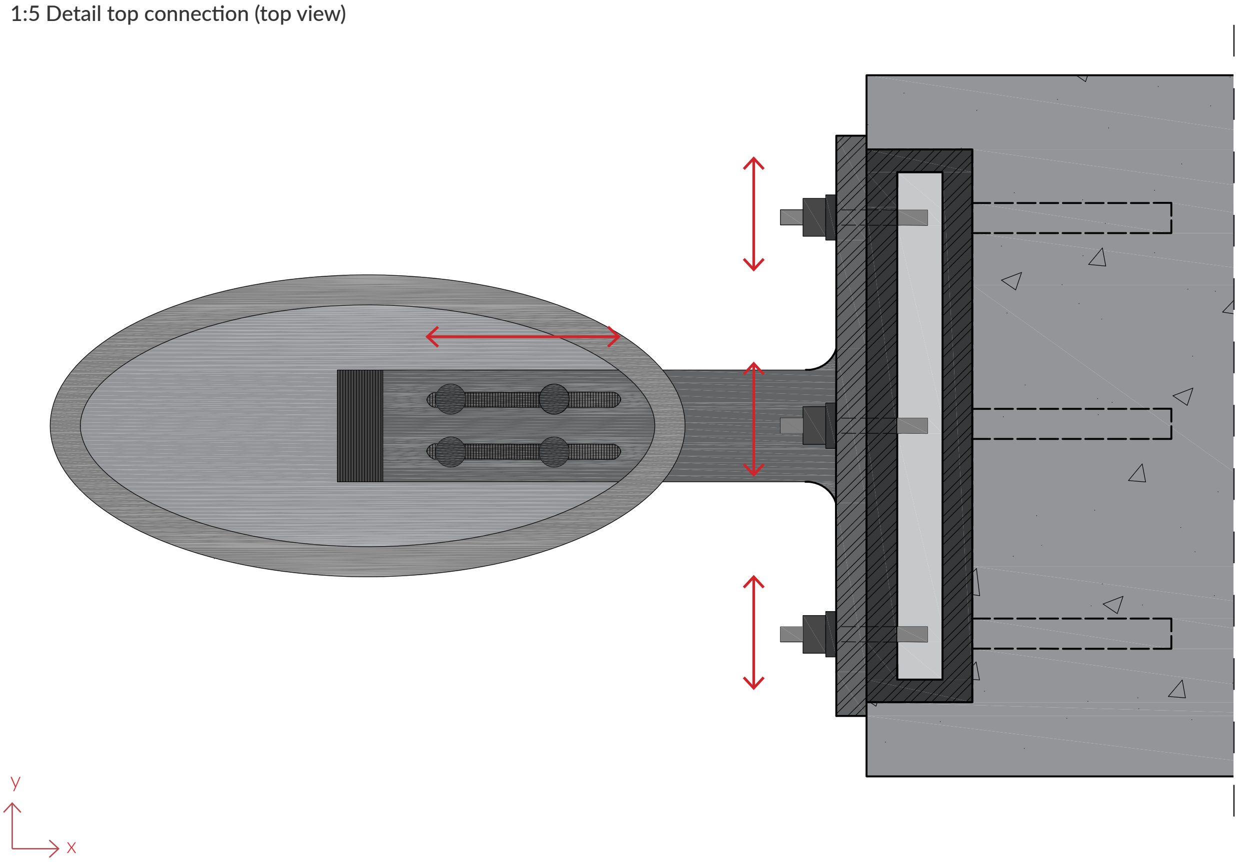


Figure 89: detail drawing of base connection

1:5 Detail top connection (top view)



1:5 Detail top connection (section view)

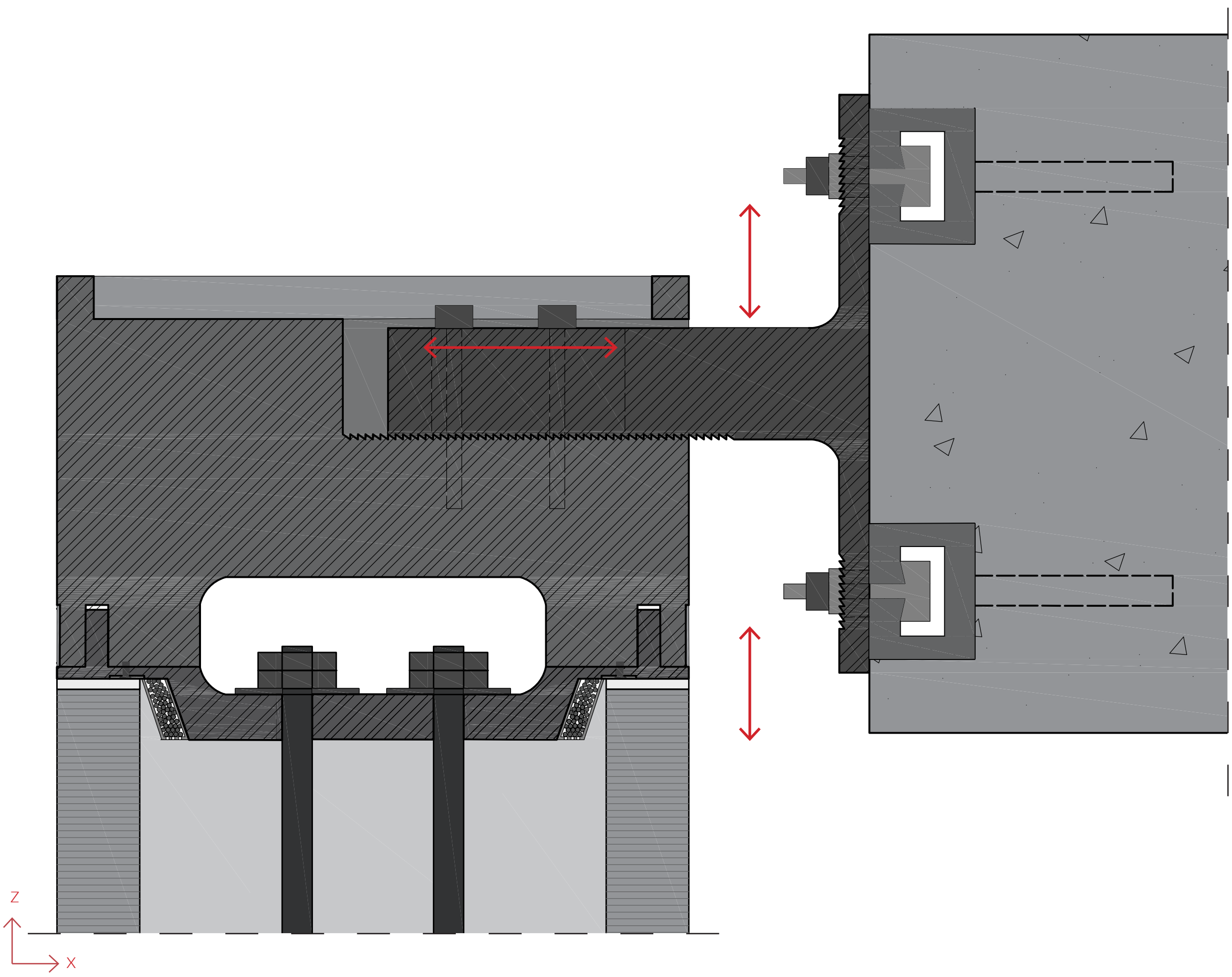


Figure 90: detail drawings of top connection

IX: IMPRESSIONS OF IMPLEMENTATION

To test the potential of the designed system for architectural implementation, visualisations are made showing the potential new addition to the toolkit in a number of architectural settings. Aesthetics are very important in architectural glass designs and although the beauty of the newly designed system is not assessed directly in the potential rubric, it would not have much merit if it didn't appeal to designers of the built environment adn average urban viewers.

What the designed system will be assessed on is the amount of visual variation it adds to the current toolkit, which is a second reason for including visualisations.

Visualisations in three different architectural settings are included to show the potential in a wide variety of contexts. All settings include an overview image and an image from close-up.

The images will be briefly discussed, highlighting certain aspects in an architectural and arguably very subjective manner. This is done more so to add a description with the images from the designer's standpoint than to provide a scientific analysis.

In the first setting the designed system is implemented in a rural art exhibition space which could also be part of a museum.

In the overview image it's notable how well the design blends into nature, accentuating the simplicity of the concrete shell, showing the beauty of the trees and letting in as much natural light as possible.

In the close-up image it's notable how the varying thickness section playfully distorts the perspective slightly. The system looks friendly with its curved surfaces and not as strict as a structural fin could come across, fitting this rural setting especially well.

Figure 91: overview visual impression of the dimensioned design in a rural setting

Figure 92: close-up visual impression of the dimensioned design in a rural setting

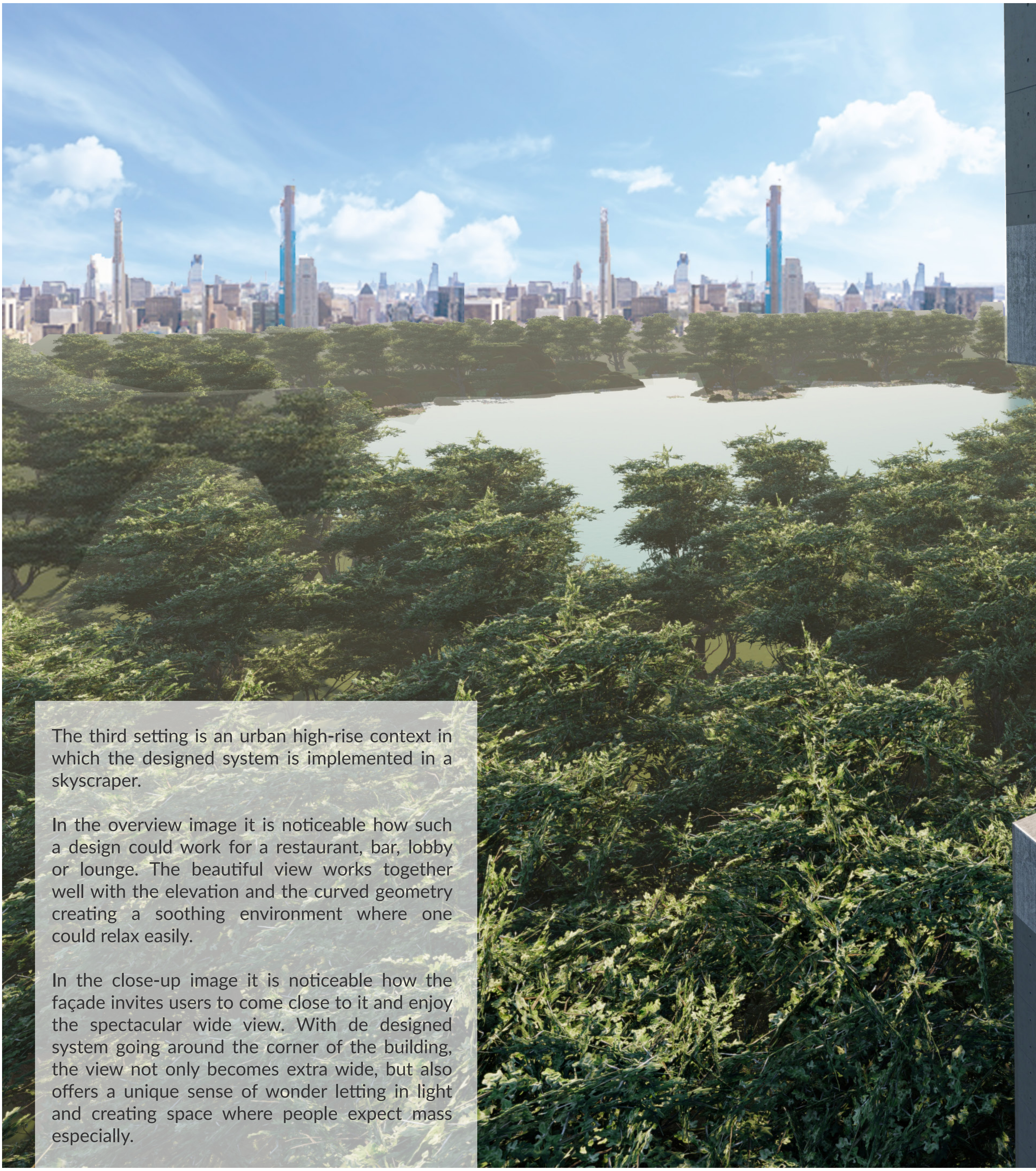
The second setting is an urban coastal context in which the designed system is implemented in a pavilion on a small beach.

In the overview image it is noticeable how such a design could work as a meeting point for citizens, a sightseeing point for tourists or a premium space for leisure. The space invites visitors to walk around the edges of the façade, enjoying a 360 degree view around the building where the city gradually makes place for the beach, fully allowing the experience of the great contrast.

In the close-up image it is noticeable how when the sunlight falls on the curved geometry, it creates unexpected effects and glares which constantly shift as you walk along the façade, always keeping it interesting. The fully transparent façade also always keeps users engaged with the river bank and the water in all kinds of weather. Always providing a special experience.

Figure 93: overview visual impression of the dimensioned design in a pavilion

Figure 94: close-up visual impression of the dimensioned design in a pavilion



The third setting is an urban high-rise context in which the designed system is implemented in a skyscraper.

In the overview image it is noticeable how such a design could work for a restaurant, bar, lobby or lounge. The beautiful view works together well with the elevation and the curved geometry creating a soothing environment where one could relax easily.

In the close-up image it is noticeable how the façade invites users to come close to it and enjoy the spectacular wide view. With de designed system going around the corner of the building, the view not only becomes extra wide, but also offers a unique sense of wonder letting in light and creating space where people expect mass especially.

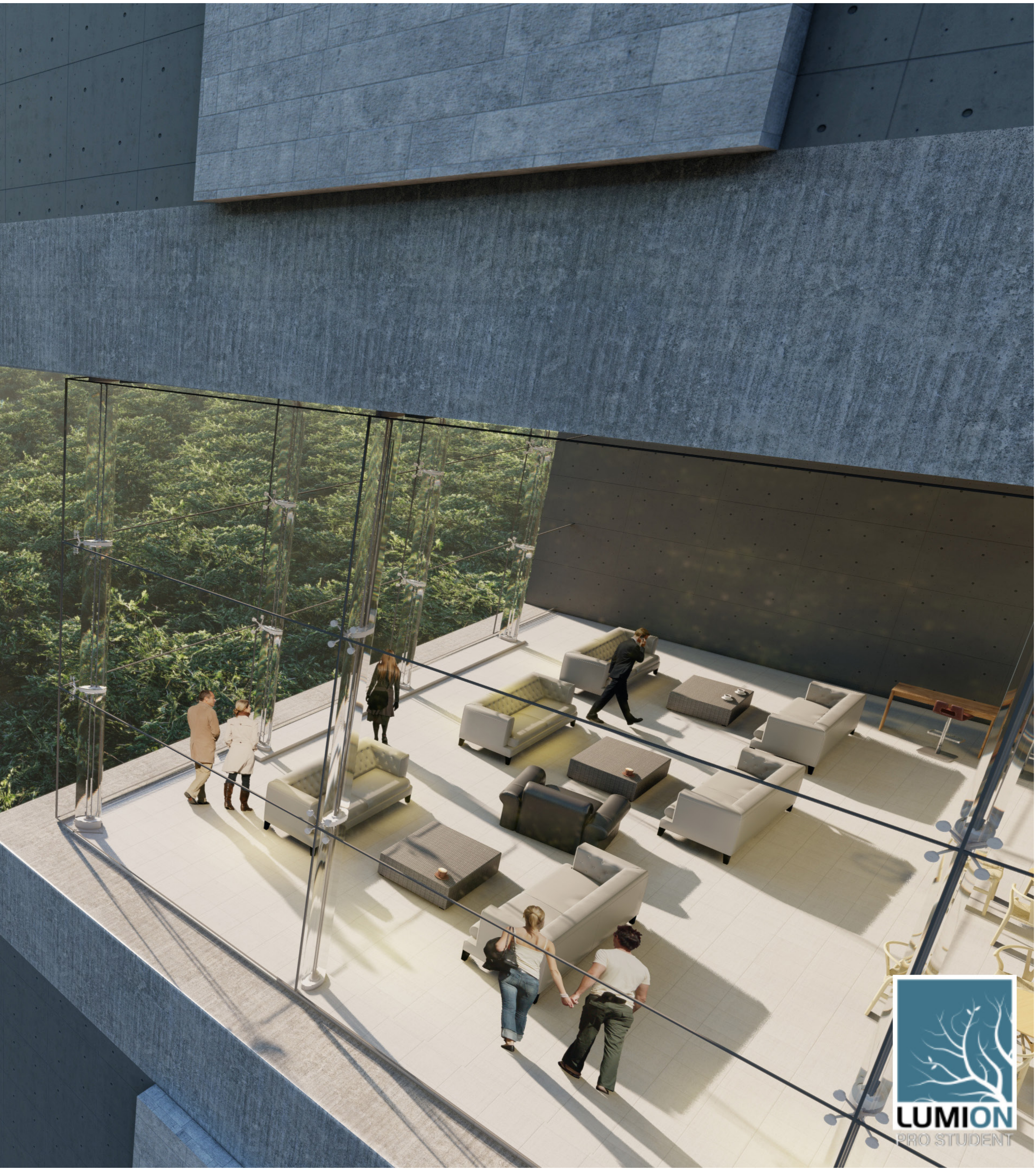


Figure 95: overview visual impression of the dimensioned design in a skyscraper

Figure 96: close-up visual impression of the dimensioned design in a skyscraper

X: DESIGNING WITH EXISTING SYSTEMS

To be able to offer a fair comparison and being able to evaluate the newly designed extruded system against current systems, the same façade column will be also be designed with its current main competitor which is almost solely implemented: the glass structural fin. The goal is to globally make a design to make a comparison against. This will especially be true for the dimensioning of the system. The goal is to know whether the dimensions of the extruded system are similar or not to existing products, not to get the needed dimensions of a structural fin exactly right.

The general parameters are exactly the same as they were for the extruded system, meaning that also here there will be a very high load without safety factors.

Glass structural fin

As explained the glass structural fin is the most widely used section active glass structural system. It is very minimalistic as glass panes are often laminated together in an alternating fashion and the seams between the glass panes are not very noticeable.

General design

For this design the fin will be clamped at both ends as is the extruded system. It will also make use of the same points to convey the load from the façade panels to the column, but it could also be imagined that the system would make use of line loads instead of point loads, supporting the façade panels along the entire height. One of the standard thickness of the panes is 12 millimetre. That's why the thickness of the column will be a multitude of that.

Safety concept:

The chosen safety concept is that of residual strength. This is achieved by having at least two layers of which one can be shattered.

Building sequence

Glass fins are produced out of laminated float glass panes.

Generally speaking, the installation comprises of the following steps:

1. The glass fin arrives in one piece at the building site with the base connections already attached.
2. The fin is lifted upright and is carefully lifted in position.
3. The fin is bolted in place.
4. The façade panels can be attached.

Dimensioning

First, the strength of the glass has to be calculated. To do this the equation from the 'Structural use of glass in buildings' (second edition) by the Institution of Structural Engineers is used and can be found in figure 97.

For the dimensioning of the fin the following calculations are performed to find the governing load case:

1. Max stress in the glass due to moments
2. Critical normal force
3. Critical moment

Max stress in the glass due to moments

The max stress in the glass is first calculated by hand and then checked by finite element analysis software DIANA. The hand calculation can be found in figure 99. The calculation of the stress is estimated to be slightly off because in the calculation the ends are not clamped.

When choosing the section dimensions, as seen in the figure 99, the stress in the glass is calculated to be over the calculated strength, but simulation shows that the maximum stress in the glass matches the maximum strength well.

For now the maximum stress in the glass due to moments is the normative parameter. The found dimensions will be used for the next test and can only get bigger, since otherwise it will not pass this test anymore.

Critical normal force

The next test is buckling due to normal force. For this also an equation from 'Structural use of glass in buildings' (second edition) by the Institution of Structural Engineers is taken. It is shown in figure 101. For this formula it is assumed that one pane is vandalized. This is necessary because the normal force is always the same and cannot be reduced for this calculation. When a pane is vandalized, the construction still has to be safe.

This parameter is estimated not to be normative because the column only has to carry its own weight and not a roof construction. This appears to be true since the found critical normal force is found to be lower than the actual normal force, which means the dimension from the previous test pass this test too.

For now the max stress in the glass due to moments is still the normative parameter. This is why the same dimensions are carried over to the next test.

Finding characteristic strength of toughened glass

$$f_{g;d} = \frac{k_{mod}\, k_{sp}\, f_{g;k}}{\gamma_{M;A}} + \frac{k_v\,(f_{b;k}\, f_{g;k})}{\gamma_{M;v}}$$

with

$f_{g;d}$ characteristic strength of the toughened glass
k_{mod} factor for load duration
k_{sp} factor for glass surface profile
$f_{g;k}$ characteristic strength of basic annealed glass
$\gamma_{M;A}$ material partial factor
k_v factor derived from the method of strengthening of the glass
$f_{b;k}$ characteristic bending strength of pre-stressed glass
$\gamma_{M;v}$ material partial factor for surface pre-stressed glass

$$f_{g;d} = 70.7\ N/mm^2$$

Figure 97: finding characteristic strength of toughened glass for dimensioning glass structural fin. Equation from (O'Regan et al., 2015)

Finding second moment of area needed for glass section

$$\sigma_{max} = zM/I_{needed}$$

with

σ_{max} maximum stress in glass because of wind load ($f_{g;d}$)
z maximum distance from center profile
M moment due to wind load
I_{needed} second moment of area

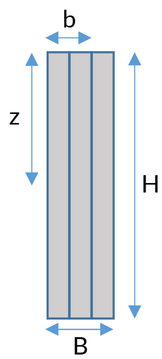
$$I_{needed} = 1.89 * 10^8\ mm^4$$

Figure 98: finding second moment of area needed for glass section structural fin for moment. Equation from (O'Regan et al., 2015)

Determining needed dimensions of glass structural fin for stress moments

H depth of glass structural fin
B width of glass structural fin
b reduced width of glass structural fin (upon vandalism)
z maximum distance from center

$$I_x = 1.52 * 10^8\ mm^4$$
$$I_y = 1.44 * 10^6\ mm^4$$
$$I_{y\ weakened} = 4.26 * 10^5\ mm^4$$



Chosen dimensions
H = 370 mm
B = 36 mm
b = 24 mm

Figure 99: determining needed dimensions of glass structural fin for stress caused by moments and relevant second moments of area

Model name:	Stress structural glass fin
Default Mesher type:	Hexa/Quad
Default Mesher order:	Quadratic Linear Interpolation
Geometry	Structural solid
Material(s):	Glass fin
Load(s):	Point loads
Supports:	T1 T2 T3

Figure 80: simulating the glass fin with the chosen dimensions of figure 99, the maximum stresses in the glass are found to be within allowable ranges. Equation from (O'Regan et al., 2015)

Critical elastic buckling moment

The next test is buckling due to the moment. For this another equation from the 'Structural use of glass in buildings' (second edition) by the Institution of Structural Engineers is taken. It is shown in figure 102. For this formula it is assumed that no pane is vandalized since the chance of vandalism in the most extreme load conditions is minimal. The outcome of this calculation will determine which moment would be fatal to the system in weakened state.

There are three variants to the equation:

1. For beams that are fully restrained along one edge of their length
2. For beams with intermediate restraints
3. For unrestrained beams

All three will be calculated to include a wide range of variants to the design.

This parameter is estimated to be normative because this is often the case and a relatively large moment is applied to the column. However, the column is not that long and clamped at both ends. This appears to keep it from being normative since the found critical elastic buckling moment is found to be higher than the occuring moment. This means the dimension from the previous test passes this test too.

The conclusion is that the stress in the glass due to the moments is normative and the found parameters in that calculation will be kept.

Costs

The following cost estimation is a very rough estimation mentioned in conversation with Professor J.D. O'Callaghan:

“By estimation a glass fin façade wall would cost approximately between €2500/m^2 and €4000/m^2 to be fabricated, shipped and built on site. The larger the fins (greater than 10 meter tall) the more expensive this would be. Large glass, over 10 meter long is significantly more expensive per area than glass under 8 meter for example. It’s not a linear relationship.

So, if you took the above as a guide and you assumed that the cost of the glass is around 40% of the overall installed cost, then you could say that glass fins are approximately €1000/m^2 to €1600/m^2 to make.”

This gives plenty of a reference for the purpose of this thesis.

Finding critical normal force

$$N_{cr} = \frac{\pi^2 EI}{L_{cr}}$$

with
N critical normal force under which it would buckle
E young's modulus of the glass
$I_{yweakened}$ stiffness of the column about the axis it will buckle
L_{cr} height of the column

$$N_{cr} = 8{,}2\ kN$$

Finding occurring normal force

$$N_{occuring} = H * b * L * \rho$$

with
H depth of glass structural fin
b reduced width of glass structural fin (upon vandalism)
L height of the column
ρ density of glass

$$N_{occuring} = 1.75\ kN$$

Figure 101: hand calculations critical normal force glass fin. Equation from (O'Regan et al., 2015)

Finding critical elastic buckling moment
variation: fully restrained one edge

$$M_{cr} = \frac{(\pi/L_{ay})^2 (EI)_y \left[\frac{H^2}{12} + {y_0}^2\right] + (GJ)}{(2y_0 + y_h)}$$

with
M_{cr} critical elastic buckling moment
L_{ay} distance between points of effective rigid rotational restraints
$(EI)_y$ effective rigidity for bending about the minor axis
H depth of beam
(GJ) effective torsional rigidity
y_0 distance of restrain to the neutral axis of the loading element
y_h location from the neutral axis of the loading point

$$M_{cr\ restr.\ one\ edge} = 86.8\ kNm$$

Figure 102: hand calculations critical elastic buckling moment glass fin. Equation from (O'Regan et al., 2015)

Finding critical elastic buckling moment
variation: intermediate restrains

$$M_{cr} = \left(\frac{g_1}{L_{ay}}\right) \left[(EI)_y (GJ)\right]^{1/2}$$

with
M_{cr} critical elastic buckling moment
g_1 coefficient of slenderness
L_{ay} distance between points of effective rigid rotational restraints
$(EI)_y$ effective rigidity for bending about the minor axis
H depth of beam
(GJ) effective torsional rigidity

$$M_{cr\ interm.\ restrains} = 106\ kNm$$

Figure 103: hand calculations critical elastic buckling moment glass fin. Equation from (O'Regan et al., 2015)

XI: FINAL COMPARISON

For the final comparison the rubric as formulated in the methodology is filled in after which the rubric's results are discussed.

Discussion

Structural performance: medium potential. This is mostly because the characteristic strength found in tests was not great. Very likely the strength and also the consistency can be upgraded by adding a quality control with the structural purpose of the elements in mind. Another way of improving the material's performance is improving the introduction of forces. So even though the structural performance could be improved and the geometry has certain advantages, it has to be said that at this point in time it's hard to beat the efficiency of structural fin which is a highly optimized system already.

Building sequence: high potential. In theory it could be installed by others than specialists however in practise there would still be an expert on site to guide the process. The segments delivered on site are of no especially large size which means they can be delivered by a regular truck. This is also an advantage it could have over structural fins, which always have to come pre-assembled as a whole. Additionally, individual parts can be replaced, which is practically impossible for a structural fin.

Safety: high potential. It is hard to make the designed elements have residual strength because layering them is hard due to the geometry and tolerances. This makes the system prone to be vandalized easily. However, it does make the façade stay in place by the steel rods, has a structural reserve through second load paths and is made out of a safety glass. Another point regarding safety which is not included in this rubric specifically is fire safety. The borosilicate glass used for the extruded system is much more heat resistant then the glass used currently for structural fins (O'Regan et al., 2015).

Sustainability: very high potential. The entire system is modular and dry-assembled so it can be taken apart easily. Also all parts of the system can be recycled. It has to be mentioned that structural fins can be recycled too but re-usage is tough because the system has to be reused as a whole instead of being able to alter the dimensions.

Costs: high potential. There are currently no facilities to produce the needed glass elements which heightens start-up costs. However if it would be widely implemented the production could be optimized which would lower the costs to make it probably compete against the structural fin.

Aesthetics: high potential. Although this naturally is the most subjective category, it could be argued that it offers great variation to the current toolkit. The elliptical cross sections, the connections and the rods within are all new to the structural glass toolkit and section active structural glass toolkit especially. Besides the criteria in the rubric, it could very well be argued that the designed system has the luxurious, well-engineered, and modern aesthetic that fits the toolkit for architectural glass so well.

Discussion by experts

The rubric is discussed by Ir. A. H. Snijder and Prof. J. D. O'Callaghan who commented the following on the assessment of the potential rubric:

Structural performance:
Structural performance is quite a broad term. There are two main components to it: geometrical stability and material strength. In terms of material strength this system is not as good as that of a structural glass fin, because of this you could argue that it has medium potential. However in terms of geometrical stability it's much better. Structural glass fins have an unrestrained edge which makes them weak for buckling. Suction caused by wind is often the governing load case for such systems. The fact that the extruded design doesn't have an unrestrained edge makes it far more stable. Because of this, you could even argue it has a very high potential.

Building sequence:
Regarding building sequence, the installation of the designed system might not be quicker than that of the structural fin, but surely less risk is involved. This comes into play again regarding the costs.

Sustainability:
No additional comments needed.

Costs:
The costs could be lower than that of structural fins. The material is generally speaking a third of the costs, another third is installation, the last third is a combination of all other things, like logistics, insurance, et cetera. The tooling costs of this product is high, while the material costs are low. This means the product is really most suitable for high volumes. You could manufacture this product in a number of standard dimensions. Instead of producing custom pieces for a hole in

	Exceeding optimal current glass designs	*Comparable with optimal current glass designs*	*Little below standards of current glass designs*	*Far below standards of current glass designs*
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
Structural performance	Structural performance of element better than structural fin of the same dimensions.	Structural performance of element comparable with structural fin of the same dimensions.	Structural performance of element worse than structural fin of the same dimensions, but still reasonably applicable.	Structural performance far worse than structural fin of the same dimensions. Silly dimensions needed to make it applicable.
Building sequence	Very fast installation, requires no man hours on site. Easy maintenance and replacement of parts. Better building sequence than structural fin façade.	Fast installation, requires little specialist man hours on site. Easy maintenance and replacement of individual parts possible. Comparable with installing structural fin façade.	Medium fast installation, requires some specialist man hours on site. Maintenance requires special equipment and/or people and replacement of individual parts is hard.	Slow installation, requires a lot of specialist man hours on site. Maintenance requires special equipment and people and replacement of individual parts is very hard or not possible.
Safety	Element gives timely warning before failure. Element well resistant to vandalism: no health danger for people upon failure and losing very little structural capacity.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is resistant to vandalism. Comparable to safety glass brick façade or glass structural fin.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is little resistant to vandalism.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is very little resistant to vandalism.
Sustainability	Designed system is modular, re-usable, and recyclable.	Designed system is Re-usable and recyclable.	Designed system is recyclable.	Designed system is not modular, re-usable, or recyclable.
Costs	Cheaper than glass structural fin	Comparable regarding costs with glass structural fin	Slightly more expensive than glass structural fin.	Much more expensive than comparable glass brick façade
Aesthetics	Offers a very different experience than existing products, adding great variety.	Offers a different experience than existing products, adding good variety.	Offers a slightly different experience than existing products, adding little variety.	Offers a very similar experience as existing products, adding very little variety.

Table 17: the potential rubric filled in for the final comparison

the building, the hole in the building should be sized to the pieces available. A structural glass fin will to some degree always be a custom solution with respect to dimensions but also to where the holes are. Furthermore you will always have to laminate it, raising labour costs.

So initially the costs will be higher as equipment to extrude glass elements of these sizes need to be developed, but once it is optimized it has the potential to be cheaper. It could also be cheaper in terms of risk. A glass fin has a higher chance of breaking during installation because of its size and when it breaks the financial and logistical consequences are bigger.

Aesthetics:
Ate: “Although I think it looks much better than a structural fin, I would say it offers a slightly different experience, adding little variety. You could say it is a combination of a structural fin and a cable net façade”.

James: “I believe you have succeeded in adding great variety".

Figure 105: a visualisation of the final design from close-up

Conclusion

This research aimed to explore the potential of section-active extruded glass structural elements for architectural design. Based on methodically weighing design alternatives, experimental research, qualifying forces, quantifying forces and comparing it to existing systems, it can be concluded that the the overall potential of section-active extruded glass structural elements for architectural design is high. The results indicate that the design has a promising potential.

Naturally physical testing is needed to affirm estimations and more research has to be done into almost every aspect to get the system market-ready. However the first indications and explorations necessitate to think positively towards the possibilities of such an extruded system. Important factors that need affirmation are:

- The structural performance of the design in bending. This is needed to affirm computer simulations.
- The exact costs of glass extrusion for elements of the desired dimensions. This is needed to estimate in what volumes it could be produced economically.
- The tolerances of the production process when extruding elements of the desired dimensions. This is needed to estimate how precise the system can be assembled and also how the glass segments play with the light once installed.

Recommendations

To further develop a section-active extruded glas structural system, the following steps are highly suggested:

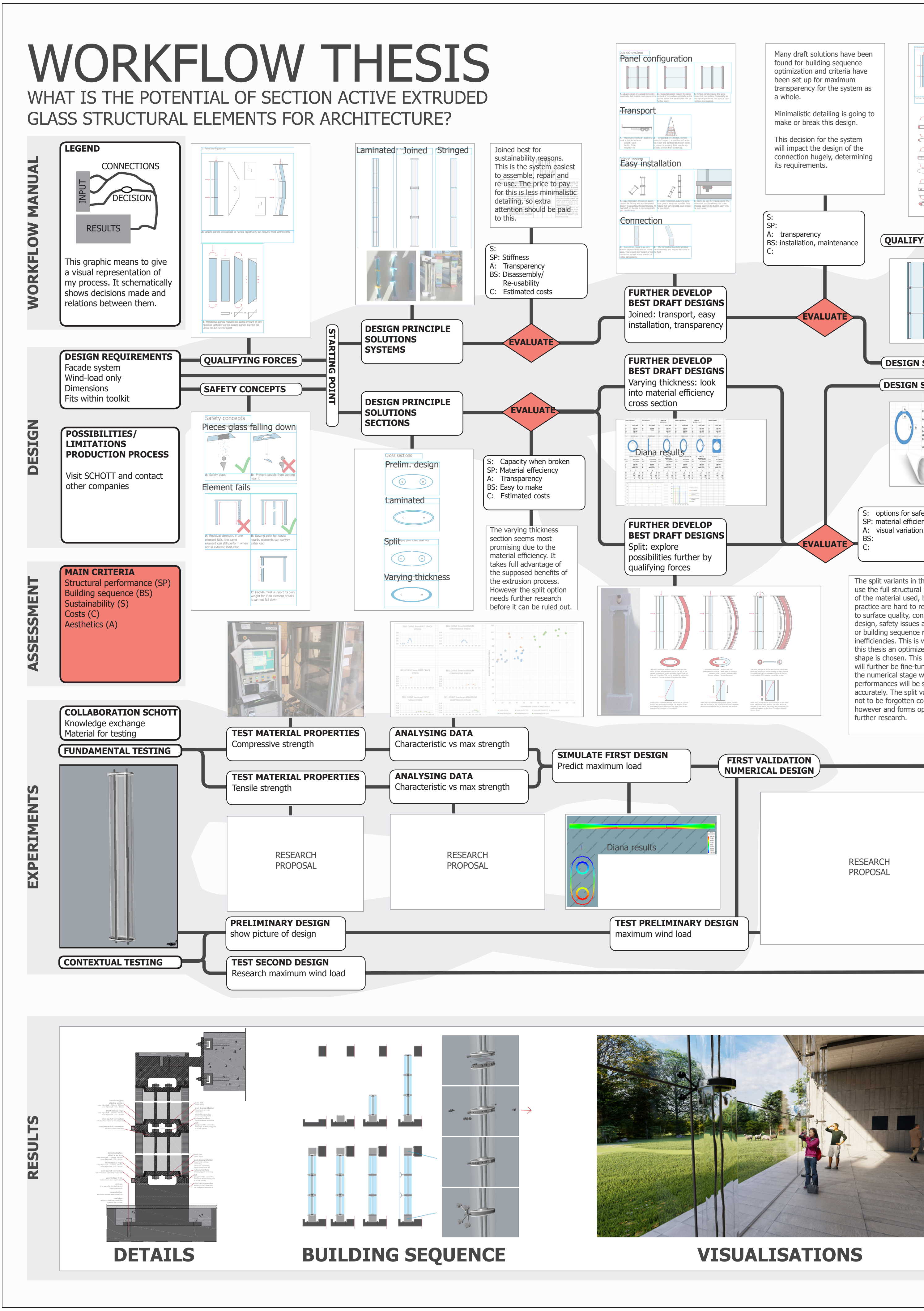
- To still execute the experiments as suggested in the research proposals written in the attachments. These experiments will give a proper indication of the structural performance of the designed system. To actually produce an element. This could be a costly operation as to the knowledge when writing this, no equipment exists with the dimensions needed to produce the designed system. Producing an element would give a good insight into the teething problems of the production and manufacturing process.
- To consult with potential manufacturers and research the costs of producing the designed system better.

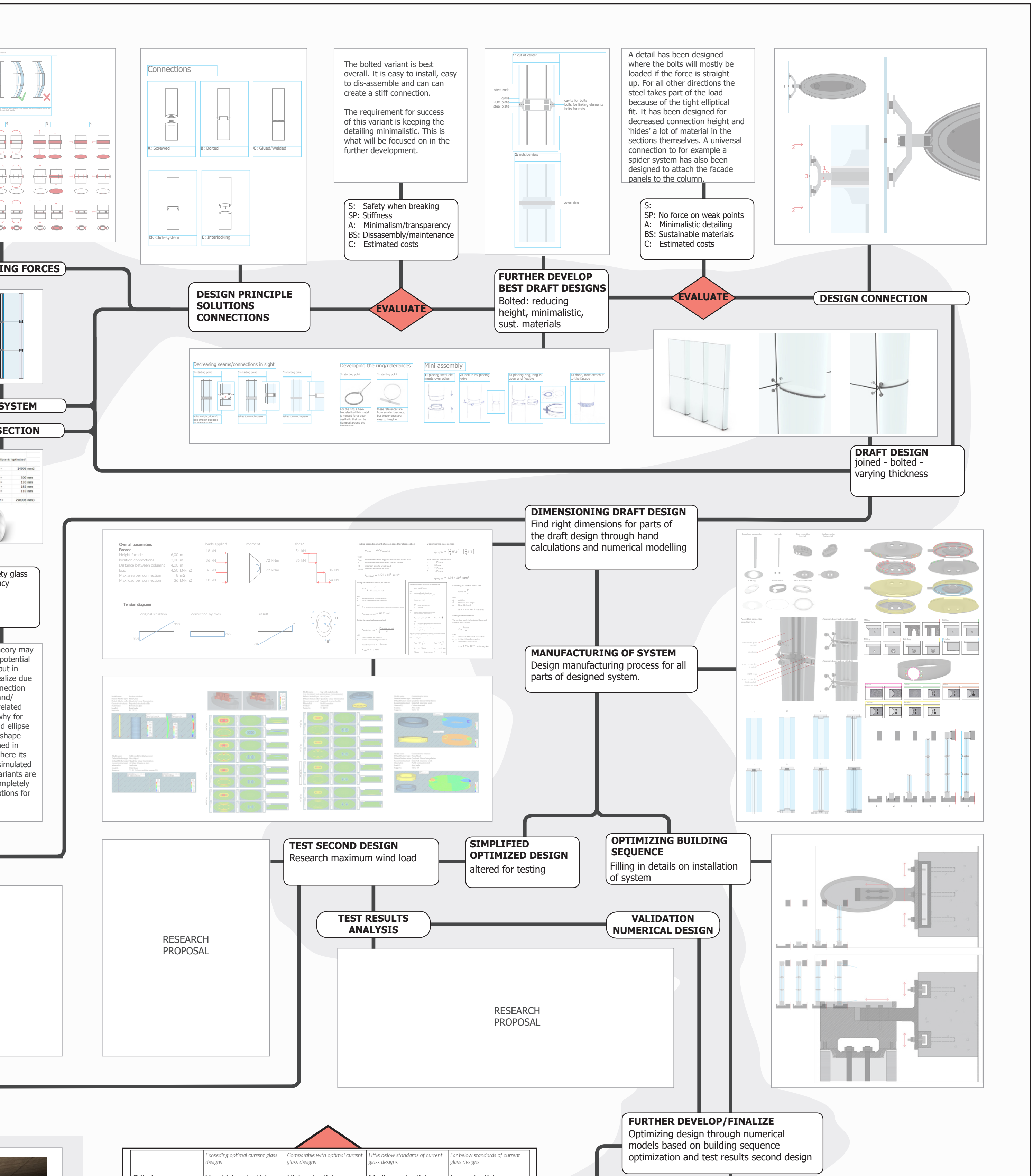
Also it could be worth looking into design ideas that did not make it but have potential value. A number of them are listed here:

- A split forces section. Regarded as aesthetically not as minimalistic as the varying thickness section, this design idea still has potential. It could be structurally speaking an interesting alternative.
- To only have one rod for post-tensioning instead of two. In the current design, two rods were chosen for being more stable in case of total failure of glass elements. One rod of slightly greater radius could convey the same post-tensioning as two thinner rods having the same combined surface area. However, as they are placed apart their second moment of inertia is greater than the one thicker rod. This doesn't mean that the one rod doesn't have advantages. It could aesthetically be more pleasing, simplifying the look and also mirrorring the single seam between the façade panels meeting at the column.
- Scaling the system up for larger buildings. When having tested the structural performances of the designed system, the design could be strechted to fit larger façades and finding the limits to the possibilities is very valuable for understanding it as an element of the toolkit.
- Optimizing the introduction of forces through other interlayers, different dimensions of interlayers and different connections like point connections. This could enhance the structural performance of the system significantly.
- Standardize the desiccant holder so the system will be cheaper. Designing is always a battle between performances, aesthetics and costs. Shaping the desiccant holder is especially an example of one of those battles. It could be imagined simpler and thus cheaper. The same logic applies to other components of the system as well of course. The logic could also be reversed and make the system more aesthetically pleasing or enhancing the performance but potentially adding costs. Once again the goal of this study was to explore the potential, not to come to the only design possible.

Workflow (completed)

Now all decisions required to find a final answer are made, the workflow is completely filled in and can be found in figure 106.


WORKFLOW THESIS
WHAT IS THE POTENTIAL OF SECTION ACTIVE EXTRUDED GLASS STRUCTURAL ELEMENTS FOR ARCHITECTURE?
WORKFLOW MANUAL
LEGEND
CONNECTIONS
INPUT
DECISION
RESULTS
This graphic means to give a visual representation of my process. It schematically shows decisions made and relations between them.
DESIGN
DESIGN REQUIREMENTS
Facade system
Wind-load only
Dimensions
Fits within toolkit
QUALIFYING FORCES
SAFETY CONCEPTS
STARTING POINT
POSSIBILITIES/ LIMITATIONS PRODUCTION PROCESS
Visit SCHOTT and contact other companies
Laminated
Joined
Stringed
Joined best for sustainability reasons. This is the system easiest to assemble, repair and re-use. The price to pay for this is less minimalistic detailing, so extra attention should be paid to this.
S:
SP: Stiffness
A: Transparency
BS: Disassembly/ Re-usability
C: Estimated costs
DESIGN PRINCIPLE SOLUTIONS SYSTEMS
EVALUATE
DESIGN PRINCIPLE SOLUTIONS SECTIONS
EVALUATE
Safety concepts
Pieces glass falling down
Element fails
Cross sections
Prelim. design
Laminated
Split
Varying thickness
S: Capacity when broken
SP: Material effeciency
A: Transparency
BS: Easy to make
C: Estimated costs
The varying thickness section seems most promising due to the material efficiency. It takes full advantage of the supposed benefits of the extrusion process. However the split option needs further research before it can be ruled out.
Panel configuration
Transport
Easy installation
Connection
FURTHER DEVELOP BEST DRAFT DESIGNS
Joined: transport, easy installation, transparency
FURTHER DEVELOP BEST DRAFT DESIGNS
Varying thickness: look into material efficiency cross section
Diana results
FURTHER DEVELOP BEST DRAFT DESIGNS
Split: explore possibilities further by qualifying forces
Many draft solutions have been found for building sequence optimization and criteria have been set up for maximum transparency for the system as a whole.
Minimalistic detailing is going to make or break this design.
This decision for the system will impact the design of the connection hugely, determining its requirements.
S:
SP:
A: transparency
BS: installation, maintenance
C:
EVALUATE
QUALIFY
DESIGN S
DESIGN S
EVALUATE
S: options for safe
SP: material efficier
A: visual variation
BS:
C:
The split variants in th use the full structural of the material used, practice are hard to re to surface quality, con design, safety issues a or building sequence r inefficiencies. This is w this thesis an optimize shape is chosen. This will further be fine-tur the numerical stage w performances will be s accurately. The split va not to be forgotten co however and forms op further research.
ASSESSMENT
MAIN CRITERIA
Structural performance (SP)
Building sequence (BS)
Sustainability (S)
Costs (C)
Aesthetics (A)
EXPERIMENTS
COLLABORATION SCHOTT
Knowledge exchange
Material for testing
FUNDAMENTAL TESTING
TEST MATERIAL PROPERTIES
Compressive strength
TEST MATERIAL PROPERTIES
Tensile strength
ANALYSING DATA
Characteristic vs max strength
ANALYSING DATA
Characteristic vs max strength
SIMULATE FIRST DESIGN
Predict maximum load
FIRST VALIDATION NUMERICAL DESIGN
RESEARCH PROPOSAL
RESEARCH PROPOSAL
Diana results
RESEARCH PROPOSAL
CONTEXTUAL TESTING
PRELIMINARY DESIGN
show picture of design
TEST SECOND DESIGN
Research maximum wind load
TEST PRELIMINARY DESIGN
maximum wind load
RESULTS
DETAILS
BUILDING SEQUENCE
VISUALISATIONS



	Exceeding optimal current glass designs	*Comparable with optimal current glass designs*	*Little below standards of current glass designs*	*Far below standards of current glass designs*
Criteria	**Very high potential**	**High potential**	**Medium potential**	**Low potential**
Structural performance	Structural performance of element better than structural fin of the same dimensions.	Structural performance of element comparable with structural fin of the same dimensions.	Structural performance of element worse than structural fin of the same dimensions, but still reasonably applicable.	Structural performance far worse than structural fin of the same dimensions. Silly dimensions needed to make it applicable.
Building sequence	Very fast installation, requires no man hours on site. Easy maintenance and replacement of parts. Better building sequence than structural fin façade.	Fast installation, requires little specialist man hours on site. Easy maintenance and replacement of individual parts possible. Comparable with installing structural fin façade.	Medium fast installation, requires some specialist man hours on site. Maintenance requires special equipment and/or people and replacement of individual parts is hard.	Slow installation, requires a lot of specialist man hours on site. Maintenance requires special equipment and people and replacement of individual parts is very hard or not possible.
Safety	Element gives timely warning before failure. Element well resistant to vandalism: no health danger for people upon failure and losing very little structural capacity.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is resistant to vandalism. Comparable to safety glass brick façade or glass structural fin.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is little resistant to vandalism.	Element gives timely warning before failure or there is no health risk for people upon failure. Element is very little resistant to vandalism.
Sustainability	Designed system is modular, re-usable, and recyclable.	Designed system is Re-usable and recyclable.	Designed system is recyclable.	Designed system is not modular, re-usable, or recyclable.
Costs	Cheaper than glass structural fin	Comparable regarding costs with glass structural fin	Slightly more expensive than glass structural fin.	Much more expensive than comparable glass brick facade
Aesthetics	Offers a very different experience than existing products, adding great variety.	Offers a different experience than existing products, adding good variety.	Offers a slightly different experience than existing products, adding little variety.	Offers a very similar experience as existing products, adding very little variety.

Figure 106: the empty workflow as designed to aid the design process

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APPENDIX A: EXPERIMENT
COMPRESSIVE STRENGTH EXTRUDED BOROSILICATE GLASS

Relevance
Structural behaviour of glass products vary per production technique, finishes applied, introducing of forces and geometry. This is why it is important to establish certain characteristics of extruded glass products used for this design. like maximum compressive stress and maximum tensile stress. To be able to validate accurate numerical models and to gain a better understanding of the structural behaviour of the design, these fundamental properties need to be researched ultimately in order to research the potential of section-active extruded glass structural elements for architecture.

General
Goals
The goal of this experiment is to find an input parameter for the design of the section active extruded glass structural glass system, especially in order to make accurate numerical models.

Main question
What is the maximum compressive stress the glass samples can be subjected to without showing defects?

Sub questions
- What is the maximum compressive stress to which the samples can be subjected to without failing?
- How does observed sample quality relate to test performance?
- How do the performances of the hardened samples relate to the non-hardened samples?
- Are the forces induced equally?
- How does the glass fail and why?

Methodology
1. Theorize: what will happen when the samples are tested? What is needed? What are the hypothesis?
2. Choose setup: determine what would be the right machine/setup for the experiment. Things to take into consideration: safety, applying the force in the proper manner and from the proper direction, force needed, and availability.
3. Inspect samples: inspection of samples was extra important for our experiment because the samples had been in storage for a long time and some of them were already rejected or used for other experiments.
4. Perform tests: this is where the actual tests were performed.
5. Analyse: were the hypothesis true? How can what happened be explained?
6. Conclude: give final answer to the main and sub questions.

Material property vs element property
Three different groups of samples with different dimensions are selected for this test. Comparing results of the different dimensions will paint the relationship between material properties and shape factors. This relationship can then also be extrapolated roughly to larger sections.

The samples will in theory be tested for their weakest spot because the compression would be the same everywhere. In reality this could be different because of the introduction of forces which is done by the POM layers. It should be noted that the edges of some of the samples are not of great quality meaning that there could be peak stresses there even despite the POM.

Characteristic strength vs average strength
In practice the average strength is not the normative value as obviously about half of the elements would fail when the maximum load is applied. Rather, characteristic strength is used to perform calculations with.

Characteristic strength is defined as that level of strength below which a specified proportion of all valid test results is expected to fail. For this experiment no specified proportion is set beforehand, rather afterwards the characteristic strength will be defined. To help find this value, normal distributions of the test results will be made.

Hypothesis
The theoretical maximum compressive stress is 220-380 N/mm^2 according to material database CES (Granta Design Limited, 2019). However, this will only be the case with perfect surface quality and introducing of forces. In reality this maximum stress will be lower. How much lower will be hard to tell for now.

The maximum compressive force the samples can take without showing defects will be lower

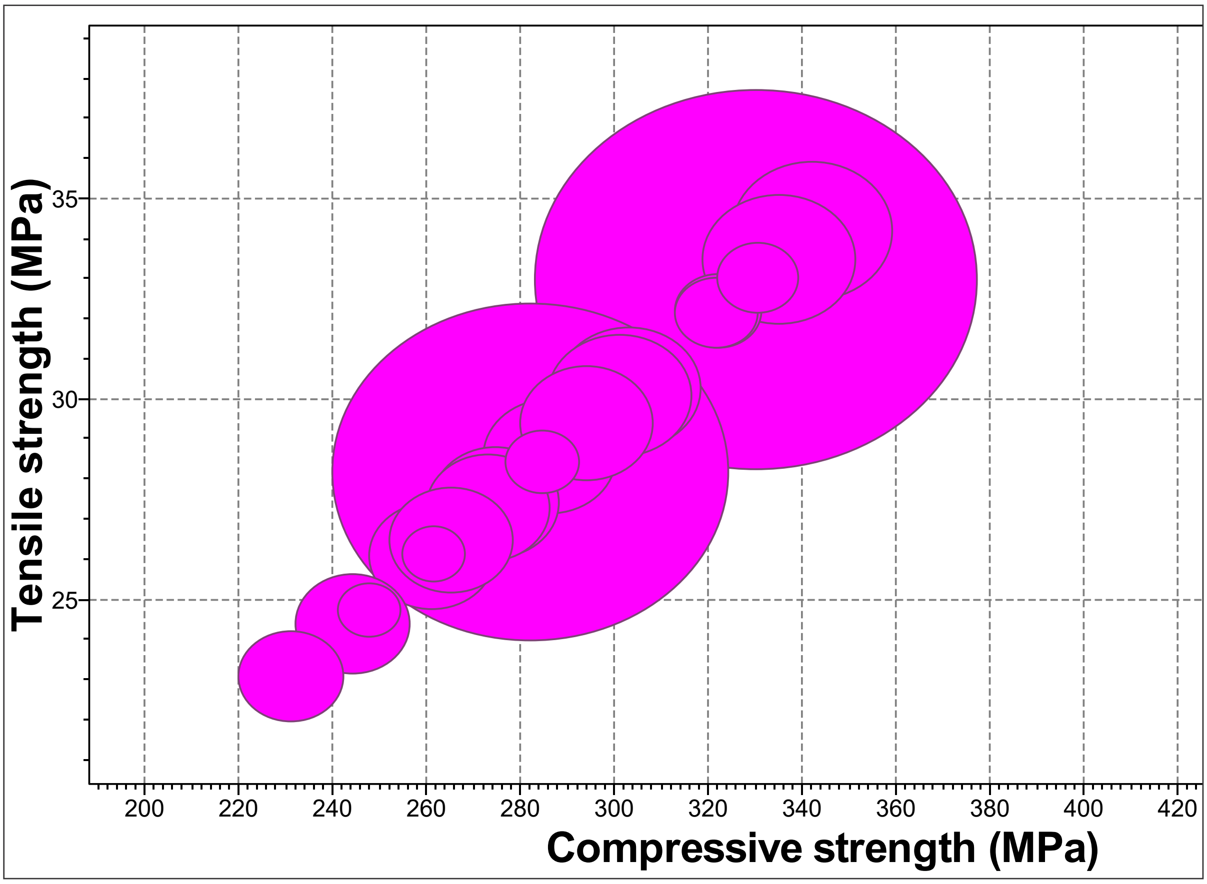

Figure 102: the tensile and compressive strengths of borosilicate glasses (CES, 2019)

than the maximum compressive force. If the forces are induced perfectly however and the samples are flawless, the sample would shatter at the maximum compressive force without prior defects. This is because the stress level in the entire element will be raised over the threshold at the same time.

The samples will not be of flawless quality and the introduction of forces will not be perfect so they will fail differently. They are expected to have cracks over the height of the element, shattering parts of the sample. This will likely result in little or no residual compressive capacity.

It is expected that the forces are mostly induced equally. This is because of the hinging platform in the Toni-bank. This platform corrects automatically and ensures that the sample is not loaded eccentrically. However, the samples could have irregularities in shape. If this is the case, the sample will still be loaded eccentrically. To find out if the samples are loaded correctly, two samples will be checked by strain gauges to see if they are loaded evenly.

The hardened samples are expected to have a higher maximum compressive stress. When glass is hardened, it's characteristic strength increases with about a factor 1.5. It is reasonable to also expect this from these samples.

Considered set-ups

Toni bank

Not a lot of alternatives are researched for this experiment because the available option didn't have real drawbacks.

What was used is the Toni-bank which is mostly used as a cube crusher for concrete samples. It is capable of generating forces up to 3000kN through oil pressure. The ball head on one end ensures it's level with the sample at all times.

There are two major settings: motion controlled and force controlled. Motion controlled was chosen for this experiment because it is more controlled and 'leftovers' can be inspected better. It is needed to keep in mind that most displacement will be because of the POM. The glass has such a high E-modulus that it will hardly change shape before failing.

Variations on Toni bank

There are other similar machines which could also perform this test. A more accurate variant was also available for example, but the estimated force needed couldn't be generated by this piece of equipment.

Inspection samples

As the samples have been in storage for a while and some of them are rejected for other projects, inspection on edge quality and surface quality was extra important. Almost every sample had flaws. It is expected that flaws in the middle of the element do not matter if they are only minor. Peak stresses are expected along the edges, dictating where the cracks will be. This is why edge quality is leading in categorizing them.

Four distinctively different qualities were observed:

1. (almost) Flawless. No observable imperfections along the edges.
2. Slightly flawed. One or two observable minor imperfections along the edges.
3. Flawed. One or more obvious imperfections along the edges.
4. Incomplete. Large piece of glass missing along the edges.

If a sample is observed to comply with group 4, it will be placed there. Otherwise it is checked whether it complies with group 3. If not it is checked whether it complies with group 2. If not it is automatically placed in group 1.

Samples are checked by holding them towards the light and looking into the cross-section and surface while turning the sample looking for distortions of the image. Then the edges are checked extra by running fingers over the outer edges and feeling for bumps, dents etc. For each sample the perceived flaws and irregularities are documented by drawing them on a set template.

Two flawless samples are fitted with strain gauges to see if the forces are induced equally around the entire shape of the sample. Samples of the first category are chosen to see if in such a perfect case the forces are applied properly. If they were fitted on a sample with lower quality and the data would show the forces are not induced equally, this could also be a result of bad sample quality.

It is expected that when these products would be applied in architecture, quality control would prevent all samples not of the first category to be considered suitable. These samples are still tested for this experiment however to get an insight in the relation between performances and perceived quality.

Equipment used

- Toni-bank connected to computer with controlling software
- Samples: 17x 5mm WT (wall thickness) 70mm OD (outer diameter) glass tubes, 6x 9mm WT 70mm OD glass tubes, 10x 5mm WT 120mm OD glass tubes (hardened)
- Material for between machine and glass to induce forces equally
- POM plates with at least 20mm space on all sides
- Camera for pictures/videos
- Protection against glass shrapnel
- 6x Strain gauges

Strain gauges

Strain gauges are devices to measure strain on an object. The kind used for this experiment has a metallic foil which resistance changes as the sample deforms. There are two elements which will have strain gauges during this experiment. A 9mm sample and a 5mm sample. These elements have three strain gauges each distributed equally along the cross-section and in the middle of the length of the tube. If the strain gauges of a sample all report the same deformation over time, that means that the force is most probably distributed equally.

It would be most ideal to have all samples equipped with strain gauges. However, due to budgetary reasons only two samples are equipped with strain gauges. This will most likely also gives a good insight in how other samples are loaded too.

POM plates
In this experiment POM plates will be used as interlayer between the machine and the samples. POM is a high-end plastic which is 'softer' than glass. It will compress more than and before the glass will. It will form itself around the glass and make sure the forces distribute equally. It has been successfully used in other structural glass projects as intermediate layer.

Safety instructions
Previously to performing the test, we received a general safety instruction by Peter de Vries and we also discussed safety concepts for our experiment specifically. Kevin Mouthaan supervised this experiment. Both are Delft University of Technology's Civil Engineering staff members.

Results
The graph in figure 105 shows data of all samples. It shows the force building up over time (data points). The sample names are built as follows: [sample number].[observed quality: 1-4]_[group: 9mm/5mm/hardened]_[day of testing: D1-D3].

The samples tested the first day were recorded with many more data points per second than the others. For this graph they have been modified to

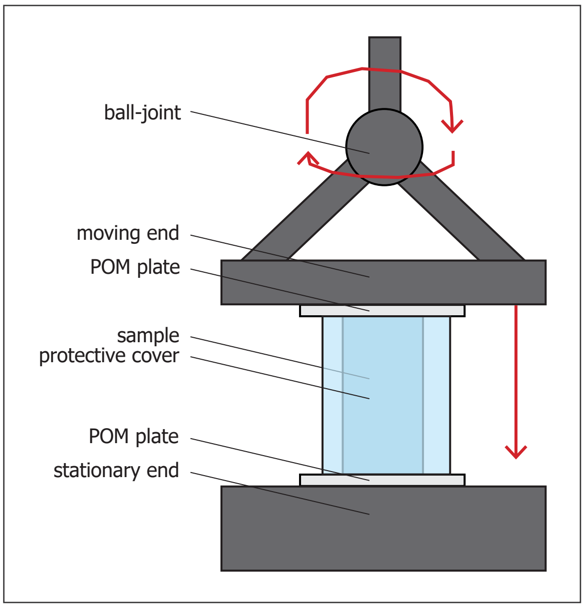

Figure 103: schematic drawing of the Toni bank set-up

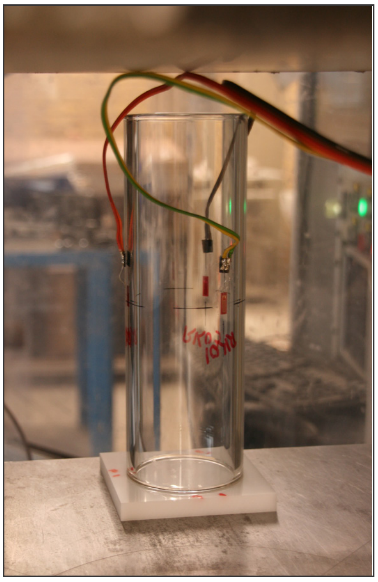

Figure 104: pictures of the strain gauges (left) and Toni bank set-up (right)

fit in with the rest of the graph and give an easier visual conclusion by deleting five out of six data points. They are still not on an equal time scale with the others, but that is not significant for this purpose.

It is obvious that the hardened samples needed most force to destroy and the 5mm group the least force. However, that does not conclude anything until it is divided by the section area. That will give the stress and this value will be compared.

Wat is remarkable about this graph is the fact that samples often had a lot of residual capacity after failing. Failing often meant a piece of glass missing from top to bottom. Sometimes similar force levels could be conveyed with only half of the profile still standing. This is a sign of the fact that the actual maximum compressive stress of glass is much higher than the values found. Because Force is equal and surface of cross section is lower, the stress level is higher.

This strain gauge data shows the strain against the force. The data of the strain gauges are cut off after the strain gauge has broken off after failure. This gives an easier visual conclusion and the deleted data points are not relevant.

It is clear that the sample of 5mm was equally stressed. There is almost no difference in strain. Even when the sample fails, there is very little difference. From this it is safe to say that the POM worked nicely and the experiment is conducted well.

For the 9mm sample it is less obvious. From the start it moved in a slightly different direction. What we see is that the blue line has a 30% difference along the time of the experiment. From this it can be concluded that the forces were not induced perfectly. However, it could still be acceptable as in practice the elements could be loaded slightly eccentric too.

In this table all final data is displayed: compressive force at first crack, compressive stress at first crack, maximum compressive force, maximum compressive stress and z-distribution.

The z-distribution is a normal distribution with a mean of zero and standard deviation of 1. Almost all (about 99.7%) of its values lie between –3 and +3 according to the Empirical Rule. Values on the Z-distribution are called z-values, z-scores, or standard scores. A z-value represents the number of standard deviations that a particular value lies above or below the mean (Rumsey, 2016).

The maximum compressive stress is in some cases even higher. This is possible because a large section of the sample may have shattered already and the sample was still able to withstand the same or even a higher compressive force than when still whole. This means that the force was still equal while the surface area got smaller. Since it's not possible to accurately calculate this and also the machine adjusts to induce the force equally (and not load it eccentrically as it would in a 'real' situation) this factor has not been accounted for.

All values marked in red are left out as the results differed too much to assume that the bad observed quality of the sample didn't matter for the performance. The values marked in orange are values lower than expected but with less of an obvious visual explanation. It is still assumed that by quality control in the form of visual inspection or quick testing these apparently bad quality samples are filtered out. They are still included in the result graphs on the next page. Here all rejected data has a grey centre.

The graphs above show the normal distributions of all groups for first crack stress and maximum stress. Also the relation between the compressive stress at first defect and maximum compressive stress is displayed.

From this it can be noted that the 9 mm group was most consistent as well as for first defect stress as for maximum stress. The 5 mm group was least consistent as well as in first defect stress and maximum stress. However, this group had the least samples and many of them were of a bad observed quality.

Also clear to see is the benefits of the hardened samples. Their stress at first defect as well as the maximum stress is much higher than the non-hardened samples.

Observations

- Many samples cracked during loading from top to bottom instantly. The next crack would then be opposite of this crack. This indicates that forces were in these cases mostly distributed equally.
- Many samples would fail through buckling. This happened when cracks from top to bottom would get close to each other. This part would then be separated from the rest of the profile. With the new smaller buckling factor, it would fail instantly.
- Sometimes a sample would fail soon and part of the profile would even disappear completely. However, the new smaller section (remainder of complete section) would be able to convey a higher force. This means that the potential maximum compressive strength is a lot higher than found in many of these cases. This confirmed that not only a material property is tested, but also a product property.
- The POM plates worked well visually distributing the forces. After a test, shape left in the POM plates would be precisely fit the sample with all imperfections.

Conclusions

What is the average maximum compressive stress the glass samples can be subjected to without showing defects?
For not-hardened glass this value would be approximately 35 N/mm². For hardened glass this value would be approximately 74 N/mm².

What is the average maximum compressive stress to which the samples can be subjected to without failing?
For not-hardened glass this value would be dependent on the section. It is implied that the thicker the profile, the lower the maximum compressive strength. During this experiment it ranged from: 65 N/mm² for the 9mm thickness samples to 85 N/mm² for the 5mm thickness samples. For hardened glass this value would be approximately 96 N/mm².

How does observed sample quality relate to test performance?
It seemed sometimes relevant. It could cause peak stresses in which cases the glass failed under relatively small loads. It didn't matter always though, some of the samples with observed 'bad quality' outperformed the flawless ones. Table 13 shows all data including data that was rejected. On many occasions, this data of rejected samples were also samples of perceived very bad quality in which the flaws led to immediate peak stresses (marked in red). On other occasions, the sample of the rejected data had only minor flaws and the inferior quality could less obviously be predicted.

How do the performances of the hardened samples relate to the non-hardened samples?
The hardened samples performed more consistent and had approximately twice the strength at showing first defect.

Were the forces induced equally?
It can be concluded that for most samples the forces were induced equally. When testing product properties this is more than sufficient as when used in practice, it will also likely not be loaded perfectly. Some elements failed very quickly which can only be attributed to peak stresses. This could have to do with the force introduction, but also with imperfections in the profile.

How does the glass fail and why?
It usually cracks from top to bottom multiple times shortly after one another. Then one of the smaller newly created sections buckles."

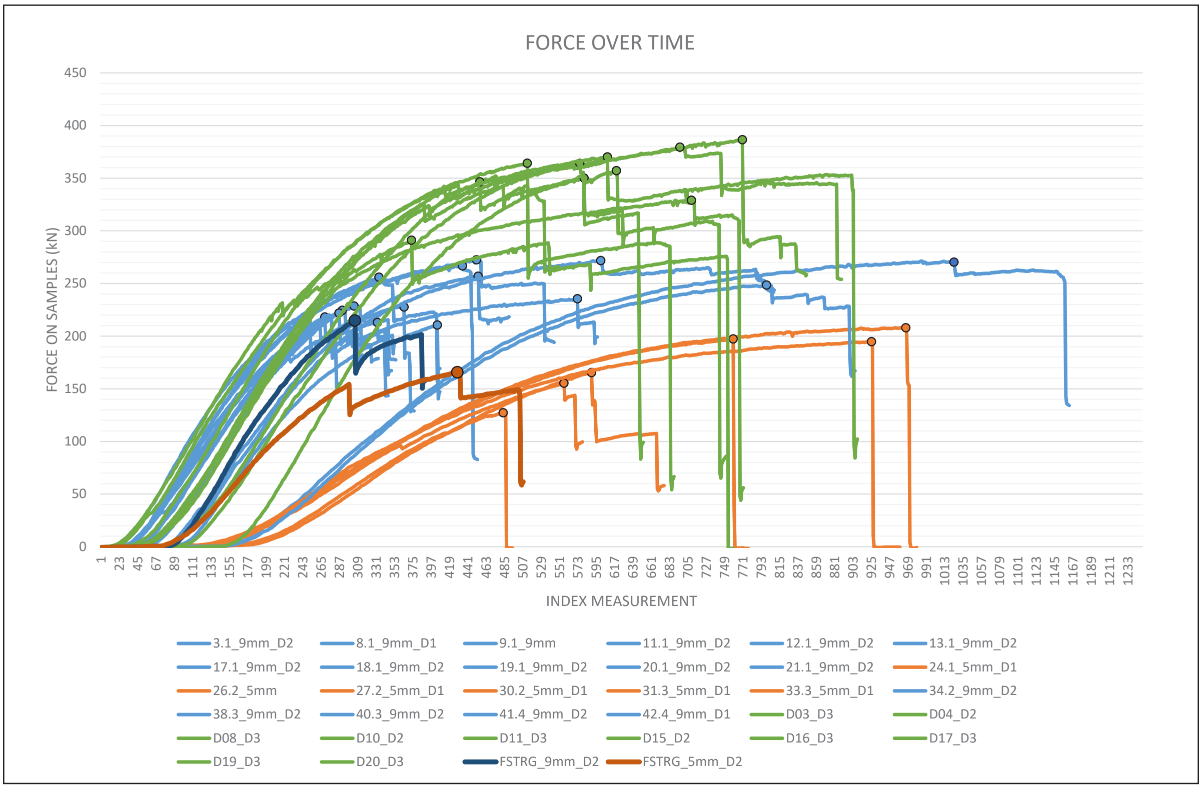

Figure 105: raw data of compressive test

Overview Summary

			compressive force at first crack [kN]	compressive stress at first crack [N/mm2]	z-distribution	maximum compressive force [kN]	maximum compressive stress [N/mm2]	z-distribution
group name	**9mm**	STRG	134	36,2	0,0867	214,8	58,0	0,037
area	3704 mm2	3.1	136	36,7	0,0792	220,4	59,5	0,047
OD	70 mm	8.1	110	29,7	0,0569	271,3	73,2	0,023
WT	9 mm	9.1	101	27,3	0,0237	228,2	61,6	0,060
		11.1	147	39,7	0,0341	272,8	73,6	0,020
samples	17 #	12.1	109	29,4	0,0526	266,6	72,0	0,030
Avg first crack	33,9 N/mm2	13.1	59	15,9	2E-06	218,0	58,9	0,043
SD	3,9 N/mm2	17.1	140	37,8	0,0624	256,9	69,3	0,048
Avg max	64,5 N/mm2	18.1	117	31,6	0,0858	235,5	63,6	0,066
SD	6,0 N/mm2	19.1	118	31,9	0,0892	228,5	61,7	0,060
		20.1	135	36,4	0,0831	256,0	69,1	0,049
		21.1	33	8,9	1E-10	225,1	60,8	0,055
		34.2	135	36,4	0,0831	221,8	59,9	0,050
		38.3	52	14,0	2E-07	271,7	73,4	0,022
		40.3	9	2,4	5E-16	212,9	57,5	0,034
		41.4	52	14,0	2E-07	210,6	56,8	0,030
		42.4	29	7,8	2E-11	248,5	67,1	0,061
group name	**5mm**	STRG	81	38,2	0,171	166,0	78,3	0,032
area	2121 mm2	24.1				165,4	78,0	0,0312
OD	70 mm	26.2	75	35,4	0,171	155,3	73,2	0,0181
WT	5 mm	27.2	41	19,3	3E-34	208,0	98,1	0,0169
		30.2	8	3,8	2E-119	127,4	60,1	0,001
samples	6 #	31.3	43	20,3	8E-31	197,3	93,0	0,0307
Avg first crack	36,8 N/mm2	33.3				194,9	91,9	0,0337
SD	1,4 N/mm2							
Avg max	85,4 N/mm2							
SD	9,3 N/mm2							
group name	**hardened**	D03	324	87,8	0,0176	350,0	94,8	0,0558
area	3691 mm2	D04	329	89,1	0,016	386,5	104,7	0,0258
OD	120 mm	D08	364	98,6	0,0064	364,2	98,7	0,0521
WT	5 mm	D10	250	67,7	0,0253	357,1	96,8	0,0559
		D11	255	69,1	0,0263	364,0	98,6	0,0522
samples	10 #	D15	230	62,3	0,0199	291,1	78,9	0,0032
Avg first crack	74,0 N/mm2	D16	202	54,7	0,0112	346,5	93,9	0,0543
SD	14,3 N/mm2	D17	260	70,4	0,027	370,1	100,3	0,0464
Avg max	95,8 N/mm2	D19	312	84,5	0,0213	379,3	102,8	0,0349
SD	7,1 N/mm2	D20	206	55,8	0,0124	329,0	89,1	0,0359

Table 18: overview of results

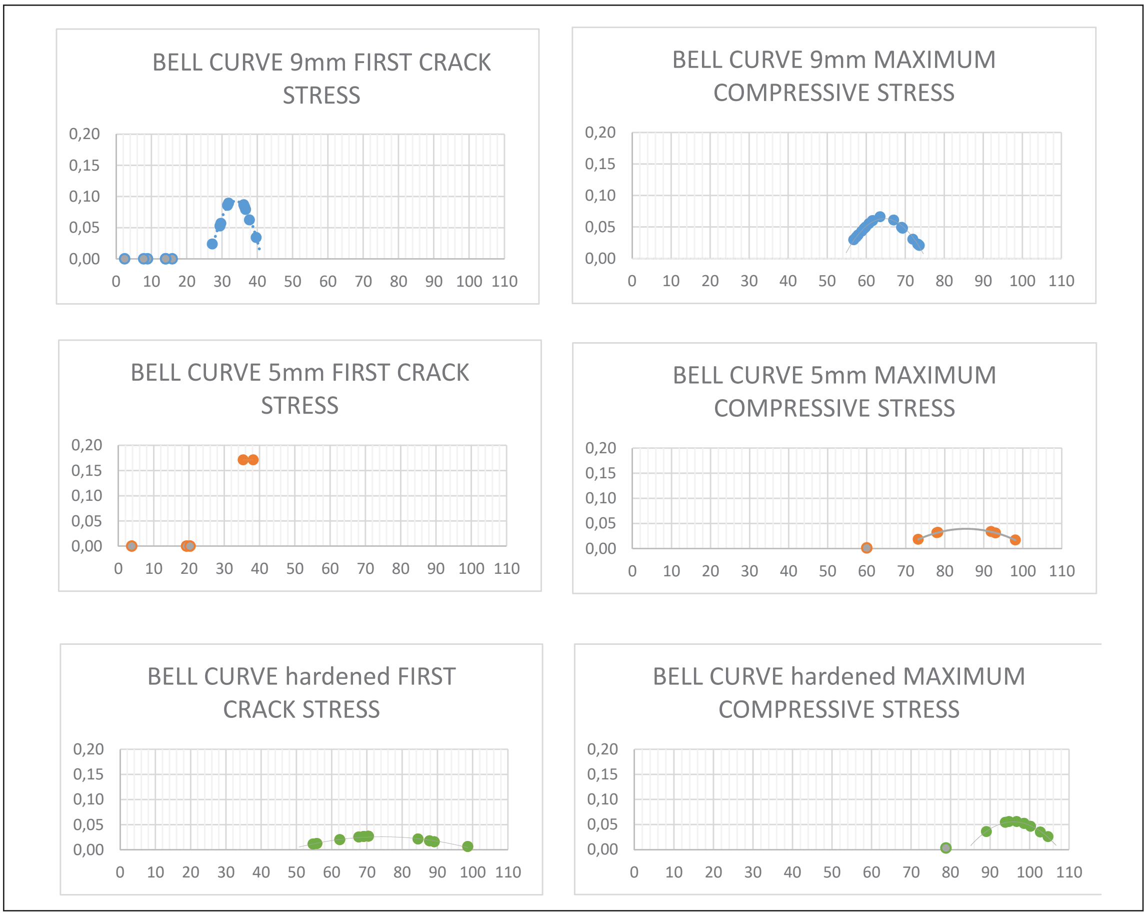

Figure 106: bell curves for all test groups, displaying the consistency of the samples

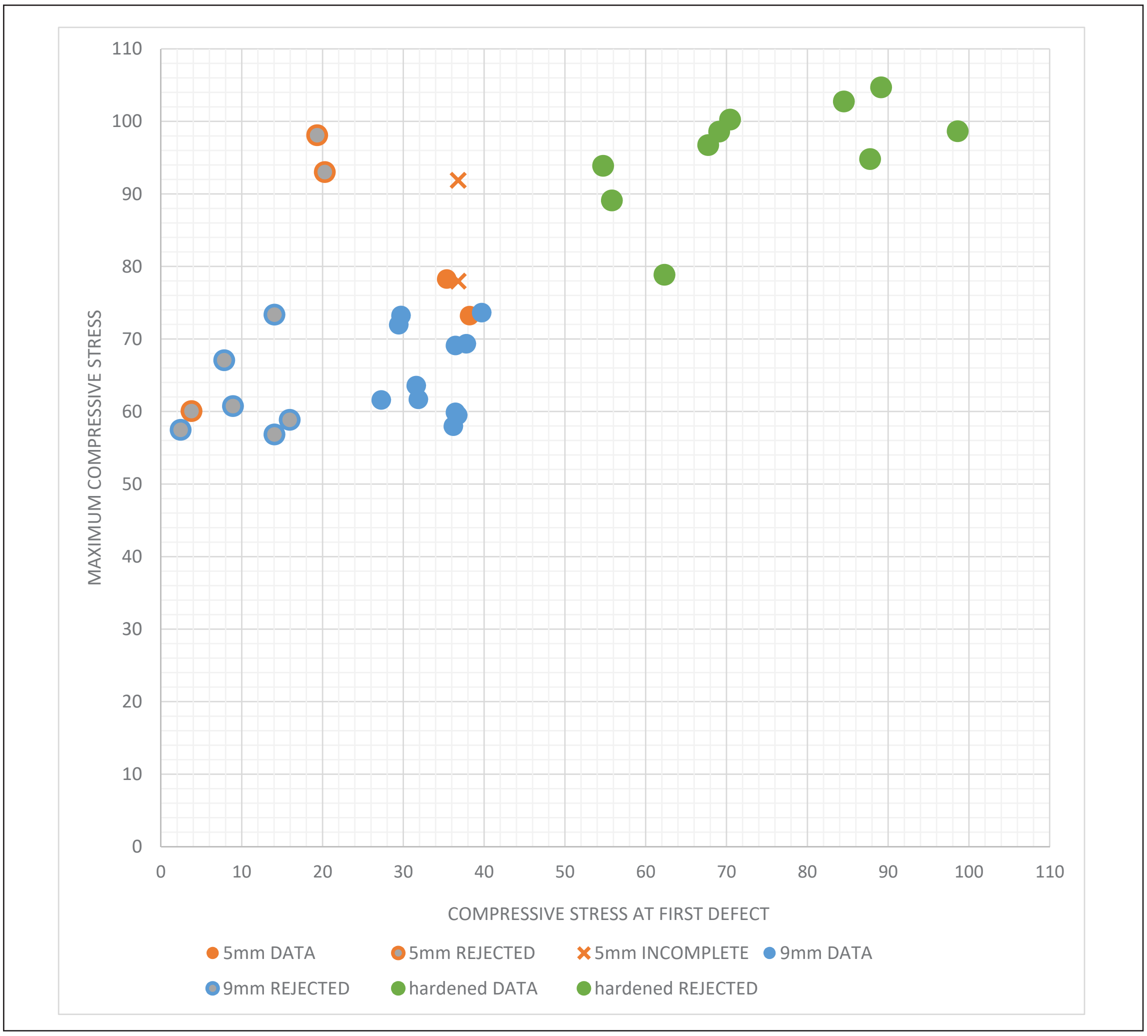

Figure 107: overview of results visualized

Figure 107: hardened sample (DURATAN©) photographed after inspection of the samples


Figure 109: a sample with flaws on the edge found during inspection of the samples


Figure 108: shrapnel blocking tube was placed over the samples to avoid glass particles causing potential harm

Figure 110: a picture of how the setup in action

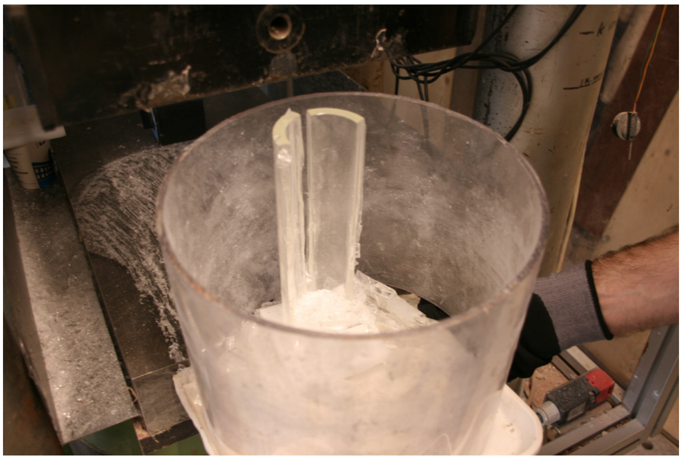

Figure 111: remainder after a test, still visible are the long cracks over the entire height of the sample ultimately leading to complete failure

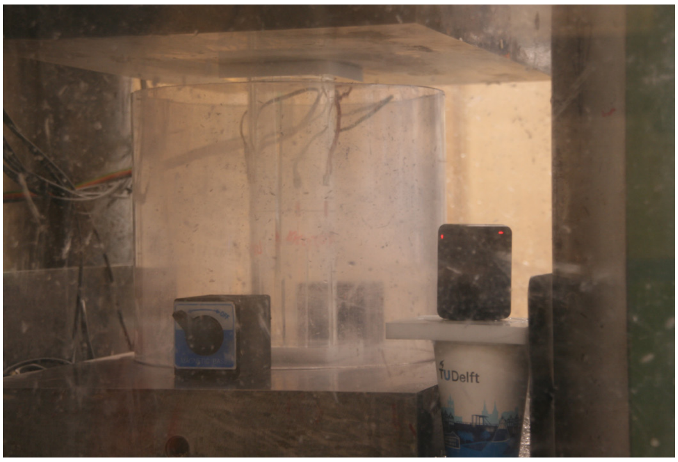

Figure 100: the tube for catching shrapnel was held in place by magnets and most experiments could be filmed

Figure 112: the hardened smaples would display these kinds of shattering patterns

FIgure 114: a crack along the entire height of the profile splits the section

Figure 113: shattering pattern of hardened samples, held together by duct tape

FIgure 115: remainder of sample after a test, leaving a lot of shrapnel

APPENDIX B: RESEARCH PROPOSAL
TENSILE STRENGTH EXTRUDED BOROSILICATE GLASS

This research proposal is part of a series of research proposals that collectively and with synergy contribute especially to evaluating the potential of section active extruded glass structural systems for architectural design.

Introduction

The architectural language of glass buildings is relatively new and especially the toolkit of structural glass elements has only begun to really develop lately. Glass buildings are mostly one of a kind public buildings and as glass has throughout its history always had an air of luxury and the smell of engineering miracles, nowadays they shine as the jewels of the built environment. They captivate people and offer a truly special experience.

Meanwhile firstly the demand for glass buildings is rising which means that the toolkit needs to be kept developing to avoid too much repetition and take away some of the wonder. Secondly the building requirements are getting stricter and we need to prevent being wasteful of material and energy which means that new additions to the toolkit should be safer and more sustainable.

A potential promising way of adding to the current toolkit is the extrusion of glass. This technique which is experimental for architecture could offer great visual variation to the toolkit while also benefitting of the properties of the borosilicate glass which is used in the production method.

Who has an interest in the topic?
Designers of the built environment and engineers working with glass structures in particular. Positive results of this experiment contribute to the architectural potential of an addition to their toolkit in shaping our world; specifically the toolkit of section active extruded glass structural elements.

How much is already known about the problem?
The structural performance of glass elements is determined not only by material properties but also by shape properties and surface quality. This is true because glass inherently has small cracks in its surface. The surface quality determines how big and frequent the cracks are. These cracks are especially important when the element is in tension because the cracks get pulled open. This is how large cracks come to be and they prelude the failing of the element. This means the amount of surface of the element is important too as it also determines the amount of small cracks.

What is missing from current knowledge?
Currently there is one building with extruded glass structural elements. These elements are vector active elements and are not used in tension. If you want to make section active system out of extruded glass element, the tensile strength needs to be known. Specifically tensile strength needs to be known for elements with the dimensions suitable for the built environment.

What new insights will your research contribute?
As the maximum tensile strength, characteristic strength, consistency and variation of it with the sample's dimensions become clear the material can be designed with structurally in tension. This is needed to evaluate the potential of the element for architectural implementation.

Why is this research worth doing?
To keep up with expectations and future building requirements, the toolkit of structural glass elements needs to be updated continuously. Positive results of this experiment contribute to the potential of adding a new production technique for making new elements for this toolkit. This new production technique would bring visual variety and also contribute to better performance properties like (fire) safety.

This research creates a basis for further research as the potential of extruded glass section active systems gets uncovered.

Problem statement

To be able to evaluate the architectural potential for section active extruded glass elements, the tensile strength needs to be known. As the tensile strength is not only influenced by material properties, but also by shape properties and surface quality, samples need to be tested with dimension that could potentially be useful for architectural systems.

Research questions

Main research question:
What is the maximum tensile stress to which the glass samples can be subjected to without a

defect?

Sub research questions:

- What is the maximum tensile stress to which the glass samples can be subjected to without failing?
- How does observed sample quality relate to test performance?
- How does the sample's dimensions relate to test performance?
- How do the performances of the hardened samples relate to the non-hardened samples?
- How consistent are the test results?
- Are the forces induced equally?
- How does the glass fail and why?

Research design and methods

The type of this research is quantitative research through material testing. To answer the research questions, the following methods are suitable. The best method depends on availability of samples and test equipment. This is why advantages and disadvantages of all methods are discussed.

Split cylinder test

The split cylinder test is a test oftentimes used for concrete cylinders, but it works for tube-like profiles too. A profile lies on a side and gets squeezed by squashing it from the top in a standard testing machine like a Toni-bank. Tension gets induced by creating a moment. The moment and with it the stress is greatest where the arm for the moment is longest and this is likely where the glass will fail. The tension in the glass is calculated after reading strain gauges attached to the sample.

Advantages of this test method are:

- it's simple to prepare because no special test equipment needed
- the right kind of samples can be used without having to alter them

Disadvantages of this test method are:

- not only tension will be induced, there will also be some shear

Probably this is the preferred test method because of balance between accuracy and practicalities.

Four point bending test

A four point bending test is a standard test in the field of researching material properties. The profile is simply supported on two points and gets pressed down in-between by two point loads. The advantage of two points instead of one is that the moment is stable where the translation is the largest. This is where the glass is expected to fail. As the tensile strength is almost certainly much lower than the compressive strength, the stress calculated to be in the material upon failure is the max tensile strength.

Advantages of this test method are:

- it's simple to prepare because no special test equipment is needed

Disadvantages of this test method are:

- not only tension will be induced, there will also be some shear
- because the preferred sample is a tube it's hard to induce forces equally and as needed because peak stresses need to be avoided, this method is best for testing rods

Probably this is not the best method because it's hard to load the tubular samples properly and as discussed earlier shape properties and dimensions are important for structural performances of glass which is why the tubular samples cannot be substituted by rods without losing significant accuracy in the results.

Rubber slice test

In this test a slice of rubber is placed inside a sample of small section height. The rubber is pressed down upon and due to its material properties, it translates this vertical load to horizontal expansion and it pushes against the glass with the aim to create omnidirectional pressure. Similar to the split cylinder test, the tension in the glass is calculated after reading strain gauges attached to the sample.

Advantages of this test method are:

- it's more accurate than the split cylinder test and the four point bending test. Because the stress is equal everywhere in the sample, the glass will fail at its weakest point. In the split cylinder test the stress could be highest where the glass is strongest (has least amount of imperfections) and the lowest stress the glass will fail at could possibly not be detected

Disadvantages of this test method are:

- the equipment needed for this test is not standard, if the equipment likely needs to be built from scratch which is more expensive and takes more time
- the samples can only be of little section height. This means that most likely the samples need to be altered before they are suitable. Additionally the samples are limited in wall thickness because otherwise the rubber will not generate enough pressure to make the glass fail
- the rubber slice does not really create omnidirectional pressure. It does not distribute equally over the height due to how it will expand

Probably this is not the best method because the equipment is non-standard and it might not be worth the effort of acquiring the equipment and right samples because of the still not entirely equally distributed stress in the material.

Hydraulic pressure test

This test method is similar to the rubber slice test. Except that in this test the pressure is created by a fluid which is being compressed by a hydraulic press.

Advantages of this test method are:

- it's more accurate than the rubber slice test, split cylinder test and the four point bending test because now the stress is really equal everywhere in the sample

Disadvantages of this test method are:

- the equipment needed for this test is even more special and also harder to build from scratch than the equipment for the rubber slice test
- as is also the case for the rubber slice test the samples can only be of little section height and the samples are limited in the wall thicknesses they can have

Probably this is not the best method because the equipment is even harder to come by than the equipment for the rubber slice test. If that is not a problem, this test is preferred over the rubber slice test (and the four point bending test) because of its accuracy. However, for this explorative research an answer with that accuracy is not needed. For now it's about feeling out the structural potential of this material. When designing a system, more tests need to be performed to evaluate the exact performances of the elements used.

Introducing of forces

To truly assess the tensile strength of the glass, peak stresses should be avoided. The most common way of doing this is by having a 'soft' material or intermediate layer between the glass and the load introducing surface. A material known to work well and easy to work with is POM, which is a high performance plastic. For the split cylinder test however, a simple MDF wooden plate would probably suffice.

Practicalities

The experiment can be carried out in a manner of hours.
Before not being able anymore to conduct the experiment ourselves we already inspected, photographed, and documented most materials for one samples suitable for this test. With a proper collaboration these materials could possibly still be used.

Suggested equipment

- Toni-bank connected to computer with controlling software
- Samples (already acquired and inspected): 17x 5mm WT 70mm OD glass tubes, 6x 9mm WT 70mm OD glass tubes, 10x 5mm WT 120mm OD glass tubes (hardened)
- Material for between machine and glass to induce forces equally: MDF plates
- Camera for pictures/videos
- Protection against glass shrapnel
- At least 2 strain gauges per sample

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APPENDIX C: RESEARCH PROPOSAL

STRUCTURAL PERFORMANCE PRELIMINARY DESIGN SECTION ACTIVE EXTRUDED GLASS SYSTEM

This research proposal is part of a series of research proposals that collectively and with synergy contribute especially to evaluating the potential of section active extruded glass structural systems for architectural design.

Introduction

The architectural language of glass buildings is relatively new and especially the toolkit of structural glass elements has only begun to really develop lately. Glass buildings are mostly one of a kind public buildings and as glass has throughout its history always had an air of luxury and the smell of engineering miracles, nowadays they shine as the jewels of the built environment. They captivate people and offer a truly special experience.

Meanwhile firstly the demand for glass buildings is rising which means that the toolkit needs to be kept developing to avoid too much repetition and take away some of the wonder. Secondly the building requirements are getting stricter as we need to prevent being wasteful of material and energy which means that new additions to the toolkit should be safer and more sustainable.

A potential promising way of adding to the current toolkit is the extrusion of glass. This technique which is experimental for architecture could offer great visual variation to the toolkit while also benefitting of the properties of the borosilicate glass which is used in the production method.

Who has an interest in the topic?

Designers of the built environment and engineers working with glass structures in particular. Positive results of this experiment contribute to the architectural potential of an addition to their toolkit in shaping out world; specifically section active extruded glass structural elements.

How much is already known about the problem?

Section active structural glass systems are widely implemented in the architectural language of glass buildings. They are mostly structural glass fins. This well-known system has different accents structural challenges than a section active extruded glass system would have. Because of the ability of making tubular shapes it does not have to account for lateral buckling for example. Because of the freedom in designing the geometry of the glass sections it holds a lot of structural potential.

What is missing from current knowledge?

There currently are no section active extruded glass structurally elements implemented in architecture. The material properties have already been researched, but to get a proper understanding of the structural performance of such elements a designed system needs to be tested for the first time. It's important to also get an understanding of how the designed element fails. Does it fail in a safe way? Can it be foreseen? Can shrapnel hurt bystanders? And also, how can the designed system be altered to enhance its performance regarding structural performance and safety?

What new insights will your research contribute?

This research will offer a better understanding of extruded glass section active structural systems in practice as it aims to push it to its structural limits and seeing what maximum load it can withstand. This could be one of the last steps in proving the potential of such systems for architectural implementation.

Why is this research worth doing?

To keep up with expectations and future building requirements, the toolkit of structural glass elements needs to be updated continuously. Positive results of this experiment contribute to the potential of adding a new production technique for making elements for this toolkit. This new production technique would bring visual variety and also contribute to better performance properties like (fire) safety.

This research creates a basis for further research as the potential of extruded glass section active systems gets uncovered.

Problem statement

To be able to evaluate the architectural potential for section active extruded glass elements, a draft designed system needs to be tested to get a better understanding of behaviour and structural capabilities. From the failing of the system, unexpected factors may be unveiled which can then be taken into account for further designs.

Research questions

Main research question:

- What is the maximum load the designed system can withstand without a defect?

Sub research questions:

- What is the maximum load the designed system can withstand?
- How does the designed system fail?
- Are there timely warning signs before failure?
- How consistent are the test results?
- Are the forces induced equally?

Research design and methods

The type of this research is quantitative research through material testing. To answer the research questions, one obvious method seems most suitable. This is why no other methods are discussed here.

Four point bending test

The most contextual accurate way of testing a draft design would be to connect three segments of the designed system and perform a four point bending test on a universal test machine. The loads could then be conveyed on the connections at they would in reality.

Introducing of forces

To truly assess the structural performance of the designed element, peak stresses should be avoided. This is why the system should only be loaded on the connections only as the system is designed for.

Practicalities

The experiment can be carried out in a manner of days, production of the samples can take longer.

Suggested needed equipment

- Four point bending set-up
- Samples: If possible, two or even three copies of the designed system three segments each
- Camera for pictures/videos
- Protection against glass shrapnel

APPENDIX D: RESEARCH PROPOSAL

STRUCTURAL PERFORMANCE DIMENSIONED DESIGN SECTION ACTIVE EXTRUDED GLASS SYSTEM

This research proposal is part of a series of research proposals that collectively and with synergy contribute especially to evaluating the potential of section active extruded glass structural systems for architectural design.

Introduction

The architectural language of glass buildings is relatively new and especially the toolkit of structural glass elements has only begun to really develop lately. Glass buildings are mostly one of a kind public buildings and as glass has throughout its history always had an air of luxury and the smell of engineering miracles, nowadays they shine as the jewels of the built environment. They captivate people and offer a truly special experience.

Meanwhile firstly the demand for glass buildings is rising which means that the toolkit needs to be kept developing to avoid too much repetition and take away some of the wonder. Secondly the building requirements are getting stricter as we need to prevent being wasteful of material and energy which means that new additions to the toolkit should be safer and more sustainable.

A potential promising way of adding to the current toolkit is the extrusion of glass. This technique which is experimental for architecture could offer great visual variation to the toolkit while also benefitting of the properties of the borosilicate glass which is used in the production method.

Who has an interest in the topic?

Designers of the built environment and engineers working with glass structures in particular. Positive results of this experiment contribute to the architectural potential of an addition to their toolkit in shaping out world; specifically section active extruded glass structural elements.

How much is already known about the problem?

Section active structural glass systems are widely implemented in the architectural language of glass buildings. They are mostly structural glass fins. This well-known system has different accents structural challenges than a section active extruded glass system would have. Because of the ability of making tubular shapes it does not have to account for lateral buckling for example. Because of the freedom in designing the geometry of the glass sections it holds a lot of structural potential.

What is missing from current knowledge?

There currently are no section active extruded glass structurally elements implemented in architecture. The material properties have already been researched, but to get a proper understanding of the structural performance of such elements a designed system needs to be tested for the first time. It's important to also get an understanding of how the designed element fails. Does it fail in a safe way? Can it be foreseen? Can shrapnel hurt bystanders? And also, how can the designed system be altered to enhance its performance regarding structural performance and safety?

What new insights will your research contribute?

This research will offer a better understanding of extruded glass section active structural systems in practice as it aims to push it to its structural limits and seeing what maximum load it can withstand. The major difference between the two is that this proposed test is the last step for validating a section active extruded glass structural system and is only carried out if the preliminary design test results were promising and contributed positively to the potential for architectural implementation.

Why is this research worth doing?

To keep up with expectations and future building requirements, the toolkit of structural glass elements needs to be updated continuously. Positive results of this experiment contribute to the potential of adding a new production technique for making elements for this toolkit. This new production technique would bring visual variety and also contribute to better performance properties like (fire) safety.

This research creates a basis for further research as the potential of extruded glass section active systems gets uncovered.

Problem statement

To be able to evaluate the architectural potential for section active extruded glass elements, a draft designed system needs to be tested to get a better understanding of behaviour and structural capabilities. From the failing of the system, unexpected factors may be unveiled which can then be taken into account for further designs.

Research questions

Main research question:

- What is the maximum load the designed system can withstand without a defect?

Sub research questions:

- What is the maximum load the designed system can withstand?
- How does the designed system fail?
- Are there timely warning signs before failure?
- How consistent are the test results?
- Are the forces induced equally?

Research design and methods

The type of this research is quantitative research through material testing. To answer the research questions, one obvious method seems most suitable. This is why no other methods are discussed here.

Four point bending test

The most contextual accurate way of testing a draft design would be to connect three segments of the designed system and perform a four point bending test on a universal test machine. The loads could then be conveyed on the connections at they would in reality.

Introducing of forces

To truly assess the structural performance of the designed element, peak stresses should be avoided. This is why the system should only be loaded on the connections only as the system is designed for.

Practicalities

The experiment can be carried out in a manner of days, production of the samples can take longer.

Suggested needed equipment

- Four point bending set-up
- Samples: if possible, two or even three copies of the designed system three segments each
- Camera for pictures/videos
- Protection against glass shrapnel