THE ALL TRANSPARENT COLUMN

Exploring the effects of post-tensioning an all glass column of the bundled type to enhance slenderness and promote safe failure behavior

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Preface

For the past decade glass has risen to great heights in the field of structural design. Much has been researched and written on its use in beams, fins, plates, walkways and parapets. Glass columns, however, have been somewhat ignored to date. The lack of legislation combined with the difficulties of producing complex 3D-oriented elements results in only several realised all glass columns in the world.

As an aspiring engineer the discrepancies between architects and structural engineers have always been of a wonder to me. Two fields of engineering, both with their own ways and traditions, which when combined can result in amazing architectural feats of strength. But the two field of engineering don't always come together easily, the architect often has beautiful ideas of large uninterrupted spaces where the structural engineer simply knows this won't be achievable without sufficient structural elements.

The discussion between architect and engineer about uninterrupted spaces versus load bearing structural elements is a discussion that most likely goes way back to the very origins of architecture; trying to build that which is virtually impossible. But rather than having a well-educated structural engineer who offers advise, a trial-and-error type of approach was applied in those times. It is my belief that this discussion can soon come to the ultimate compromise by introducing structural elements that have reliable mechanical behavior and are almost completely transparent. Glass is undergoing very extensive research and I know that within only a few years it will be possible to apply glass in structural ways I would have thought impossible years ago.

I fell in love with this fascinating material during my studies and I hope this thesis research can be a small contribution to overcoming the difficulties of designing with glass.

Erik van den Broek

The Hague, The Netherlands, December 2016

Acknowledgements

When I was still working on my bachelor degree I often wondered what mastertrack would suit me best. Initially I thought I would end up in Architecture, then I thought in Urbanism, but three people in particular have inspired me to choose the Building Technology track for which I am very grateful. Mick Eekhout, Fred Veer and Marcel Bilow have all inspired me in a very unique way and I thank them for being the inspiration they are. The mastertrack Building Technology has been such a perfect fit for me, combining theory, design and prototyping. The 'design and build' approach has a solid base in this mastertrack and has guided me through multiple very interesting projects in The Netherlands and all the way into Turkey.

During my studies I have been involved in numerous activities that connected me to many wonderful people I now call my dearest friends and girlfriend. I wish them all the very best in their own path and thank them for being a sounding board when I needed to complain or just needed a chat.

During this thesis an entire group of people have been of immense help to me. First and foremost Faidra Oikonomopoulou, my main mentor during this entire project, has always been helpful with a no-nonsense method of guiding me. Telesilla Bristogianni for kind advice and selflessly helping me without having been asked to do so. Again, Marcel Bilow, but this time for being my second mentor in this process, never failing to guide my work and thoughts in the right direction with a direct and thorough vision. Sylvia Jansen as delegate of the board of examiners for her time and feedback. Having spend many hours at the faculty of Civil Engineering I also want to thank Kees Baardolf for his very proactive attitude towards all research being conducted there. He has helped me produce elements for my research I could not have been able to do so myself. Also thanks to Fred Veer for his time and advice on the physical experiments during this research, and the entire Stevin Lab crew and Christian Louter for any help they have offered me during the physical tests of the columns.

I feel very fortunate to have been able to discuss my work with James O'Callaghan who is a visiting professor at the Delft University of Technology, taking his time to listen to my ideas and thinking along about possibilities. Finally I also want to thank the engineers of ABT Delft for providing me with detailed information and inspiration regarding their preceding research into the topic of glass columns.

Six wonderful years as a student of the Delft University of Technology have almost come to an end. Even though the young me always said he would probably never go to any university because it was more theory than practise I now realise I couldn't have made any better choice. I feel very fortunate to have been given to priviledge to study at this wonderful university and for that I must thank my parents the most. They have always been supportive and have been a great inspiration for me to keep pushing my limits and to never stop learning. I will never be able to thank them enough for this.

Abstract

The long and slender structural member, the elastic column, fails due to buckling. Buckling is a predictable, and visible, mode of failure allowing for timely repairs or replacement. This is no longer true when we look at long and slender columns made out of glass as glass is a brittle material. At the moment the critical buckling force is reached the column does not deform as much but suffers from explosive brittle failure, because of this it is unpredictable and extremely dangerous. As a result of this brittle failure behavior we apply safety factors twice as high when designing with glass compared to other construction materials, leading to excessively large, heavy and costly elements.

Research focused on creating load bearing glass colums has been conducted and has led to a few preceding glass columns. These columns did lack either mechanical or architectural desirability though. New research is being conducted into producing a glass load bearing column by laminating solid rods together, this research is very promising but is still limited by the boundaries generated as a result of this immense safety factors.

Increasing the cross-sectional properties of such a column does increase the column's resistance to buckling, but again leads to excessively large structural elements with increased weight and cost. But what if we can, rather than accepting the consequences of the high safety factors, reduce the safety factors by increasing the mechanical behavior during buckling, transforming the brittle and explosive failure into a more gradual and ductile failure.

This thesis researches the potential of post-tensioning a bundled glass column in an attempt to transform the explosive brittle failure into a ductile mode of failure. In order to verify this behavior a total of six slender glass columns have been produced with a length of 2400 millimeters, three of these where loaded with around 3000 kilograms of prestress and all six were destructively tested. A prestressed member appears to be a more flexible element than a similar non-prestressed member and has post-breakage load bearing capabilities.

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List of symbols

Symbol	Description
A	Area
E	Young's modulus
EI	Bending stiffness
F	Force
I	Second moment of area
GPa	Gigapascal
HV	Hardness - Vickers
kg/m^3	Density
L_e	Effective length
M	Bending moment
MPa	Megapascal
N	Newton
N/mm^2	Newton per square millimeter
N/m	Torque
m	Meter
mm	Millimeter

Abbreviation	Description
FTG	Fully tempered glass
HSG	Heat-strengthened glass
ULS	Ultimate limit state

1. Introduction

In this chapter an introduction into the topic of all glass columns is provided. Why do we want a glass column, and is it a viable option? These questions are explained and justified. Finally the objective, scope, methodology and research questions of this graduation research are presented.

1.1. The fascination of glass

Glass has always been a fascinating material, being a very solid and strong material while still being completely transparent. Our captivation for this material is nothing new; it has been used for centuries in the form of panels providing us with daylight in our homes. The glass allowed us to bring in daylight, but also create awareness of our surroundings, bringing the surroundings inside our homes, softening the hard border the envelope of our buildings resemble. The use of glass in the building envelope reached a milestone with the development of the Crystal Palace in 1851 (See "Figure 1: Crystal Palace"). The invention of the cast plate glass method in 1848 by James Hartley made the production of large sheets of cheap but strong glass possible, and its use in the Crystal Palace created a structure with the greatest area of glass ever seen in a building and astonished visitors with its clear walls and ceilings that did not require any interior lighting. Since the days of the Crystal Palace, glass has remained to be a fascination of designers, engineers and architects. The pursuit of all glass structures continued, and still continues to this day.

1.2. Architect versus Engineer

Although architects and engineers perform many parallel functions that all contribute to the design and realization of buildings and structures, there are also some key distinctions between the two. Architects and engineers often approach projects from very different perspectives. The architect has a more creative mindset in order to create space, form and ambience. Whereas the engineer generally has a more practical and mathematical approach in order to ensure structural integrity of the design. The combination of these two principles can lead to fantastic results where architectural, and structural design, are integrated into one grand design. But these two different approaches can also clash during this process, during which a compromise will have to be made. The architect will always want beautiful, uninterrupted spaces, but the engineer will always say this is not possible because buildings don't float and need supports; and these supports block the continuous view the architects wants to create. This debate has always been around and has caused friction between the two fields of engineering (See "Figure 2: Architect versus Engineer"). This debate however, might come to an ultimate compromise as new building materials are being researched and used in the field of architectural engineering. If we can design load-bearing columns made out of a transparent material, we can satisfy the needs of both the architect and the engineer.

1.3. Why glass columns

The obvious reason people have wanted to use glass is the transparency property. This is the key aspect that sets glass out from materials like concrete and steel. Next to the transparency property, there are a few key properties which allow glass to be the material of choice in many structural applications. Glass has a very impressive strength under compression (close to 300MPa in practice), and it is also a very durable material that does not deteriorate. Another great aspect is that glass is fully recyclable (with the exception of possibly added foils and adhesives). But if these properties are so fantastic and arguably better than those of steel and concrete, why don't we always use glass in structural applications? That issue lies in glass' weak properties; the main issue is the very brittle nature of glass. Glass is a very brittle material that is great at handling compression, but is extremely incapable of handling tensile forces (See "Figure 3: Mechanical properties of common materials"). Another aspect following the brittle nature is its behavior when exposed to these tensile forces, glass does not show any visual defects before failure but fails in a very sudden and explosive manner, losing all load-bearing capacities. This unpredictability makes it a rather unsafe material in constructions subject to both compressive and tensile forces (which are almost all constructions). Another aspect is that glass is highly prone to imperfections on the surface. Scratches cause a loss of stress, which means that fixed values for its strength are difficult to use (Veer, 2000). What we do know however, is that glass' key strength is its compressive strength, making it an ideal material to produce load-bearing elements subject to compressive forces, such as columns.

Figure 1: Crystal Palace

Figure 2: Architect versus Engineer

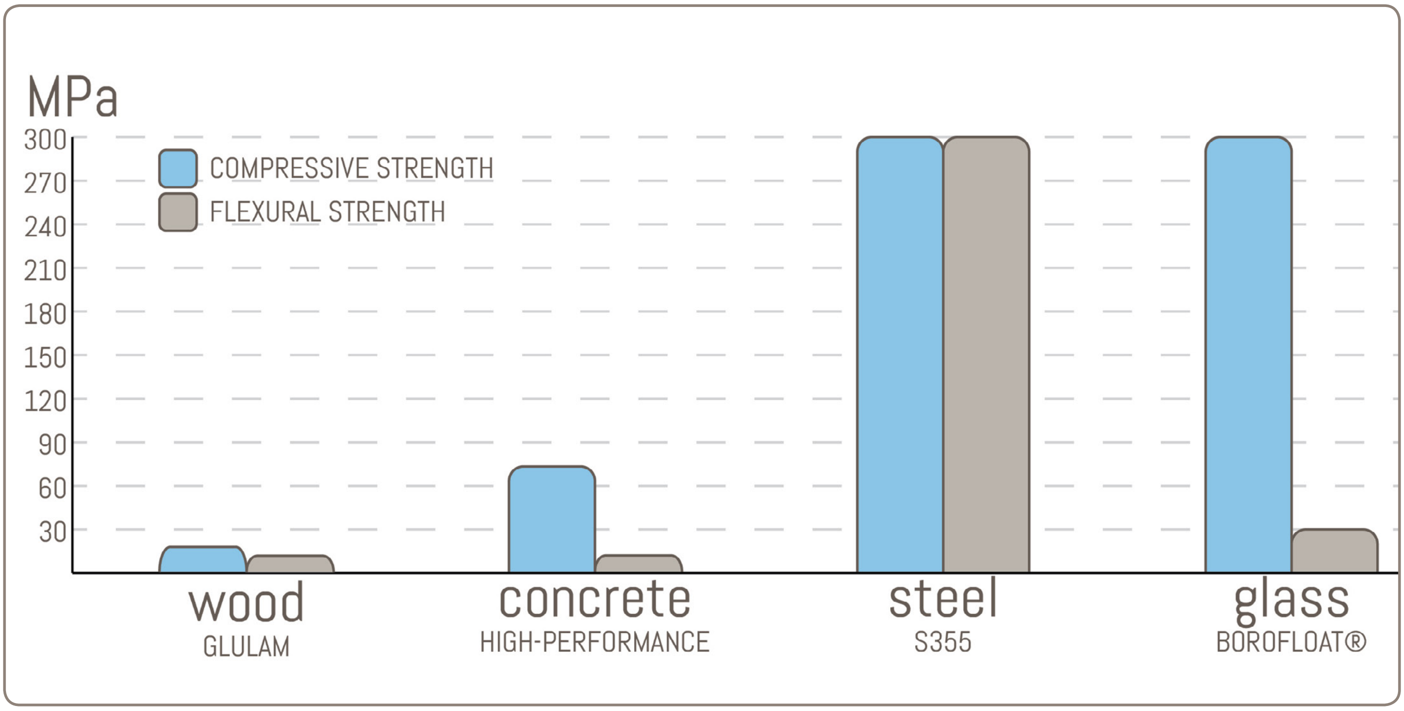


Figure 3: Mechanical properties of common materials

1.4. Objective

The main focus and aim of this graduation thesis is:

> "Exploring the possibilities of post-tensioning an all-glass column of the bundled type to enhance its slenderness and to promote safe failure behavior."

1.5. Scope and Methodology

For over a decade people have been fascinated with the idea of producing load bearing glass columns. This fascination is nothing weird because glass most definitely has the potential to be used in such a way. Research regarding glass load bearing columns has been around for several years as well, but so far this research only resulted in a handful of realized columns in a structural application.

This research is divided into four main scopes. This first part consists of a literature studies regarding all aspects around glass as a material, potential types of all glass columns, structural safety and methods and effects of post tensioning. Part two is a qualitative research into problems arising around the production of an all glass column made by bundling solid rods of glass. The mechanical behavior will be addressed and tested to verify its behavior. The result of this part will be the design of the main element of the column and the system to apply the post tensioning to it.

Following the previous part, in part three we will consider all mechanical behavior of part two as boundary constraints for the design of the connection details of the explored column. The design and development of the connection details will be a 'Research by Design' type of research. All of this research will be case driven, and the final models and design will be tested regarding realistic constraints of this case.

Combining part two and three into one, the result of this period will be a complete and tested column with post tensioning system designed into it, and a method and design for mounting of the column in its connection details which also are as transparent as possible. The result of this thesis a combination of both a physically tested column and theoretically designed connection details, after this the thesis is concluded with a discussion in which future applications for glass compressiive members are discussed.

1.6. Case location

Free-standing all glass columns are still in an early stage of research and thus have been rarely applied in practise as we saw earlier. Rob Nijsse described the five possible types of free-standing all glass columns. Research is being conducted in order to realize an all glass bundled column. This research is being conducted by the Delft University of Technology in corporation with ABT. The case location where this column will be realized is in the ABT office in The Netherlands.

Because of the choice to apply the design to the ABT office in a case study method, there are several aspects we have to take into account. As it is a specific location where the column will, theoretically for now, be placed, there are fixed values for variables such as the height of the column and the load this column will have to deal with. These values will be the boundary constraints regarding the research by design part of this thesis.

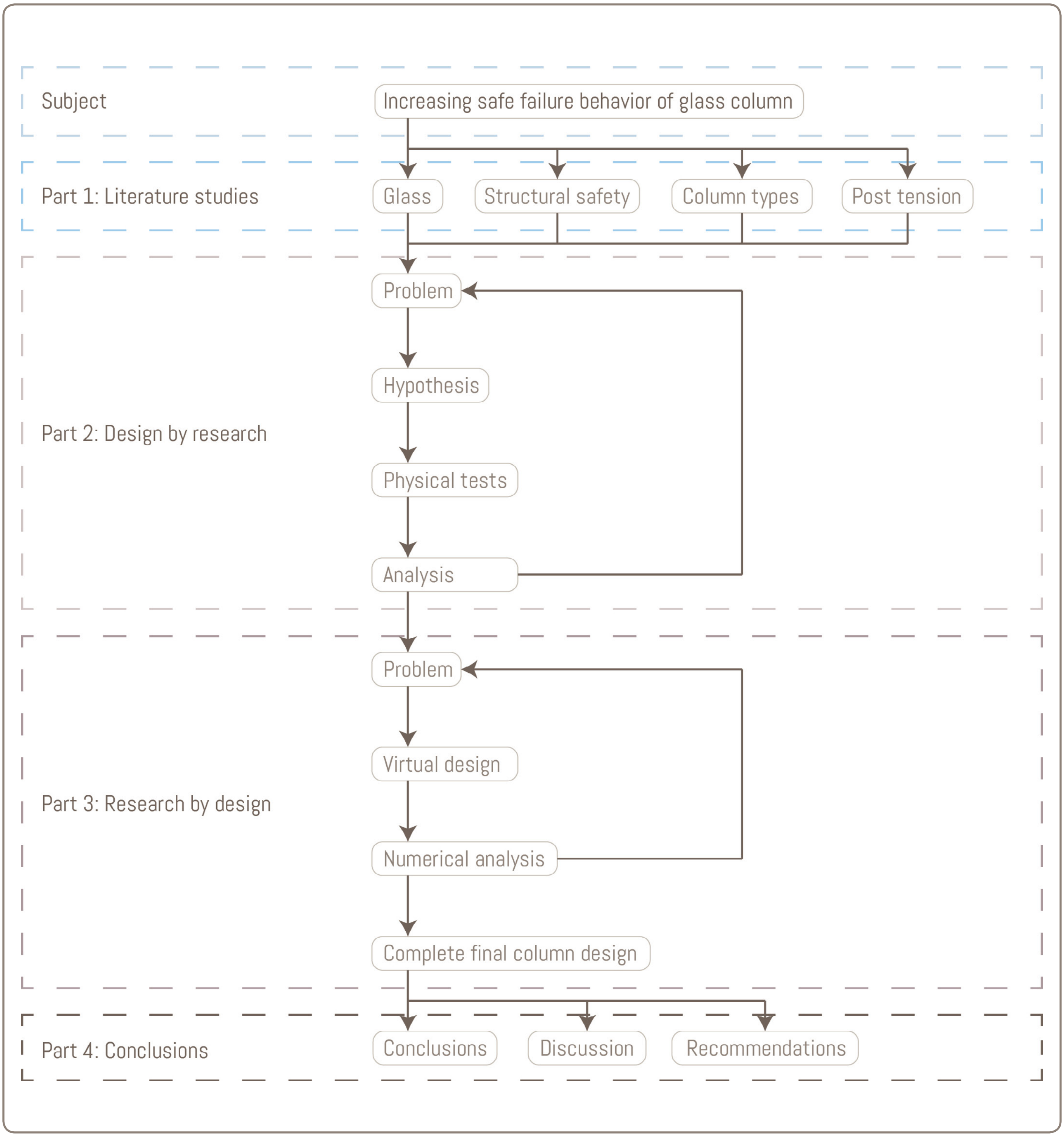


Figure 4: Research design

1.7. Design questions

Part 2 and 3 of the proposed research methodology each have a very specific focus of research. The ‘Design by Research’ chapter is all about increasing and proving the mechanical behavior of the column. Whereas the ‘Research by Design’ chapter has its focus in increasing the architectural values associated with the glass column.

The design questions have a main focus in either of the two phases of this research and will be presented as such.

1.7.1. Design questions for the ‘Design by Research’ phase

“How to produce a 2900mm long column out of 1500mm long elements?”
“What is the optimal design of the head-to-head glass connections arising from the lamination of the rods?”
“How can we apply prestress to the column is the safest way, assuming large eccentricities and margins in the glass elements?”
“Can we reach the proposed design load, including a safety factor of four with a column this slender?”
“Does the column show (more) plastic failure behavior after prestress is applied?”
“If the column shows plastic failure behavior, to what safety factor can we drop while respecting structural integrity?”

1.7.2. Design questions for the ‘Research by Design’ phase

“How can the connection details for a glass column look?”
“How many elements that were previously designed in aluminum or steel can be replaced with glass counterparts?”
“How can we optimize the production process of the column to increase accuracy and transparency?”
“How does this reflect on the ABT office case study?”

2. Literature

As explained in the research methodology; this specific chapter is focused around literature studies regarding glass as a material, possible types of columns and their mechanical behavior, failure modes of columns and ways to deal with this. Finally a specific choice for which type of column will be further researched is explained.

2.1. Glass production

2.1.1. Origin of glass

Little is known about man's first attempts at making glass. We do know that in the ancient world the first uses of glass were weapons and decorative pieces made out of natural occurring volcanic glass, namely obsidian (See "Figure 6: Natural occuring obsidian"). Amulets and solid beads were made in Mesopotamia as far back as 2500BC. Glass making was further developed in Egypt around 1500BC. The development of glass production was very slow because in the small furnaces they could make around 1500BC they simply couldn't reach the temperature to effectively melt the glass (Douglas & Frank, 1972). For the next 500 years, Egypt, Syria and the other countries along the eastern coast of the Mediterranean Sea were continuously improving their glass production process and for over 500 years this process kept improving. But even in these times, production was still very slow because the heat required to melt glass is very high. The discovery of glassblowing around the 1st century BC was a major breakthrough in glass making (See "Figure 5: Modern glass blowing"). This discovery was made by a Syrian glass producer and revolutionized the glass industry. Throughout the 2000 years that followed the invention of the glassblowing process, a lot has happened in the field of glass production. But even in the 1800's glass was still considered an expensive material because it had to be made by hand. In 1888 machine rolled glass became available, but it wasn't until 1959 that float glass as we know it was invented by Sir Alastair Pilkington (Walker, 1987).

2.1.2. What is glass?

Glass is an inorganic, nonmetallic material that does not have a crystalline structure (See "Figure 7: Crystalline versus Amorphous"). Materials like this are considered to be amorphous and are virtually solid liquids cooled at such a rate that crystals have not been able to form (Turnbull, 1969). Typical glass applications range from the soda-lime silicate glass for soda bottles to the extremely high purity silica glass for optical fibers. In history most glass products have been produced using glassblowing techniques. In recent times most flat glass has been produced using the float process.

The core ingredient of glass is silicon dioxide ($SiO2$). The most common form of silica used in glassmaking has always been sand. Sand by itself can be fused to produce glass but the temperature at which this can be achieved is about 1700 degrees Celsius (Rosenblum, 1917). Fusing glass at this temperature would be very energy inefficient; adding other chemicals to sand can considerably reduce the temperature of the fusion to increase efficiency. The addition of sodium carbonate ($Na2CO3$), which is also known as soda ash, in a quantity to produce a fused mixture of 75% Silica ($SiO2$) and 25% of sodium oxide ($Na2O$), will reduce the temperature of fusion to about 800 degrees Celsius. However, a glass of this composition is water soluble and is known as water glass (Turnbull, 1969). In order to coop with this effect, other chemicals like Calcium Oxide (CaO) and magnesium oxide (MgO) are needed. The raw materials used for introducing CaO and MgO are their carbonates, limestone ($CaCO3$) and dolomite ($MgCO3$), which when subjected to high temperatures give off carbon dioxide leaving the oxides in the glass. The European standard in EN 572 Part 1 describes the boundaries in which the production of this glass should be executed to be able to guarantee a certain quality and safety. In most cases, a small amount of waste glass is also added to the mixture; since this glass is already heated and in a molten state it makes the melting of the raw materials easier (Schittich, 1999).

2.1.3. Float glass

How does the production of glass look nowadays? In the 1950's, Sir Alastair Pilkington thought of a way to make really big sheets of flat glass. The idea was to pour glass onto a really smooth surface, and then to wait till the glass cooled. But on what type of surface should you be doing this? If you take a close look at any solid surface, you will find imperfections that will cause weak points in the final glass product. Because of this, it was Pilkington's idea that the glass would have to be cooled, not on a solid but rather on a liquid surface. Perfectly still water has a perfectly smooth surface, but as we all know, glass outweighs

Figure 6: Natural occuring obsidian

Figure 5: Modern glass blowing

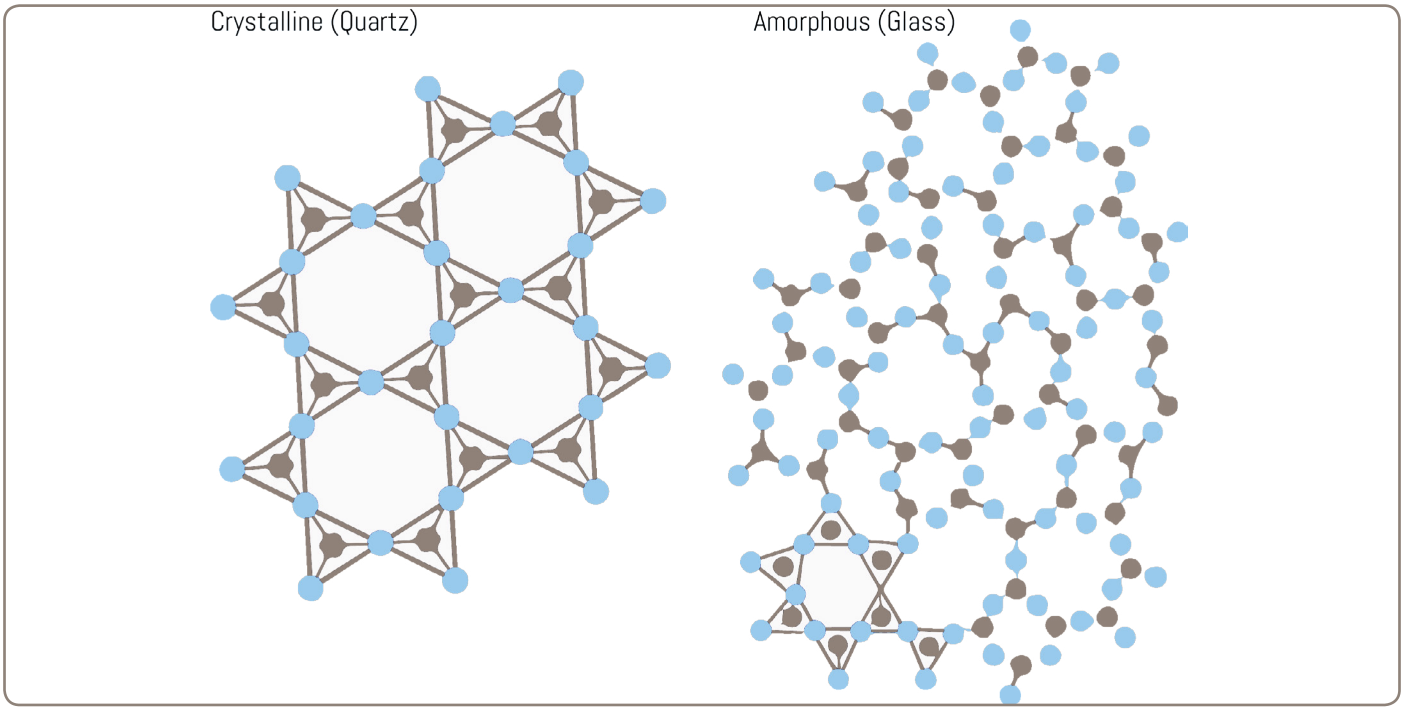


Figure 7: Crystalline versus Amorphous

water so the glass will just sink if you try this. Not only does it outweigh the water, but the temperature of water would also generate considerable thermal shock to the molten glass. So you need a liquid that's denser than glass at a high temperature. Molten tin is denser than glass, and it also remains molten even after the glass has cooled. The molten glass is poured in the molten tin bath in one end (roughly 1100 degrees Celsius), and slowly flows to the end of the bath (at which moment it has been cooled to around 600 degrees Celsius) as new glass is being fed into the line. This tin bath, or float bath as we call it, is commonly about 50 meters long and 3-4 meters wide (See "Figure 10: Diagram of a float line"). The maximum standard size of glass is 6*3.21 meter. However, it is also possible to obtain greater lengths. After the tin bath, the glass panel is annealed (cooled slowly) to avoid residual stresses caused by sudden cooling. Improper annealing can lead to spontaneous fracture during cutting due to internal stresses (Veer, 2007).

Usually the float lines produce one thickness only to be more economical, as changing the thickness of the glass that comes out of the float line takes a very long time. And any glass produced during the transition has to be broken down and recycled as it is not a continuous thickness over the panel nor is it a thickness anyone wants. Commonly achieved thicknesses for flat glass are up to 15mm thick. Glass panels with a thickness of 19, 22 and 25 mm are usually special orders and are therefore 30 – 50% more expensive (Akerboom, 2016).

2.1.4. Cast glass

Rather than using the float line to produce flat panels of glass, we can also use another method to produce glass which results in more 3D oriented shaped glass. Casting glass is the oldest manufacturing techhnique for glass and is an ideal solution for producing unique 3D shaped objects and for achieving monolithic elements with a thickness of over 25mm as this thickness cannot be attained using the float glass method. For this method a preformed mold is used, this mold can be made out of sand, plaster or graphite. You can also use wood to make a template for the mold which is then firmly pressed into the mold material to create the mold. Once the mold is ready the heated glass (up to 1200 degrees Celsius) is poured into it and left to cool (See "Figure 8: Casting glass"). It should again be noted that proper cooling to relieve all residual stresses is an important factor that determines the final production time of glass elements as this takes a very long time for large objects, an example of this will be presented in the final part of this literature reseach chapter.

2.1.5. Extruded glass

Extrusion of a material is a method that is widely applied nowadays. This method is being applied to plastics, aluminum, steel and more recently also glass. The extrusion method focusses on producing elements with a unique, but constant cross-section like we see in aluminum window frames, steel structural piping etc. This method can be applied in a cold and a hot manner, cold extrusion is performed at room temperature and for hot extrusion the material is firstly molten and allowed to cool and recrystallize to set in its new cross-section. For glass the cold extrusion is not much of an option because of its brittle nature. But hot extrusion of glass is a very convenient process which allows for consistently shaped elements (See "Figure 9: Extruded glass profile"). This method can be used for a sectional thickness of up to 100mm (Version 2016; CES EduPack, 2016). Hollow cross sections can be produced in greater cross sections. For thicker cross-sections another method has to be applied, casting glass is a good option for this. As with most similar production methods the production of the die through which the material is pushed is expensive to produce. Because of these costs this method becomes financially feasible around 1000 unit's production size (Version 2016; CES EduPack, 2016).

Figure 8: Casting glass

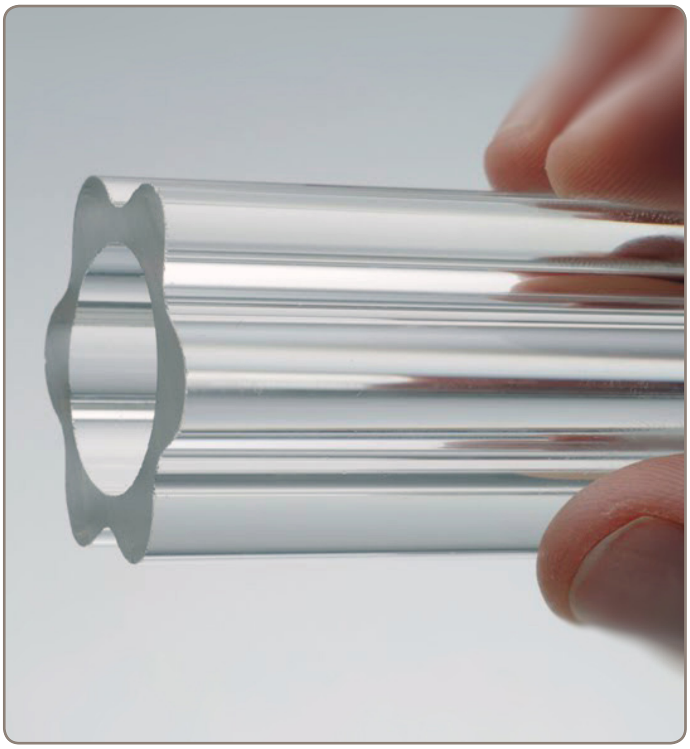


Figure 9: Extruded glass profile

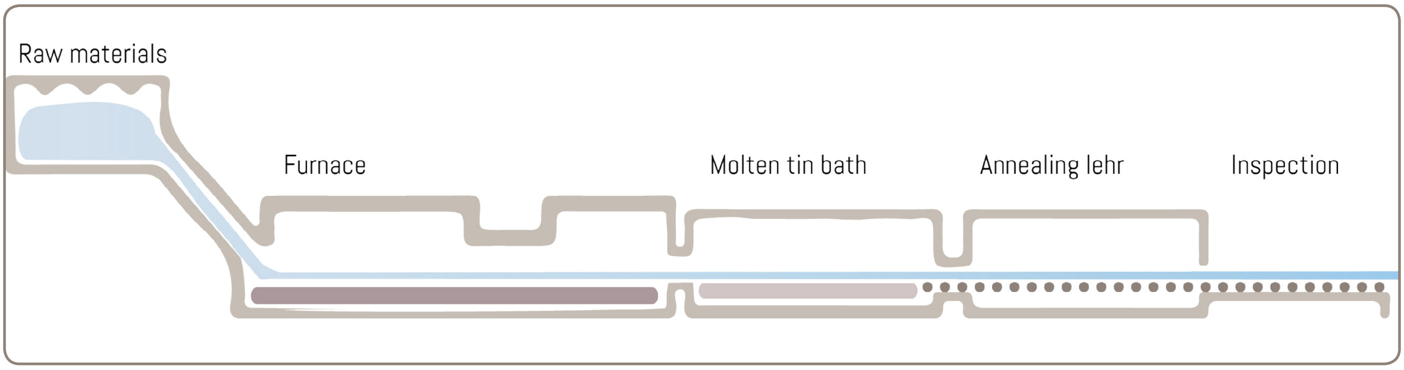


Figure 10: Diagram of a float line

2.2. Mechanical properties

Glass is an elastic, isotropic material and exhibits brittle fracture. In contrast to other construction materials, no plastic deformation occurs prior to failure. Therefore, local stress concentrations, occurring for instance close to bolt holes, are not reduced. The brittle characteristic of glass is of concern when constructing with glass as a load bearing element (Haldimann et al., 2008).

2.2.1. Types of glass

There are four basic categories of glass that we can distinguish. These categories are based on the chemical composition of the glass (Gupta, 2014).

Soda-lime glass is the most common type of glass we see, roughly 90% of all glass produced is of this type, and this type is the least expensive form of glass. It usually contains 60-75% silica, 12-18% soda, 5-12% lime. Common uses include window panes and laminated structural glass.

Lead glass is somewhat more expensive than soda-lime glass and is favored for electrical applications because of its excellent electrical insulating properties.

Borosilicate glass is any silicate glass having at least 5% of boric oxide in its composition. It has high resistance to temperature change and chemical corrosion. Because of this it is most commonly used in kitchenware and laboratory equipment.

High-silica glass contains up to 96% silica and is produced by removing alkalis from borosilicate glass. This type of glass has a very high thermal serviceability limit (up to 1200 degrees Celsius).

2.2.2. Borosilicate

Borosilicate glass is an "engineered" glass developed specifically for use in laboratories and applications where thermal, mechanical and chemical conditions are too harsh for standard soda lime glass. When we compare soda-lime glass to borosilicate glass, we see that they have a lot of properties in common. Both have roughly the same density and the optical quality is comparable. There are a few aspects that set borosilicate glass out from soda-lime glass however; the thermal expansion of borosilicate glass is twice as low when compared to soda-lime glass (4.5 to 9 μm/m-K) and the strength-to-weight ratio is over twice as high (130 to 50 kNm/kg) for borosilicate glass. Because of these properties borosilicate glass is the safer choice to use in structural applications.

2.2.3. Strength of glass

Typically glass has the following values for tensile strength (Louter, 2011):

45 MPa	Annealed Glass
70 MPa	Heat Strengthened Glass
120 MPa	Fully Tempered Glass

These values cannot be used as design guidelines however. One example is the aging of glass, as glass ages it loses its strength. This is not the case for HSG and FTG but does influence the behavior of annealed glass quite significantly. Annealed glass ages down to roughly 6 MPa strength wise (including safety factors). The 70 and 120 MPa values we see for HSG and FTG in the initial table are without any form of safety factor. If we add generally accepted safety factors for glass these values will generally drop down to and be assumed at (at which 99,5% of all specimens fail at higher values):

6 - 20 MPa	Annealed Glass
40 MPa	Heat Strengthened Glass
80+ MPa	Fully Tempered Glass

For our design we are using a borosilicate glass that has been thoroughly tested and therefore we use the value of 25 MPa for the tensile strength. See “8.1. Appendix A; BOROFLOAT33 specifications” on page 112.

2.3. Legislation

Over the last decades we have seen more and more glass structures being realized. Starting with glass parapets and staircases, leading up to beams and fins constructions made out of glass. But if we look at the legislation of glass structures, we can find surprisingly little. Most we can find are examples like the German code DIN18008, which covers the maximum allowed tensile stresses in glass, or the Dutch code NEN-EN-ISO 12543 which sets out the guidelines for glass laminates. But there is no clear legislation on structurally applied glass columns. Because of this we, as engineers, have to be very careful on what we assume to be safe. Generally, a structural element should show visual defects to indicate failure. Does a material lack the possibility to provide an early warning, there should be enough time between structural failure and the moment people can evacuate the building, or repair the element in order for it to be safe (Nijsse and ten Brincke, 2014).

2.4. Factor of safety

Worldwide, engineers use safety factors in all aspects of engineering, but what are these safety factors? If we assume theoretical values like calculated permanent loads, and optimize our structures using these values there is no margin for error. Factors of safety are in essence forced margins of error. A higher factor of safety required can have many causes, ranging from material or production quality, inaccuracy of material properties and general uncertainties. This means that thoroughly tested materials and applications can have a significant reduced factor of safety. An area of engineering where we see this being pushed to the limits is in aerospace engineering where a low factor of safety is critical for the functioning of airplanes (as higher factors of safety mean more weight to get airborne). A safety factor this low, 1.2 in case of aerospace engineering, does require very strict quality and maintenance controls and thorough testing of materials and components though.

In general we use safety factors between 1,25 and 4. But if we have to deal with unpredictable materials with brittle and sudden failure behavior, these values should be doubled (Oikonomopoulou, 2012). As a result glass structures commonly have to deal with safety factors of 5. This is also the factor of safety suggested by F.A. Veer. Applying a safety factor of 5 also means that the structuural elements will have to be overdimensioned significantly, severely increasing weight and costs. But through thorough research and future legislation on the material glass we should be able to assume better safety factors in the future. But until there is said legislation regarding structural glass applications, it is up to the engineer to apply glass in structures in safe ways. A method that is being used to identify risk is called a qualitative risk analysis, or more commonly ‘Risk = Consequence * Probability’, using this method an engineer can make wise decisions regarding the use of glass in structural applications.

2.5. Qualitative risk analysis

The lack of legislation regarding glass columns can be seen as both problematic and as a positive influence. The downside is that there are no real guidelines to test criteria against. The upside is that thorough research can be conducted by experts without being bothered by legislation, after which legislation can be based on proper research. This does mean that is it up to the engineer or researcher to define criteria on which to base conclusions. Furthermore he also has to decide what aspects pose a significant risk for the design of the research. For the identification of risks we understand that risk is both based on the probability of something happening and on the consequences when this happens. A high probability generally means that this issue should be addressed to keep the consequence as low as possible, and vice versa. In order to analyze each potential risk, a 5*5 (or 6*6, 10*10, etc.) matrix can be setup with on one axis the probability of said risk happening, and on the other the consequence of this risk happening (See "Figure 14: Risk analysis matrix") (Modarres, 2006). Each risk is then graded by multiplying the probability with the consequence. As this is a relative grading system, separate risks with the same outcome should not be taken lightly but thoroughly analyzed. For example, a high-probability low-consequence risk has the same outcome as a low-probability high-consequence risk. In case of the high-probability risk minor safety adjustments can be taken in order to try and prevent these risks from happening. A risk with a high consequence but low probability tends to be a more catastrophic risk. For these you should do what you can to reduce the impact they'll have if they do occur, and you should have contingency plans in place just in case they do (Cox et al., 2005). To understand how this works, and how other engineers deal with this method we will have a look at three examples; the Kravis Center of the Claremont McKenna College (See "Figure 12: Kravis Center"), the Temple d'Amour (See "Figure 13: Temple d'Amour") and the Apple store in Stanford (See "Figure 11: Apple store Stanford").

2.5.1. Claremont McKenna College Kravis Center

Architect:	Rafael Viñoly
Engineer:	Nabih Youssef Associates
Location:	Claremont, California, USA

The Kravis Center is a 5 story tall academic and administrative facility. Its most novel feature is its all glass Living Room (aka the "Kube") that floats on a Mesabi black granite reflecting pool. The glass used in this design functions as walls of the pavilion as well as the fins behind these walls as stabilizing elements. The pavilion is always open for both students and personnel, so if any of the glass elements fail this could have very severe consequences as human injury is always a very serious risk to consider. What about the probability of anything happening to the glass? There are a few things that could happen, people could run into the glass but they could need quite a bit of force to actually damage the glass. But another thing that can happen, and is significant, is anything happening to the fins behind the wall (cleaning equipment or other maintenance equipment. Such equipment generally has more momentum than a person running into it, and a fin is a weak element at resisting such a force. Because of this we also have to assume, at least, a medium chance of probability. To counter these risks, the engineering focus was to try and eliminate the probability of this happening, which is arguably easier than reducing consequences. How this was done was the assumption of a safety factor of ten. This is immensely high and results in glass of over seven centimeters thick (six layers of 12mm thick fully tempered glass).

2.5.2. Temple d'Amour

Architect:	Kraaijvanger
Engineer:	ABT
Location:	Burgundy, France

An eighteenth century folly has been redesigned into a private residence. Above the folly a wooden roof was realized resting on top of glass walls to appear floating above the original folly. The design was realized in 2001. The probability of anything happening to the glass is not extremely high, but people could run into it, causing local failure, or external loads like snow and wind could cause eccentric forces on the glass walls. Even though this is a medium probability, the consequence is something to think of because there could be people inside and the risk of people getting hurt is always a serious consequence. In a design like this it is very hard to reduce any consequences. Because of this the focus was to reduce the probability as much as possible. To ensure a low probability a high safety factor was used, the safety factor used was equal to five.

Figure 12: Kravis Center

Figure 13: Temple d'Amour

Figure 11: Apple store Stanford

2.5.3. Apple store Stanford Mall

Architect:	Bohlin Cywinski Jackson
Engineer:	Eckersley O'Callaghan
Location:	Palo Alto, California, USA

This project is an Apple store with a big glass façade, realized in a highly seismic area. If this glass façade is load-bearing, even small seismic activity could be enough the shatter the glass and send the roof crashing down. As it is a highly seismic area, the probability of this happening is extremely high (probability: 5) and the consequence would be very high as well as people inside the building would be severely injured (consequence: 5).

So how was this risk dealt with? The glass façade is designed without any external load-bearing capacity, and is only a self-supported system. In the very thin edged roof is an entire system of steel cables that will carry the entire load of the roof should there be no support under it. Because of this the very severe consequences were reduced to practically zero.

2.54. Comparison

If we look at the three previous examples of determining risk based on consequence and probability, you can see that you can reduce risks if you know what you are designing for. In the Apple story the glass doesn't suffer from eccentric forces because there is no load resting on top of it during an earthquake, this reduces the probability of the glass damaging, and greatly reduces consequences because the roof cannot drop down as there is a secondary system at work. The Kravis Center pavilion and Temple d'Amour focus on lowering the probability as much as possible by over dimensioning the glass structural elements.

Looking back to the risk matrix we described earlier, we can (roughly) say that the initial (red) medium to very high risks have been reworked and designed (blue) to only have a low to medium risk now.

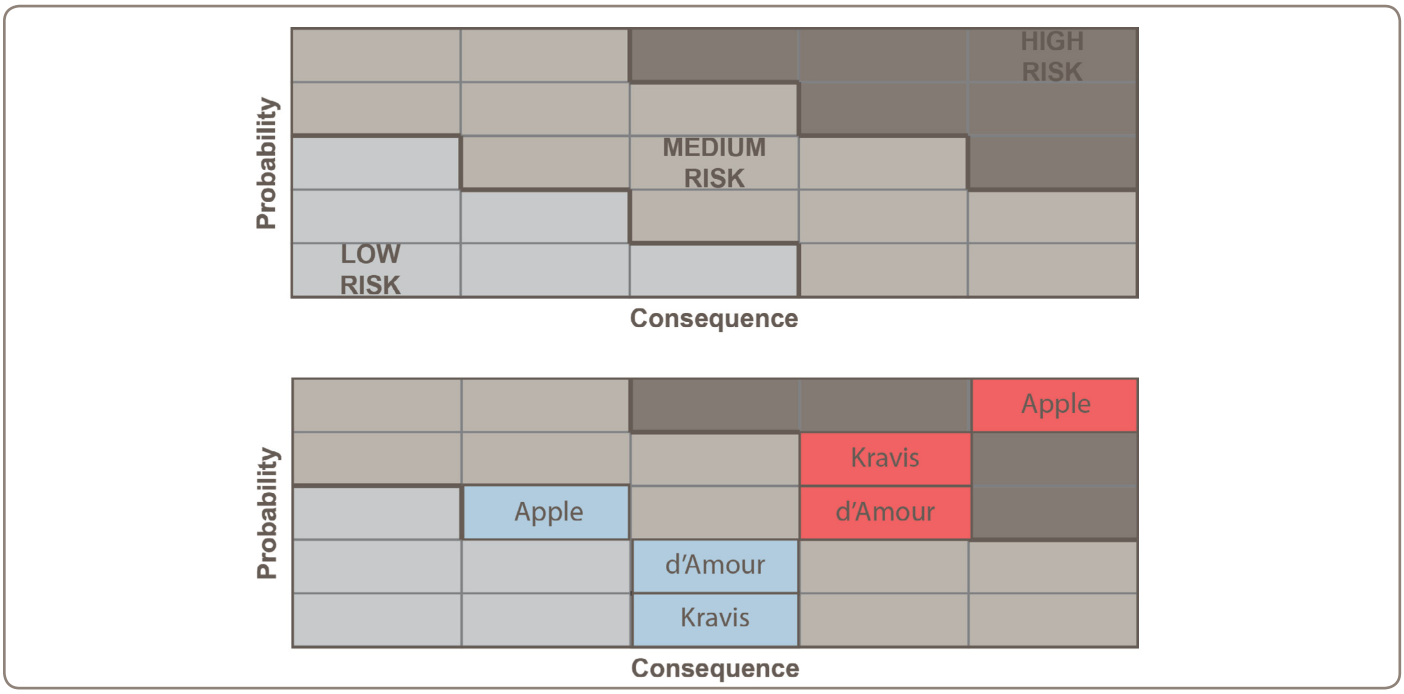


Figure 14: Risk analysis matrix

2.6. Failure modes of columns

The load carrying capacity and modes of failure of a column are based on the slenderness ratio. Slenderness ratio is defined as the ratio of effective length of column to its radius of gyration. The effective length of a column depends on its support conditions at ends (Hognestad, 1951).

2.6.1. Failure mode 1, pure axial compression:

A perfect column (i.e. without eccentricities or imperfection) that is only axially loaded will not show any lateral deformations until a critical buckling force is reached. When the loads are high compared to the cross-sectional area of the column, the glass reaches its maximum yield stress and the column fails without undergoing any lateral deformation. The glass column is crushed and the column failed due to material failure. Or in other words, if the critical buckling force is greater than the compressive strength of the material, the column will fail by material failure before buckling.

2.6.2. Failure mode 2; combined axial, torsional and lateral stress:

Columns in structures are generally not only loaded under compression, but also experience bending moments and lateral movement. This is especially true for relative long columns, as these columns tend to undergo greater lateral forces and deformations. This type of failure is the most common kind of failure when looking at columns.

2.6.3. Failure mode 3; lateral torsional buckling:

Lateral torsional failure is mostly applicable to beams, rather than columns. But if a column experiences lateral loads (heavy winds or similar forces) a column can also fail under these loads. What happens in this case is that the combination of axial and torsional loads exceeds the elastic limit of the material and the center of the column twists away from under the axial load. Since rotations around the longitudinal axis are only restricted at the supports, cross-sections will rotate more towards the center of the span. This effect can be countered by using a torsional resistant cross-section. This failure mode is one you don't want to see in glass columns so a typical steel profile section should not be applied to glass columns.

2.64. Failure mode 4; elastic instability:

Long columns with a small cross-section are very slender. Under such conditions, the load carrying capacity of columns is reduced drastically for given cross-section. When this type of column is subjected to smaller loads, they tend to become unstable and buckle to any side. This happens when the critical buckling force is reached. This phenomenon is especially crucial in glass columns because buckling means deformations. These deformations cause peak tensile forces, and unlike steel which flows under said forces, the glass column will fail in a –very- explosive manner.

A glass column of building scale will most likely fail because of elastic instability (buckling). This is especially true in columns with a high slenderness ratio. If a column is grossly over-dimensioned to reduce its slenderness, the associated failure mode will move towards the combined failure mode. In extreme cases it might even lean towards pure compressive failure.

2.7. Post-tensioned columns

Post-tensioning is a method of reinforcing (strengthening) concrete or other materials with high-strength steel strands or bars, typically referred to as tendons. A typical steel strand used for post-tensioning has a diameter of 15.7mm and a tensile strength around four times higher than an average non-prestressed piece of rebar. Post-tensioning tendons are considered “active” reinforcing. Because it is prestressed, the steel is effective as reinforcement even though the concrete or another material may not be cracked. Post-tensioned structures can be designed to have minimal deflection and cracking, even under full load (Post-Tensioning Institute, 2000).

This post-tensioning causes residual normal stresses along the longitudinal axis of the member. From structural analysis theory it is known that normal actions can have an influence on the torsional rigidity, and thus on the buckling resistance (Belis, 2006).

Another result of post-tensioning a column is that you reduce to total load bearing capacity of said column, but you get more torsional rigidity in return. What we expect will happen to glass columns is that the elastic limit will be reached and the column will buckle well before the material limit is reached. Using a post-tensioning system we can increase the load-bearing capacity before failure caused by buckling, while still remaining within the load-bearing capacity regarding compressive forces.

2.8. Critical buckling force

Buckling is characterized by visible failure of a structural member subjected to relative high compressive forces. At the point of failure the compressive stress is below the compressive strength of the material. So the material did not fail, but as a result of a (too) slender profile section the member collapsed (Boresi et al., 1993).

Under what kind of compressive loads a member fails can be calculated, but in reality the member will always fail before said load is reached. This is due to the theoretical approach of the calculation, assuming a perfect member in all senses (no inclusions in the material and no production errors for example). However, fluctuations of the loads, variability of the material properties, eccentricities caused during production and uncertainties regarding the analytical models all aid to lowering the probability of flawless behavior (Madsen et al. 2006). Because of this these calculated loads are always handled with safety factors. This over-dimensioning of structural members ensures structural reliability and safety.

The force at which a structural member will fail because of buckling is dependent on several aspects. The length of the column is an important factor, but the way the column is suspended is also a key aspect. If a column isn't rigidly fixed but the connections act like a hinge, the effective buckling length is twice as high. Finally the second moment of area and the material properties influence the buckling behavior of the column.

Slender columns can be analyzed using the Euler column formula:

$F = \pi^2 E I / L^2$

In which:

F = allowable load (N)
E = modulus of elasticity (N/mm2)
L = effective length of column (mm)
I = Moment of inertia (mm4)

What do we mean with effective length of the column? Depending on the connection conditions (hinged, clamped or a combination), the way the column buckles varies. Because of this difference in deformation, the bending moment diagram for each column also changes. The result of this is a location on the column where the bending moment is 0 (or on two locations in case of a double clamped connection). The effective length of the column is the region between two of these M=0 locations, or the longest part of the column between M=0 and the support.

The critical buckling force (F) resulting from the formula is the theoretical maximum force a column can handle. But it is most likely the column will buckle or fail earlier. It is however important to define these maxima as these values are used with a safety factor to decide when a column is safe to use or not. For this research there will be compressive tests carried out of column specimens of different lengths. Using the Euler formula we will calculate the theoretical maximum each column combined with each suspension will be. We can then use these values as reference for comparison later. We can use these results to analyze the compressive tests and the way the specimens failed, and we can use them to determine when a column is safe compared to what safety factor.

2.9. Using glass structurally, safely

If we want to use glass in a structural way, there are a few ways we can enhance its behavior to provide better safety. Some of these aspects are treatments to the glass; others are focused on how the glass should be handled.

2.9.1. Design by redundancy (increased safety factor)

Structural elements are subject to external forces which can be calculated pretty accurately. The resistance to these forces can also be calculated if accurate material properties are available. If the external forces overcome the resistance forces, the structure fails. So you introduce a safety factor in the designed elements. If the expected force is 5kN for example, a safety factor of 2 implies it can handle forces up to 10kN. For materials like steel the material properties are very consistent and therefore a relative low safety factor is applied. For glass more research is required into the failure behavior before we can use values like this. So when designing with glass you should design with a form of redundancy, making sure the external forces never come even close to resistance forces, this does significantly increase the weight and cost however. It is common to use a safety factor of 5 when designing glass elements (Veer, 2014).

2.9.2. Laminating glass (reduced consequences)

Laminating glass in essence means using an adhesive interlayer to join multiple layers of glass into one element (See “Figure 17: Laminated glass” on page 37). This method can therefore be very effective when structures are too tall to be created out of one glass pane. This lamination process can be used for several aspects. The most common aspect is in order to create safety glass. Because of the adhesive interlayer, a single layer of the lamination can break but the interlayer will still hold most of the pieces together, enabling the structural member to still carry loads without failure of the structure. This post breakage characteristic also makes laminated glass an excellent glazing material for architectural applications, including safety glazing, overhead glazing, and glazing that must remain integral when broken. In fact, most architectural applications of laminated glass derive directly from provisions in model building codes that require safety when human impact constitutes a likely factor in potential glass breakage (Norville et al., 1988). Another common reason the use an adhesive to laminate glass is the creation of a so-called ‘sacrificial layer’. A sacrificial layer is a layer of glass on the service side of the glass element. This layer is designed to take any damage done to the element, and if it happens to be so, break. This layer is a thinner layer of glass and laminated using an easier to remove adhesive which allows for easy replacement of said part (See “Figure 15: Replacement of sacrificial layer” on page 37). Some good examples where we can see this method of designing are in all glass staircases and parapets. Glass elements in these members are almost always designed by laminating three panes of glass, and have the addition of a thinner sacrificial layer where people walk or are likely to damage the surface. This method of improving safety is also being used in the design of the all glass tubular column by F.A. Veer (Veer, 2000). This method is less relevant for the research of the bundled column as the failure behavior regarding this column is improved using redundancy, but laminating might be important in the design of the connection details, or in the beam to which it is connected.

2.9.3. Better processing

During the production of glass there is always the possibility of micro flaws to occur. This could be the result of small air bubbles or some contamination. These flaws can be very small and invisible to the naked eye, but they do affect the structural behavior of the final element. So in order to have a safe element, you should make sure to only use the best quality of glass available. But not only the quality of the glass influencing this safety point, also the way the glass is handled and finished after the production process is important. Glass cannot deal with peak stresses and these stresses can occur when the edges are improperly treated for example. As glass float out of the molten tin bath in the production process of glass, it is cut into big pieces at the end of this line. These big glass planes can be used or divided into smaller glass panels, but the cutting of these sheets causes damage at the edge of the panel. These small imperfections may seem insignificant but it is at these locations where stress peaks are focused and these can therefore be the reason for breakage of the glass. Results show clearly that edge finishing is the dominant factor in determining the glass strength. This edge finish is determined by both the cutting and finishing processes (Veer & Zuidema, 2003). The glass that comes out of the float glass process is known as ‘annealed glass’. When this glass comes out of the line at room temperature all residual stress has left the glass and further modifications to the glass can take place. As we saw earlier this glass can now be strengthened, using either heat or chemical strengthening. What this strengthening process does however, is creating residual stresses. Because of this, any other modifications to the glass must take place before the strengthening process; otherwise the glass will instantly break trying to adjust the glass afterwards. Modifications can be anything from cutting, sanding, polishing or adding holes for future connections to the glass.

As glass floats out of the float line it is automatically checked for flaws and cut into large panels. These large panels can then be cut into even smaller panels. This is mainly done by computer controlled cutting machines or using water jet cutting (See “Figure 16: Waterjet cutting”). Because of these cutting processes and lot of small cracks occur on the edge of the glass panels. And as we saw earlier it is these small cracks that will a source for local peak stresses, ultimately leading to failure of the glass. Because of this these edges should be sanded and polished carefully (See “Figure 18: Edge finishing” on page 39). If the glass is cut using a waterjet cutter, no further edge finishing is required, assuming the waterjet cutter is set to the right settings (Felekou, 2016).

2.94. Tempering glass (increasing strength reduces probability of failure)

Toughened glass starts life as float glass. Float glass, when shattered breaks into big and sharp pieces and this can be harmful to anyone near it, it is therefore unsuitable for some applications. Before undergoing the toughening process the glass parts must be cut to size and any additional machining (holes for connections etc.) must be completed before the glass is toughened as it would shatter if it was cut in its toughened state (Todd et al., 1999). During the toughening process, the surfaces of the glass are heated to temperatures of over 600 degrees Celsius in a furnace. The hot glass is then rapidly cooled using air blasters to blow air on the glass surface for somewhere between 3 and 10 seconds. Because of this sudden temperature change the surface of the glass shrinks and at this point in time tensile stresses develop in this surface. But as the core of the glass begins to cool the already cooled surface is forced to contract. As a result of this the surface develops residual compressive surface stresses while the interior glass zones compensate by developing tensile stresses (See “Figure 19: Tensile zone” on page 39). The tension zone in the core of the glass takes up about 60% of the cross-sectional area of the glass. Compressive surface stresses improve the strength of the glass in the same way that they do in other materials

Figure 15: Replacement of sacrificial layer

Figure 16: Waterjet cutting

Figure 17: Laminated glass

(Krohn et al., 2002). After the process the toughened glass has a greater resistance to thermal stresses and thermal shock and has improved flexural and tensile strength. The higher the coefficient of thermal expansion of the glass and the lower its thermal conductivity, the higher the level of residual stresses developed, and the stronger the glass becomes. We use three classifications to identify strengthened glass, annealed glass, heat-strengthened glass and finally the stronger one, fully tempered glass. Thermal toughening takes a relatively short time (minutes) and can be applied to most types of glass. Because of the high amount of energy stored in residual stresses, tempered glass shatters into a large number of pieces when broken (See "Figure 20: Tempered glass breakage"). The broken pieces are not as sharp and hazardous as those from ordinary glass (Bartholomew et al., 2012).

This heat strengthening process is a relative easy and little time consuming process to strengthen the glass. And as we saw earlier, using this method we can increase the strength of glass from roughly 45MPa to 180MPa. There is also another method to achieve this, namely chemically strengthening glass. But this method is mainly used on thin glass elements with a thickness of less than 3mm. Thicknesses above 3mm are generally always strengthened using heat strengthening.

2.9.5. Using other materials to overcome weaknesses

Glass is great in dealing with compression, but lacks the ability to handle tensile forces. So another way to improve the safety of structural glass elements, is introducing a material in the glass that does handle tensile forces very well. When we look at concrete (a material which also lacks tensile handling properties) this is done by using steel rebar. We can also apply steel fibers in the glass, which does not increase the glass' performance like it would in concrete; but this would allow for more ductile failure. This obviously leaves visual traces however and might not be ideal. An effective way of using steel to reinforce glass is by solely having steel reinforcement around the edges of the glass. Other research is also being conducted on reinforcing glass with microfibers.

2.9.6. Careful designing of the connection details

In construction we generally know two types of connection conditions for column-beam connections. Pinned and fixed, or also known as hinged and clamped. These are two extreme connection conditions and in reality connection are rarely 100% precise. A pinned connection means that the connection can rotate around 1 or more axis and therefore acts like a hinge. A fixed connection does not allow for any rotation. This means that a pinned connection cannot transfer any bending moments where a fixed connection is a bending stiff connection. In reality a connection will almost always be somewhere in between these two types of connections. This because it is very difficult to create a 100% fixed connection.

Why are the connection conditions important? The connection conditions alter the behavior of a structural column in two ways. Firstly the distribution of bending moments is different when the connection conditions change. Secondly the way the member buckles changes and the effective buckling length of the column is altered (Wang & Wang, 2014). The way the column buckles depending on the connection conditions we can see in the (See "Figure 21: Effect connection conditions" on page 41). This is important to realize when designing the connection details of the column. This buckling behavior will be further investigated in the design chapter of this thesis.

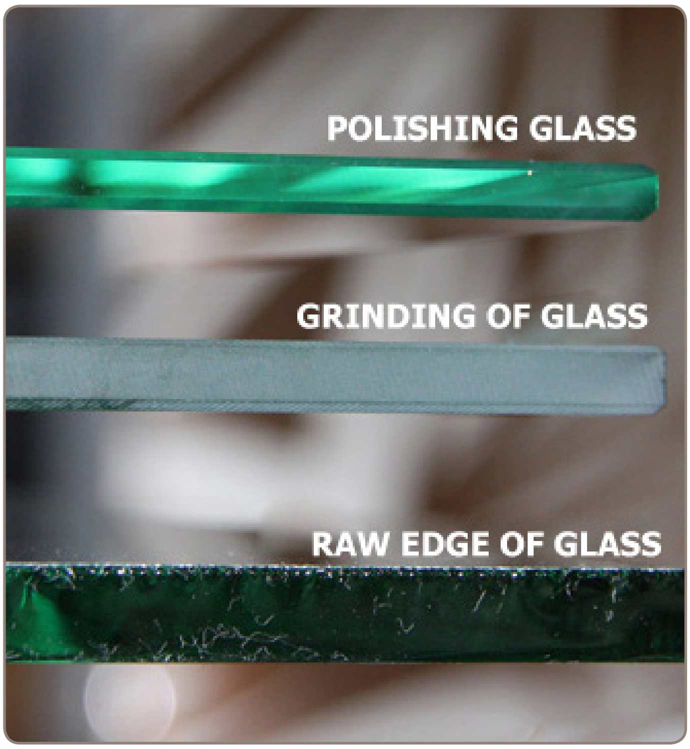


Figure 18: Edge finishing

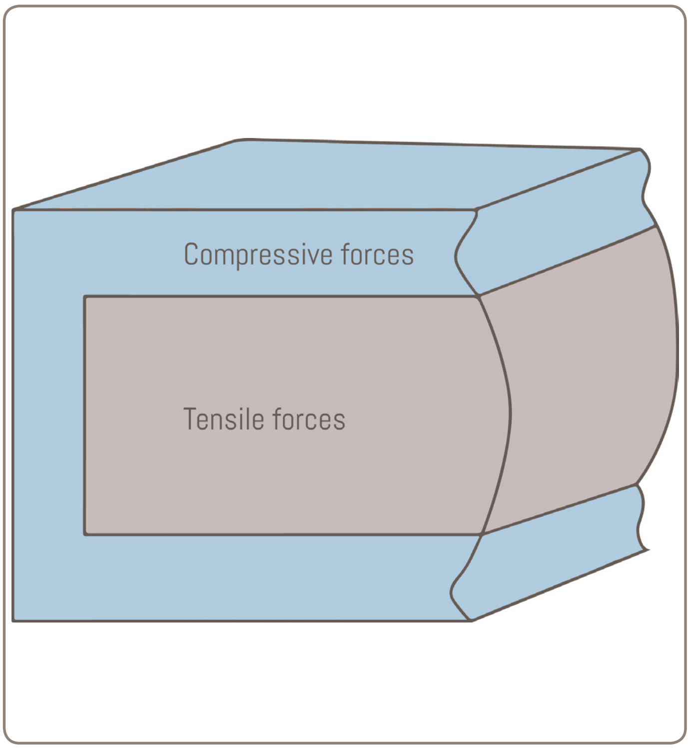


Figure 19: Tensile zone

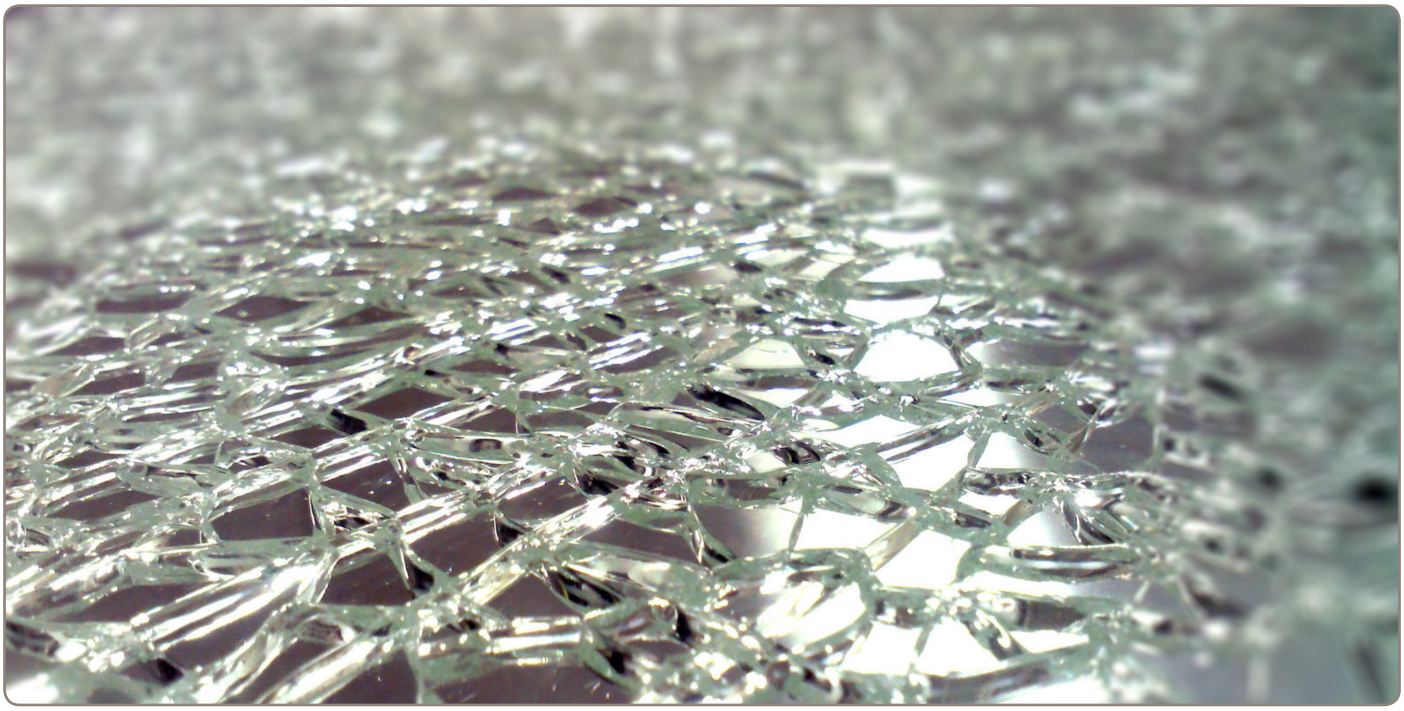


Figure 20: Tempered glass breakage

2.10. Adhesives

Glues, or adhesives, have been around for as long as we know in natural forms. Think of natural waxes, tar and adhesives derived from plants and animals. Modern manufactured adhesives arrived on the scene around 1910, when phenol formaldehyde adhesives were developed for making plywood. After these acrylic adhesives, cyanoacrylates (also known as “super glue”), epoxies, and so on were developed. A good adhesive has excellent properties of adhesion (the ability to stick to the surfaces to which it’s applied) and cohesion (the ability to stick to itself). When you pull apart something that’s been glued together and the glue comes right off the piece, that’s an adhesive failure. If the glue itself splits apart, leaving glue on either side of the joint, then that’s a cohesive failure (Petrie, 2000).

Research continues to this day on exactly what happens when two objects stick together. There’s no universally accepted theory, and given the variety of adhesives more than one process may be at work. It’s generally agreed that adhesion occurs at the molecular level; the chief processes involved being Van der Waals forces, ionic bonding, covalent bonding, and metallic bonding (Petrie, 2000).

Rather than diving into how adhesives work on a molecular level, what aspects of adhesives are relevant to understand when applied in structural design? When we look at the diagram of different forces present in structures, we have to realize that the main domain of adhesives is within the shear domain (See “Figure 22: Force domains”). Adhesives are generally weakest in tensile direction. Delamination can appear under normal load, perpendicular to the layers of the composite, or by torsional forces. Though delamination under normal load perpendicular to the layers is most sensitive, in practice, especially during bending and compressive loading shear forces are caused between the plies. Therefore reliable data on shear properties for composites are necessary (Schneider et al., 2001).

The adhesive that has been selected for the production of the bundled column we are researching has been thoroughly tested. Resulting from these tests are reliable values for the shear strength of the adhesive when applied with a 0,1mm thickness. The adhesive we will be using has a shear strength modulus of 22 MPa. See "8.2. Appendix B; DELO PhotoBond 4468 specifications" on page 113.

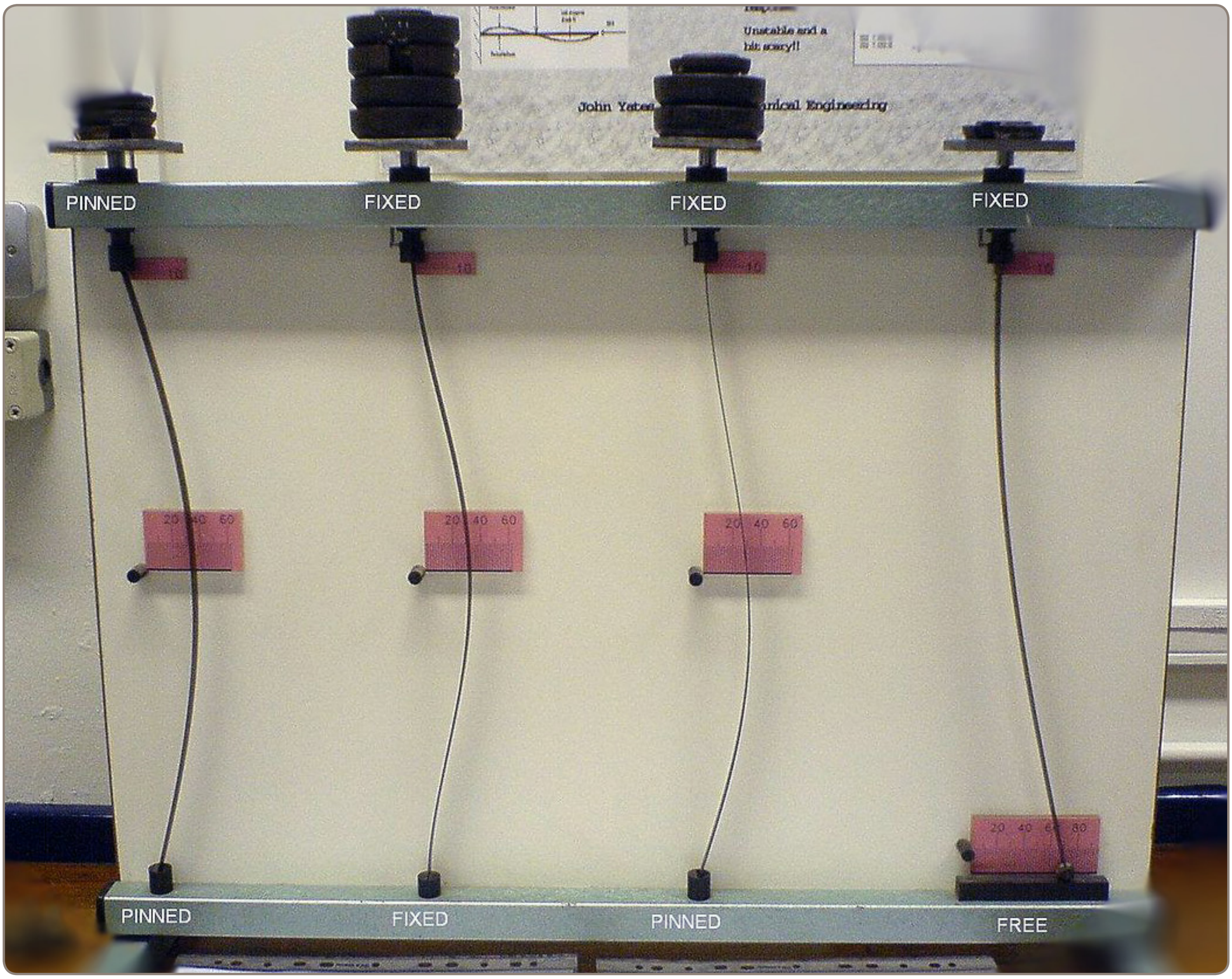


Figure 21: Effect connection conditions

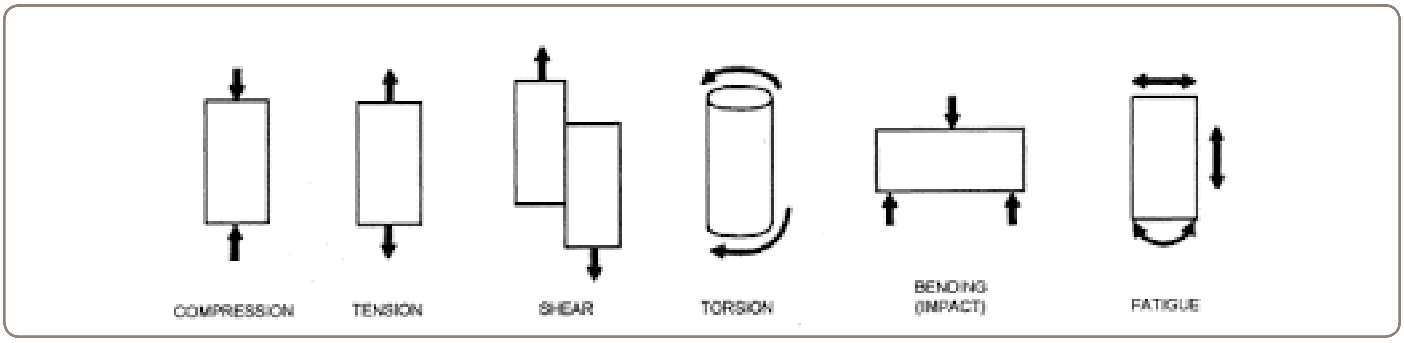


Figure 22: Force domains

2.11. Connections in glass

There are three main methods of directly joining glass elements to other (glass) elements. This first is to bolt them together using premade holes in the glass. Through these holes the bolt is connected. Another method is to use adhesive to laminate or glue elements together. A final method is a combination of the two where an external connecting system is laminated into the glass, and through which the other elements are connected to the laminated glass.

2.11.1. Bolted

Holes in glass are made using a diamond drill, since this is the only type hard enough to cut through glass (Colvin, 2005). Holes cannot be made in toughened glass; it has to be done in the float glass before the hardening process. The reason for this is that the internal tensions and the compressive stresses are released and the glass breaks due to the unbalance between the pressure and tensile zones. This method does cause many micro cracks around the cut out hole and therefore should be properly treated as we saw earlier. A common application where this method is being used is in so-called spider glass connections.

2.11.2. Adhesive

Another common method of joining elements is to use an adhesive and laminate or glue them together. Using this method no weak points in the glass are introduced. Another aspect that is true for this method is that you don't introduce non-transparent elements like bolts in the connection and therefore seems like a more clean connection. This method is not commonly applied to perpendicular connections between two structural elements however. It is rather used to connect parallel systems together the same way safety glass is created.

2.11.3. Embedded connections

Especially when it comes down to perpendicular connections, like a fin behind a plate as we saw with the Apple store entrance for example, a more complex connection system is used. Mostly this means that a steel element is laminated into the glass, in which the connections will be made. As a result of this you don't get any damage to the glass but you do get minimalistic construction details.

2.11.4. Example

One of the more well-known engineering firms that thrive to optimize, minimalize and perfect connections in glass is Eckersley O'Callaghan, lead engineer of the famous Apple flagship stores. Their work on the detailing of the most famous Apple Cube in New York led to Apple patenting the detailing. The construction details of these embedded connections are so minimalistic we can hardly even see what's going on anymore. But if we look at other Apple stores (London's Convent Garden in this case) we can more clearly see all different types of connections in harmony with each other; from the laminated beam and stairs, to the embedded steel connectors in the steps of the stairs, to the graciously winding bolt connections in the balustrade (See "Figure 23: London's Covent Garden").

Figure 23: London's Covent Garden

2.12. Where are we currently?

Resulting from improved safety aspects we see glass being used in a structural way more and more often. From the Apple stores (See "Figure 24: Manhattan Apple Store"), the Atocha Station Memorial (See "Figure 26: Atocha Station Memorial"), to the recently completed Crystal House (See "Figure 25: Crystal House Amsterdam") with a full glass brick façade. In these structures the use of all glass elements was explored. The results of this are all glass beams, fins, plates and self-supporting walls. But the amount of references regarding all glass columns is very limited. Most of these precedents are glass designs where the glass is mostly self-supporting and the glass doesn't have to deal with eccentric forces like wind load on the façade. In the case of the Apple stores and the Crystal House these forces are dealt with by dedicated glass elements, perpendicular to the main glass elements that are oriented to have their strong sectional direction in the deflected force direction. For each loading, the forces are redirected to be a very linear load case, easily handled by glass elements. So in essence what is happening in glass structures as we know them right now, out-of-plane bending is transformed into in-plane bending of another element. And in-plane bending is much easier to deal with because that means that the effective cross section of the glass is always focused on the major axis. This also hints to why we don't see glass columns on a regular basis yet. There are several reasons why glass columns are very rarely applied. The essence of these reasons is basically the difficulty of creating a 3D element from a 2D-oriented material. This will be explained for each reason specific.

2.12.1. Safety under loading

In the previous examples of all glass structures we saw very linear constructions where the glass was loaded in 1 main direction. For example the laminated fins that are used in glass portal constructions. These fins are only loaded in their strongest sectional direction. The all glass brick façade is mainly focused on dealing with its own weight; the wind load that applies a load on a different axis is handled by what in essence are also fins behind the wall, but made out of bricks. So for each loading, the forces are redirected to be a very linear load case, easily handled by glass elements. This method is a lot harder to use when designing a column, as the forces applied to a column aren't as easily separated. Thus a column requires a more 3D oriented design, strong in all directions, leading to the next problem.

2.12.2. Production process

Using methods like lamination to improve safety are pretty straight-forward, easily applied to fins and beams. But designing 3D oriented structural elements would require more complex extruded profiles which are hard to produce and extremely expensive for lengths above 1500mm. Not only are they more expensive, but also the laminating of these elements is a more tricky process. Another option for a column would be to cast it in one big glass element like done with the all glass bricks used for the façade, but the gradual cooling of this element then becomes a critical aspect. Objects the size of bricks can be cooled relatively easy, but even that process requires a lot of monitoring because of deformations and internal stresses caused by the cooling. Producing an entire column using the casting method would probably be too difficult due to the very perplexed and time-consuming annealing process of such a volume of glass in one element.

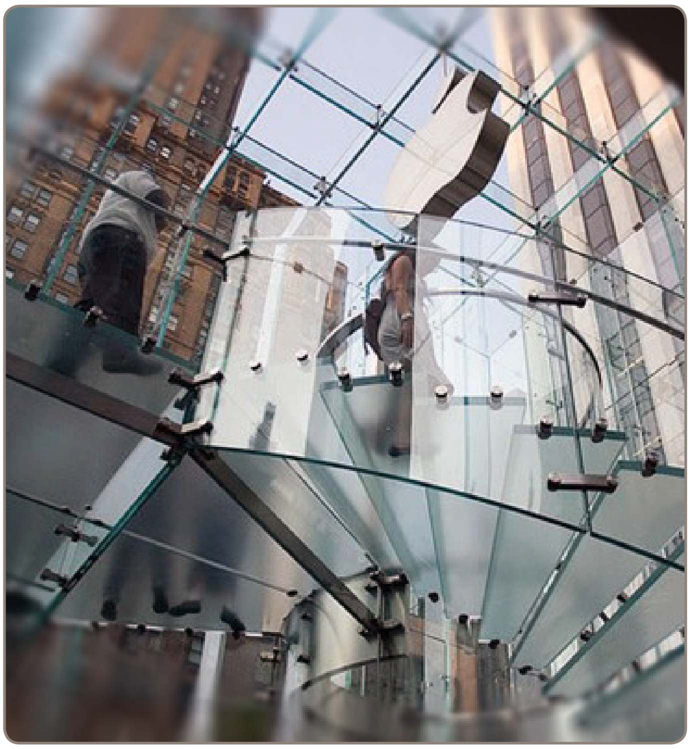


Figure 24: Manhattan Apple Store

Figure 25: Crystal House Amsterdam

Figure 26: Atocha Station Memorial

2.13. Possible types of glass columns

Taking into account the possible difficulties of producing all glass columns, Rob Nijsse discussed five different types of possible column designs: the 'profile', 'layered tubular', 'stacked', 'bundled' and 'cast' designs (Nijsse & ten Brincke, 2014).

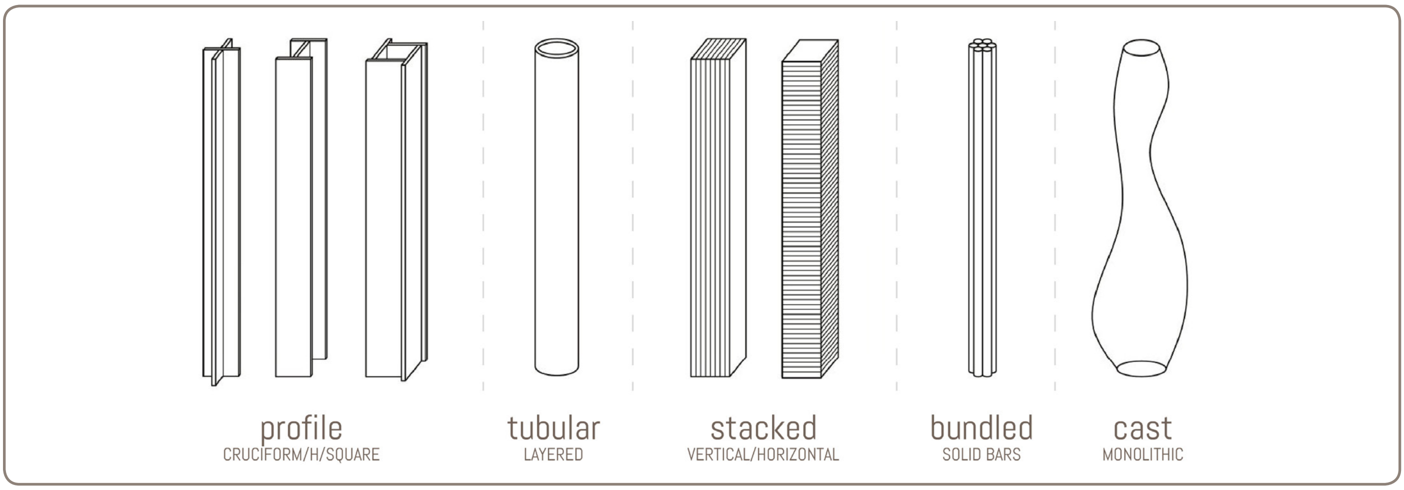


Figure 27: Five possible types

2.13.1. Profile

Based on profile sections used for steel columns, the cruciform, H and square sections are straightforward column designs. An issue with this type of column is that the profile sections often have a major and minor direction, being weaker at handling forces when loaded in the minor direction. These sections are not the most ideal to resist torsional forces, but these profiles are relatively easy to produce and therefore the only known glass columns currently realized are of this type. The first column which is of the cruciform type was realized in 1994 in St-Germain-en-Laye, France (See "Figure 28: Profile column").

2.13.2. Tubular

This column is created by laminating two concentric glass tubes using a UV curing resin (Veer et al., 2005). This type of column has been created and tested to have strength and failure behavior similar to steel columns. After further development this section shows most potential as a column because of the torsion resistance nature of a tubular section (Veer & Pastunink, 2000). The production process as described by Veer is a very extensive one however. The curing process had to be controlled carefully to laminate the two stiff glass tubes with a clear temperature-dependent resin. Because of this the creation of this column is very time-consuming and expensive. Another application where we have seen tubular glass structural elements is in the Tower Place found in London as seen in (See "Figure 30: Tower Place"). The Tower Place includes four meter long horizontal glass needles to support the wall which is the first use of glass tubes on a large scale project worldwide. In this case the glass is protected by completely hinging supports so no bending moments can damage the glass.

2.13.3. Stacked

Creating a column out of small panels is also an option and can be done in both a vertical and a horizontal manner. Laminating all these layers together is very time consuming and the visual result is not as desired. Rob Nijsse designed a house using this method of lamination in Leerdam, the Netherlands (See "Figure 29: Glass House Laminata"). In this house you can see the visual effect of having many layers of glass laminated together. Because of these reasons this type of column isn't further investigated at this moment.

Figure 28: Profile column

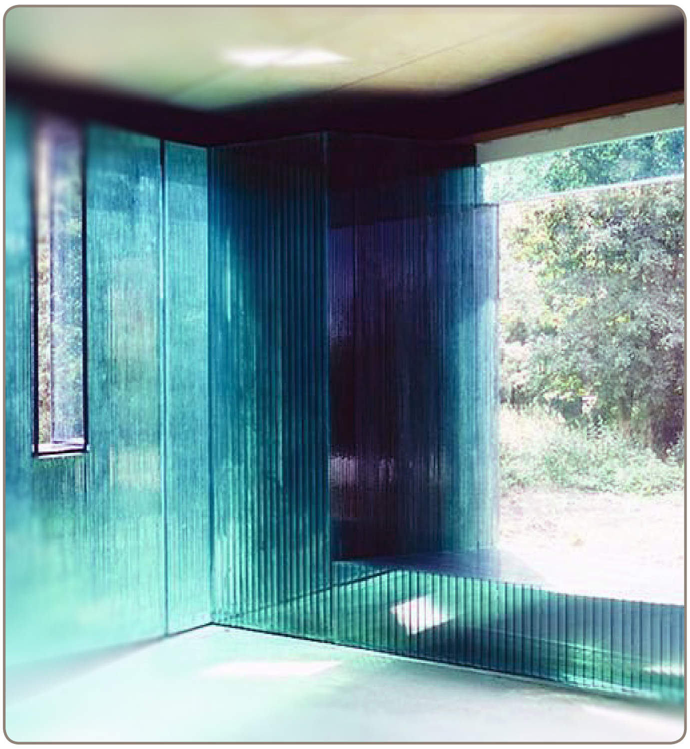


Figure 29: Glass House Laminata

Figure 30: Tower Place

2.134. Bundled

This type of column is also proposed as a safe all glass type of column. The concept of this type is having a bundle of solid glass rods bonded together using adhesives (Nijsse, 2003). By bonding these smaller rods together a larger integral cross-section is realized. The laminating of the rods is a tricky process however, as the thickness of the adhesive layer is not consistent throughout the column. Because of this you have to realize that the adhesive reacts differently to forces on different parts of the cross section. An answer to this problem has been found with the German glass producer SCHOTT, who produces extruded glass elements in different shapes (See "Figure 32: SCHOTT Conturax profiles"). Also a star-shaped profile which forms an almost perfect counter fit to the rods. Because of this the adhesive can be applied in a consistent thickness.

2.13.5. Cast

Creating a column in one piece by casting it would be the most ideal solution. Casting glass produces a monolithic whole where in other sections lamination can cause irregular and unpredictable results. But casting elements this size, and having these cooled in a controlled way is almost impossible and would take a long time, depending on the sectional properties. Creating a column out of stackable cast elements is also an option as this cuts down on the cooling time required. A complete cast column has not been realized yet but many artists have been experimenting with the casting of big glass elements. One of the most speaking projects is called 'Pink Tons' by artist Roni Horn (See "Figure 33: Pink Tons"). She used the casting method to produce huge glass blocks in several colors; this one in particular was pink. The cast glass cube measured 1219 x 1219 x 1219 mm and weighed 4536 kg. Although little is known about the annealing of this specific project, another project (only 40% of the size) called 'Untitled' had to be annealed for three to four months (Corning Museum of Glass, 2015). This very clearly marks the limitation of producing very large glass elements.

2.14. Research potential

All column types that we have been discussing have their positive features; from being easy to produce, to having great structural reliability. In order to determine what column type is best for this research, three focus points have been identified. The first focus is the architectural desirability, second is the mechanical desirability and finally the financial desirability. Derived from these three focus points is a set of two or three aspects that represent this point. Within each aspect we define the best (dark blue) and the second best (light blue).

Analyzing our (relative) grading table (See "Figure 31: Type comparison") we can say that the 'profile' and 'stacked' column types are cost efficient to produce, but especially mechanically undesirable, which F.A. Veer already concluded earlier in this research. In the architectural desirability section the 'cast' option stands out as winner, where the 'tubular' and 'bundled' rule the mechanical desirability. But by now we are aware of difficulties regarding the production, and cooling, of big glass elements, and thus choosing the 'cast' option will be too difficult with the resources available.

The 'tubular' and 'bundled' types are very interesting to research, but as the 'bundled' type came in on a second spot in both the architectural and financial sector (where the tubular one didn't); the choice for this research is with the bundled type column.

Clarifications on all the gradings can be found in "8.3. Appendix C; Column type grading" on page 114.

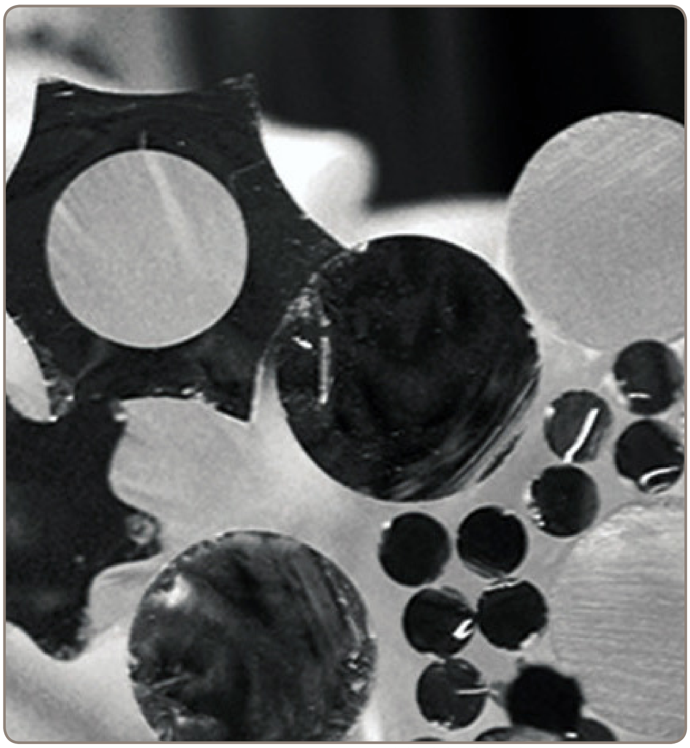


Figure 32: SCHOTT Conturax profiles

Figure 33: Pink Tons

		Profile	Tubular	Stacked (H)	Stacked (V)	Bundled	Cast
Architectural Desirability							
	Transparency		🟦			▨	🟦
	Form freedom			▨		▨	🟦
Mechanical Desirability							
	Buckling resistance		🟦			🟦	▨
	Torsional resistance		🟦			🟦	▨
	Safe failure		🟦			🟦	🟦
Financial Desirability							
	Production time	▨				🟦	
	Production cost	🟦	▨	🟦	🟦	▨	

Figure 31: Type comparison

3. Design by Research

In this chapter we will be looking at the boundary constraints of the proposed column design. In order to produce this column specimen several aspects will have to be researched and tested to verify structural behavior. From the way the column is laminated to the way the column fails. These aspects will be physically tested in order to prove the mechanical behavior of the column.

3.1. Introduction

The architect versus engineer debate, as we discussed earlier, is an ongoing discussion where the architect wants large and uninterrupted spaces which is in conflict with the engineer whose priority is structural integrity in the form of load-bearing columns. Can this discussion come to an ultimate compromise that is in favor for both of these fields of engineering? Research is being conducted in the field of structural glass applications with the aim of creating almost transparent load-bearing columns made out of glass. The goal of this thesis is to realize an all-glass load-bearing column of out glass, and the design of a post-tensioning system which enhances the load-bearing capabilities while promoting more safe failure behavior of the slender glass column. In order to test the effects of such a post-tensioning system we must first be able to produce column specimens of this size without the post-tensioning system to see how they normally perform and we can compare the effects to this neutral variant.

3.2. Design criteria and constraints

For the thesis we assume that when the column is ready for implantation, this will be done at the ABT office where Rob Nijsse is employed. From this we can assume several criteria and constraint that we will have to respect during this research. Furthermore there is also the availability over certain borosilicate extruded elements from which the research will start.

3.2.1. Case criteria

Height of column:	2900.00mm
Ultimate limit state:	112 kN (11 tonnes)
Buckling safety factor:	4

3.2.2. Mechanical properties

As we saw in the literature studies, borosilicate has a few key advantages over other types of glass for structural applications. Especially when compared to soda-lime glass, rather than to high-silica glass which is much more expensive and therefore not feasible, borosilicate has a strength-to-weight ratio of almost three times as high, and a thermal expansion twice as low. Because of these properties the choice for borosilicate was made. The elements we use are produced by a German company named SCHOTT and are extruded profiles of a borosilicate named BOROFLOAT33 and come in 1500mm lengths. The adhesive used is DELO 4468. A UV- and light curing acrylate adhesive of medium viscosity.

Mechanical Properties BOROFLOAT33

Young's Modulus:	64	GPa
Density:	2200	kg/m^3
Tensile strength:	30	MPa
Compressive strength:	300	MPa
Poisson's Ratio:	0,2	

Mechanical Properties DELO4468

Young's Modulus:	0,25	GPa
Density:	1000	kg/m^3
Tensile strength:	10	MPa
Compressive shear strength:	22	MPa

3.2.3. Column type and elements

In the final section of the literature studies we compared the possible types of columns, and the choice for the bundled column type was explained. The consequence of this type of column is that we are restricted by the elements produced at the glass factory SCHOTT in Germany. These elements are leading design constraints and our starting point of design research. The elements we will be using are all produced in lengths of 1500mm, longer specimens are possible but show greater deflections and are significantly more expensive. Because of these reasons one of the leading boundary constraints is the size of these elements. The rods we will use have a diameter of 22mm and are an almost perfect fit to the star-shaped inner profile with a hollow core. This star-shaped profile has an outer diameter of 30mm, has 6 indents to fit the rods, and has a hollow inner core of 17mm diameter.

3.24. Cross sectional properties

As a result of a fixed choice for glass elements, the dimensions for the cross section are fixed as well. Because of the choice for these elements, there are several structural aspects that we have to take for granted and we can't influence (a final conclusion can be that we need a greater cross section in order to reach the designed load however). The most important aspects are the cross sectional properties like area and the second moment of area. These values are major contributors to the critical buckling force. The second moment of area, usually denoted by I, is a geometrical property of an area which reflects how points on this surface are distributed with regard to a neutral axis. In structural engineering this second moment of area is used to determine resistance against deflection and bending moments (Beer et al., 1972). To calculate these values you can use a multiple integral over the area in question. But in this case we created the section in AutoCAD and this allows us to extract these values without performing the calculations ourselves.

Values for second moment of area:

Area:	2551.0197	mm^2
Perimeter:	329.8672	mm
Moments of inertia:	638095.2977	mm^4
Radius of gyration:	15.8156	mm

Because of the geometry of the glass elements (them being a perfect fit) optimum application of the adhesive without a difference of layer thickness is allowed. Because of this the column will be ideally loaded in compression and the adhesive will be optimally loaded on its shear properties. Because of this the individual rods will not buckle and will act like a monolithic whole (Oikonomopoulou et al., 2015).

3.2.5. Safety factor

Because of the lack of legislation regarding glass structural columns, we have to assume a factor that is realistic for this stage of research. Not a lot of tests have been performed yet, and generally a safety factor means that 99,5% of all elements can only fail after reaching this safety factor value. To ensure this type of guarantee a lot of work is still ahead of us. But we did see that when dealing with a brittle material, it is common practice to use a factor twice as high you normally would. In our case this would mean a safety factor of 4, 5 or maybe even 6. Assuming the theoretical framework of this thesis we are going to assume a final safety factor of 4.

3.3. Lamination

The final column will be 2900mm high; the glass elements are only available in lengths of 1500.00mm however. The reason for the length limitation of 1500mm is a production matter. It is possible to create elements of longer lengths, but these are expensive to make and ordinarily only available in large quantities. These longer specimens also show higher deflections (they are slightly curved) as a result of the extrusion process. So in what way should the column be laminated without affecting the mechanical properties of the column too much?

The essence of this question lies in not creating major weak points in the design of the column. Because the location where you allow for split lamination, you create a small region with a reduced second moment of area, increasing the chance of local buckling or failure.

The mechanical behavior of a column is highly influenced by the connection conditions. There is a big difference between a hinged connection and a clamped column, not only with regards to the support reaction forces, but for the entire bending moment distribution. Should you use a clamped connection on the bottom and have bending moment in your construction, there is a bending moment neutral area at roughly 1/3rd of the height of the column (See “Figure 34: Bending moment distribution”). But in a double hinged column there is no place for bending moments at all as hinges can’t transfer these kinds of forces. If we look back at the buckling deformation diagram, but add the bending moment diagrams over this, we can try to find a logical place to add the split lamination to the column.

3.3.1. Option 1

Assuming that having weak points focused in 1 area is not the ideal situation, we can look at having two main areas where the split lamination is located (where the bending moment is roughly M=0). The ideal connection condition for this is a double clamped situation because of the bending moment distribution. In this situation you have two locations where the bending moments are around M=0. This is a viable option regarding production length and bending moment distribution. There are a few uncertainties however. How can you ensure a 100% clamped connection? And varying loads or eccentric forces alter the bending moment diagram. Because of this two major weak points might not be wise, you ideally want to introduce four lamination points, two for each M=0 area. This is a viable option, but with present weak points.

3.3.2. Option 2

The second option focuses on not wanting to focus weak points too much, but rather spreading them out over an area. When you completely spread out the weak points, the influence of the connection conditions is also less important. This option for lamination also presents a more monotonous image where the gaps spiral up along the length of the column. See both options as a schematic over in “Figure 35: Split lamination schemes”.

3.3.3. Comparison

Option one has slightly focused weak points, where option two spreads them all out. Depending on how the gaps are designed, option two shows more potential to be used as an architectural addition to the column. Both are viable options but for this research we will be using the second option as this looks most feasible and we simply don’t have the time and material to test full scale specimens in quantaties this high.

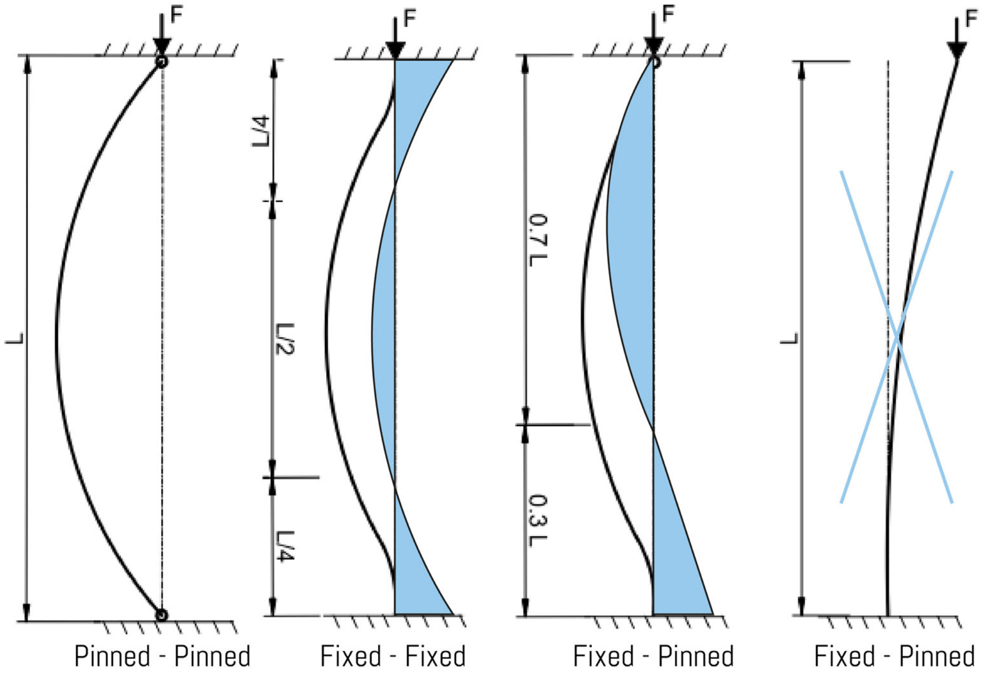
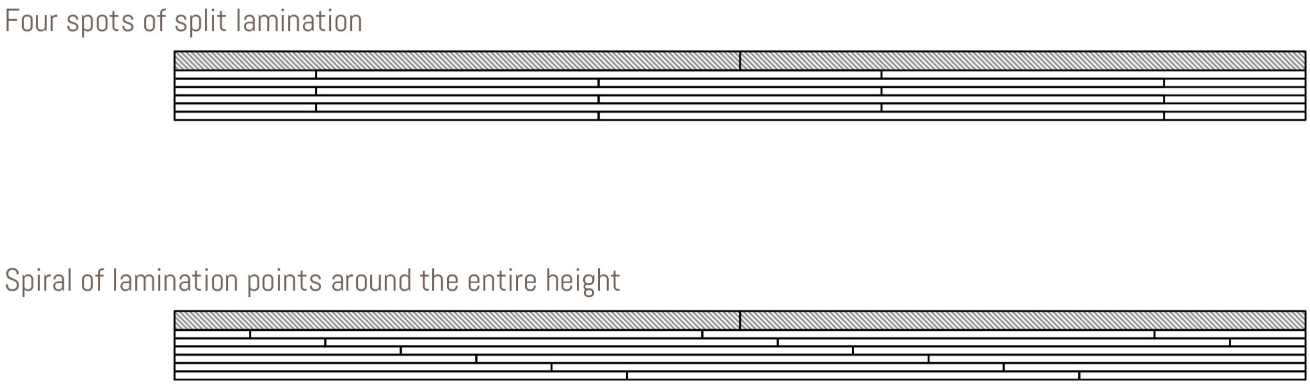


Figure 34: Bending moment distribution


Four spots of split lamination

Spiral of lamination points around the entire height

Figure 35: Split lamination schemes

3.4. Lamination gap influence

Because of the requirement for lamination to produce the column, we need to pay special attention to where two rods would touch each other, head to bottom, because these locations will be weak point. A glass on glass direct connection is excluded because statistically this will be hard to produce clean enough to prevent peak stresses, the result of this would be local failure of the glass before the final failure load is reached. In order to test the influence of the small gaps occurring near laminating regions, three types of gaps were tested on specially designed specimens consisting of three rods where one is interrupted (See “Figure 36: Three rod setup”).

3.4.1. Type 1; Small clearance

The idea behind this type is to prevent the glass rods endings touching each other. Because they don’t touch, they can’t locally fail. But then again, they can’t transfer loads either. So using this method you would have a locally reduced moment of inertia, lowering the strength of the whole column, but only by a small amount.

3.4.2. Type 2; Adhesive to bridge the gap

The reason behind the thick adhesive is similar to that of the empty one, there are no directly connecting surfacing which can cause failure, but in this case the adhesive might be able to still pass on some of the forces or redirect stresses at the glass edges. So the adhesive fill should in theory work better compared to the empty one, but leaves a more prominent visual impact as the adhesive we can use for this is not completely transparent.

3.4.3. Type 3; Aluminum disc

Leaving an open gap is likely to be mechanically undesirable, but a thick translucent element will lack architectural desirability. As a compromise of this, aluminum might work better. It’s not transparent, just like the adhesive, but it does have a slightly lower young’s modulus than the glass; the theory behind this is that peak stresses will not break the glass, but rather compress the aluminum while still transferring significantly more loads compared to the adhesive option (See “Figure 37: Specimen with aluminum disc”).

Two of these options are not a transparent option, but rather a translucent or even opaque one. But if we can test the behavior of the empty, adhesive and aluminum options, we might be able to determine an even better alternative. For example, if it’s proven that the aluminum inlay works better (because of higher moment of inertia values to prevent failure for example) we can look for another material with a similar young’s modulus, but with a higher degree of transparency like a hard plastic or maybe even glass. As benchmark to grade the mechanical behavior of these samples, another sample will be one of full glass, without any gap. This will serve as comparison material.

3.4.4. Test setup

Test parameters of glass specimens are the following:

Constants: test arrangement, the type of support; length of glass specimens (470 mm); glass material (BOROFLOAT33); interlayer material (DELO4468); edge finishing (sanding); aluminum holders with lead inlay; temperature (+23 ± 5 °C); rate of loading: 1mm/min.

Variables: material in the gap (Empty; DELO4496; Aluminum).

Of each type, three samples (See “Figure 38: Production of specimens”) will be produced and destructively tested to ensure test reliability and validity.

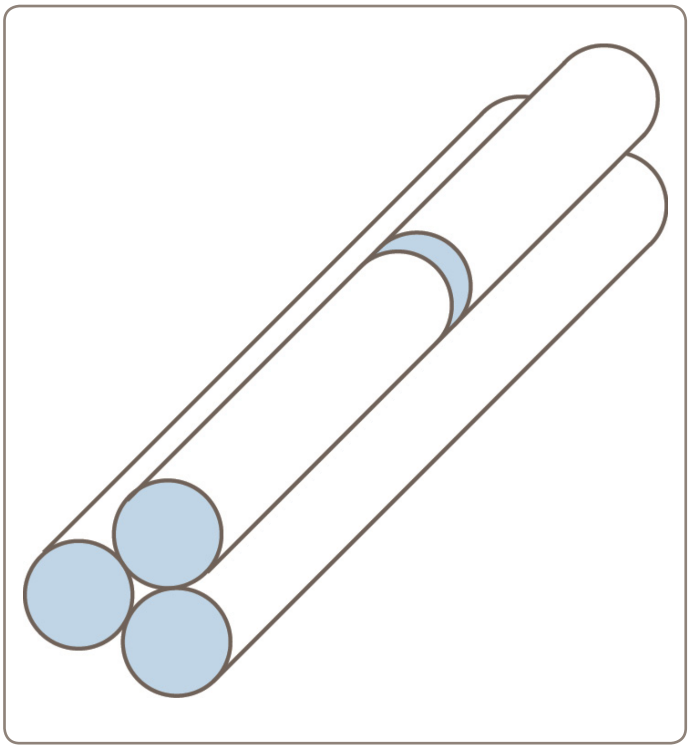


Figure 36: Three rod setup

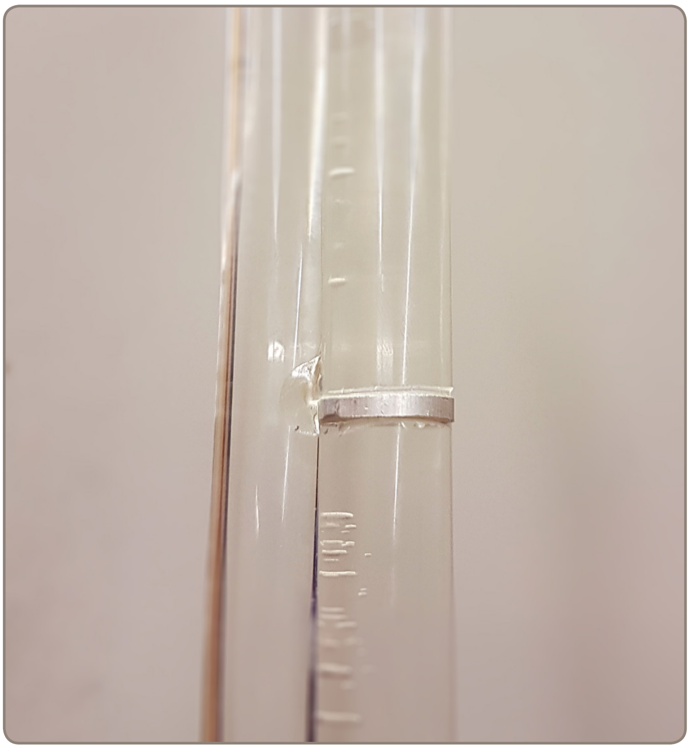


Figure 37: Specimen with aluminum disc

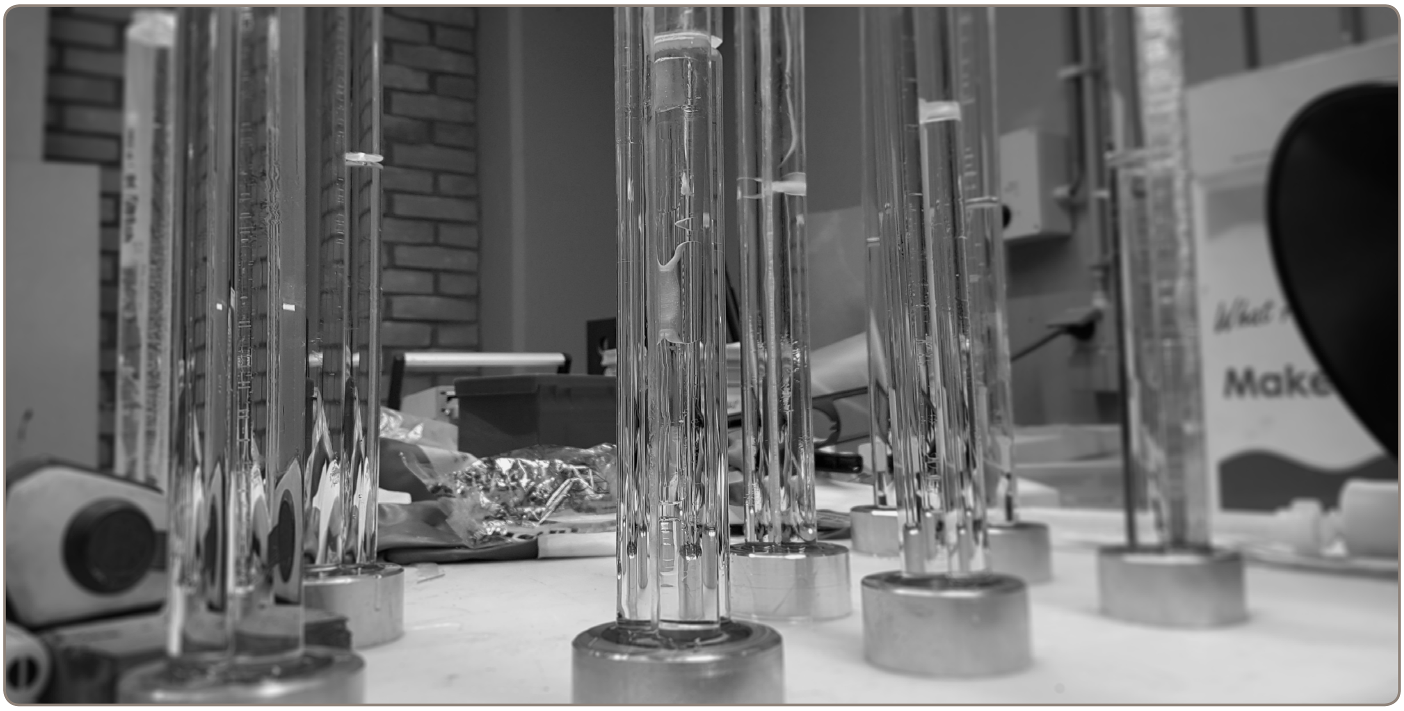


Figure 38: Production of specimens

34.5. Physical tests

The 12 specimens, three of each type for validity, were destructively tested (See “Figure 39: Broken sample”) at the Delft University of Technology. At first this was attempted at the faculty of Mechanical, Maritime and Materials Engineering using the compression bench in the Materials Science lab (See: “Figure 40: Compression bench 3mE”). After an initial run on the first specimen (empty type) at became clear that this machine could not reach the forces required to break the specimens. The test was resumed at the faculty of Civil Engineering where the 12 specimens were finally destroyed under forces ranging between 95 and 277kN (9,5 and 27,7 tonnes of force) (See “Figure 41: Compression results”).

34.6. Analysis

Looking at the samples, we can grade them on several aspects, but we will look at the two most prominent aspects for our column design; transparency and mechanical behavior. Ideally you would want extruded elements of up to 3000mm so you could produce the column out of single elements. This would be beneficial for both the mechanical behavior and the transparency. But as this is not possible at this moment in time we have to accept the visual defect the lamination will cause. An empty void would been ‘most transparent’, but this is still a visual disturbance. The adhesive is a translucent layer which will become dirty over time, and the aluminum is the least transparent option. We could argue that we should not just accept the visual defect, but rather embrace it. Aluminum will be the most clean joint, improving visibility of the column without disturbing the transparency, and is mechanically most close to the monolithic variant.

Mechanically the aluminum option performs over average at around 86% of the full glass sample. But if we look at the adhesive, which performs at roughly 55% of the benchmark, and finally the empty gap which clocks in at 35%.

34.7. Conclusion

Out of the options we tested we can only draw one clear conclusion; the aluminum option is the way to go. Mechanically you want a material that is as close to, but not higher than, the Young’s Modulus of the glass. A direct glass on glass connection is not possible because it would be statistically impossible the create a perfectly smooth contact surface that does not create peak stresses. For possible future research, you want a more transparent option, it is possible to look at extremely thin plastic layers or regular sized 3D printed elements. As the production of the glass continues to improve, in the future it will be possible to laminate the column using fullsize elements, eliminating the need for these small inlays.

For our research we will be using aluminum inlays in the future column specimens during the upscaling of our tests.

The complete Excel graph with some small notes taken during the testing can be found at “84. Appendix D; Lamination gap influence” on page 120.

Figure 39: Broken sample

Figure 40: Compression bench 3mE

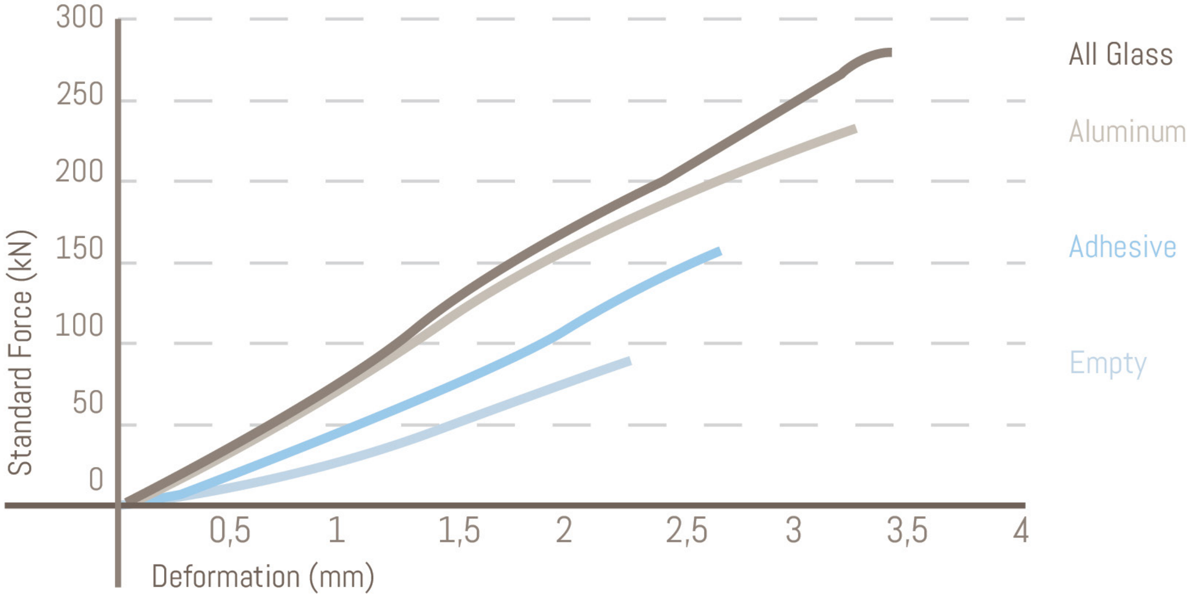


Figure 41: Compression results

3.5. Upscaling the column

In earlier research, full cross section columns have been tested. These tests consisted of samples of 500mm and 1500mm long. All of these samples did not require split lamination schemes, for the next step in the upscaling of this column that is required. Now that we have determined how to laminated the column, and how to handle the points where the glass rods come together, we can use this information and produce a 2400mm long column. This will again be done three times for scientific validity.

3.5.1. Analysis earlier tests

Before testing the 2400mm specimens, what did we already test before and what were the results of that? Can we recognize certain trends in these tests that we expect to continue with these tests? Before this research there have already been physical tests of 500mm and 1500mm specimens.

Specimen type		Initial cracks (MPa)	Nominal compressive strength (MPa)	Failure mode
500mm	1	-	468	Compression
	2	-	517	Compression
	3	-	517	Compression
1500mm	1	n/a	129,7	Buckling
	2	101,9	152,57	Buckling
	3	47,0	199,36	Buckling

Figure 42: Table with earlier results

In the table above we can see a few key aspects. Looking at the 500mm samples we see that they all failed within very close proximity of each other, in two cases at the exact same nominal strength. This means that either the compressive strength of the glass has been reached, or that the compressive shear strength of the adhesive has been reached. Comparing to regular borosilicate, which has a compressive strength of ~300MPa it is a realistic assumption that the compressive limit of the glass was reached and that the glass has very impressive compressive strength values.

Another key aspect that we can see happening is that change in failure mode. Both columns were made with the same cross section. This means that the longer the column gets, the greater the slenderness ratio becomes. Because of this slenderness buckling becomes the dominant mode of failure. Any column with the same cross section will always fail by buckling at lengths greater than tested samples.

If we calculated the critical buckling force for the 1500mm samples, we get a value 367kN at which these columns should buckle. Sample #1 and #2 failed at respectively 331kN and 389kN, this is almost as expected and nothing shocking. Could we now conclude that we can use Euler's formula for the buckling of slender members is accurate to describe failure behavior or the specimens? Let's look at sample #3, this specimen failed at 509kN, which makes no sense looking at the Young's modulus of the borosilicate used. Should the borosilicate have a Young's Modulus of over 80GPa, the load of 509kN would lay within expectations, but this is significantly higher. Because of this we can hardly predict the moment of failure for the specimens, all we can predict is roughly the minimal value at which it -can- start failing.

In "Figure 43: Buckling curves" two buckling curves for these columns are shown. The earlier tests were realised in the Clamped-Hinged situation, coming tests will be done Hinged-Hinged. The only conclusion we can really draw is that the borosilicate by SCHOTT averagely is a lot stronger than they claim it to be.

3.5.2. Expectations

All the samples we have been tested (full cross section) and will be testing have the same cross section as a result of the extruded element choice. This means that the taller we make the column, the higher the slenderness ratio will become. From a structural point of view we can safely say that a long and slender member will fail by buckling. This trend we already saw with the 500mm and 1500mm samples, where the 500mm samples failed by compression the 1500mm samples all failed by buckling.

From this point on the physical tests will be performed in a hinged-hinged situation. This means that the effective length of the column is twice as high compared to a fully clamped situation. Because of this the column will start buckling a lot sooner, but this allows up to closely observe the buckling behavior, and this is especially convenient when we start comparing the non-prestressed samples to the prestressed ones.

Using the Euler formula for buckling of slender members, the 2400mm long column will fail by buckling at 48kN (4,8 tonnes). Will the column actually fail at this value however? Most likely not, as we have seen earlier a lot of aspects influence the mechanical behavior of a column. In our case it could worsen the behavior by showing eccentricities caused by the production process of the borosilicate elements. What is more likely however, is the column failing at forces greater than the calculated 48kN. The Young's Modulus supplied by SCHOTT is a factor they can guarantee for 99,5% of the samples they produce, because of this it is very well possible that the actual Young's Modulus is not 64 GPa, but rather 68 for example. Assuming a Young's Modulus between 64 and 70GPa and a Hinged-Hinged connection, the column will start buckling between 50 and 67kN.

The entire graph with buckling curves according to connection conditions and explanation can be found at "8.5. Appendix E; Buckling curves" on page 121.

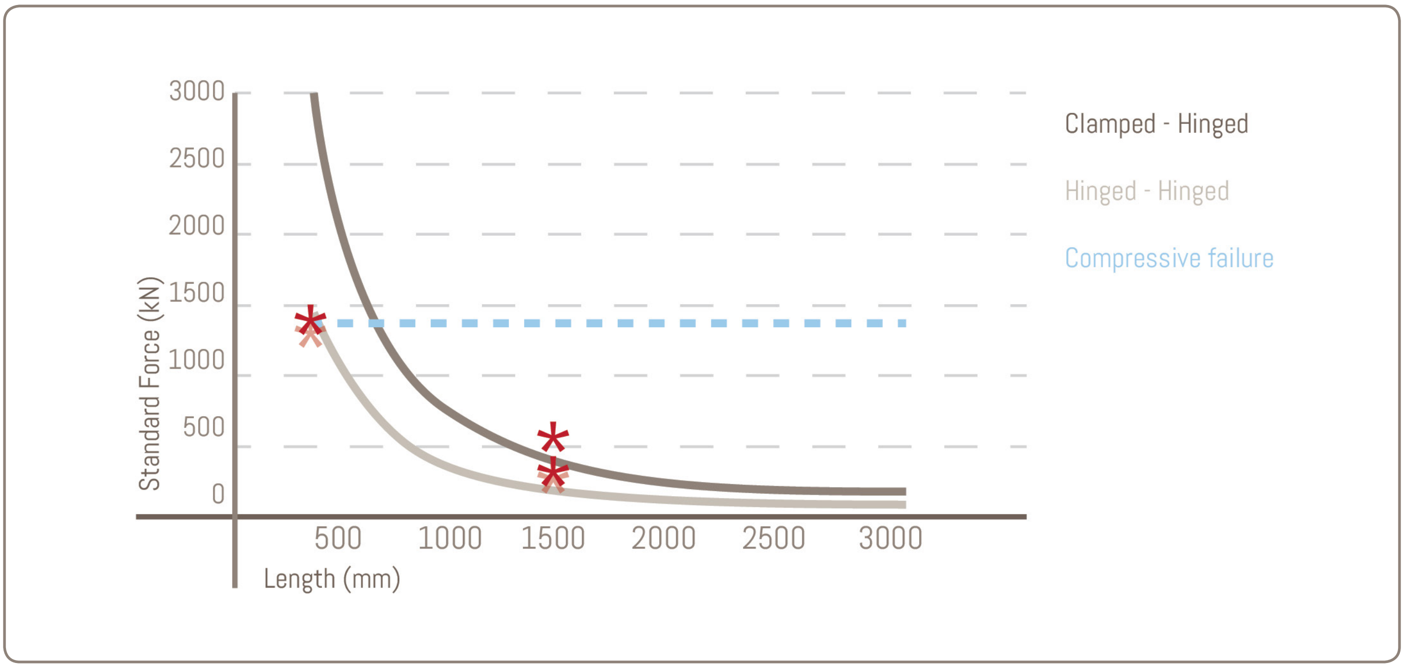


Figure 43: Buckling curves

3.6. Production of the 2400mm columns

From the previous chapters we have learnt everything we need in order to produce the columns for the next phase of this research. Upscaling the column to 2400mm high and analyzing the failure behavior. Again this will be done with three samples for scientific purposes, and producing three specimens does require some preparing and producing.

3.6.1. Preparations

For the 2400mm long column the split lamination scheme has been designed, resulting in the lengths of rods we will have to cut our of the 1500mm long SCHOTT elements. As these rods are not cheap we do want to optimize the use of these rods so a cutting scheme has been created which allows for a maximum of 10cm wasted glass per rod (See “Figure 46: Split-lamination and cutting scheme”).

Following the cutting scheme a total of 15 rod pieces have to be cut out of 10 rods, this is done using a diamond blade saw. After the cutting the ends are sanded to make sure no imperfections will be at the joining of the elements (See “Figure 45: Rods cut and sanded”). After the glass has been cut and sanded, the aluminum discs are also cut and cleaned to be a nice and clean joint with the glass.

3.6.2. Laminating process

With all the materials prepared we are going to use a UV-curing adhesive to laminate all the individual pieces together to form the column. In its most basic form, UV curing involves a photo-chemical reaction which converts a liquid or semi-liquid compound to a hard plastic-like polymer. The heart of this reaction is a special compound, known as a “photoinitiator”, which absorbs light and then uses the absorbed light energy to initiate and propagate the curing reaction. Unlike conventional drying processes which use heat to evaporate water or solvents from a material, UV curing involves a total conversion of liquid material to a solid state.

3.6.3. Dealing with eccentricities

Using a ‘Design & Build’ type of research you always encounter points of friction. Issues that are a perfect match on paper show slight deviations and cause friction or problems during the production process. It is important to allow for these margins in a design and to deal with them in a careful manner. The rods and profiles produced by SCHOTT appear perfectly straight, but because of the horizontal extrusion process they do in fact show deformations and eccentricities. In the photograph “Figure 44: Eccentricity profiles” you can clearly see this effect. The rod is laying flat on top of the star-shaped profile, but because of the eccentricity in the element it actually curves up around five millimeters. To deal with this the rods will not be laminated in one go, but rather in smaller zones which allows for manual adjustment of the eccentricity to ensure an optimal adhesive layer.

3.64. Finishing

After all rods have been carefully joined to the star-shaped profile using a UV-curing adhesive the top and bottom of the column are checked to see if all rods line up properly. If any rods extend just a slight bit this could compromise the compressive strength of the entire column. Any extended glass parts are sanded untill they nicely align to form a flat surface. Once the column has two perfectly flat heads the next step is to mount the aluminum heads which act as protection of the glass in the compression machine. Inside the aluminum head is a one millimeter thick layer of lead to account for any imperfections, on which the glass column is placed. Once the column is aligned to be neatly in the center of the aluminum head a two-component resin is carefully mixed and poured inbetween the glass and aluminum to create a rigid head. This resin is left to dry for at least 16 hours after which the other side is treated the same way. After this process the column is ready to be destroyed.

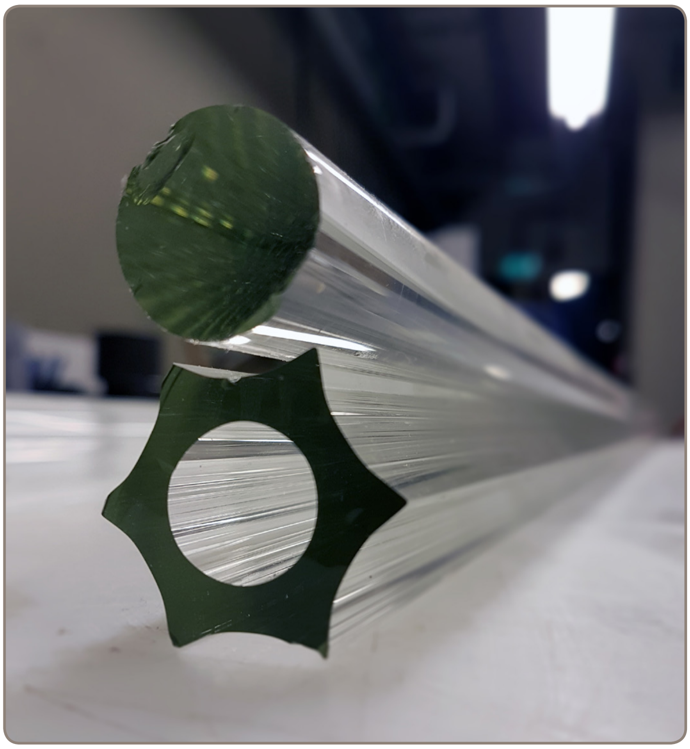


Figure 44: Eccentricity profiles

Figure 45: Rods cut and sanded

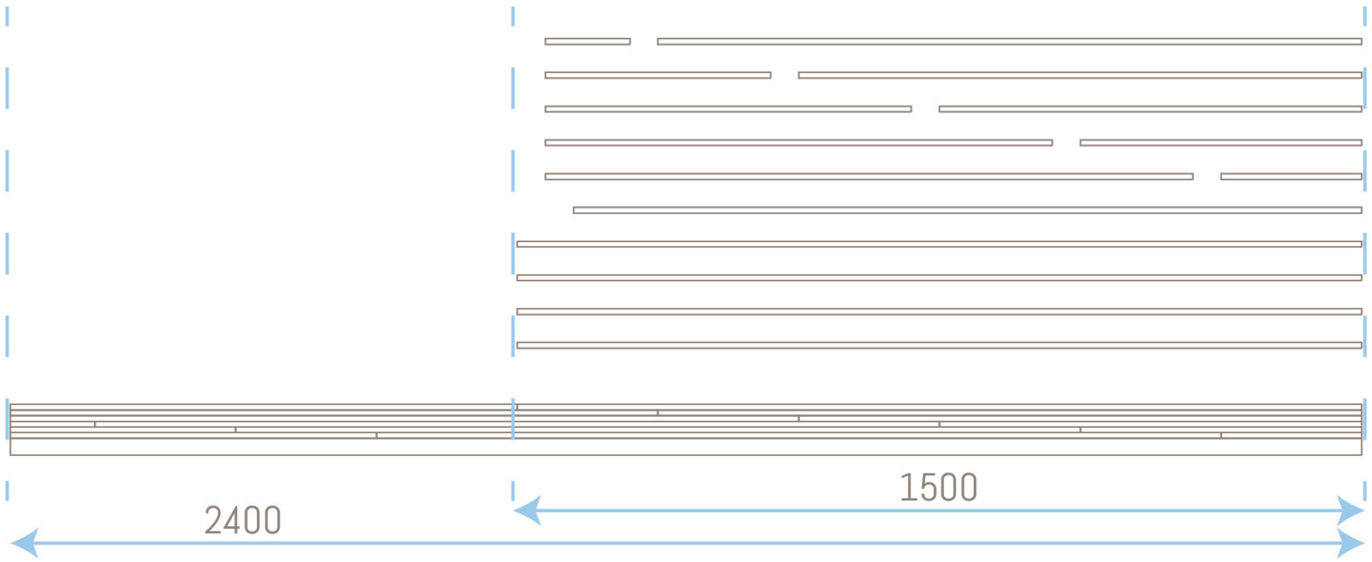


Figure 46: Split-lamination and cutting scheme

3.7. Physical tests and analysis

As explained in the previous chapter, three identical columns with a length of 2400mm were produced, these serve as a benchmark for coming research. These three columns are destructively tested at the Stevin Lab II located in the Faculty of Civil Engineering in a 500 tonnes compression machine (See "Figure 48: Physical test setup"). The columns will not come near the compressive limit of the machine, but this machine is one of the few with enough height to actually fit the columns. Using Euler's formula for buckling of slender members we earlier calculated that the theoretical value at which the columns should start buckling is around 50kN (5 tonnes of loading).

3.7.1. Test results

The three columns that were tested had a significant failure range to them. As expected they all failed by buckling, but this buckling started occuring at very different loads. The weakestt column failed at 60kN, the next at 75kN and finally the last one at 90kN. We can see several stages during the loading of the column which could explain these deviations. If we look at the middle column (See "Figure 49: Test result neutral column"), we can define five dominant regions in the flow of forces.

1: This is the setting of the machine, making good contact with the column before actual loading, this is very common and not a critical issue.

2: After initial setting of the column in the machine the first linear period starts where the column deals with the forces and is compressed slightly, this is the expected behavior.

3: This tabletop in the graph might look weird, but in all columns this flat part occurs at exactly the same moment. This is the small layer of lead (protection) is compressed and makes sure the glass does not damage.

4: The second linear period. During this period the column is loaded until critical damage or buckling can occur. This is normal compressive member behavior.

5: This is the most critical moment in the loading of the coluumn. It is at this moment that the critical buckling force is reached and thhe column starts swaying from underneath the load. During this stage the column can not handle any extra load anymore and the column wants to buckle out. Once the sideway deformations become to large, the tensile forces in the glass reach a peak at a very specific point (See "Figure 47: Origin of glass failure") and the column fails completely, losing all load bearing capacities.

The reason the buckling occurs at earlier or later moments means that the production accuracy must influence the mechanical behavior of the column quite significantly. Another option is that the glass has a very large range of mechanical deviations. The 60kN specimen behaves as expected, but maybe the other two specimens were produced out of a batch of glass with much greater strength values.

3.7.2. Conclusion

WIth this column we could thus load a clamped-clamped variant with 150kN. But if we assume a safety factor of 5, this design load can only be one of 30kN. The design load for the ABT office case is 119kN. This means that in order to realize our case column, we need to increase the column's cross section by a factor of four! Resulting in a very costly and heavy element with significant reduced slenderness. Not to mention, the column showed great deviations in the results, so this won't happen.

The complete Excel graph with some small notes taken during the testing can be found at "8.6. Appendix F; Physical test results 2400mm samples" on page 122.

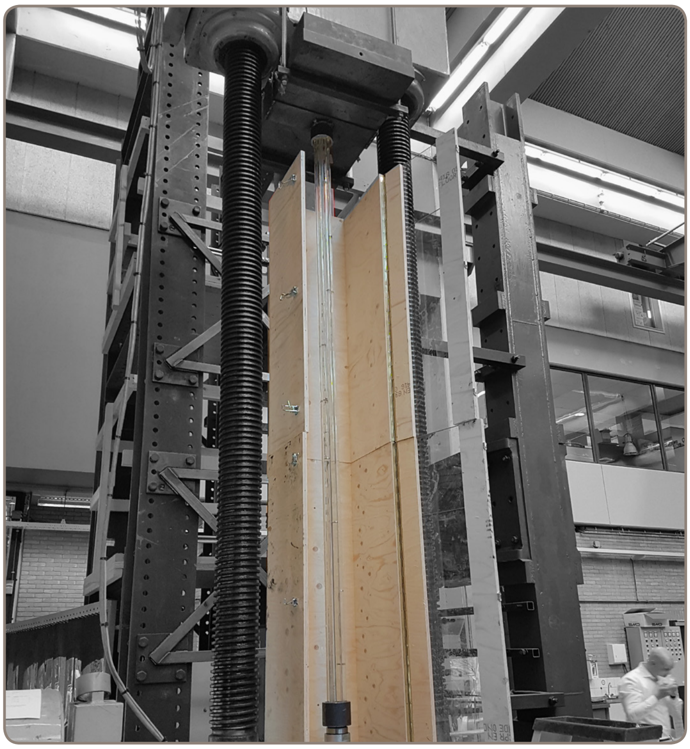


Figure 48: Physical test setup

Figure 47: Origin of glass failure

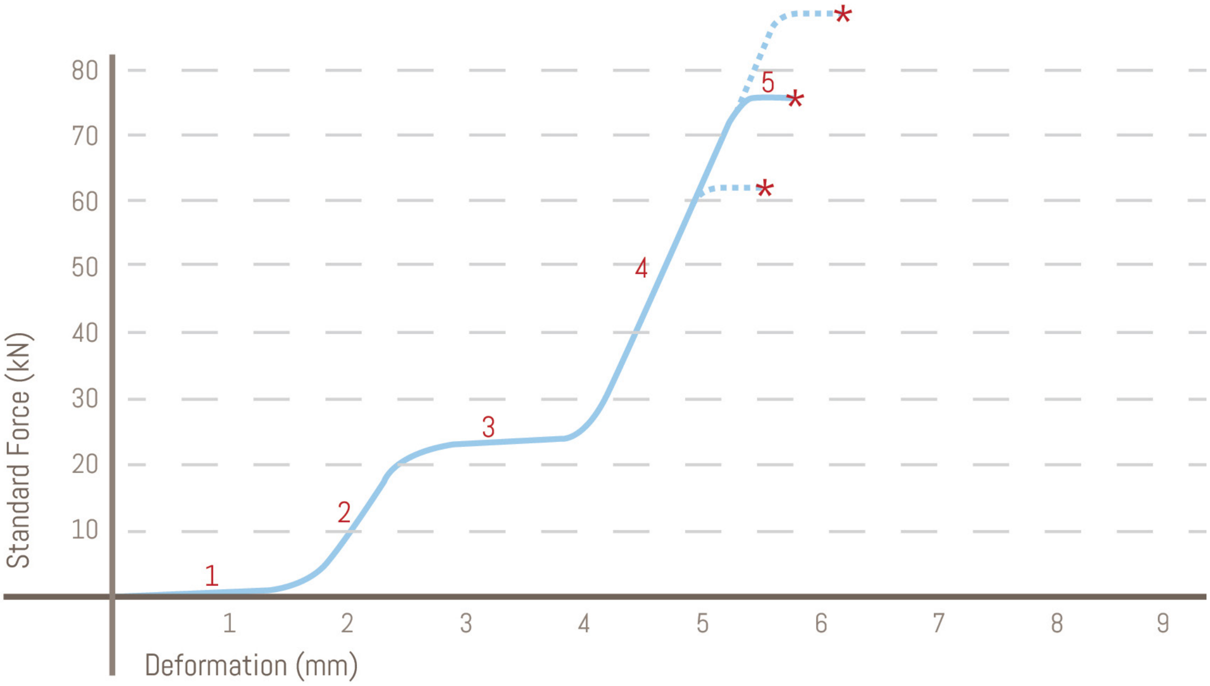


Figure 49: Test result neutral column

3.8. Why post-tensioning

The design of a slender column is a tricky process. A slender column will generally always fail by buckling well before the compressive strength of the material is reached. Buckling is not necessarily a problem though, if we can produce a very consistent element buckling is a very predictable failure behavior. Not only is it predictable, it is also a visual effect. When a column is about to fail by buckling the visual warning will provide enough of an early warning for the building to be evacuated and for the element to be replaced. When it does become a problem is in combination with a (very) brittle material. This is the case because the deformations caused by the buckling generate tensile forces in the column material (See “Figure 52: Cross section and buckling”). And as we have seen plenty of times so far, tensile forces break the material, the more brittle the material the more explosive and sudden the tensile failure. Because of this we have to deal with very high safety factors, for this research we assumed that to be at 4.

If it is possible to alter the brittle behavior under buckling failure to be more plastic (like steel columns), the buckling effect becomes a more gradual effect that becomes visible before the column fails under the tensile forces introduced. The idea behind the post-tensioning of the glass column is that we introduce a member under tensile forces into the column. When the column will start to buckle, this prestressed tendon can relieve some of these generated tensile forces, and gradually deform the column rather than spontanuous failure occuring (See “Figure 51: Proposed prestress effect”).

The main effect we want to realise with this design is allowing the glass column to show plastic failure behavior (See “Figure 50: Expected failure behavior”). If this is achieved we can assume a safety factor as low as 2 for the implementation of the final column as it no longer shows brittle failure. This greatly helps in reaching the proposed design load that is applied to the column. There are also some other, less important, effects this post-tensioning should show. Having prestress in the element will postpone initial crack forming, which lower the mechanical behavior when it does occur. A final aspect that increases the mechanical behavior is the effect that the extra force compressing the glass initially prevent the delamination caused by the buckling movement, because of this the moment the buckling occurs is postponed slightly which results in greater load bearing capacities.

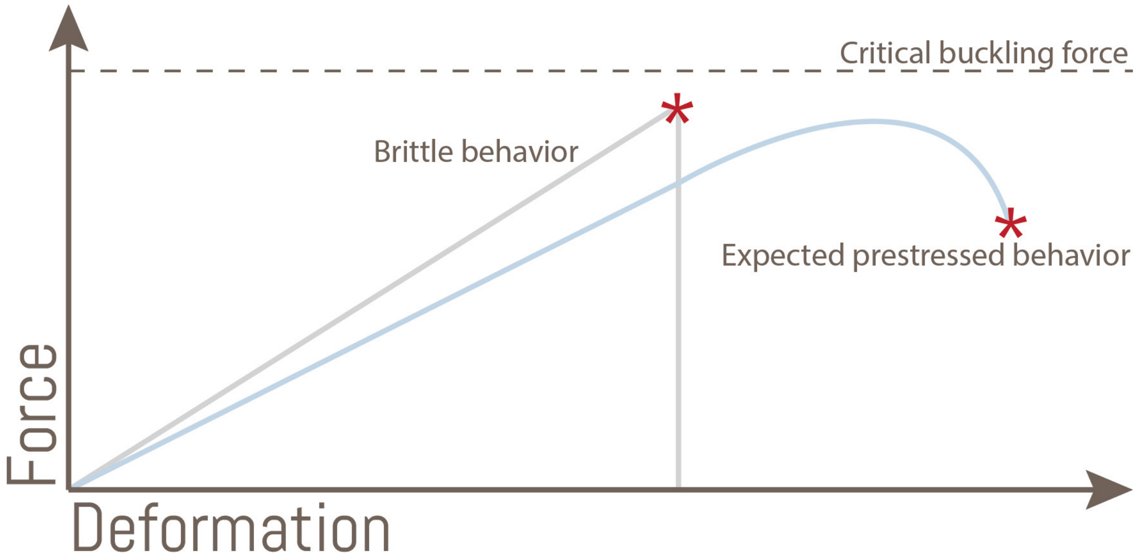


Figure 50: Expected failure behavior

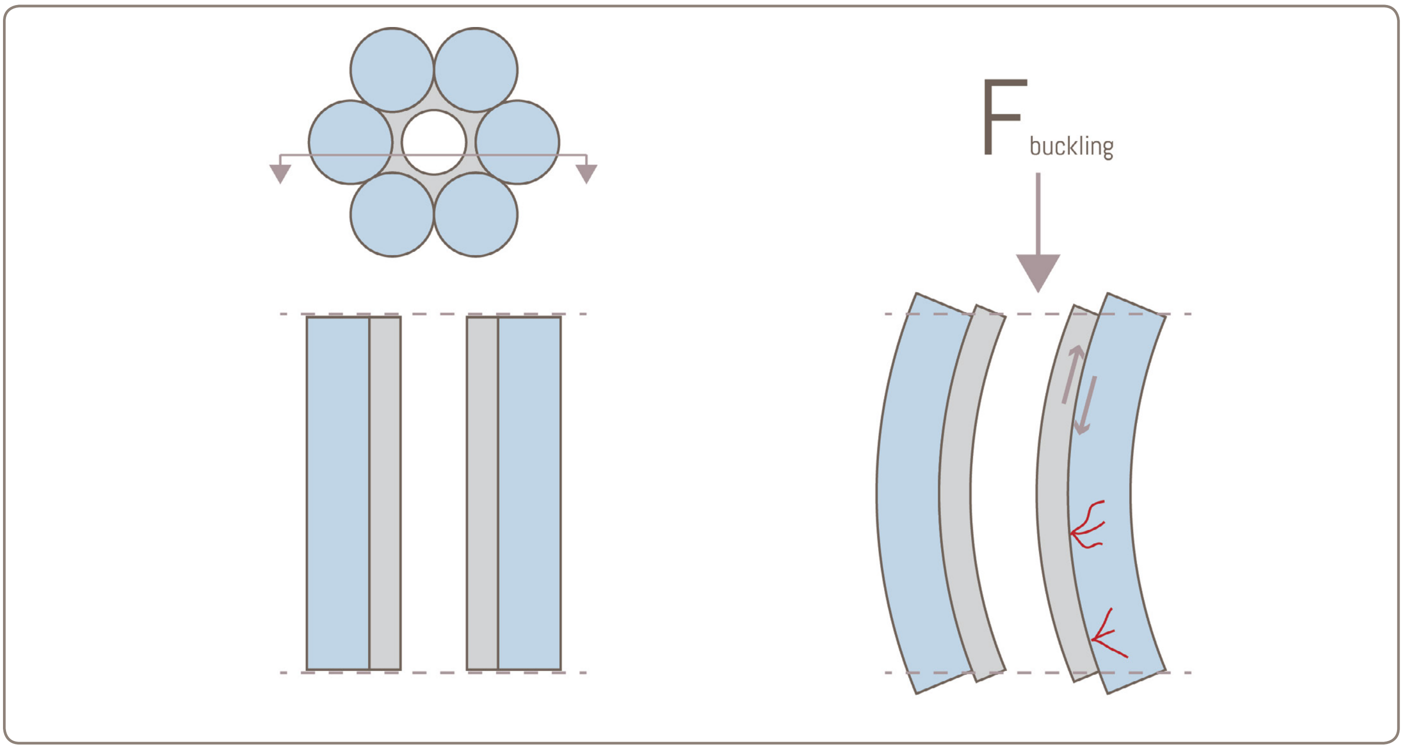


Figure 52: Cross section and buckling

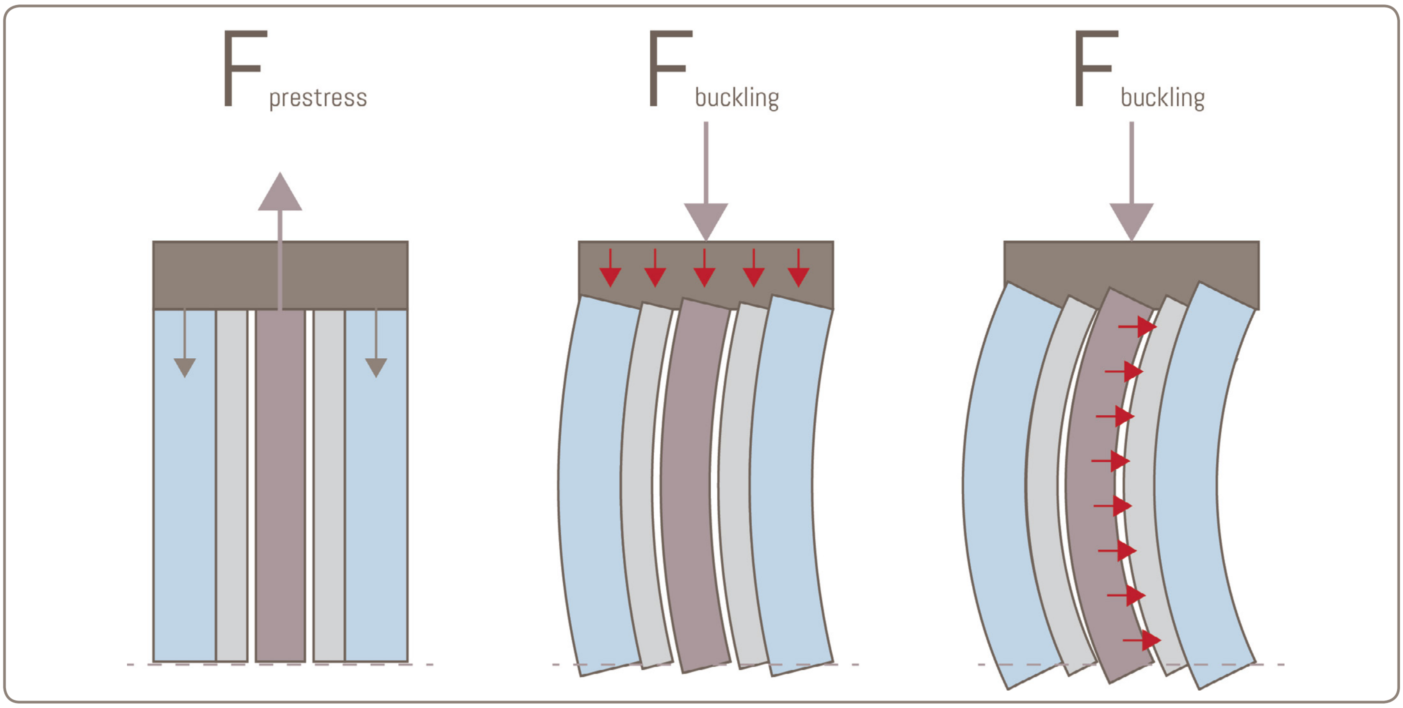


Figure 51: Proposed prestress effect

3.9. Design of the post-tensioning system

The star-shaped profile that we use as core for the bundled column has a hollow core with a diameter of 17mm, within this core the post-tensioning rod will be located. However, within the extruded profiles we have to deal with significant margins and eccentricities as shown earlier. How can we design this element in the safest way possible so it won't crack and fail during the application of the prestress?

3.9.1. Bonded versus Unbonded

If we look at conventional ways of implementing tendons for the application of post-tension we can define two diffirent methods, one is the use of a bonded tendon and the other method is the use of an unbonded tendon. A bonded tendon has direct contact with, and is attached to, the material like in concrete and is prestressed once the material is hardened around it. The unbonded tendon is generally a steel rod in a sheathing so it does not make direct contact with the material.The bonded variant has several aspects that make it a tricky method for us to use. If we use an adhesive to laminate the steel to the glass, and then apply prestress, we get shear forces at the contact surface of the glass and this can quickly lead to cracking of the glass. We could also apply the prestress during the curing of the adhesive so the adhesive will not cause shear forces, but this will most likely become a very messy situation with adhesive leaking everywhere.Using the unbonded method is the safest option, the sheathing protects the glass from the steel and there is no adhesive required. But the sheathing does require several millimeters of space, reducing the possible size of the tendon and thus lowering the possible amount of prestress.

3.9.2. Tendon options

Looking at "Figure 53: Tendon options" we can see three configurations for the post-tensioning system. Ideally you would like a tendon the is a perfect fit to the core (including some protective layer to prevent peak stresses etc.) but in practice this is not going to work. If we look at the production sheets from SCHOTT we can see that our star-shaped profile has +/- 2mm of margin on the accuracy of the glass. A 16mm rod makes a lot of contact with the glass and has to be forced down the core, damaging the glass. Because of this, the first option is not an option at all. The M16 rod does not provide enough margin to be safely inserted into the center core, but we don't want to use a very small rod either. As stated in ACI 318 Section 18.2.5: "If the prestressing steel is in complete contact with the member being prestressed, or is unbonded with the sheathing not excessively larger than the prestressing steel it is not possible to buckling the member under the prestressing force being introduced." (American Concrete Institute, 2004). This means that we need either a bonded option, or an unbonded with narrow margins. Bonded tendons come with undesirable side-effects which we don't need right now. And as this test is mainly a proof of concept for the post-tensioning effect on the failure behavior of the column, using PVC-tubing with its undesirable yellow colour is acceptable. Because of this, and because it's simply the safest option, we will be using the PVC-tubing with an M12 rod inside as tendon (See"Figure 54: Tendon"). It is important to realize here that PVC is not UV-resistant. Using ordinary PVC and laminating the column afterwards will melt the PVC tube away. Because of this a special type of PVC has to be used.

3.9.3. Design

In the core of the column the PVC-tubing with an outer diameter of 16mm is somewhat forced (without damaging the glass because it is a soft material), and this tube has an inner diameter of 13,6mm. In this tube an M12 rod is easily applied and protected from the glass. Before putting on the steel head, a protective layer of lead on the top and bottom is added and between the column and the steel head is a 3D printed or resin cast interlayer that ensure that the column is right in the middle of the steel head. After this a washer and bolt close the system and can be tightened to apply prestress.

All of this can be seen step-by-step in "Figure 55: Materialization".

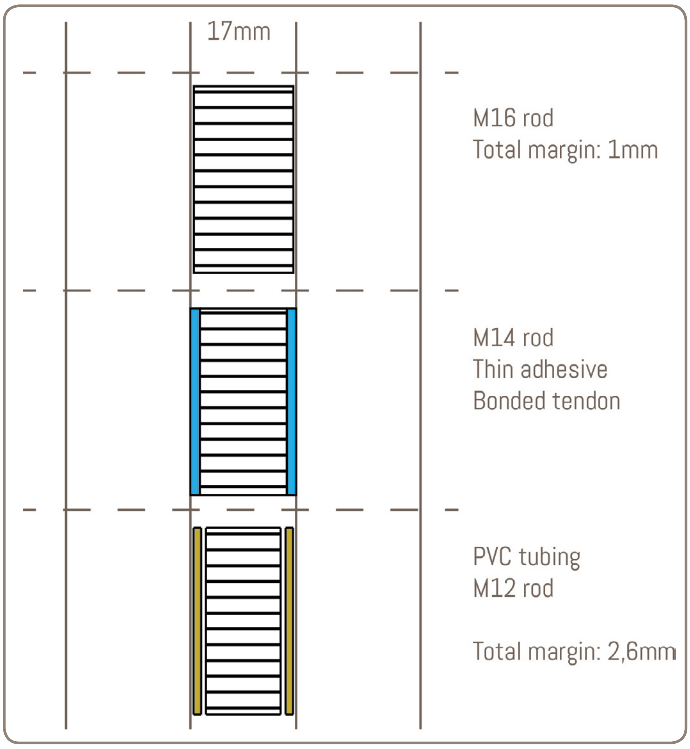


Figure 53: Tendon options

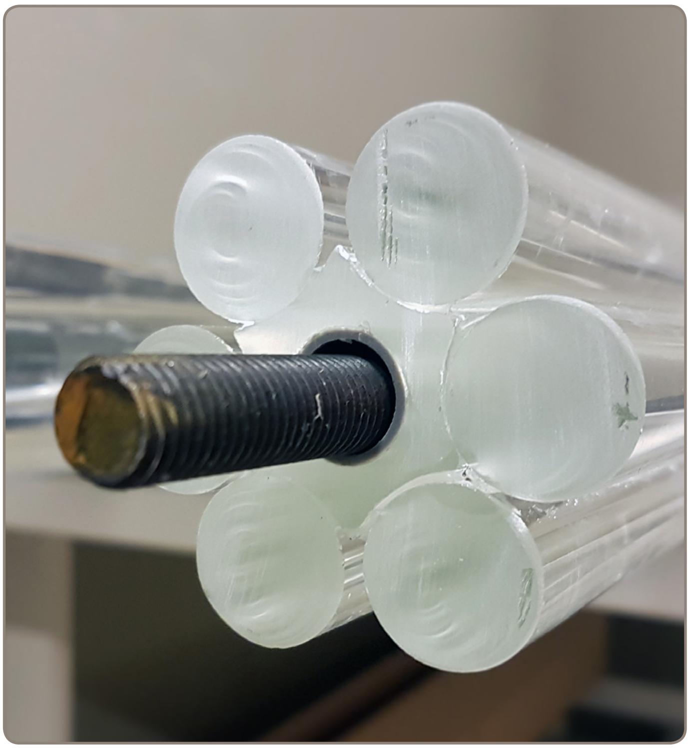


Figure 54: Tendon

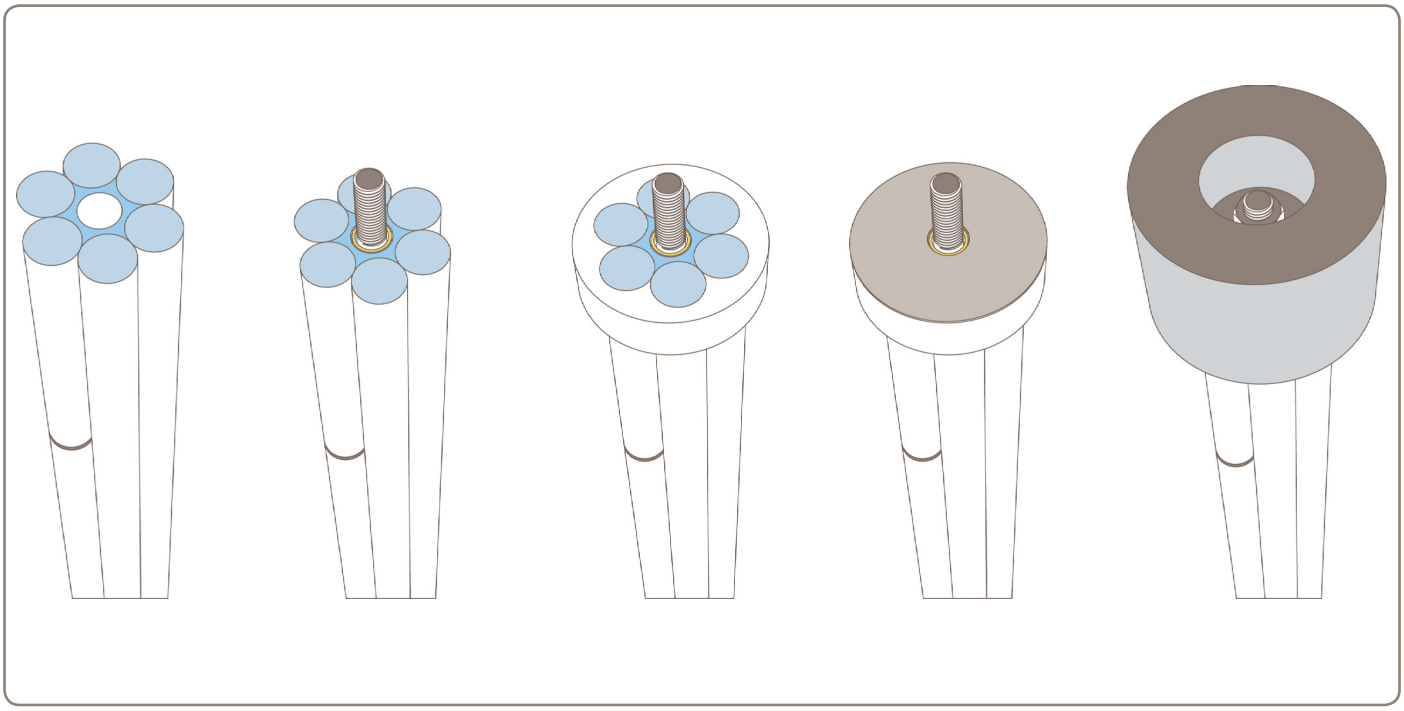


Figure 55: Materialization

3.10. Production of 2400mm columns and application of post-tension

The results of this test will be compared to the results of the 2400mm long column without any form of post-tensioning. Because of this it is important that the base of the column is exactly the same as before. The same batch of materials will be used, the production process is in the same clean environment and the same split lamination scheme is used. The only thing different will be the steel elements that are added to apply the prestress to the column. Also the testing setup and conditions are the same so we can clearly compare the results to each other. For test reliability and validity again a sample size of 3 is maintained.

It is still important to realise that in order to get accurate results from all of our tests, thorough attention should be paid to the production of the columns. Any small piece of dirt between the steel and glass will cause peakstresses in the glass causing premature failure. To ensure the most best result the very top and bottom of the column will be cut and sanded once more after all the laminating has been done, resulting in a perfectly flat connection to the steel caps (See "Figure 56: Cutting of the column").

Constants: test arrangement, the type of support; length of glass specimens (2430 mm); glass material (BOROFLOAT33); interlayer material (DEL04468); edge finishing (sanding); lead inlay to protect bottom and top edges; aluminum discs at the lamination gaps; temperature (+23 ± 5 °C); rate of loading: 1mm/min.

Variables: none in this batch, but applied prestress compared to previous test (35 kN).

3.10.1. Amount or prestress applied

The torque wrench we have available can deliver 100N/m, but depending on the quality of steel we can only apply a certain amount of prestress. If we use 4.8 quality steel with a nominal tensile strength of 400N/mm^2 we could only load the bolt and thread with a prestress of 44N/m, which translates to 18kN. This is based on 85% of the bolt's yield strength. But if we use quality 8.8 steel this becomes a prestress of ~85N/m, which translates to 35,5kN of prestress (See "Figure 57: Nominal torque values"). This sounds like a realistic value at which we can expect a visual difference in failure behavior of the column, and this value of a safe one to apply to the glass as it is well within the elastic limit and loads expected during the tests.

3.10.2. Application of the prestress

Applying the calculated N/m to the bolt and thread should be treated very carefully and is dependant on the torque wrench at hand. The square drive's dimensions used should match the torque drive's, if this is not the case then the actual torque value has to be recalculated to reach the designated effect. If this is not checked it is very well possible to apply too much prestress which could be dangerous. The torque wrench we use is a Stahlwille 730/10 with corresponding square drive, so in our case there is no adjustment of the torque value required. But regarding safety this is an important aspect to check, especially when not using your own equipment.

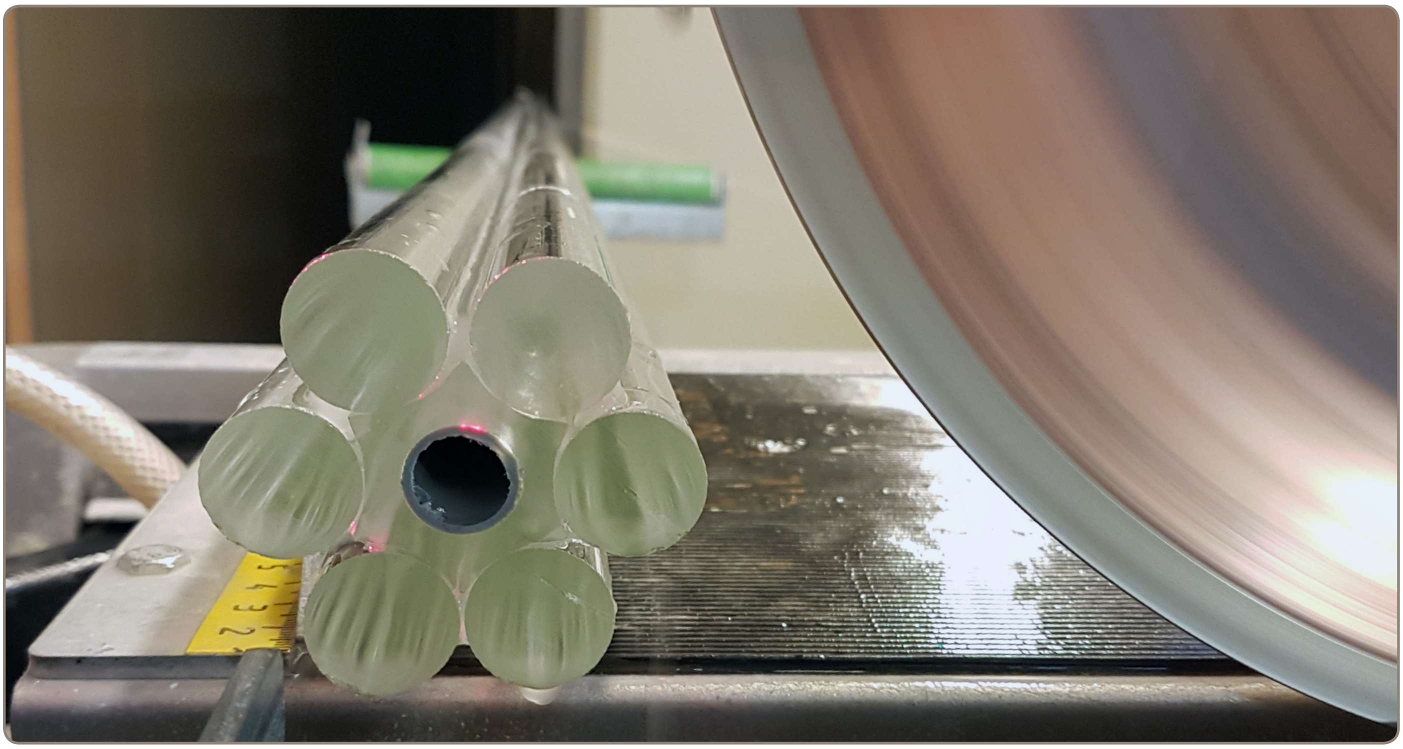
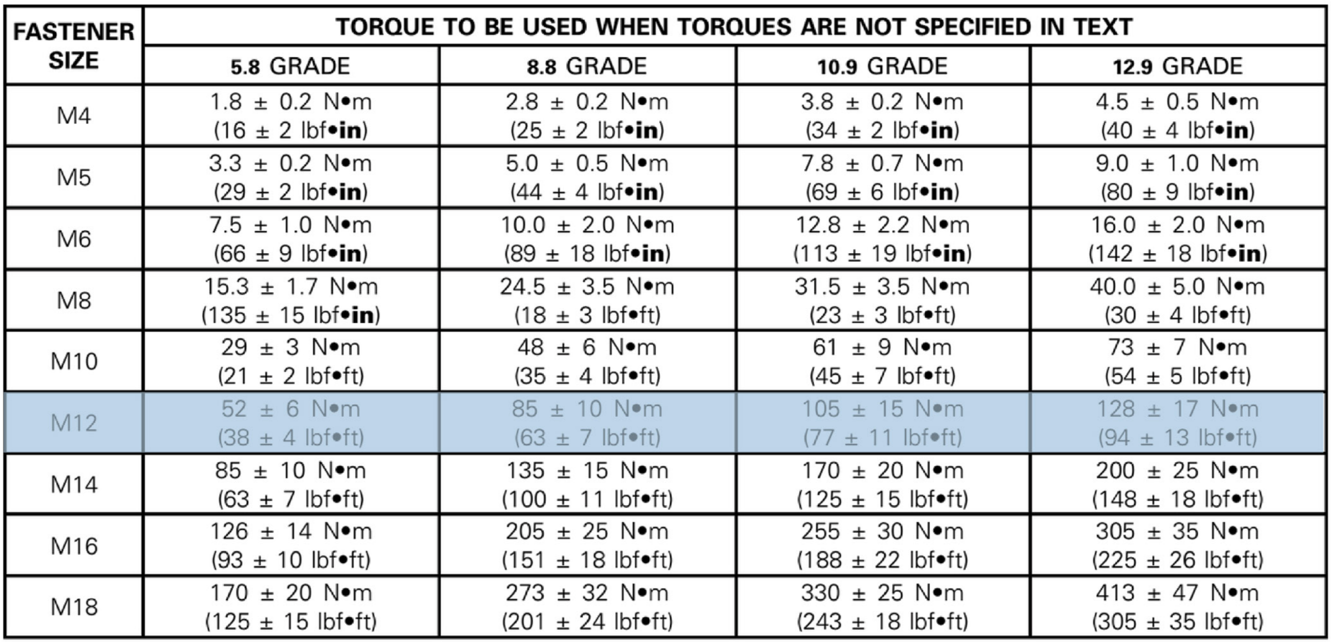


Figure 56: Cutting of the column



FASTENER SIZE	TORQUE TO BE USED WHEN TORQUES ARE NOT SPECIFIED IN TEXT			
	5.8 GRADE	**8.8** GRADE	**10.9** GRADE	**12.9** GRADE
M4	1.8 ± 0.2 N•m (16 ± 2 lbf•**in**)	2.8 ± 0.2 N•m (25 ± 2 lbf•**in**)	3.8 ± 0.2 N•m (34 ± 2 lbf•**in**)	4.5 ± 0.5 N•m (40 ± 4 lbf•**in**)
M5	3.3 ± 0.2 N•m (29 ± 2 lbf•**in**)	5.0 ± 0.5 N•m (44 ± 4 lbf•**in**)	7.8 ± 0.7 N•m (69 ± 6 lbf•**in**)	9.0 ± 1.0 N•m (80 ± 9 lbf•**in**)
M6	7.5 ± 1.0 N•m (66 ± 9 lbf•**in**)	10.0 ± 2.0 N•m (89 ± 18 lbf•**in**)	12.8 ± 2.2 N•m (113 ± 19 lbf•**in**)	16.0 ± 2.0 N•m (142 ± 18 lbf•**in**)
M8	15.3 ± 1.7 N•m (135 ± 15 lbf•**in**)	24.5 ± 3.5 N•m (18 ± 3 lbf•ft)	31.5 ± 3.5 N•m (23 ± 3 lbf•ft)	40.0 ± 5.0 N•m (30 ± 4 lbf•ft)
M10	29 ± 3 N•m (21 ± 2 lbf•ft)	48 ± 6 N•m (35 ± 4 lbf•ft)	61 ± 9 N•m (45 ± 7 lbf•ft)	73 ± 7 N•m (54 ± 5 lbf•ft)
M12	52 ± 6 N•m (38 ± 4 lbf•ft)	85 ± 10 N•m (63 ± 7 lbf•ft)	105 ± 15 N•m (77 ± 11 lbf•ft)	128 ± 17 N•m (94 ± 13 lbf•ft)
M14	85 ± 10 N•m (63 ± 7 lbf•ft)	135 ± 15 N•m (100 ± 11 lbf•ft)	170 ± 20 N•m (125 ± 15 lbf•ft)	200 ± 25 N•m (148 ± 18 lbf•ft)
M16	126 ± 14 N•m (93 ± 10 lbf•ft)	205 ± 25 N•m (151 ± 18 lbf•ft)	255 ± 30 N•m (188 ± 22 lbf•ft)	305 ± 35 N•m (225 ± 26 lbf•ft)
M18	170 ± 20 N•m (125 ± 15 lbf•ft)	273 ± 32 N•m (201 ± 24 lbf•ft)	330 ± 25 N•m (243 ± 18 lbf•ft)	413 ± 47 N•m (305 ± 35 lbf•ft)

Figure 57: Nominal torque values

3.11. Physical tests and analysis of post-tensioned column

The three column specimens we tested earlier failed at 60, 75 and 90kN. These results were very inconsistent and failed very sudden and explosive. Those three samples showed exactly why glass is not just a common structural material. Small inconsistencies during the production of the glass or the column have significant influence on the behavior of the entire column. Our goal is to suppress these inconsistencies, and improve the failure behavior of the glass. By applying prestress to the column, initial crack forming is suppressed and forces the column to act more monolithic by preventing initial delamination. The most important aspect we want to achieve is transforming the failure behavior into a more ductile failure, this way the column doesn't just explode but fails more gradually.

3.11.1. Test results

Looking at the graph of the three samples we see that we have achieved a lot of improvement. There is a few key aspects to note here. Firstly, all columns failed at roughly the same load, showing very reliable structural behavior. Secondly, at step 5 (buckling) we see that the buckling doesn't occur out of the blue, but is in fact a much more ductile occurance. And lastly, the columns didn't fail in an explosive manner, but rather show significant post-breakage load bearing capabilities. After buckling, the rest of the column actually still carries 25% of the load and is still standing (See "Figure 58: Post-breakage capabilities"). This is a fantastic result for a very marginal visual disturbance in the transparent column.

In the graph of the test results (See "Figure 60: Test results graph") we can again identify several phases of the loading of the specimens.

1: This is again the setting of the column in the machine, making direct contact before actual loading.

2: The first linear period where the column is handling the load.

3: This tabletop in the graph is again the lead being compressed while protecting the glass from the steel.

4: The second linear loading period of the column, leading up to failure of the column.

5: Deformations showing the buckling of the column start a lot sooner and the entire buckling process takes up significantly more time and deformations compared to the earlier column. Finally the column does have to give in to the forces and buckles.

6: But this time the column did not break and fail, but rather only buckle for half of the column (See "Figure 59: Broken column") and the column remains standing up, and proceeds to carry between 15 and 35% of the buckling load!

3.11.2. Conclusion

The three samples failed at very similar loads and this shows the reliability and structural integrity of this column. The buckling became a lot more visible, and a significant increase in deformations during buckling was achieved. After failing by buckling the columns did not fall down but still had a post-breakage load bearing capacity for between 15 and 35% or the buckling load.

The complete Excel graph with some small notes taken during the testing can be found at "8.6. Appendix F; Physical test results 2400mm samples" on page 122.

Figure 58: Post-breakage capabilities

Figure 59: Broken column

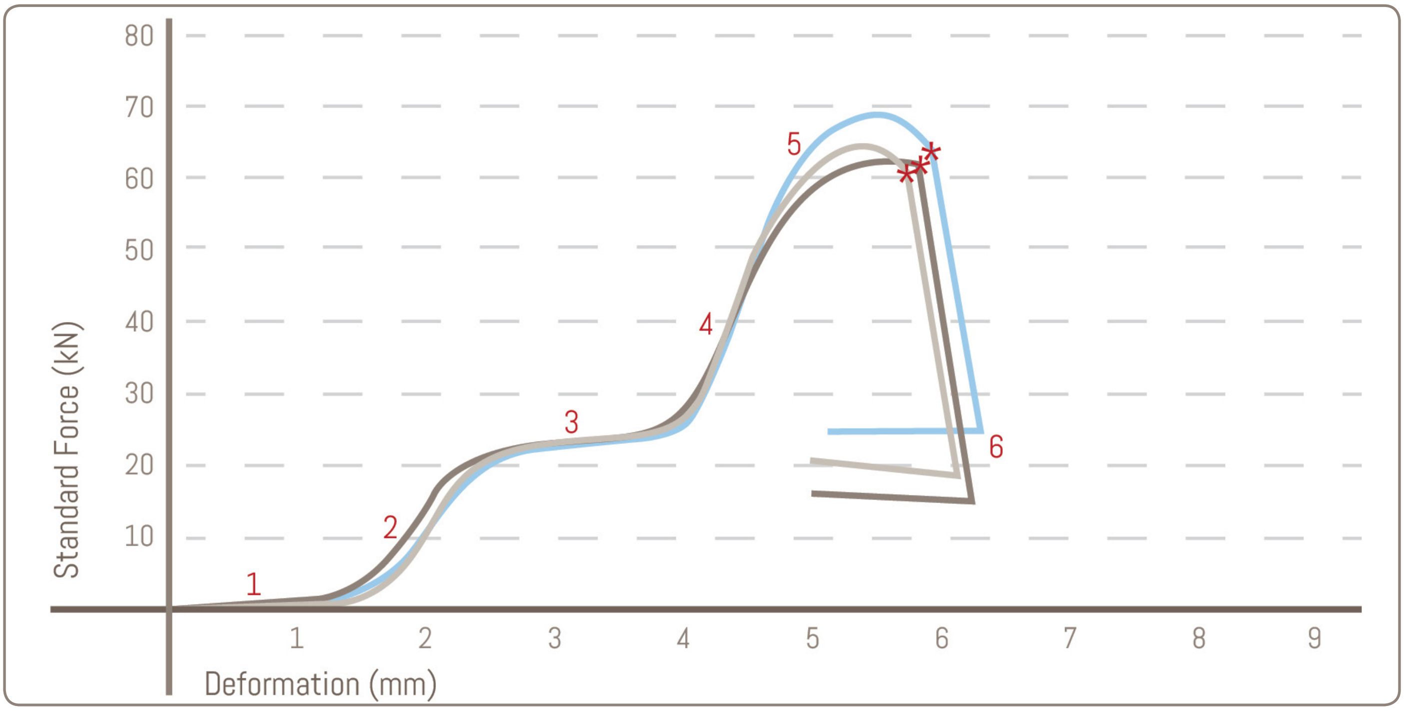


Figure 60: Test results graph

3.12. Analysis post-tensioning effect

In the previous chapter we concluded that a post-tensioned column behaves much more consistent, shows increased ductility and experiences post-breake load bearing capabilities. But why is this the case, and how do they stack up against the regular columns?

3.12.1. Ductility

The biggest problem we encounter when designing with glass in structural applications is the brittle nature of the material. We have seen this problem during the physical tests of the neutral columns, where once a critical failing load is reached the column fails in a sudden and explosive manner.

When we take a close look at the physical test results of both column types (See "Figure 62: Neutral vs Post-tension") We can see that the 'neutral' or the columns without any prestress applied reaches the critical buckling force and after a short time (tabletop in graph) fails completely. We don't see this failing coming until it is actually happening. But if we look at the post-tensioned options, these columns show much greater (up to 300%) deformations during the buckling process. Making the failure visible and this effect lasts for a longer time.

3.12.2. Post-breakage behavior

At some point all glass columns fail, what we saw is that the post-tensioned column takes much longer (with greater deformations) compared to the neutral column, but eventually it fails. But one of the most important things we saw happening during the failure of the post-tensioned is the inability to completely fail. During the buckling failure, only one side of the glass column could break away, but the steel tendon prevents the other side from complete failure (See "Figure 61: Breakage diagram"). Because of this the column is still standing upright after failure, still able to carry between 15 and 35% of the compressive load.

The post-breakage characteristics of this column makes it structurally a much more reliable member. People still have time to flee the scene when they see the column deforming, or can even still evacuate after failure. The huge reduction in explosive failure also significantly reduces the consequences caused by flying shards of glass (See "Figure 63: Post-breakage"). A result of this is a much lower risk when using this column in a structural application.

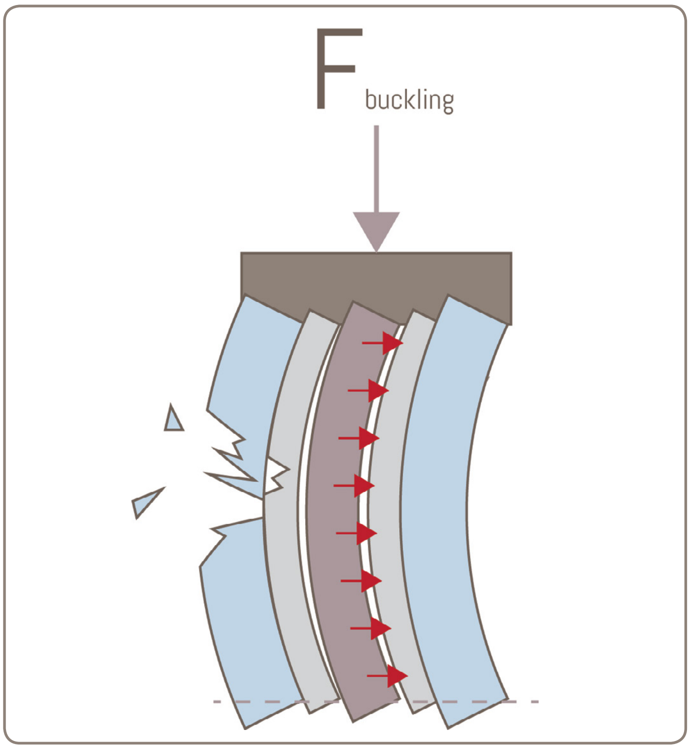


Figure 61: Breakage diagram

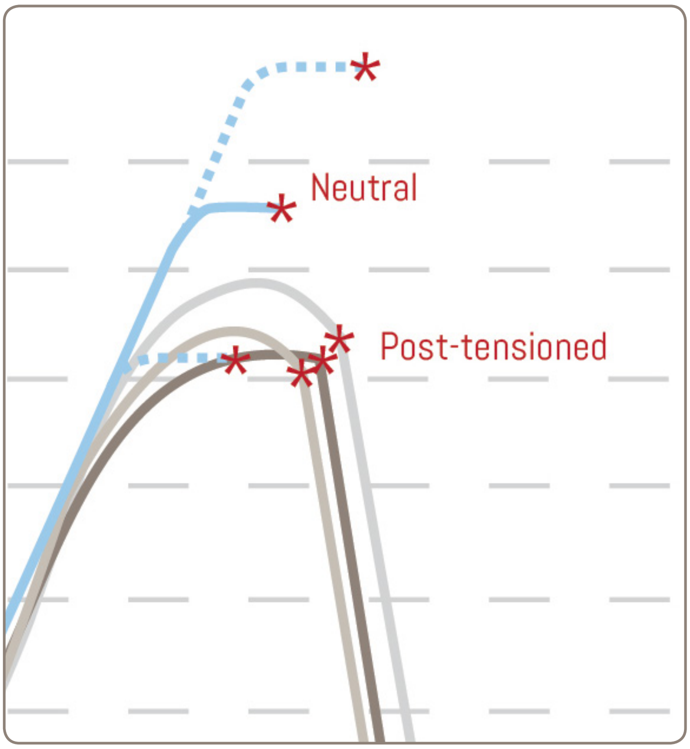


Figure 62: Neutral vs Post-tension

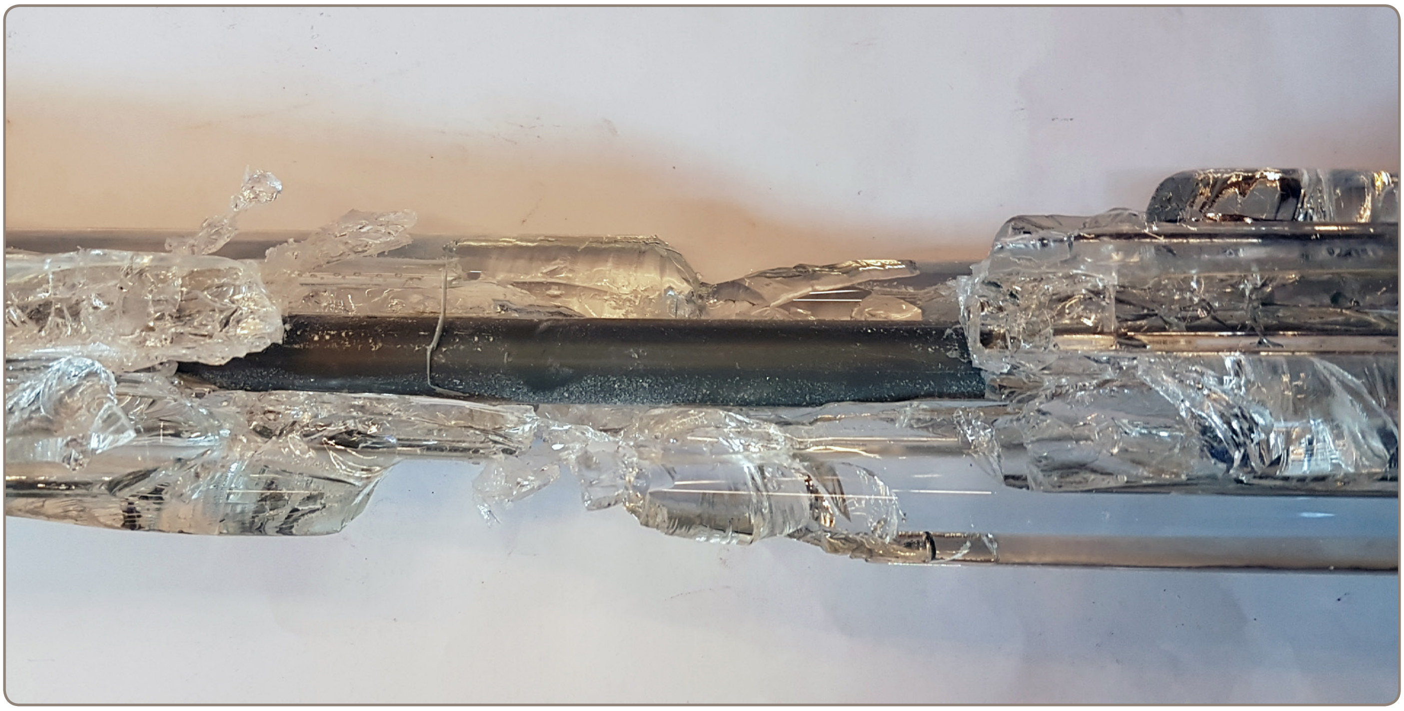


Figure 63: Post-breakage

3.12.3. Speculation on results

We have taken a look at the test result and noticed the post-breakage load bearing capacities, and the more ductile failure. But something peculiar is still going on that we have not yet addressed to. In the graphs of the results we identified two linear phases, one before and one after the compression of the lead interlayer. The second linear phase is the phase where the column is loaded until a failure mechanism is activation, in this case this is always a buckling mode of failure. But if we take a look the moments this deviation from the linear phase occured, we can identify another interesting aspect.

We did see that the post-tentioned column is more ductile, but if we compare this to the actual moment of activation with corresponding forces applied we can notice something we assumed to be correct earlier. The neutral columns activate their failling at roughly 63, 75 and 90kN (See "Figure 64: Failure mode activation"). The post-tensioned options all start showing their failure mechanism all the way down at 45kN, which is well below the expected buckling force.

Earlier we assumed that the post-tensioning tendon was sufficiently in contact with the sheathing and glass so that this column could never fail solely under the prestress applied. We can now see that this was in fact not the case. The column starts failing 30kN earlier compared to the average neutral columnn, the exact amount of prestress we applied.

This means that optimisation of the tendon in the future can guarantee an increase of 30kN, allowing for the failure mechanism to be set into motion at the same time the neutral variant would. This means a significant increase in load bearing capacities compared to the neutral column, with a greatly increased ductility and post-breakage load bearing capabilities (See "Figure 66: Speculation on effect").

3.124. Comparison to expected behavior

What we expected from the post-tensioned column (See "Figure 50: Expected failure behavior" on page 66) was not perse an increase in load bearing capabilities. It was much more about the failure mechanism. The failure mechanism (See "Figure 65: Failure mechanism") we see occuring greatly compares to the expected behavior. A side-effect we did not account for originally was maybe much more important, namely that the column can no longer completely fail as we saw in the breakage diagram. This greatly reduces the consequences in case of structural failure. As the test was a proof of concept, we also noticed that where we assumed an M12 thread to be in close enough contact, this was not the fact and this needs further research but shows great promise.

3.13. Conclusion

A post-tensioned compressive members made out of glass shows greatly increased ductility and appears to be a much more flexible member. The same member without prestress applied fails in a sudden, explosive and dangerous way, the prestress member can not completely fail and shows very promising post-breakage characteristics.

The prestressed failure shows up to 300% greater deformations during failure and maintains between 15 and 35% post-breakage load bearing capabilities. These effects combined with the fact that the column can no longer fail in an explosive manner shows great potential for a prestressed glass compressive member to be used in structural applications.

Additional research is required to verify the behavior with a more suited post-tensioning tendon. This tendon should be in much more tight contact with the protective tubing inside the glass. After this additional research we can conclude that this is a safe structural column, and we can safely reduce safety factors to two.

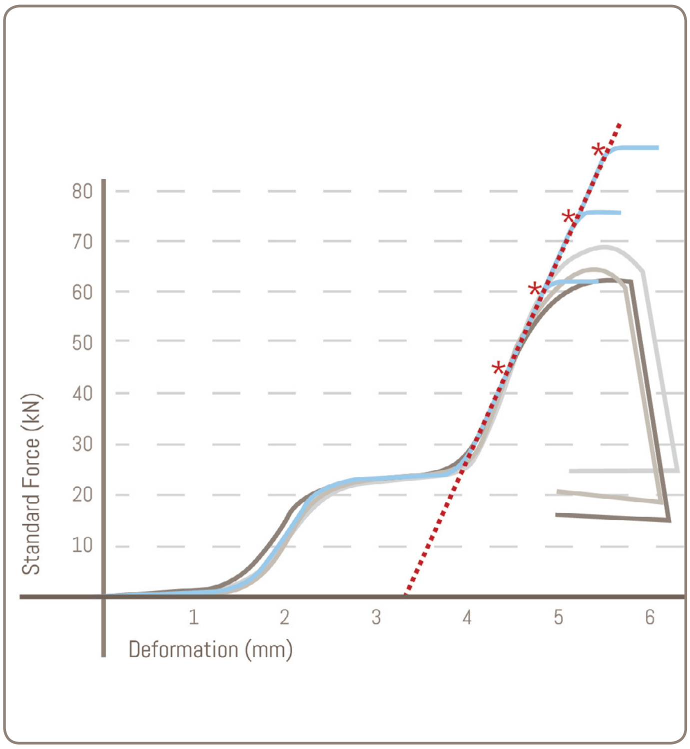


Figure 64: Failure mode activation

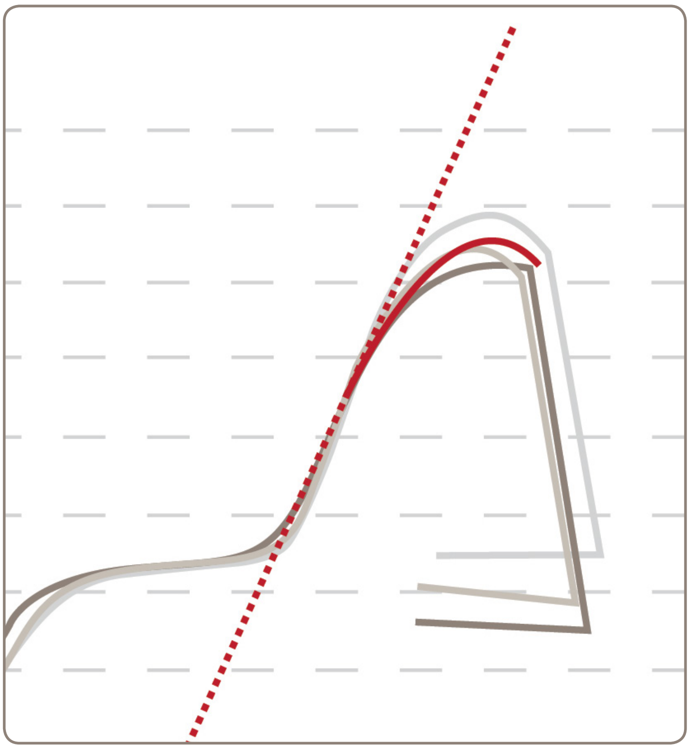


Figure 65: Failure mechanism

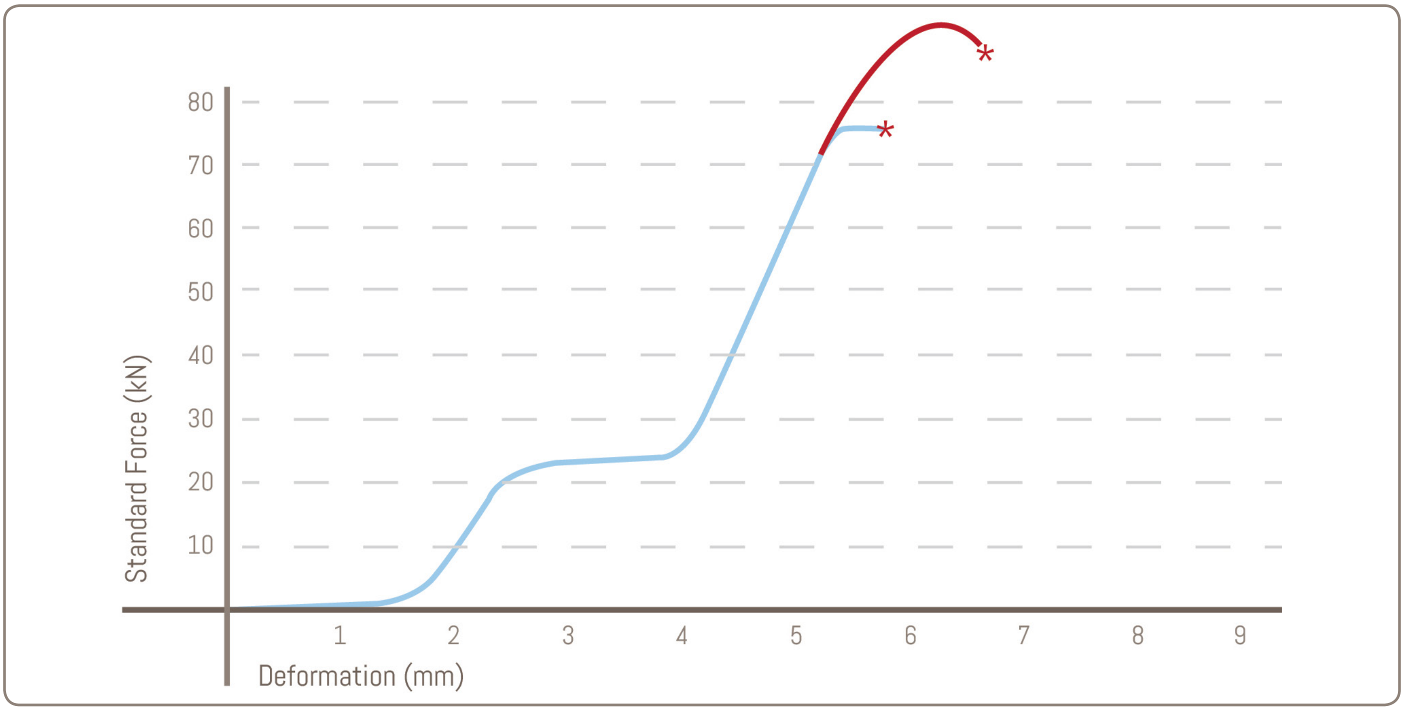


Figure 66: Speculation on effect

4. Research by Design

Where the previous chapter was about proving the mechanical behavior of the bundled column, this chapter focuses on increasing the architectural value of the column. What elements that weren't previously made out of glass can become transparent and how will the connection details look based on the structural behavior of the column. All the aspects from the previous chapter will be respected and used as boundary constraints for this chapter.

4.1. Introduction

Chapter 3 of this thesis research had it's main focus on forming hypothesis about the mechanical behavior and testing these hypothesis in a proof of concept type of manner. Columns were destructively tested, data was analysed and conclusions were drawn. This chapter will focus on the theoretical approach of increasing the architectural value of the column. So rather than proving mechanical behavior, this chapter focuses on providing and increasing the architectural value of an all glass column.

A reflection of the mechanical behavior will be applied to the ABT office case, connection details will be designed and researched. Any aspects of this column that were previously designed in steel or aluminum will be reflected upon to see if they can be replaced by a transparent option. Finally methods of improving the production process of the glass column will be discussed and other possible improvements to the cross section of the column will be opted.

4.2. Reflection on the ABT case study

The prestressed columns that we have been testing where a proof of concept. The tendons that were used to apply the prestress were not in tight contact with the sheathing, and these have to be optimized to increase the mechanical behavior. At this moment the failure mechanism was activated at 45kN. This is the maximum value we can use for now until new data is available, because we can't try to install a column that is expected to be in a buckling state of behavior.

Using Euler we can reverse calculate that a critical buckling force of 45kN with an effective column length of 2400mm means that the bending stiffness, or EI, of the column is 26262450000N/m^2. This is a conservative value though because the starting point of the failure mechanism is influenced by the prestress applied which is already at a maximum.

The Ultimate Limit State, as calculated by ABT engineers, is set to be 112kN. We do know that buckling is inevitably the leading mode of failure, and we concluded that (after some more research has been conducted) we can use a safety factor of 2. This means that we can use Euler to reverse calculate the maximum column length for a critical buckling force of 224kN with the bending stiffness value we calculated before.

Looking back at Euler's formula of buckling ($F = \pi^2 E I / L^2$) we see that we have a fixed value for F and the bending stiffness, the only variable is then the Effective Length, L. Calculating this L with F=224 and EI=26262450000 we see that this column has an effective length of 1075mm.

In other words, the maximum effective length column we can realise at ABT is 1,075m tall. The key word here is effective though, this means that a fully hinged column can only be 1075mm, but a clamped column has a significantly reduced effective length. A clamped column, compared to a hinged column has an effective length of only half as high. This means that we can realise a 2150mm long, fully clamped, column in the ABT office.

We do have to realise that mounting a column, especially a glass column, in a fully clamped situation bring the negative side-effects of occuring bending moments in the column. This can cause the glass to fail in more unexpected ways and therefore more research is required to subdue this effect.

Assuming the fact that we can mount a clamped column of 2000mm in our case study, this leaves us with 400mm of clearance between floor and the supported beam. This is actually not a problem at all, because we didn't touch an entire subject yet. The column can not just be placed in between the concrete, but still needs specially designed supports to transfer the loads and protect the glass, the design of these supports will be the next chapter in our research.

Noted on the Euler calculations can be seen in "8.7. Appendix G; Notes on Euler calculations" on page 123.

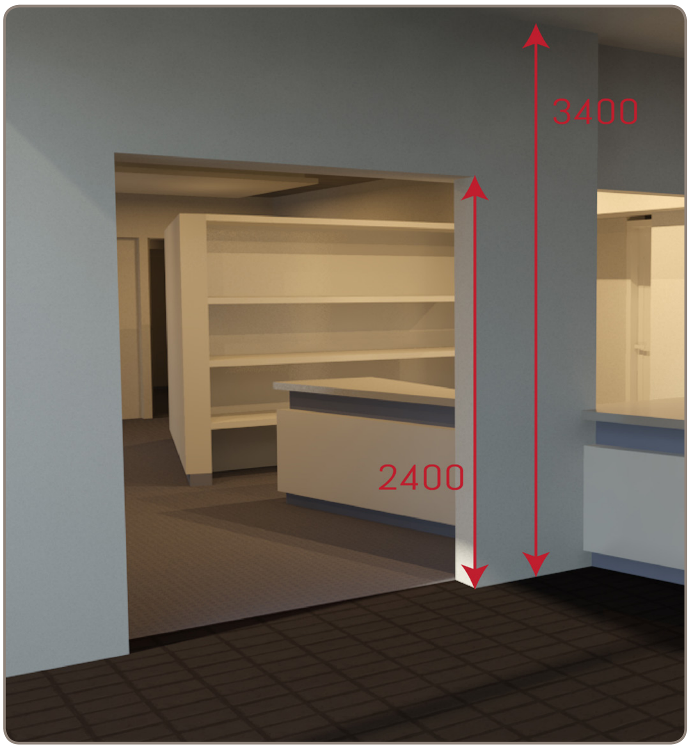


Figure 68: Design location

Figure 67: ABT proposition

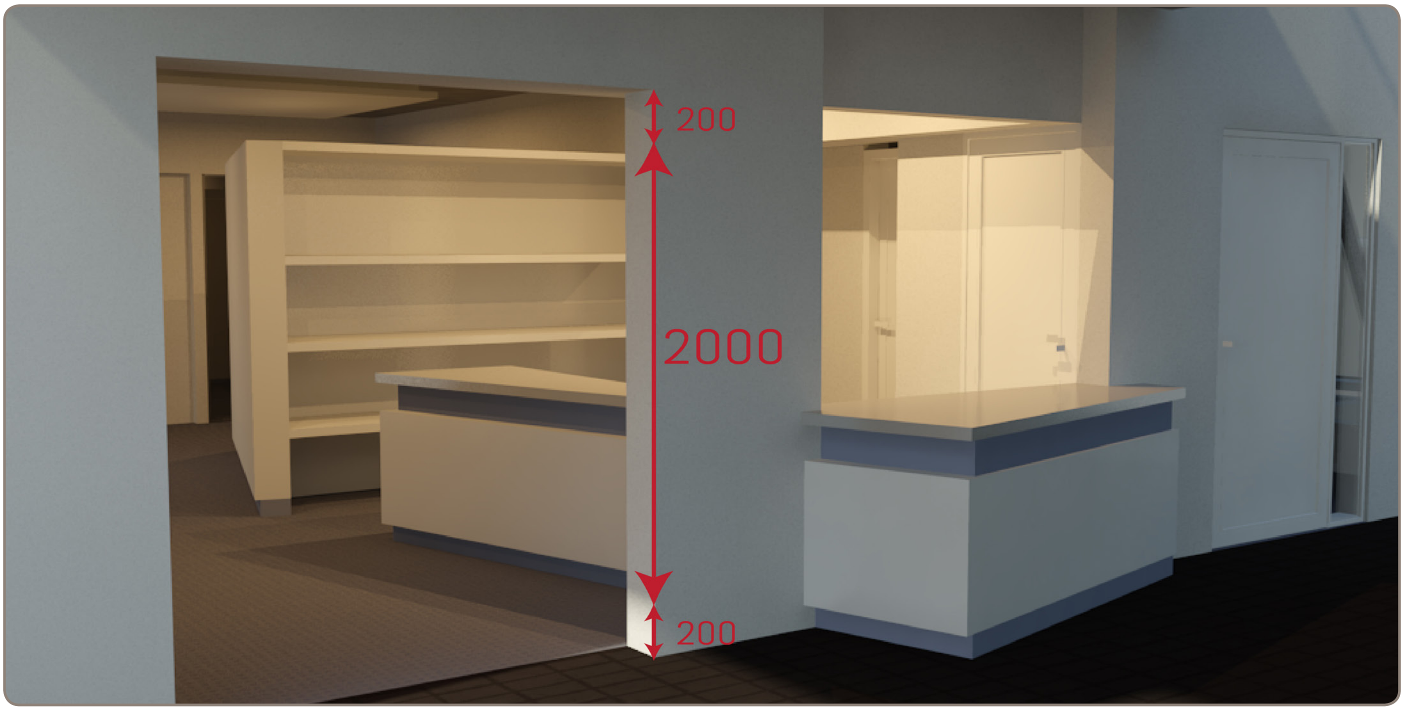


Figure 69: Design proposition

4.3. Support conditions

A big consideration in structural design is the choice between different types of supports. A fully hinged column is not subject to bending moments, but has a minimal effective length. Furthermore, an entire building can, per definition, not be supported solely by hinged columns, as the building would just collapse down to one side. Different types of supports for different columns in a building cause fluctuating bending moments in the supported beams, which is also not optimal. For our column, a hinged-clamped situation would most likely be the ideal solution, as the effective length is more significant and the amount of bending moments is kept low. But as we saw in the previous chapter, we actually need a fully clamped-clamped situation for our column, as otherwise we simply can not reach the design height of the column.

For this chapter research was started assuming a hinged connection, but this is a theoretical part so for now this does not matter. Research was conducted using a topology optimization method. If we want to create the most optimal structural element volume-wise, we can apply a loadcase and analyse the flow of forces through the element. Any part that has less flow of forces through itself can be removed in small steps. In the end you will end up with an element that has close to equal flow of forces through its entire body. This process is what we call topology optimization. This calculation sequence can be modelled in GrassHopper for Rhinoceros 3D using a plug-in called Millipede. This plug-in requires three inputs of volume (Boundary representations) in the form of the support, the load area and a volume that we be shaped into the optimized element (See “Figure 70: Boundary constraints”). These volumes serve as a base for the Millipede component, but this component requires more input namely the amount of steps of optimization, the amount of volume removed per step, and a smoothing factor (See”Figure 71: Millipede plug-in”). With all of these components the Millipede component will run the set amount of sequences in order to optimize the original volume (See”Figure 72: Flow of forces”).

Should we follow the optimized design as connection detail for our column? Glass is not a forgiving material, if we optimize the volume of the glass connection, it means pushing closer to the mechanical limit of the material. This is great, but can also be dangerous of not handled carefully. If we just optimize the glass for axial loads, even something as little as a small kid running into the column could send it crashing down because the optimization did not take a perpendicular load into account.

In my opinion a mostly axially loaded element (concentric) is not all that interesting to be subjected to topologically optimization and it is both easier and safer to design this element using common sense and performing finite element method calculations to prove the functionality of that element. What I mean with easier is that in an axial simulation the optimal stress trajectory through the element will always be a straight line between the edges of the two joined elements and with that in mind it’s easy to design any axially oriented structural member.

The entire GrassHopper script used for this test can be seen in “8.8. Appendix H; GrassHopper script topology optimization” on page 124.

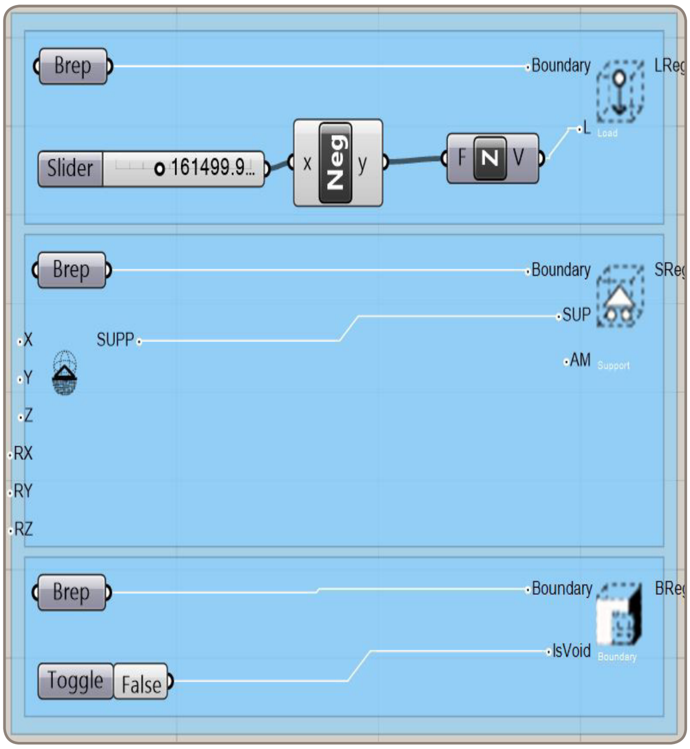


Figure 70: Boundary constraints

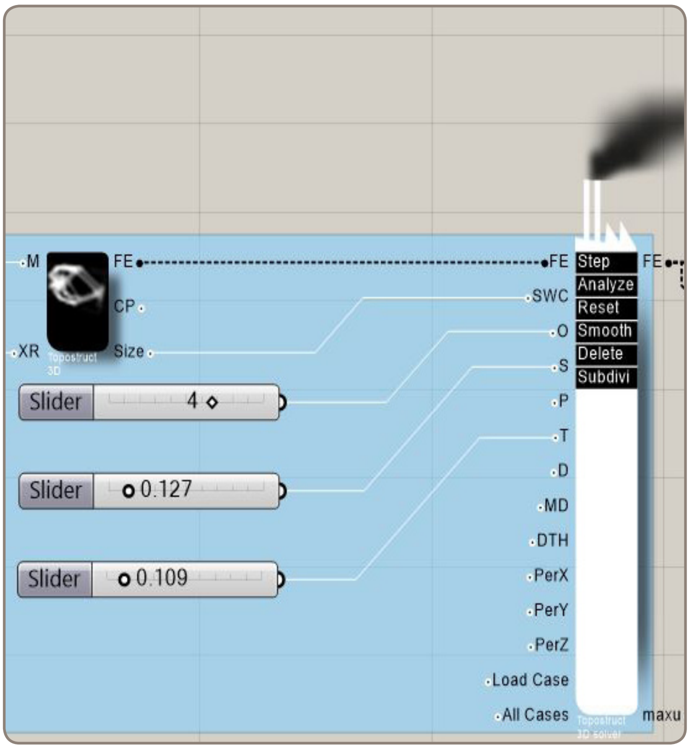


Figure 71: Millipede plug-in

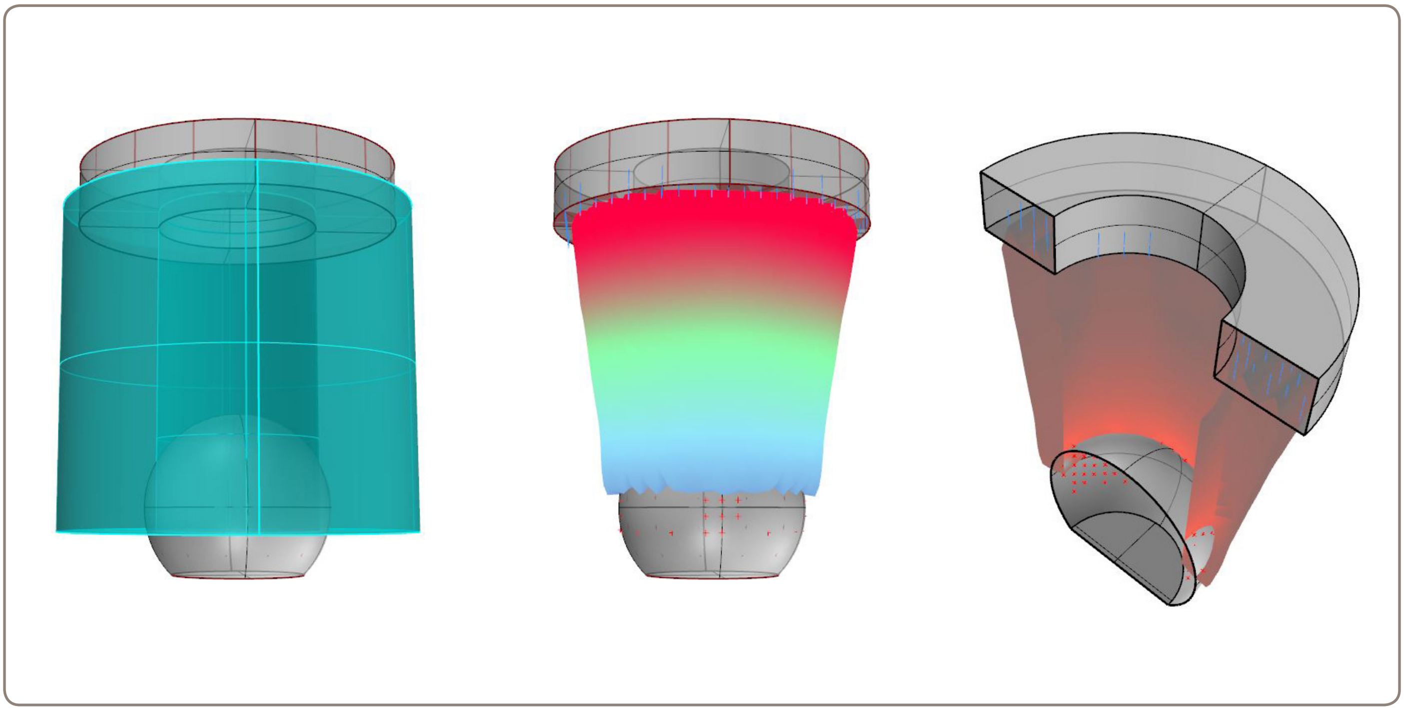


Figure 72: Flow of forces

4.4. Architectural design supports

The lessons we learned from the topology optimization test are that for mainly axially loaded components the ideal flow of forces is a straight line between the two elements, and that we should not forget about secondary load cases such as people leaning into or even running into the column. Such a secondary load case could be catastrophic to a fully optimized element for a single load case. Keeping this in mind a building engineer can safely design the supports for this column in an aesthetically pleasing and complimentary way.

4.4.1. Hinged support design

Even though we can not use a hinged connection in the ABT office case study, for the functionality of the entire column research a hinged support has been designed (See "Figure 73: Clamped and hinged support"). The choice has been made to design the supports out of steel and aluminum rather than glass, to draw focus to the slenderness of the glass column. A side-effect of this research is supposed to be to deepen the trust of people in glass as a structural material. By having a more heavy-looking support, people can see that glass can carry the same loads as steel, and is maybe even better at it. The main focus of this support is a big steel ball that performs as the hinge in this support. A steel bowl to be a perfect match to this sphere forms the base of the support that is tightly secured to a heavy duty foundation plate connected to the load bearing structure with high duty concrete bolts (See "Figure 74: Exploded view bottom details").

4.4.2. Clamped support design

The clamped support resembles the hinged support almost completely, but rather than having a sphere as connection to the glass, a cylinder is used. The support base is again a perfect negative fit for this column head, and this support base is connected to exactly the same type of foundation plate using the same methods.

4.4.3. Positioning

The order in which a column is placed starts with the mounting of the top foundation plate and the steel base which holds the hinge or acts like a clamp. The bottom plate is aligned and mounted to the foundation after which the base is placed on this plate. Using bolts that can be adjusted in height, the bottom base is completely lowered, allowing for the actual column to be positioned. The column is positioned into the top support, and held into place during the raising of the bottom support (See "Figure 74: Exploded view bottom details"). Once in direct contact and the column is tightly secured, a final cover over the bottom support is mounted to hide the setting bolts on the inside of the support.

The 2D drawings for these models can be seen in "8.9. Appendix I; Connection detail hinged" on page 125 and "8.10. Appendix J; Connection detail clamped" on page 126.

Figure 73: Clamped and hinged support

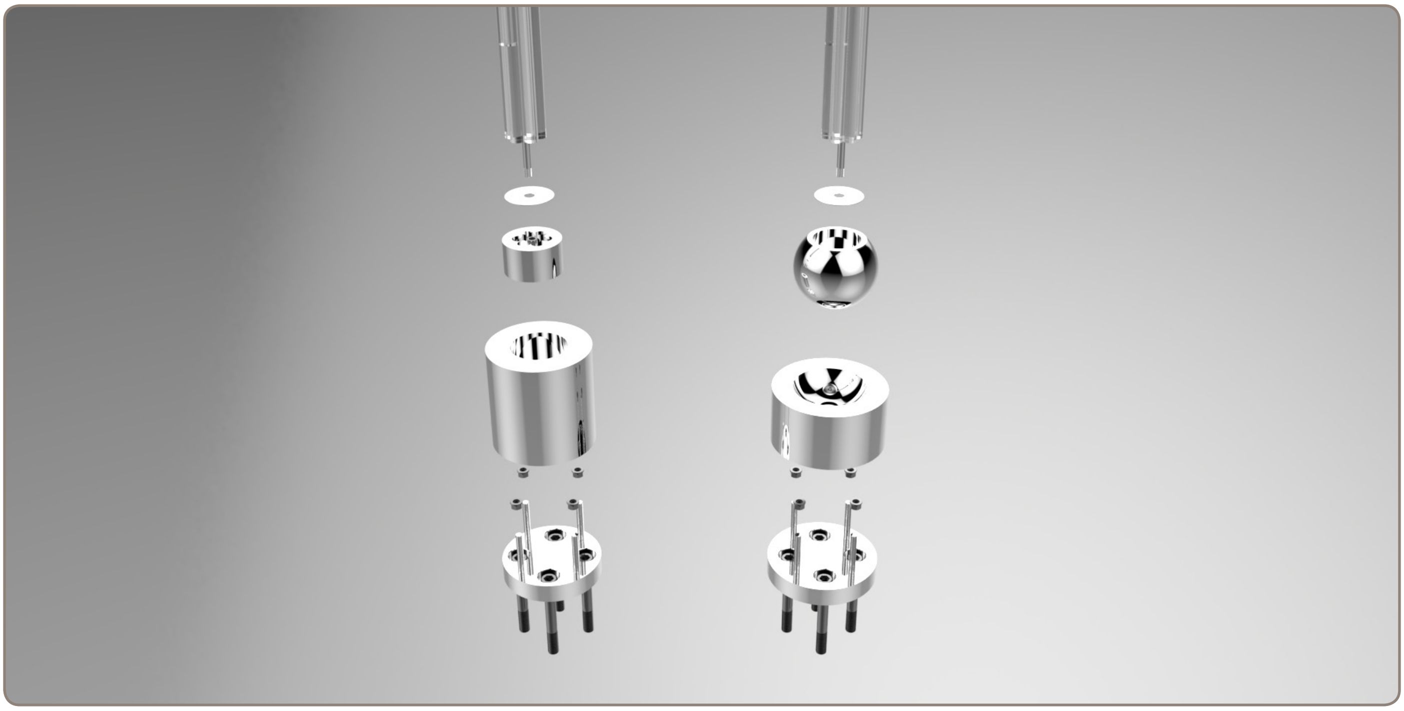


Figure 74: Exploded view bottom details

4.5. Pursuing all-glass

During the production of all the physical samples, we have have been using non-glass materials for several aspects. The column was fitted with aluminum caps in order to mount them in the compression bench, in this aluminum cap they all had a layer of lead which served as a protective layer between the glass and the aluminum. We also used aluminum discs to protect one rod of glass from breaking the other in each head-to-bottom connection caused be the split lamination. Also the architectural supports for the column embraced steel in an aesthetical way. But what if someone wants a column with everything made out of glass, or at least have every element with a high degree of transparency? Can we replace the steel, aluminum or lead parts with mechanically similar but transparent alternatives?

4.5.1. Aluminum discs

At this moment in time we need to use aluminum discs because the glass rods are not yet commonly produced in lengths of over 1500mm yet. In the future these elements with increased production accuracy (no eccentricities) will most likely become available. At that moment it will no longer be required to use an interlayer material to protect the bottom-to-head connection of the glass as they will no longer be there. But if we want to replace the aluminum at this moment in time, we can look for materials with comparable mechanical properties, for now we will focus on the hardness (70-90 HV), young's modulus (64-68 GPa), compressive strength (~230 MPa) and of course transparency.

In “Figure 75: Substitute aluminum” we see the results CES Edupack 2016 gives us for the maximum values we inserted. For the aluminum was originally chosen as a softer material compared to glass, but with a high compressive strength. The highest compressive strength in a material that made the selection generated by CES is polysulfone which is actually very comparable to aluminum in many ways, but it is slightly more expensive as a material. Another good option to replace the aluminum would be cast rigid polyester, this material is commonly used for boats, bowling balls, furniture and in the automotive industry. Materials like PET are less useful as a replacement in our design (3mm thickness) but are a viable option if there is only a thin layer of the material there as protection.

4.5.2. Lead protective interlayer

The reason we have been using a lead interlayer between the glass elements and steel, aluminum or other glass elements, is that small imperfections can and will cause peak stresses which can potentially break the glass. So it is purely a protective layer, inherent to this is that it should be a relatively soft material. So if we want to replace the lead interlayer, or need a protective layer elsewhere in the column, what kind of material could we use that does not damage the glass, does not break itself but rather deform to suit the glass. In order to find a material that could replace the lead we need to define the properties that allow lead as the protective layer. Using the software tool CES EduPack we can extract the properties we need: low hardness, low strength and low modulus of elasticity combined with a good malleability (Version 2016, CES EduPack, 2016). Beside this we are also looking for a material with a high degree of transparency.

In “Figure 76: Substitute lead” we can see the results following values comparable to lead for the properties we described before. Most options available are Styrene Ethylene Butylene Styrenes which are transparent and generally used in sportsgoods, toys and automotive exterior parts which all have a fair UV-resistance as well. In the graph these are the red materials classified thermoplastic elastomers. There are also a few thermoplastic ionomers available, but these tend to have lower UV-resistance. The thermoplastic elastomers generally show material properties that are very suitable to replace the layer of lead. Especially the materials commonly used in the automotive industry or in sports goods should be perfect for the job.

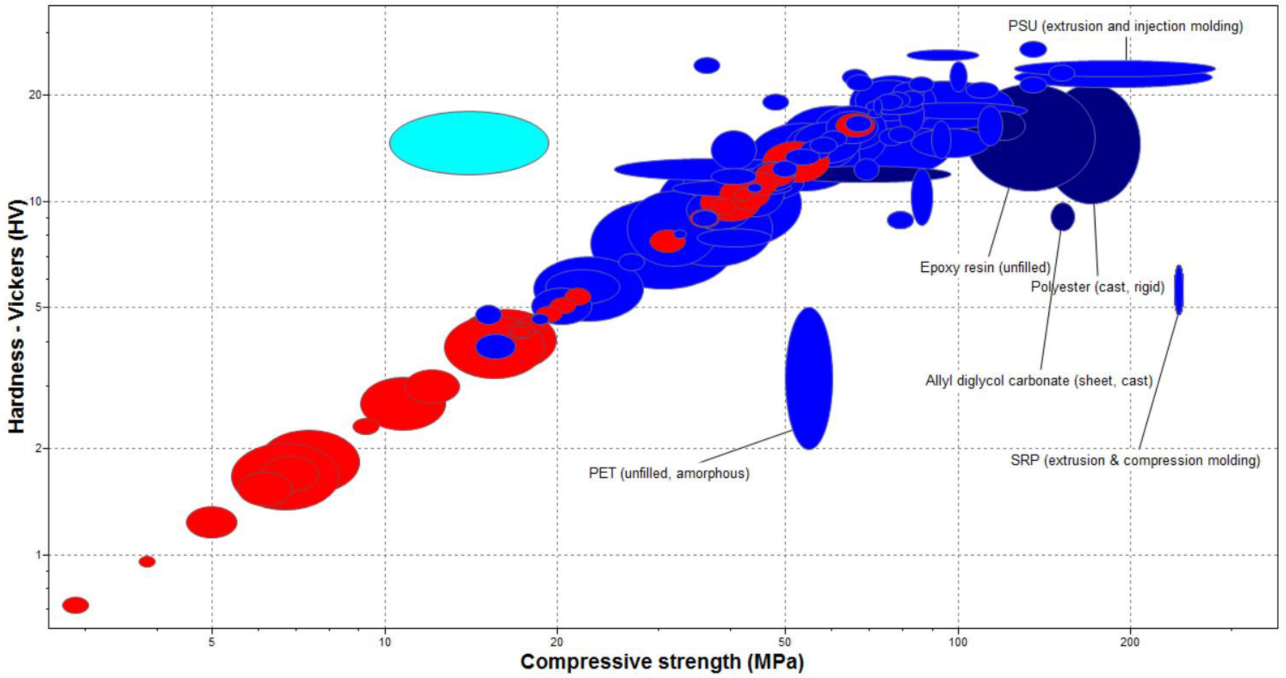


Figure 75: Substitute aluminum

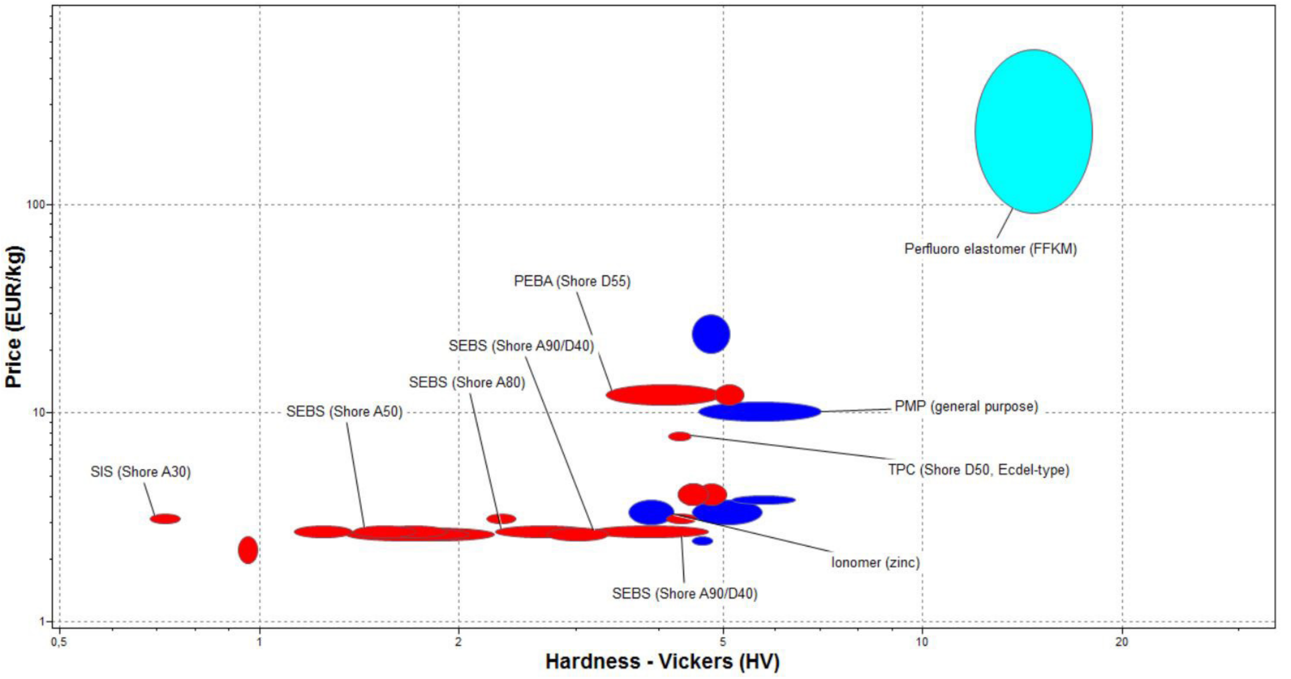


Figure 76: Substitute lead

4.5.3. Prestress system

For this research we have been using an M12 threaded rod inside of a PVC tube as a proof of concept. The M12 threaded rod was subject to tensile forces by tightening the bolt. But can we make this threaded rod, tube, bolt and washer transparent? The PVC tubing can easily be replaced by any hard plastic like PET or PLA which is also tranparent, but what about the other elements of the prestress system?

Using tendons to apply prestress to a structural member is generally something that is applied to concrete, because of this it has never been interesting to try and design a transparent tendon. What material properties would be required to create such a tendon? The tendon should have high strength and modulus characteristics coupled with excellent tension-tension fatigue performance and low creep. A type of material that does show these kind of properties are synthetic fibers, like Zylon (PBO) and Aramid (Kevlar), but these materials are not transparent.

We can conclude that having a transparent prestress tendon will not be possible, but there are several alternatives to use. The main option will always remain a steel tendon which can be polished for improved visual effect performance, but different types of synthetic fibres in sheating which are potentially stronger are also good options and can thus be applied in smaller cross sections, reducing their visibility.

4.6. Applying the column in the ABT case study

We have determined that a safety factor of 2 is, or will soon be, a feasible option. As a result of this reduced factor of safety we have calculated that with an Ultimate Limit State this column can be 1075mm tall in a fully hinged setup (which is the theoretically the ideal setup for now), this is not enough however. The actual column design is roughly 2400mm including connection details. Using a fully clamped situation we can effectively increase the column length to 2150mm. This is calculated using very conservative data as more research is still required, so in the future greater lengths will absolutely be possible especially in lower load case situations. For now we assume we can realize a 2000mm tall column and we have designed the supports for this column.

Putting all the previous conclusion together, a design proposition for the ABT office case study has been made (See “Figure 77: Proposed design for ABT”). The design respects the Ultimate Limit State as provided by ABT engineers, and is a feasible design that could be ready for implementation after further verification of the structural behavior of the column and proper addressing of the bending moments that occur in the supported beam.

The bending moments in the supported beam, which we have not calculated in this research, work in the normal direction of the beam in the direction it is positioned. A solution to dealing with these forces can be making the column more rectangular or oval, providing the column with a significant major axis towards the bending moments, but still respecting the column bending stiffness regarding buckling forces in the newly created minor axis of the column. This will be furtherly discussed in the next chapter.

Figure 77: Proposed design for ABT

5. Discussion

This thesis has been about performing research in order to realise a load bearing glass column. This chapter discussion the possibilities of applying the glass column in other applications and what this research has been relevant for.

5.1. Future uses

The research conducted has been in order to realise a load bearing column made out of glass. This column can be applied in modern architecture as a pièce de résistance, but also in more conventional architecture or restoration of churches as its slender design really suits the gothic building style many churches have been designed in. But rather than just being a load bearing column, it can act as any compressive structural member. Ranging from compressive parts of trusses to the compressive members in tensegrity modules.

5.1.1. Bridge truss

The difficulties of glass becoming a common construction material are not just material properties and overcoming certain issues, it also has a lot to do with people not being used to glass as a structural element yet. People generally don't trust that glass can be strong enough to walk on, let alone support a building. A bridge is a good way to demonstrate this material's load bearing capacity and its safety. The psychological result of creating an infrastructural object made of glass that people can walk or cycle on will be a more common acceptance of glass as a loadbearing material.

A site has been assigned for the proposed structure (The Green Village on the TU Delft campus) and the design is almost finished. However, further research and detailing is required for the proposed dry assembly construction method. Mock-ups will be produced and experimentally tested. Structural analyses will be performed and finally the bridge itself will be constructed in a collaborative effort between the Glass and Transparency group at the Faculty of Civil Engineering and Geoscience and the newly established Design of Infrastructures group within the Faculty of Architecture and the Built Environment.

As the bridge will be made out of interlocking bricks that purely rely on gravity to hold everything in place, a subconstruction will be required during the assembly of the actual bridge. This will be done in the form of two 14-meter span trusses with some of the truss elements being glass columns. These columns will be produced during the Bend&Break minor program at the Faculty of Civil Engineering, I will also be helping these students and will be informing them on how to process the glass in a safe way.

5.1.2. Bothic style church restoration

In gothic and neogothic churches we see a type of bundled column with very slender elements. Our column very closely resembles this type of column. In restorative works on these types of churches we could replace damaged columns with a glass variant, this because glass is more sustainable and durable. It also enhances the experience of the visitors of the churck by producing a much larger appearing space with more daylight.

There is a lot of debate amongst heritage architectects about renovation using unconventional materials. Some say that restoration should always be done using materials that most closely resemble the original. And -if- it is done using another material, that it should be painted in some off color to show people that this is not how it should have been, but that it has been a necessity. If we want to replace or restore a part of this heritage using glass, we should probably focus on recreating the original element shape in glass. Even though our bundled column could provide additional value to a project, the heritage should be respected in this way.

Figure 78: Gothic renovation

Figure 79: Connection detail

Figure 80: Glass bridge truss

5.1.3. Tensegrity modules

Tensegrity, short for tensional integrity, is a system in which compressive members do not touch each other, but rather ‘float’ in a web that is under continuous tension (See “Figure 81: Tensegrity module”). Because of this there can be no occuring bending moments and each element is loaded in either tension or compression. The tensile elements are generally a web of steel cables under pretension. The compressive members are normally steel or wooden elements. But as there are no bending moments or tensile forces in the compressive members, these elements are perfect to be realized out of glass.

Creating a bridge out of these tensegrity modules is something that I thought of during the M.Sc. 3 SWAT studio and this is where I designed this bridge (See “Figure 83: Impression”). All the compressive members are made of glass, and some have photovoltaic cells inside of them where others have LED lighting for pedestrian safety. On the inside of these modules is a walkway suspended that is also made out of glass (See “Figure 82: Inside tensegrity bridge”). For privacy and safety issues the walkway has a top layer of sandblast glass, providing traction and translucency.

5.2. Production optimalization

In all previous chapters we have seen and encountered problems that arise we designing with glass. These problems become most problematic when applied in a structural way because they could promote failure of the structural element. What are these issues, and how can we try and overcome them?

5.2.1. Glass production

The glass that we have been using has been produced by a German company and the glass is comparable to that being used in laboratories. This means it has to be produced in a very clean workspace, this also means that at this moment the amount of suppliers is very limited. Because of the production method they use (horizontal extrusion) the elements are very pure but show significant margins and eccentricities. This makes the glass somewhat unreliable if not dealt with properly. If we could obtain the glass using vertical extrusion, these eccentricities would be reduced alot and would improve the consistency and accuracy of the final column. Another aspect that can be enhanced is the production length of the glass. At this moment the maximum default size they deliver is 1500mm long, this means that we are forced to introduce weakpoints into the column.

5.2.2. Inconsistent adhesion

The rods are manually attached to the other glass elements, and manual work is flawed per definition. Glue thickness is inconsistent and this can cause weakpoints in the column. This can be dealt with by introducing an adhesive lint or tape that can be used. This would eliminate any inconsistencies and again improve the mechanical behavior of the column.

5.2.3. Edge finishing

The measuring, cutting and sanding of the individual pieces that are used to produce the final column is all done by hand. This again means inconsistencies in the elements. The cutting is done using a diamond-blade saw which produces a rough cut. Using a waterjetcutter for this would produce a much more clean joint. The sanding and polishing of the glass also reduces accuracy and will lead to imperfect contact surfaces for the glass to be glued to the aluminum or other glass.

5.24. Automatization

Ideally we would make this entire process an automated one. Where a laser measure the exact lengths after vertical extrusion, a waterjetcutter will be used to cut the pieces exactly the same length and eliminates the need for sanding. After this a prefabricated layer of adhesive (or a continuous applicator of liquid adhesive) is applied to the starshaped profile, and a machine precisely places the rods on top of this. This would result in 100% accuracy and therefore the most consistent behavior.

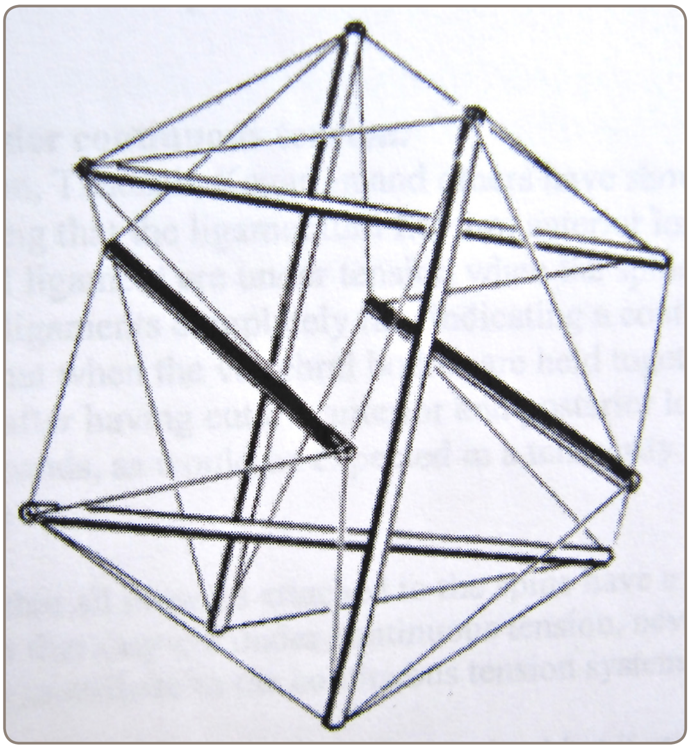


Figure 81: Tensegrity module

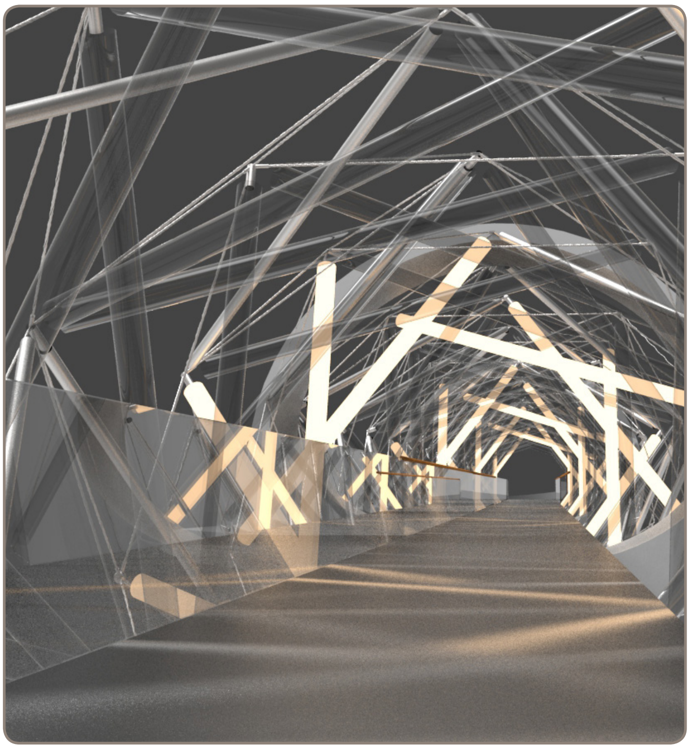


Figure 82: Inside tensegrity bridge

Figure 83: Impression

5.3. Possible future column cross sections

The column that we have been researching is one with an almost identical resistance to buckling in all directions. It is also a column with a limited cross section as a result of available glass profiles. What we have seen happening in the ABT office case study is that this column, using conservative calculations, is a feasible design, but just marginally. And even in that case it relies on a fully clamped condition which is not ideal for glass. There are residual bending moments in the supported beam that will be transfered to the column as a result of the connection conditions. Because of the bending moments, more research is needed to verify the possibility of applying our column in this case study. If the cross section is no longer sufficient an obvious step would be to use larger elements and thereby increasing the cross section, but these materials do not exist yet.

How can we use stock profiles (currently produced) and improve the column to counter bending moments for example? We can do this by introducing a major and minor axis in the cross section. The major axis will be focused on relieving the eccentric forces caused by the bending moments in the supported beam. At the same time the minor axis will be the same it is at this moment, which is sufficient to deal with the buckling forces which will again be the leading mode of failure (See "Figure 84: Bending moment resistant section").

In case of more complex load cases this cross section can be expanded in all directions by simply adding more original columns (See "Figure 85: Expanded cross section"). This can be used to counter bending moments, eccentric loading or for aesthetic purposes. Another aspect is that this column relies on redundancy to promote safe failure behavior, so this method can also be used to increase the area of the cross section in areas where there is a greater risk of damage to the column by heavy equipment for example.

54. Why is a bundled section ideal at this moment in time?

This type of column is relatively easy to produce with only stock materials. Also increased cross sections are easily produced using only the same stock materials, because of this it is a very cost efficient column to produce until more profiles become available. As we saw this column relies on redundancy, rather than laminating concentric tubes in case of a tubular column for example, as a result of this it is a column that allows for greatly increased safety compared to other column types.

At this moment in time glass is not commonly used as a structural material yet as we have seen. This means that when people see glass in a structural application, they are sceptical about the safety of the element. People have trust issues with walking over glass, but after they see that nothing breaks they begin trusting the element, and accept it as a reliable element. This is no less true for load bearing elements. People will not generally believe that we can implement glass load bearing structures with mechanical behavior comparable to that of concrete or steel (or even better for that matter). So this research is also a step towards deepening the trust people have in glass as a structural material. In glass walkways this trust is earned by using a translucent top layer on which people walk, this is in essence the same effect we are trying to achieve using the bundled column. A bundled column is not a column of optical quality, it is far from invisible. The way the light deflects throughout the column is a visual effect of aesthetic quality, but greatly increases visibility of the column. Because of this people will find it easier to trust the mechanical behavior of the column and accept glass as a structural material.

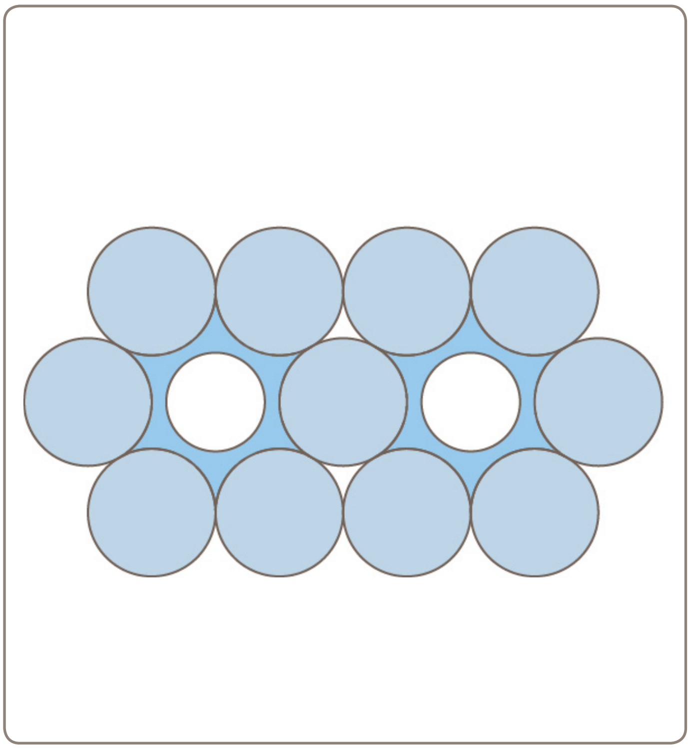


Figure 84: Bending moment resistant section

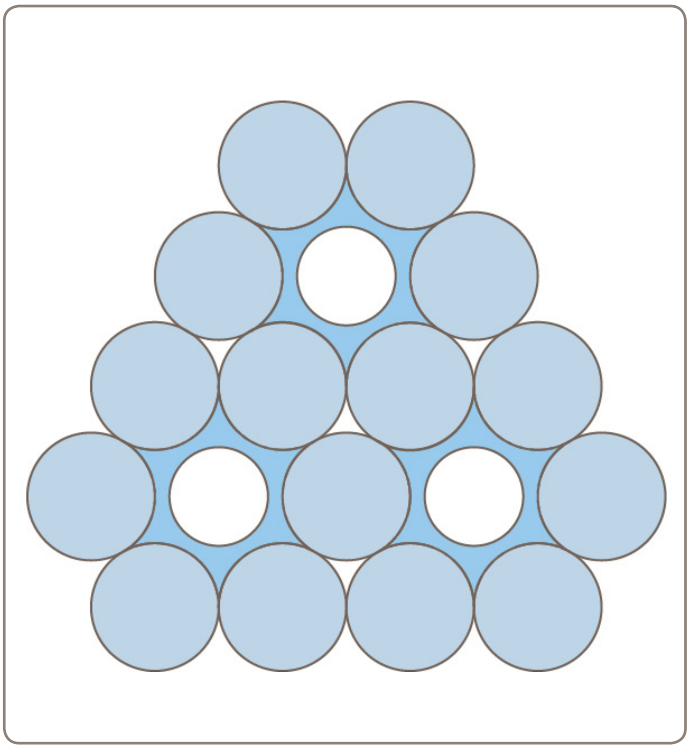


Figure 85: Expanded cross section

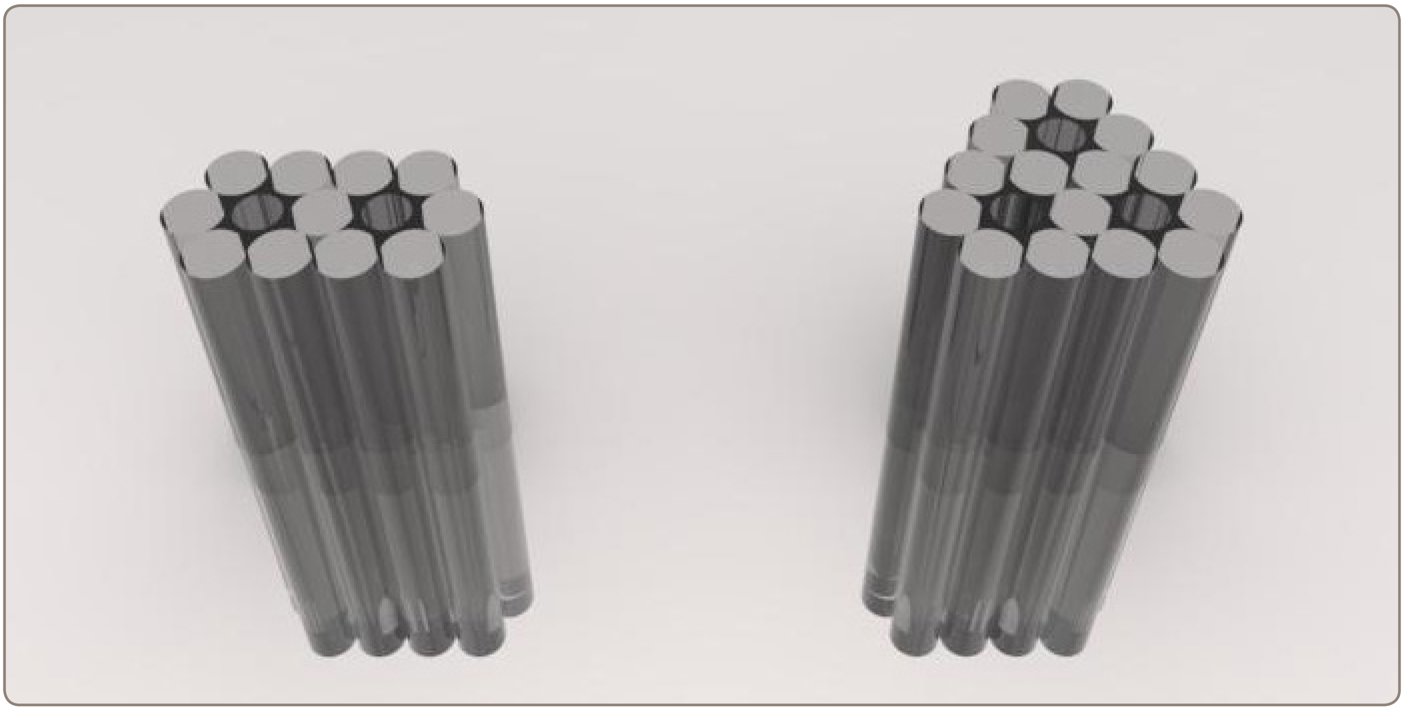


Figure 86: 3D image of the proposed sections

6. Conclusions & Recommendations

In this chapter we look back at the proposed research methodology and its corresponding research questions. What did we learn, and what is there still to be learnt? What areas of development are still recommended reerach topics and what should be paid special attention to?

6.1. Brief summary

Glass has seen a huge increase in architectural applications over the past decades and is no longer a material that is exclusively used for windows. We have seen glass being applied as parapets, stairs, walkways and even entire pavilions. Glass is a very durable and sustainable material and therefore it is nothing unexpected to see the amount of applications rise. There is one huge downside to glass however, and that is the inability to deal with tensile forces, much like concrete. The difference between concrete and glass being the transparency and following, the difficulties of reinforcing, of glass. A glass column is especially hard to realise as there is no easy way of dealing with eccentric forces without affecting its slenderness.

A slender glass column has been the fascination of many engineers, and the subject of research for some twenty years, in order to offer an ultimate compromise in the architectural engineering discussion between spaciousness and structural integrity. Several column archetypes have been described in preceding research and one of these types, the bundled column, has been further researched in a collaboration between the Delft University of Technology and engineering firm ABT.

The slender bundled column will fail by buckling, and in combination with the poor tensile properties of glass this results in an explosive and complete failure. Because of this dangerous failure, very high safety factors are applied to ensure structural integrity and safety. The main goal of this research has been to increase the safety during failure of said column by prestressing the column. An entire series of full-scale columns has been produced and destructively tested to verify the mechanical behavior.

A prestressed column shows greatly increased ductility and visibility upon failure. A prestressed column also shows post-breakage load bearing capabilities by preventing complete column failure. The result of this is that we can significantly lower the safety factors applied to the slender column. Because of these reduced safety factors the column becomes a feasible option with great structural reliability, even greater than originally expected.

6.2. Conclusions

This thesis consisted of two types of research, a design by research phase to prove mechanical behavior and a research by design phase to increase the architectural value of the column. Each phase had its own corresponding research questions that we have answered.

6.2.1. Design by research conclusions

The design questions that were connected to this chapter were the following:

"How to produce a 2900mm long column out of 1500mm long elements?"
"What is the optimal design of the head-to-head glass connections arising from the lamination of the rods?"
"How can we apply prestress to the column is the safest way, assuming large eccentricities and margins in the glass elements?"
"Can we reach the proposed design load, including a safety factor of four with a column this slender?"
"Does the column show (more) plastic failure behavior after prestress is applied?"
"If the column shows plastic failure behavior, to what safety factor can we drop while respecting structural integrity?"

During this phase physical tests have been performed to analyse what happens at the gaps that arise from the required split laminating of the column. In the future this will become obsolete with the availability of glass profiles with lengths greater than 1500mm. The tests concluded that a small disc of aluminum prevents peak stresses while still transfering forces throughout the column. The aluminum disc performs at roughly 85% compared to a monolithic variant. Utilizing the aluminum disc as an aesthetical aspect, a split lamination has been designed to spread out the weakpoints over the entire length while the aluminum discs form a spiral around it, increasing visibility of the column.

Physical tests on three 2400mm long samples that respected this design showed significant failure deviation, with the weakest column failing at 63kN where the strongest failed at 90kN. During the tests initial crack forming was observed as low as 50kN, this did not directly lead to complete failure but does lower the mechanical reliability of the column.

In order to cope with the inconsistent results and initial crackforming, in combination with an attempt to transform the sudden buckling failure into a more gradual and ductile mode of buckling, post-tensioning the entire column was discussed. The idea behind post-tensioning a glass column is suppressing initial crackforming while also preventing delamination, allowing the column to act much more like a whole. Beside just making the column act more like a whole, introducing a tensile element in the column allows for gradual release of the tensile forces introduced in the glass during buckling, making the buckling process a more ductile process while preventing the column from being destroyed completely. As a proof of concept a PVC tubing was inserted into the core of the column in which an M12 threaded rod was placed and put under tension. Prestress applied to a column in a correct design does not add to the critical buckling force. The tests were a great success and the column showed greatly increased ductility (up to 300%) and reliability. All columns failed almost identically which proves that the column acts much more monolithic than before. Not only did the columns show almost identical behavior, they also showed the ability to carry loads after complete failure. The reason for this is that during buckling, the tensile side of the column could break away, but the inside of the column would be held in place by the tendon. The post-breakage load bearing capacity is around 25% of the failing load. Because of these increased safety aspects surrounding the failure of the column, we can conclude that a post-tensioned glass column is a safe structural member and we can use design factors of safety that reflect this behavior. Using a factor of safety of 2 we can realise a glass column in a fully hinged setup for the ABT case study of 1075mm tall. This is due to the fact that it is a four-story building with a high expected load. Placing this column in a more suitable location would obviously make it more easy. Using a fully clamped situation we can boost this value to 2150mm, which is sufficient for our case study but this does mean that bending moments are introduced into the column. As a reaction to this, other possible cross sections were designed and described in the discussion chapter of this thesis.

6.2.2. Research by design conclusions

The design questions that were connected to this chapter were the following:

"How can the connection details for a glass column look?"
"How many elements that were previously designed in aluminum or steel can be replaced with glass counterparts?"
"How can we optimize the production process of the column to increase accuracy and transparency?"

Concluding the previous chapter, a fully functional and safe column with a length of 2000mm (rounded off for conservative safety) is assumed and the connection details were designed. The designs of both a fully hinged and fully clamped situation were addressed and modelled. Origininally these were designed to be made out of glass, but after the design was done the choice was made to increase the use of steel in the connection details. The reason for this is partially increasing the safety because cleaning equipment could run into this part of the column, potentially breaking it. Another aspect was that the use of glass in the connection details would draw away attention from the very slender column. Using steel in the connection details shows the observer that the glass element can handle the same forces the steel can, deepening the trust people will get in the material. Research has been conducted into which elements could theoretically be replaced with transparent alternatives and alternatives for all aspects with the exception of the post-tensioning tendon were found. The entire production process of the column was examined, and several aspects of improvement were addressed as well. The measuring, cutting and sanding was done manually and thus by definition inaccurate. Using laser measurements and a waterjet cutter could greatly increase accuracy. Using an adhesive tape would increase the adhesion consistency as well. Finally a design proposition for the ABT office case study was made.

6.3. Research relevance

Research into all glass columns has been around for about 20 years. But is this just the fascination of engineers, or is there more value to this research? Glass shows mechanical properties that are theoretically greater than those of steel. Because of this we could ask ourselves why it is not a common construction material by default. We did see that this is the case because of the negative properties that come with glass, mainly in the form of the inability to deal with tensile forces that can result from eccentricities and bending moments or that occur during buckling. Because of these reasons glass is considered to be a very dangerous material for structural applications and therefore should be handled with great care. But if we can design around the negative side-effects of glass, glass becomes a very valuable structural material. It does not show any deterioration and is highly durable, and beside those aspects glass is also completely recyclable making it a very sustainable material.

This research is thus valuable to introduce glass as a sustainable alternative for common construction materials, and not just a novel feature in contemporary architecture. Of course it will be applied in modern architecture as a 'pièce de résistance', but this research is more than just allowing for this to happen. This research also shows that glass can be used in other features where it is not just meant to look impressive and unique. The glass columns are general compressive members, and thus can be used in any relevant application such as the diagonals in a bridge truss as seen in The Green Village at the Delft University of Technology. Creating such a temporary truss (used during construction, but removed after the bridge is completed) out of steel requires mostly unique elements that have to be customly made and remelted afterwards. This all adds up to high costs and embodied energy of steel constructions that are not made using stock profiles.

Another aspect where we can use the research regarding glass compressive members is in the renovation of heritage architecture such a gothic churches. If there is significant damage to load bearing columns in churches, it is often hard to replace these without leaving visual defects. We could use glass, which obviously also leaves a visual mark, but increases the value it can have on the entire church. Increasing the spaceousness of the church while still respecting original features. Restoring with original stones is generally very hard as these are possibly no longer available, making it a very expensive happening.

For the coming years glass compressive members will remain a rare sight, and initially only seen in contemporary architecture. But the main relevance of this research will be opting glass as a very sustainable, relatively cheap and safe alternative for constructions previously made out of steel or concrete where visibility is an architectural desire.

6.4. Recommendations for future research

During this thesis research, the production of the columns and the physical tests of the columns we have encountered several aspects that require further research or that are interesting to have another look at. The column that we have designed for this research was manually produced with stock elements. These stock elements currently have significant eccentricities and margins while having a limited length. As a result of this some compromises had to be made like using aluminum discs to prevent direct glass on glass connections that could potentially break the glass in an unpredictable way. A first step towards improving the bundled column and increasing both its mechanical behavior and its transparency is to improve the production process. Steps I think should be taken involve an automated measuring and cutting system using a laser for measurements and a waterjet cutter for cutting the glass. A waterjet cutter produces a clean cut that does not require more finishing such as sanding and polishing. Eliminating manual work from the production process can greatly increase the accuracy with which the column is produced. This is also relevant for the laminating process. At this moment we manually applied liquid adhesive which is always inconsistent and decreases transparency of the column. Research into another method of laminating could greatly increase this transparency. This could be done using an adhesive foil or a different method of adhesive application.

Another recommendation is to increase the quality of the glass profiles. The profiles used for this research show eccentricities and deformations that prevent perfect contact. During the production process careful attention had to be paid to ensure almost perfect contact but this decreases the adhesive layer thickness consistency. Optimizing the glass production process can lower these margins which would allow for greatly increased production accuracy. This is also true for the center profile that we used, the inner core has a diameter of 17+/-2mm width. Because of this a much thinner post-tensioning tendon was used for our proof of concept. The code says that a member can not buckle under any prestress applied if the tendon is in close enough contact with the sheathing used. But we were forced to use a greater margin, potentially compromising the test results.

During the final physical tests we noticed that the failure mechanism was activated earlier than expected. After looking at the data, the difference was exactly that of the prestress applied. My suspicion is that the tendon was not in close enough contact with the sheathing, as a result the prestressed tendon was forced outside the neutral axis of the column, adding towards the critical buckling force. This is a result of what we just saw with the margins on the glass. If we want to have the greatest structural reliability of the bundled column, the tendon needs to be an almost perfect fit to the sheathing. This means that we should no longer use a threaded rod (which causes peakstresses on the PVC, compressing it locally which increases the rod's margin) but a solid polished rod to spread forces evenly on the sheathing.

In the chapter "5.3. Possible future column cross sections" on page 96, a method of increasing or customizing the cross section using only stock profiles was suggested. Increasing the cross section in one or more directions can increase the column's resistance to buckling or bending moments by introducing a major axis for the mechanical behavior. This is just a concept of dealing with additional forces introduced by the clamped connection conditions, but no mechanical verification has taken place. This requires more research to ensure bending moments can be properly dealt with before applying the column in a real life setting. By introducting a major axis we also allow the column to fail by new modes of failure, especially lateral torsional buckling becomes a possibility and these new cross sections should therefore be thoroughly tested and analysed.

6.5. A final word

People consider glass to be a dangerous material but nonetheless glass columns have been the topic of research for many pioneering engineers over many years. Recent, and this, research shows that we can design almost anything with glass in a safe way, and I believe that glass columns are most definitely a structurally safe element of which we will be seeing many more in the coming years. And if my work has contributed to the acceptance of glass as a structural material I can only express my gratitude one last time to all the people I have spoken over the last year and the Delft University of Technology for the fantastic opportunity of working with this beautiful material.

7. Bibliography

In the process of researching all aspects required for the production of this thesis many sources have been used. In this chapter you will find the references to all the literature sources and a list of all the figures with its corresponding sources.

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8. Appendices

Several figures and tables were simplified to be presented in this thesis work, the complete unedited versions can be found in this chapter.

8.1. Appendix A; BOROFLOAT33 specifications

The following data is supplied by Schott, the manufacturer of the borosilicate glass used for this research.

Technical Properties

The values below are generally applicable basic data for BOROFLOAT® 33. Unless stated different these are guide figures according to DIN 55 350 T12. However, they also apply to the coated versions (BOROFLOAT® AR and BOROFLOAT® M) except for the transmission data (see Optical Properties, pages 19 ff).

Mechanical Properties

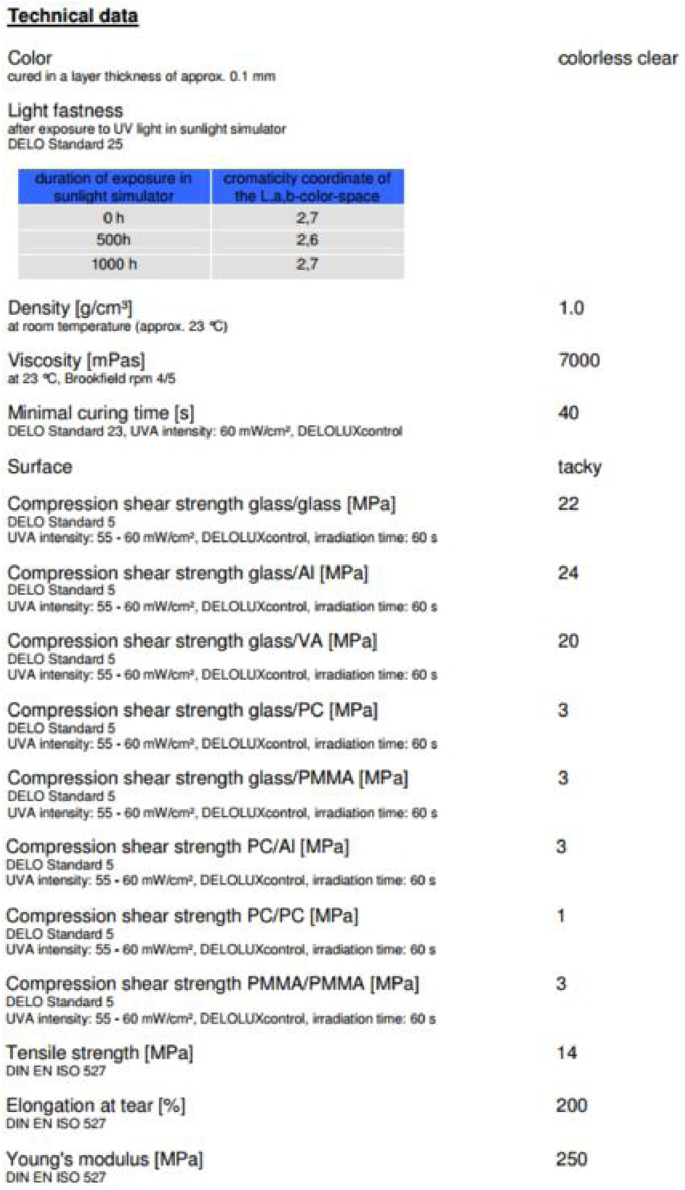
Density (25°C)	ρ	2.2 g/cm^3	
Young's Modulus	E	64 kN/mm^2	(to DIN 13 316)
Poisson's Ratio	μ	0.2	(to DIN 13 316)
Knoop Hardness	$HK_{0.1/20}$	480	(to ISO 9385)
Bending strength	σ	25 MPa	(to DIN 52 292 T1)
Impact resistance	The impact resistance of BOROFLOAT® 33 depends on the way it is fitted, the size and thickness of the panel, the type of impact involed, presence of drill holes and their arrangement as well as other parameters.		

Thermal Properties

Coefficient of Linear Thermal Expansion (C.T.E.)	$\alpha_{(20\text{–}300\ °C)}$	3.25 x 10^{-6} K^{-1} (to ISO 7991)
Specific Heat Capacity	$c_{p\ (20\text{–}100\ °C)}$	0.83 KJ x $(kg \times K)^{-1}$
Thermal Conductivity	$\lambda_{(90\ °C)}$	1.2 W x $(m \times K)^{-1}$

8.2. Appendix B; DELO PhotoBond 4468 specifications

The following data is supplied by DELO, the manufacturer of the UV-curing adhesive used for this research.



Technical data

Color cured in a layer thickness of approx. 0.1 mm	colorless clear
Light fastness after exposure to UV light in sunlight simulator DELO Standard 25	

duration of exposure in sunlight simulator	cromaticity coordinate of the L,a,b-color-space
0 h	2,7
500h	2,6
1000 h	2,7

Density [g/cm³] at room temperature (approx. 23 °C)	1.0
Viscosity [mPas] at 23 °C, Brookfield rpm 4/5	7000
Minimal curing time [s] DELO Standard 23, UVA intensity: 60 mW/cm², DELOLUXcontrol	40
Surface	tacky
Compression shear strength glass/glass [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	22
Compression shear strength glass/Al [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	24
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Compression shear strength glass/PC [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	3
Compression shear strength glass/PMMA [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	3
Compression shear strength PC/Al [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	3
Compression shear strength PC/PC [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	1
Compression shear strength PMMA/PMMA [MPa] DELO Standard 5 UVA intensity: 55 - 60 mW/cm², DELOLUXcontrol, irradiation time: 60 s	3
Tensile strength [MPa] DIN EN ISO 527	14
Elongation at tear [%] DIN EN ISO 527	200
Young's modulus [MPa] DIN EN ISO 527	250

8.3. Appendix C; Column type grading

8.3.1. Profile type

Architectural desirability		
	Transparency	As a result of the use of flat soda-lime glass the head sides of glass panels have a green glow to them which causes a translucent effect. Because of the angles and the lamination the visual effect is pretty transparent but not very desirable.
	Form freedom	The profile type column is created by laminating flat pieces of glass to create a profile cross section. This is generally comparable to steel cross sections. Because of the use of flat glass the amount of possibility is rather limited. These profiles have already been tested as well and are not architecturally desirable.
Mechanical desirability		
	Buckling	Column made in the category 'profile' are based on steel columns. These cross sections are not optimal at resisting buckling, especially lateral buckling. They also have 1 clear weaker direction.
	Torsional	The profile sections are not able to resist torsional forces very well. They tend to show torsional buckling under increasing loads. F.A. Veer described this type of column to mechanically inefficient.
	Safe failure	Even though the glass panels are laminated together, they don't show a very safe failure mode. They tend to buckle and show torsional failure under loading. Another aspect that does not help the safety of this column is the aspect that the profiles generally have fin endings which are thin elements, such as the 4 fins generated by using an H-profile. These are weak areas for a glass column as people can run into them causing damage to the fins, ultimately failing the entire column.
Financial desirability		
	Production time	The laminating process to produce this type of column has to be done very carefully. The cutting of the glass and laminating many elements together costs significant time.
	Cost	The cost is relatively low as this column is made out of flat glass.

8.3.2. Tubular type

Beside the noted points we also have to realise that this type has already been exploredbefore and is therefore less interesting to research again.

Architectural desirability		
	Transparency	The 'tubular' column shows the best results in the field of transparency. This is so because it is a continuous cross section without any eccentricities that deform the light any differently.
	Form freedom	Even though it scored great in the field of transparency, the architectural desirability is limited because the extremely limited freedom of form. The only thing that can be altered is the diameter of the cross section, but the shape will always be a big tube.
Mechanical desirability		
	Buckling	A circular cross section is the most optimal cross section to resist buckling because this cross section does not have a minor axis.
	Torsional	Just like with the buckling resistance, the tubular cross section is perfect at resisting lateral torsion. It is the ideal cross section from a mechanical point of view.
	Safe failure	The tubular type relies on the lamination of two (or more) concentric glass tubes for safety. Each of these glass tubes has the strength to carry the compressive loads generated; when one fails the other one will have enough strength to carry the entire load. The use of lamination ensures safe failure behavior according to Rob Nijsse.
Financial desirability		
	Production time	The production process as described by F.A. Veer is a very extensive one however. The laminating of the two stiff concentric tubes requires immense accuracy and this is very hard to achieve. The right type of adhesive is crucial as great expansions lead to shear stresses. The glue also has to be cured precisely to prevent other unwanted side-effects.
	Cost	Because of the extensive production process, and the use of costly materials this is not a cost efficient design to use.

8.3.3. The horizontal stacked type

Not only does it take a lot of time to laminate this many layers together, it also becomes an architecturally undesirable column. This has been tested and proven interesting for art pieces, but not interesting enough for this research.

Architectural desirability		
	Transparency	The effect on transparency cause by laminating many layers of glass together is something we have witnessed in the Glass House Laminata in Zaandam. It is not a desirable effect.
	Form freedom	You do have good control over the form as you can shape each individual layer to the desired size. Because of this freedom this method has been used to create art pieces before.
Mechanical desirability		
	Buckling	This type has decent mechanical behavior on all aspects. Not great, just decent.
	Torsional	This also counts for the torsional rigidity; it has a fair resistance against torsional forces.
	Safe failure	The safety mode this type of column relies on is the redundancy type of safety. Even though you would say this type uses lamination, it does not provide protective layers or added layers towards the safety aspect.
Financial desirability		
	Production time	This is the most time-inefficient of all to produce.
	Cost	The glass is not expensive as it is just flat float glass.

8.34. The vertical stacked type

As was the case with the horizontally stacked column, this column shows the same desirability in most aspects of the grading. It is not architecturally desirable and not interesting enough to research as there simply are better options available.

Architectural desirability		
	Transparency	The transparency is comparable to the 'stacked (H)' brother of this type. It is not a desired effect.
	Form freedom	The horizontal variant has significant control over the cross section over the height. This type also has a certain degree of freedom but less than its brother.
Mechanical desirability		
	Buckling	This is mainly dependent on the adhesive used. If the adhesive is strong enough, the mechanical behavior of this column is sufficient.
	Torsional	It has a decent torsional rigidity, but not as much as some of the other types.
	Safe failure	In this stacked type the safety is guaranteed by both redundancy and lamination. If a single layer breaks, it can be replaced relatively easy.
Financial desirability		
	Production time	This is a lot more time efficient to produce compared to the horizontal variant. But if we compare it to other types again, it is again a very mediocre option.
	Cost	The glass is not expensive as it is just flat float glass.

8.3.5. The bundled type

This type came out as the best option for this thesis research. Not only because of fantastic mechanical behavior and great architectural and financial desirability, but also because it is the least explored option to this day. The reason for the positive financial desirability is not because the elements are cheaper, but because they are standarized elements and thus require less processing.

Architectural desirability		
	Transparency	The bundled column type is not the most transparent, but because it is a bundle of rods, it does distort the light in an architecturally pleasing way. It makes the column visible to the naked eye while still being transparent.
	Form freedom	The form freedom of this type is pretty decent as there are a dozen of different extruded glass elements available. Because of this many different option for bundles are available.
Mechanical desirability		
	Buckling	Just like the tubular cross section this is a very efficient cross section from a mechanical point of view. It shows great resistance to buckling.
	Torsional	Again, just like the tubular cross section this section shows great resistance against torsional forces. It is an effective cross section.
	Safe failure	This is the main point of difference between the tubular type and the bundles type. The tubular type relies on the method of lamination to provide safe failure behavior. The bundled type relies on redundancy to promote its safe failure behavior. But it scores well in this area.
Financial desirability		
	Production time	The use of a star-shaped center profile makes the laminating of the elements very easy and thus time efficient.
	Cost	The borosilicate extruded elements are a lot more expensive when compared to float glass. This is especially true for elements above 1500mm long. These elements are available but only in larger quantities.

8.3.6. The cast type

Casting a column in a single piece shows some great features. You can optimize the column on all aspects and visually this would provide us with a stunning result. But it is simply not possible at this moment in time. Cooling of elements this size is the absolute limiting factor. Casting elements which together form the column is a possibility, but you do have to take deformations cause by the cooling into consideration.

Architectural desirability		
	Transparency	The cast column type is the most ideal option in many field, this is no less true for transparency. If you have a cast column made in 1 single element, the transparency is not influenced by different layers or adhesives. Depending on the shape of the cast column the deflection of the light is also possibly the most consistent.
	Form freedom	You have the best freedom for form with this option as you cast the glass in a preformed mold.
Mechanical desirability		
	Buckling	Because of the great freedom of form you can optimize this type of column very easily to promote buckling resistance.
	Torsional	The same is true for the torsional rigidity.
	Safe failure	This type does not rely on lamination but is rather cast in one piece. Because of this you have to rely on redundancy to promote safe failure behavior.
Financial desirability		
	Production time	The production time is the first negative point we encounter with this type. And it is a significant negative point. The larger the cast elements, the production and cooling time of the element become exponentially greater. As we have seen, casting a column in one piece is not going to be possible with the current production of glass.
	Cost	The costs will be immense if the column is cast in one piece. The gradual cooling will easily take over 1 year and this inherently costs a lot of money.

84. Appendix D; Lamination gap influence

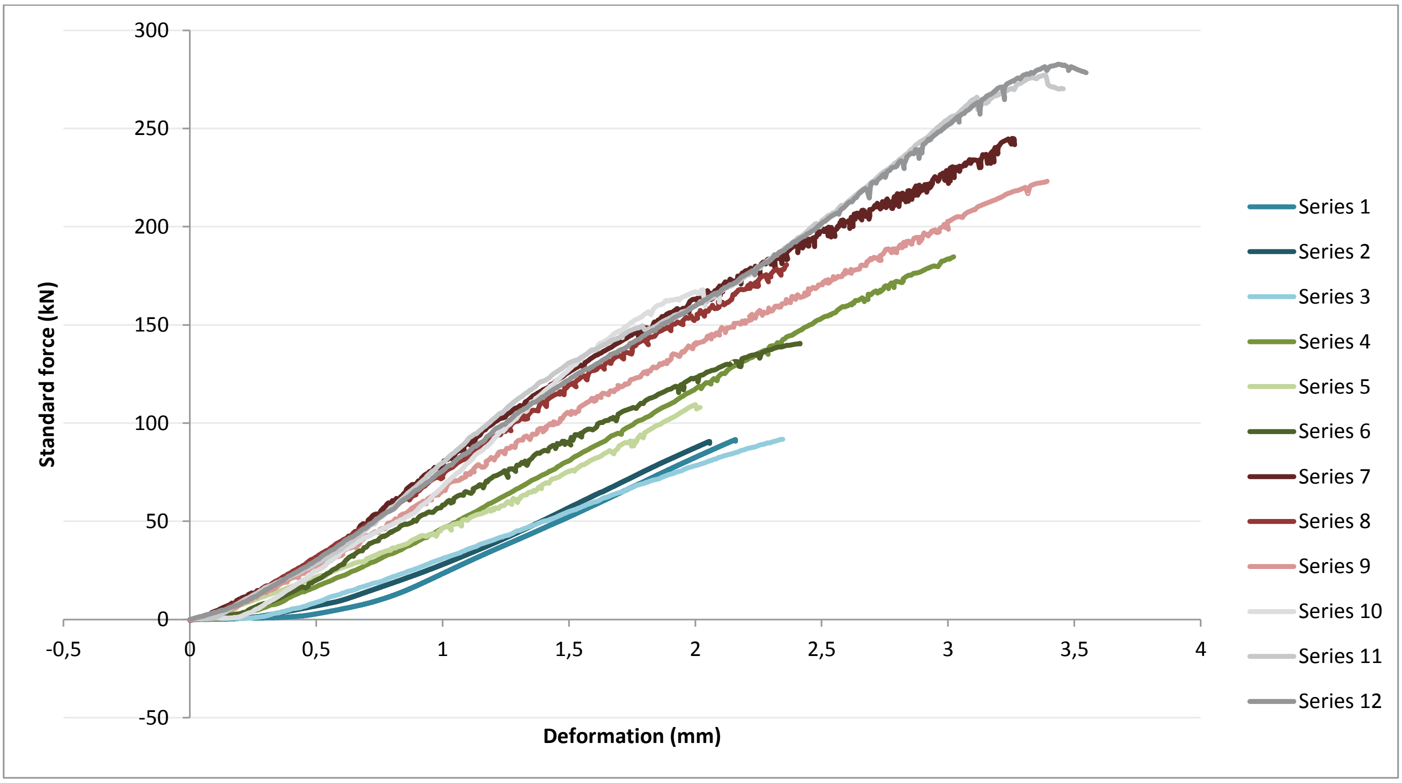
84.1. Notes

On the right you can see some simple notes that were taken during the tests. This also explains which series number is what material.

84.2. Excel graph

Below you can se the entire Excel graph that was created out of the gathered data during the destruction of the 12 samples as described earlier.

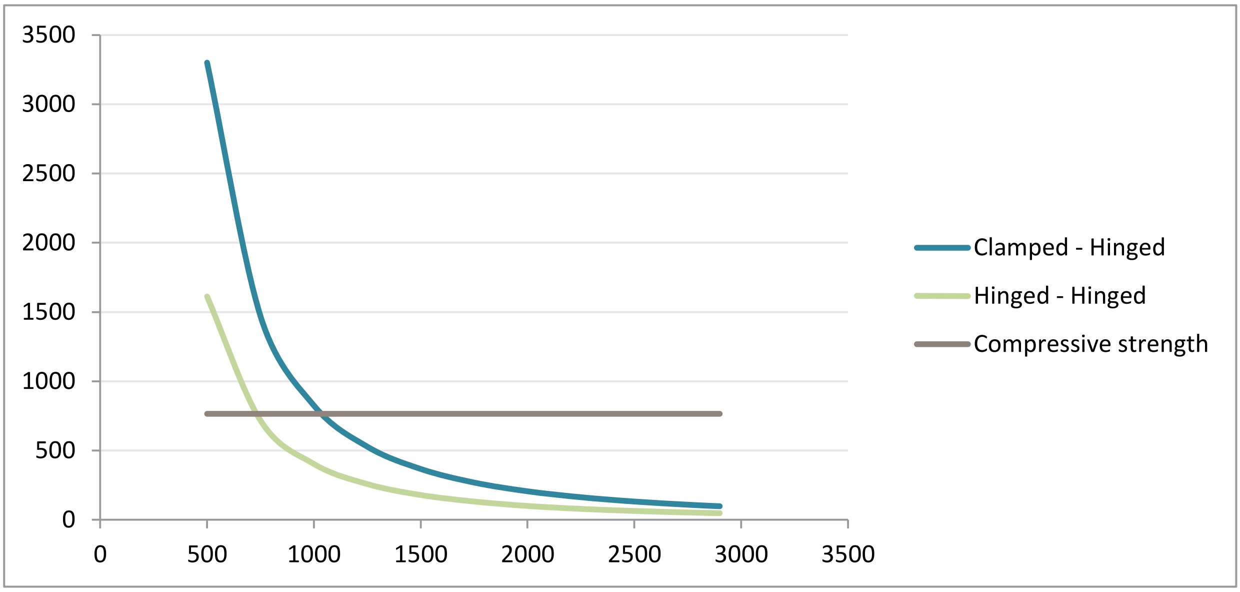
	#	Notes
Empty	1	Tested at 3me, continued at Civil
	2	Same
	3	Tested at Civil
Adhesive	4	Total failure
	5	Test stopped after significant cracking
	6	First cracks at 70 kN
Aluminum	7	Total failure
	8	Partial failure
	9	Total failure
Glass	10	Test stopped after significant cracking
	11	Total failure
	12	Total failure



8.5. Appendix E; Buckling curves

In this graph you can see the theoretical buckling curves for our column with two types of connection conditions. The Clamped-Hinged is comparable to the first tests that have been performed. And the 2400mm tests will be performed in a Hinged-Hinged situation. The compressive failure line that is introduced into this graph is based on the average strength of a borosilicate glass. As results showed us however, the actual compressive failure line will most likely be higher due to increased material strength delivered by SCHOTT.

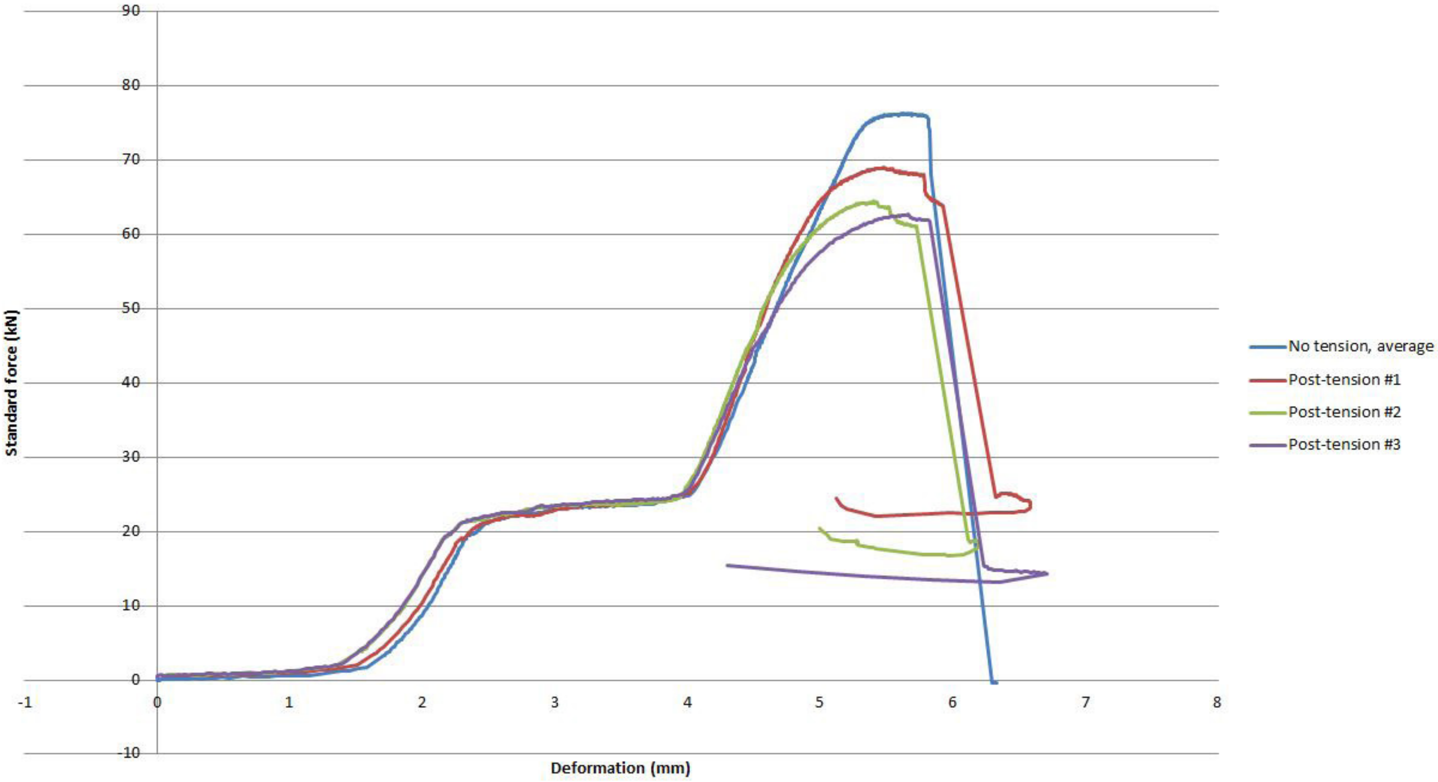
Length	Clamped-Hinged Standard force (kN)	Hinged-Hinged Standard force (kN)	Compressive failure Standard force (kN)
500	3300	1612	765
750	1470	717	765
1000	825	403	765
1250	528	258	765
1500	367	179	765
1750	269	132	765
2000	206	100	765
2250	163	79	765
2500	132	64	765
2750	109	53	765
2900	98	48	765



8.6. Appendix F; Physical test results 2400mm samples

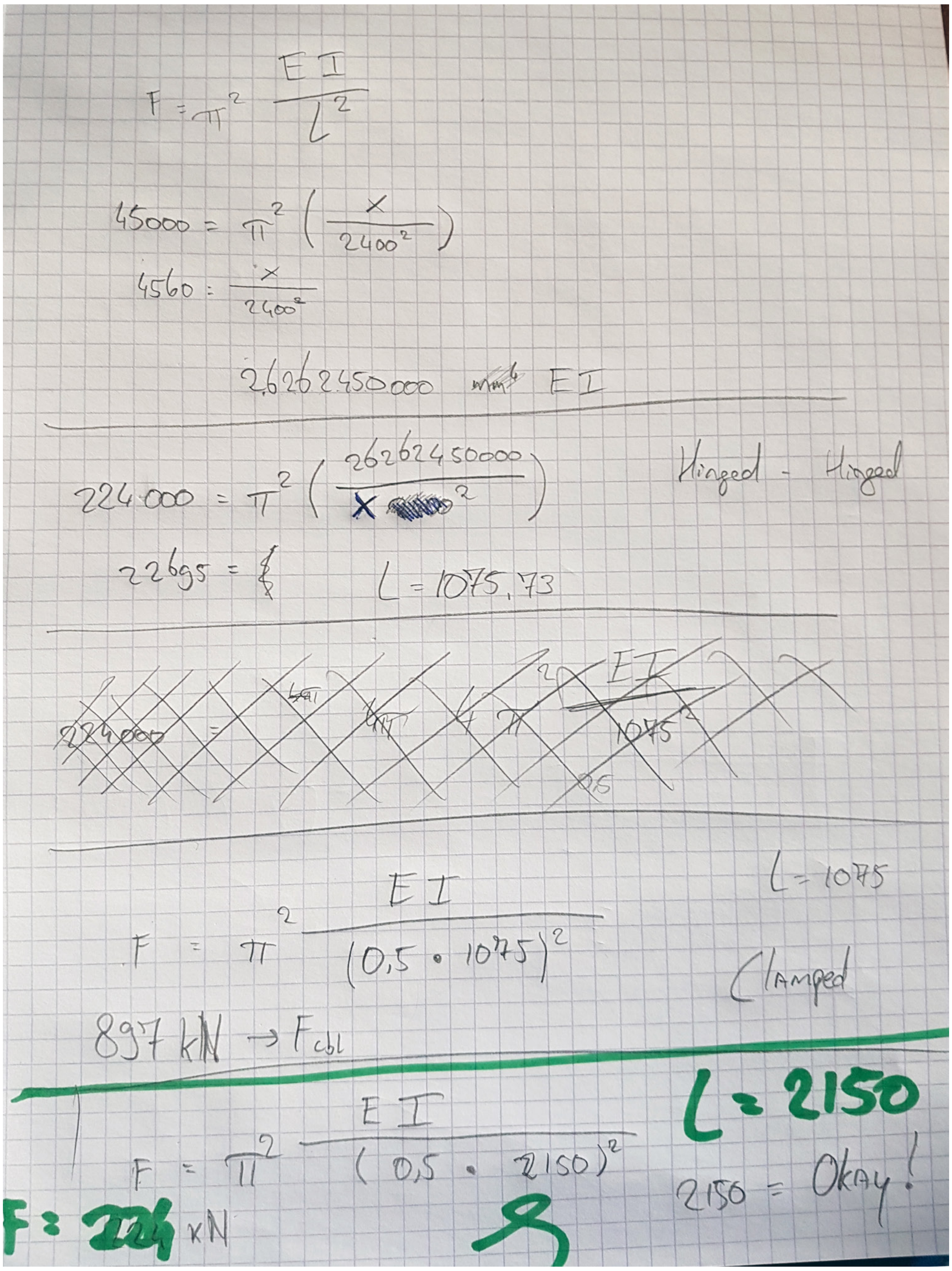
The following graph shows the data obtained during the physical testing of the 2400mm long column samples. The first two, non-prestressed, columns were not yet hooked up to the electrical measuring device and therefore lacks data. These first two were manually checked and failed at 63kN and 90kN, showing the same graph flow of the one shown in this graph.

The post-tensioned variants show greatly increased ductility (300%), but start their failing mechanism 30kN earlier. This means that the prestress applied (30kN) did in fact contribute to the buckling force, which in turn means that the tendon was not in close enough contact with the sheathing.



8.7. Appendix G; Notes on Euler calculations

The prestressed columns started their failure mechanism at roughly 45kN. This value was used to reverse-calculate the bending stiffness of the column (as if it weren't prestressed). Using this value, we determined the length a column could possibly be in our case study. This is a very conservative value to use as the actual failure load is 30kN greater.



$$F = \pi^2 \frac{EI}{L^2}$$

$$45000 = \pi^2 \left(\frac{x}{2400^2} \right)$$

$$4560 = \frac{x}{2400^2}$$

2626245000 mm⁴ EI

$$224000 = \pi^2 \left(\frac{2626245000}{x^2} \right)$$

Hinged - Hinged

22695 = [illegible]

L = 1075,73

~~$224000 = 4\pi^2 \frac{EI}{1075^2}$~~

L = 1075

$$F = \pi^2 \frac{EI}{(0,5 \cdot 1075)^2}$$

Clamped

$897 \text{ kN} \rightarrow F_{cbl}$

$$F = \pi^2 \frac{EI}{(0,5 \cdot 2150)^2}$$

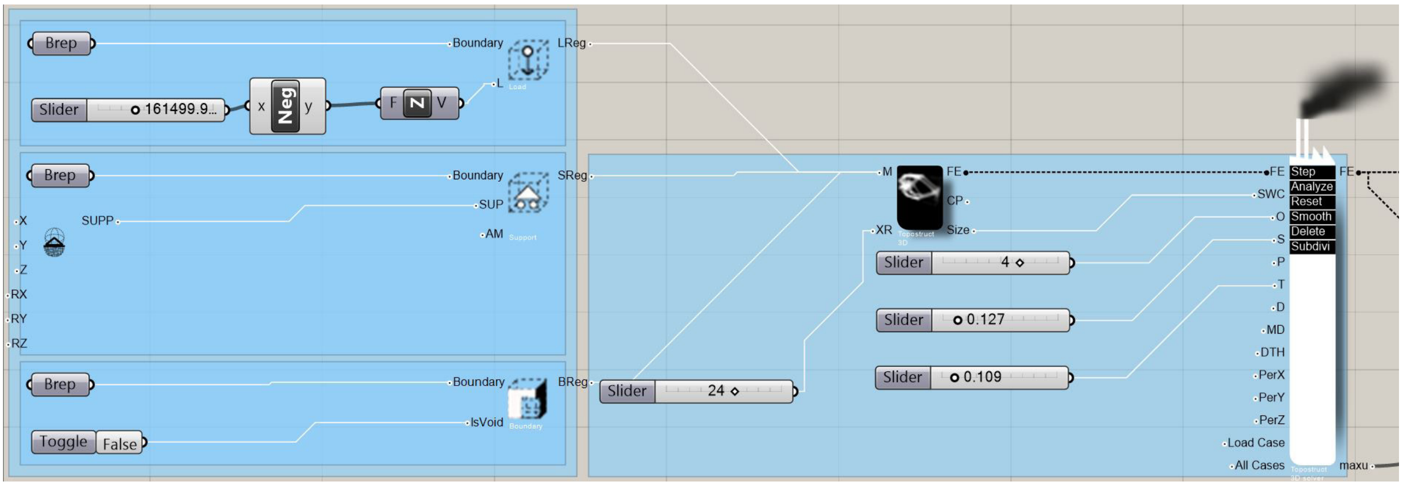
L = 2150

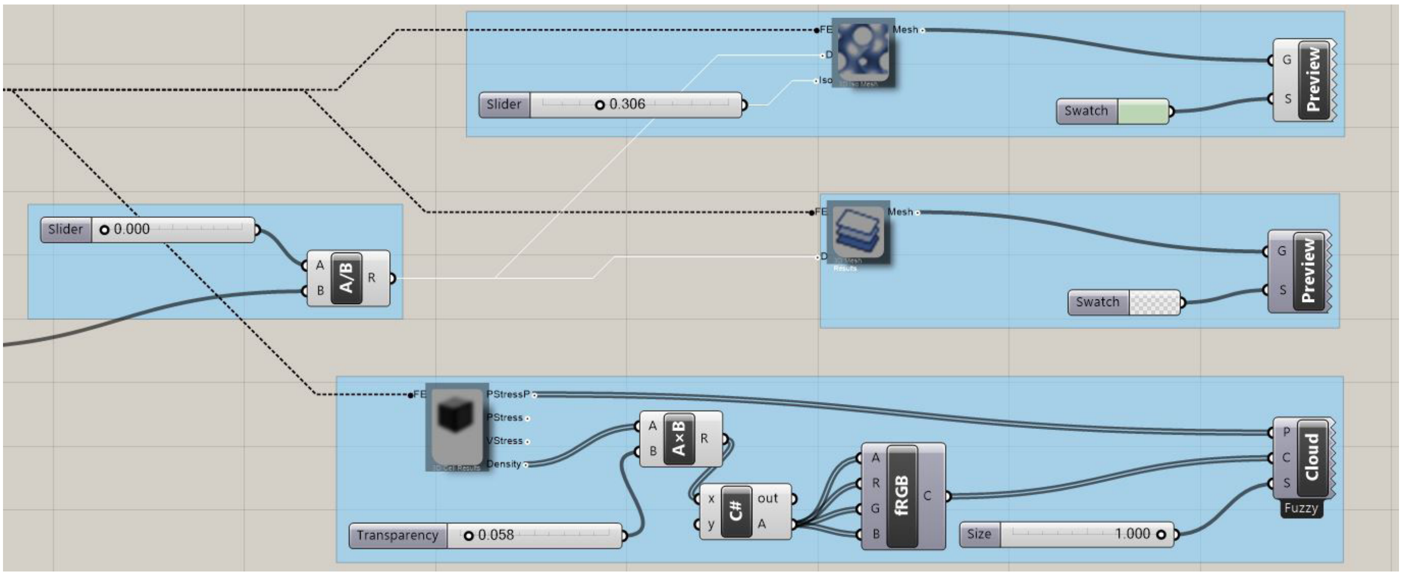
2150 = Okay!

F = 224 kN

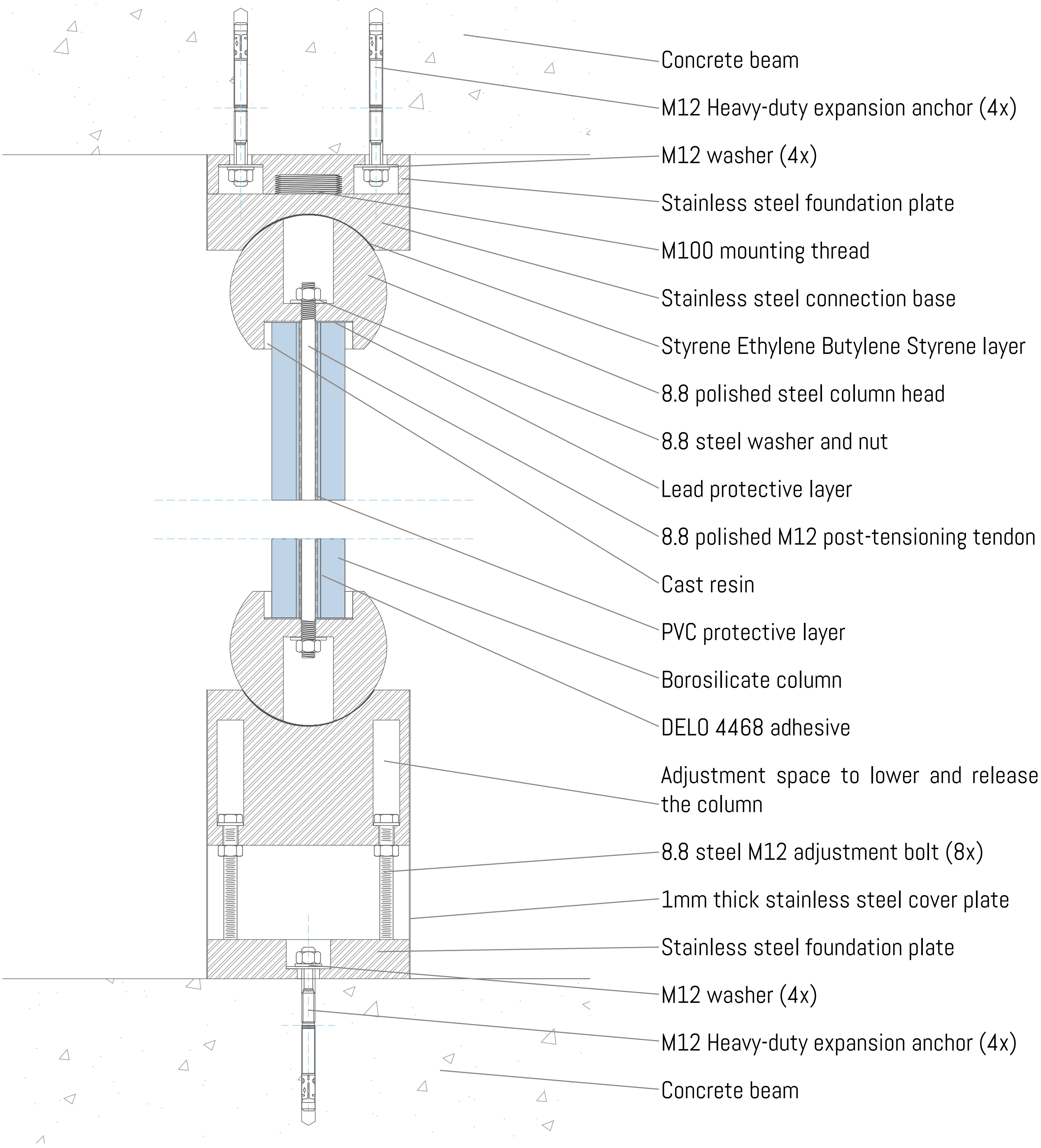
8.8. Appendix H; GrassHopper script topology optimization

A GrassHopper script was written using the Millipede plug-in. This script investigates the ideal flow of forces through the connection details. This method proves to be less usefull when applied to a purely axially loaded element. Modelling this with multiple load cases becomes too complex for this research. Lessons learned from this script is that secondary load cases should be kept in mind, and that the ideal flow of forces in an axial situation is a straight line between the several elements.





8.9. Appendix I; Connection detail hinged



8.10. Appendix J; Connection detail clamped