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Graduation Studio

Name / Theme: Building Technology
Teachers (involved): Faidra Oikonomopoulou
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Graduation project

Title of the graduation project: All transparent column

Goal

Context

In the early 20th century modernist architects such as Frank Lloyd Wright saw walls and rooms as downright fascist. The spaciousness and flexibility of an open plan, they thought, would liberate homeowners and office dwellers from the confines of boxes. The typical open-plan office of the first half of the 20th century contained long rows of desks occupied by employees. In 2011, the organizational psychologist Matthew Davis reviewed more than a hundred studies about office environments. He found that, though open offices often fostered a symbolic sense of organizational mission, making employees feel like part of a more laid-back, innovative enterprise, they were damaging to the workers' attention spans, productivity, creative thinking, and satisfaction (Davis et al, 2011).

The reason for open offices not working as intended is pretty simple, noises and distractions. The original open offices did not provide any form of privacy; they literally were huge open spaces. Offices that are being realized today are more flexible and allow for compartmentation of the space using glass walls for example. The result of this is a visually connected open office, but without the drawbacks such as noise and distraction, while maintaining the positive effects such as open vision around the office and the allowance of sunlight into the workspace which is very beneficial to the health of employees. It is key to realize here that people do want light in their office, and have a visual connection to peers, but without the drawbacks of a literal open space.

In the image we can see the Manhattan office of Paris-based Pernod Ricard; in this office we see the open office effect of a visually connected space, while maintaining more intimate zones. This is realized using glass separation screens. The office we see here is a very open office, but maybe there is much more room to improve this image? Would this open effect not be much stronger if you could introduce glass columns as well, allowing for even more daylight to enter all workspaces, without introducing the negative effects of the original open offices?

http://www.dancker.com/blog/open-office-spaces-create-lofty-goals/

Why glass?

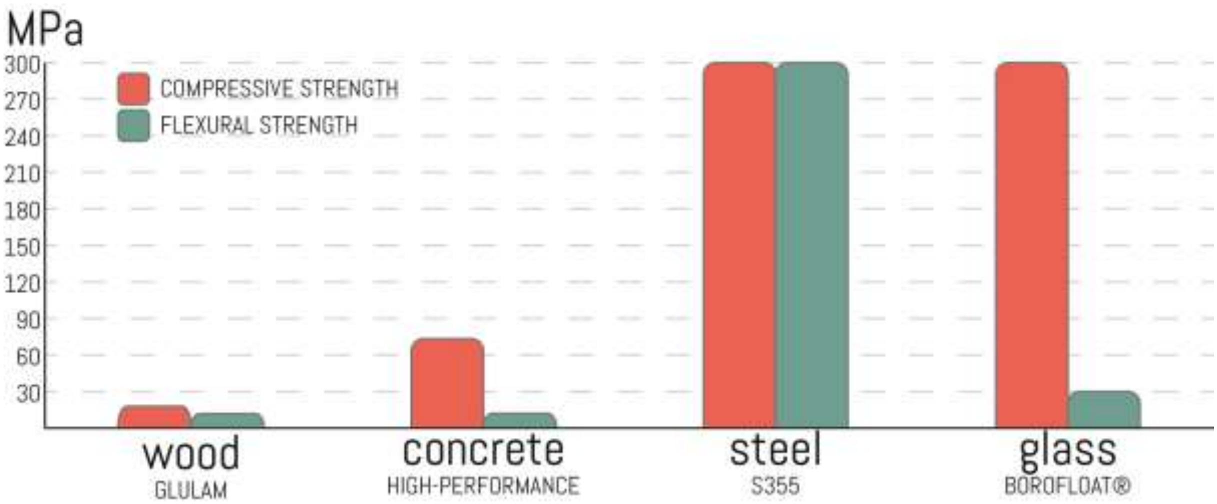
Glass has always been a fascinating material, being a very solid and strong material while still being completely transparent. Our captivation for this material is nothing new; it has been used for centuries in the form of panels providing us with daylight in our homes. The glass allowed us to not only bring in daylight, but also create awareness of our surroundings, bringing the outsides 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. The invention of the cast plate glass method in 1848 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.

Why glass as a structural material?

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. The way we observed glass in the Crystal Palace was great, but not enough. The actual structure consisted of thin cast iron elements, in which the small glass panes were suspended. But in order to achieve maximum transparency, these structural elements would also have to be transparent.

Properties of glass

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 applications. These properties are its very impressive strength in compression, and the fact that it's a highly durable material that does not deteriorate.



Problems using glass in structural applications

So why isn't glass being used as the structural material of choice by default? 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. 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. This unpredictability makes it an extremely dangerous structural 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).

The rise of structural glass elements

Resulting from improved safety aspects we see glass being used in a structural way more and more often. From the Apple® stores (**image**), the Atocha Station Memorial (**image**), to the recently completed Crystal House (**image**) 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 (See image). 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, but we will look into this in the next subchapter.

Problems with an all glass column

There are several reasons why all 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.

1 Safety under loading

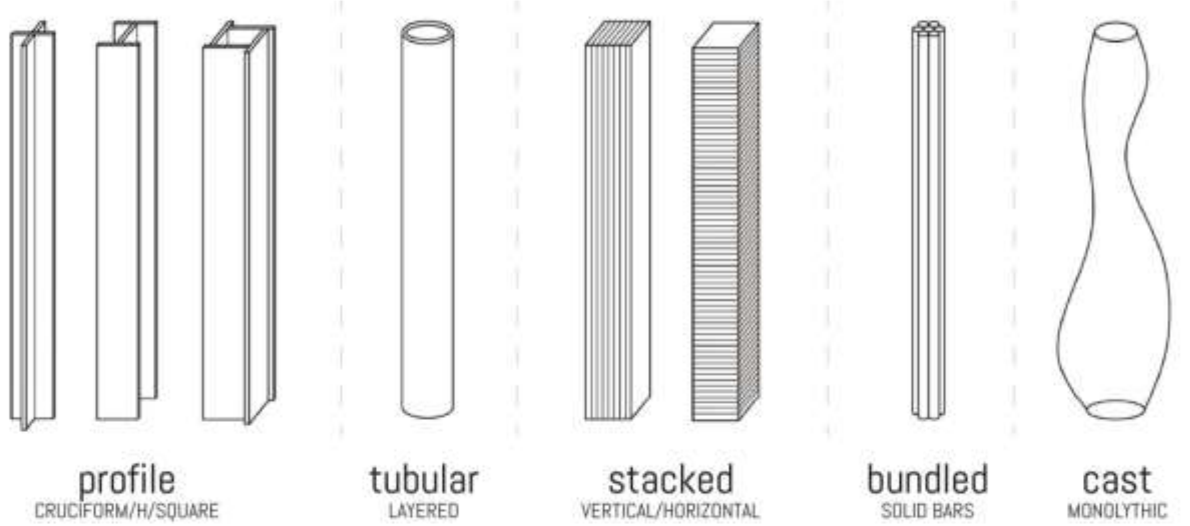
In the previous examples of all glass structures we saw very linear constructions where the glass was loaded in 1 main direction. For example the laminated fins that are used in glass portal constructions. These fins are only loaded in their strongest sectional direction. The all glass brick façade is 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 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 would be to cast glass elements like done with the all glass brick façade, but gradual cooling of the elements 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 in 1 element.

Possible types of free-standing 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).



__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.

__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.

__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. 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.

4 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. In order for this cross-section to work, the degree of collaboration between the separate rods is a key aspect. The stronger the adhesive, and the higher the collaboration because of this, the more the single rods act like a whole and prevent buckling and failing of the single rods.

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 causes 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.

Choice type of free-standing column

The 'profile' type of column is relatively easy to produce but is rather limited for future research. The profile sections are architecturally undesirable and mechanically inefficient (Veer, 2000). The 'stacked' type of column also lack architectural desirability and are very time-inefficient to produce. Using the 'cast' type of column would be ideal, but because of the size of a column the casting process and additionally the controlled cooling process would take extremely long and be too expensive.

So the 'tubular' and 'bundled' types of columns show most potential right now. The tubular column has the highest transparency degree, but the bundled column doesn't lack far behind and results in a visually pleasing result different from the tubular column in a playful manner. The tubular column relies on lamination to promote safe failure behavior whereas the bundled column uses redundancy to improve its safety. The tubular section does not have a weak axis where the bundled type of column has 3 strong directions and 3 slightly weaker directions, but both are by nature great at resisting torsional forces. Either column would be interesting to research at this moment, but the choice for this research is with the bundled column. The Delft University of Technology is currently researching the bundled column, so for this graduation research the bundled column proved to be more interesting.

State of research

Preceding research at the TU Delft explored the possibilities of creating all glass columns. Research has been conducted in order to realize a tubular column. This was done by laminating two concentric glass tubes with a clear adhesive in between. Because of the time-consuming and thus expensive process of producing laminated tubular glass columns, another experiment into glass columns was performed in 2005. The experiment involved glass columns made out of flat glass, or as we saw earlier, the profile type of column.

Since 2005 new research has been focused on the development of the bundled column type. This research is currently (April, 2016) ongoing and at the following points in research:

- Extruded borosilicate profiles to be used have been determined
- The adhesive that will be used in the production of this column has been chosen
- Compressive tests on 500mm and 1500mm long specimens have been conducted, analyzed and published
- Preparations for compression test of specimens over 1500mm long are taking place

More information on the tested specimens and the results of the tests.

Objective

The main focus and aim of this graduation thesis is:

"The design of an all glass column of the bundled type, and using finite element analysis to set up design constraints for the design of the connection details of said column."

Scope and Methodology

This research is being performed alongside and in the aid of the ongoing research at the Delft University of Technology with the aim of producing an all glass loadbearing column. In the field of all glass columns research is still very limited and young, so most of this research is a combination of theoretical (numerical) research and experimental research where we will be testing the theoretical research. Some research has already been conducted, and following this research several choices for materials have been made. These earlier made decisions will be respected and handled like design constraints in this research. The result of this is a more narrow scope which allows us to get into more numerical research in an earlier stage of this graduation research.

This is a qualitative research into problems arising around the production of an all glass column made by bundling solid rods of glass. From this qualitative research insights will be gathered and used to determine constraints and guidelines to design the connection details of said column. The design and development of the connection details, if we get this far, will be a research by design type of research. This means a preliminary design will be proposed and tested, as a result of these tests the originally proposed design will be altered and improved until there is a satisfactory result. All of this research will be case driven, and the final models and design will be tested regarding real life constraints of this case.

At the point where I am joining this research, specimens of 500mm and 1500mm long have already been tested. This research will focus on the analysis of these specimens and making predictions using finite element analysis regarding the 2000mm and 2900mm specimens to be tested during this research. All problems that we encounter in this period will also be addressed and the aim is to find optimal results for said problems.

Time planning

The typical graduation structure consists of five phases, covering a span of roughly seven months excluding holidays; commencing during the MSc 3 phase of the entire master track, finishing at the end of the MSc 4 period. These five phases (P1 through P5) generally include graduation focus (P1), literature research (P2), graduation research (P3), closing of the graduation research (P4) and a final, formal presentation open for public (P5). The research for this graduation report started April 2016, and is intended to be finished and presented February 2017. How these five phases of graduation are planned you can see in the overview.

<u>P1, April 19th</u>

This moment defines the aim of the following graduation research. This research aim is supported with the choice for a first graduation mentor. At the time of writing this time planning this phase of graduation is already completed.

<u>P2, June 13th</u>

During the period leading up to this moment the initial graduation aim is specified further. Research questions are formulated and researched. At the P2 presentation most of the literature research should be concluded and at this time the planning for the next phase has begun. The focus of the graduation research should be clear and supported by literature. The P2 presentation tends to be a deadline moment at which the transition from literature to graduation research takes place.

P3, October

Before the P2 moment all literature research on the field of structural glass and glass columns should be concluded. Leading up to the P3 moment own research is being conducted in order produce an all glass column. Real time tests are being conducted to tests compressive behavior of the column. These tests will be analyzed and used to improve the column design. Any design problems that arise during this period will be addressed and tried to resolve. After this moment this research continues and aims to keep improving the column towards P4.

P4, December

The research regarding the production of the glass column and its connection details will be finished up towards the P4 presentation. All findings will be reported and any unresolved issues will be addressed. The final report with all this information will be written into a final draft version before this presentation. The last weeks before the presentation the focus will be on the draft report and the production of the presentation.

P5, January or February

All feedback received in the P4 phase will be addressed and the report will be adjusted accordingly. Any remaining work following the P4 phase should be finished as soon as possible during this phase. The rest of the weeks in this period will be used to produce the final presentation for the public presenting. The P5 period is a relatively short period of normally between 5 and 10 weeks. Because of Christmas holidays this period will be a bit longer and this time can be used to finish up any remaining unfinished work.

[1.13] Case location

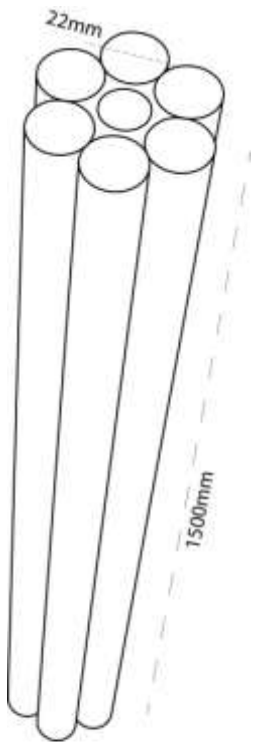
Free-standing all glass columns are still rare and in an early stage of research as we saw earlier. Rob Nijsse described the five possible types of free-standing all glass columns as seen the previous chapter. Research is being conducted in order to realize an all glass bundled column. This research 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 design this following 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, 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 design part of this research.

Design boundary conditions

Height of column: 2900.00mm
Axial load: kN
Safety factor: 4
Servicability Limit?
Variable load factor: 1.5?

Element boundary conditions



Fabrication height of individual elements: 1500.00mm
Glass rod diameter: 22.00mm
Glass inner profile: OD 30.00mm / ID 17.00mm

All elements are extruded borosilicate profiles. The adhesive used is DELO 4468. A UV- and light curing acrylate adhesive of medium viscosity.

<u>Mechanical Properties BOROFLOAT33</u>

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

<u>Mechanical Properties DELO4468</u>

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

Design questions

<u>(Analysis) What is the degree of collaboration between the adhesive and the glass rods?</u>
To predict the structural behavior of the full-length column, it is important to know what happens during failure of a smaller specimen. Does the column fail by failure of the lamination, or because the compressive limit of the glass is reached? **This part of research will be done with the help of finite element analysis. Accurate models of the tested specimens and analysis of the data on where the specimen SHOULD have failed. Were stress peaks reached in the adhesive or did buckling occur?**

<u>(Production) How to produce a column of 2900.00mm using 1500.00mm elements?</u>
The column design is one of 2900.00mm high, but the elements are only 1500.00mm long. How do you produce a full-length column with respect to buckling/failure behavior? What is the optimal scheme for split lamination or should you focus on welding the glass to create a more monolithic whole?

<u>(Safety) What happens when 2 individual glass rods break and how to handle this failure behavior?</u>
Can the column still handle the forced when one or more rods individually fail? The failure behavior is essential for a structural element in order to ensure the safety of the people occupying the structure.

<u>(Production) Taking into account earlier conclusions, what type of connection (hinged/clamped) is required for this column?</u>
The degree of collaboration and the production of the column taken into account, what is the safest way to design the column connection details? For example, is buckling a leading design factor that demands for a clamped column?