THE ALL TRANSPARENT COLUMN

Final reflection

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

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Introduction

During my master studies I have been involved in many interesting projects, ranging from designing and building a refugee shelter completely out of cardboard, to the design of a modular pedestrian bridge in Izmir, Turkey. During these studies glass has captured my imagination and I have been fortunate enough to be given the possibility to further research glass as a viable option for a load bearing column. Over a period of 8 months I have been researching glass as a material, its fantastic mechhanical properties and its troublesome failure behavior. This research has led to the proposal of a safe all glass column and the design of its corresponding connection details.

How did this research go, was my timeplanning a realistic one and did I manage to answer all the questions I set out to answer? This document is a reflection on my motivation and attitude towards this research project and the obtained results.

Social context

We could start off this reflection by looking at how the research went and what could have gone better, but why are we doing this research in the first place? Why should we make a load bearing column out of glass? Is it just the fascination of some engineers, or is there a much wider social context and desire for such columns?

Reason to explore possibilities

From an architectural point of view glass has always been a fascinating material, but load bearing columns are hardly ever classified as 'fascinating material'. Columns, in the architect's eye, are more generally seen as annoying and viewblocking material. This has been the leading cause of discussion between projectengineers and the architect, where the architect wants large uninterrupted spaces but the engineer needs to have columns as supports somewhere in that open space. It is this very discussion that is enough of a reason the explore the possibilities of transparent columns. They don't block the view, allow for daylight to enter deep into spaces, and still offer structural reliability for the entire structure.

Material qualities

It is not just the desire for uninterrupted spaces that allows for this research to take place. If we look at the material itself, transparency is not the only property that sets it out from more conventional construction materials such as concrete and wood. Looking at the compressive strength of the material we see values comparable to those of steel, which is very impressive. As a material glass is a lot like concrete, with impressive compressive strength figures, but lacking the ability to deal with tensile forces very well. The reason concrete is so widely used, is the ease of applying reinforcement to the material, this is generally done using steel rebar. We could also apply this method to glass and create laminated safety glass this way, but this would counter the most promising aspect of the glass, namely the transparency. If we can find ways of either reinforcing, or improving the failure behavior of glass, we could say that glass is arguably the better material compared to concrete. Glass is fully recyclable, does not deteriorate, transparent and strengthwise comparable to steel.

Legislation and state of research

Glass is becoming more and more prominent in structural applications worldwide. From staircases, facades, beams and fins, to columns. A lot is being researched and legislation is becoming more common for most applications, but not for columns. Columns made out of glass are still very rare and hardly ever seen in a load bearing manner. The reason for this is that glass is a very 2D oriented material whereas a column requires a very 3D oriented design.

In all applications glass is becoming a standard option, especially parapets and ballustrades made out of glass are a very common sight. A lot of research has happened to make that happen, standardized tests have been documented and legislation is very clear on what is considered safe and what is not. This legislation is the cause people start to trust glass as a structural material. This is not the case for more uncommon applications where glass is the leading structural component however. Glass is being used as walking paths of bridges in Asia where people are frightened to step on the glass even though it is greatly overdimensioned.

Because of these reasons this research is mandatory. Using this, and other, research proper legislation can become available over the coming years, and the amount of references where glass is being used safely in a structural application can rise so people can get used to glass being a safe material.

Design of the bundled column

In the category of free standing, load bearing columns made out of glass, Rob Nijsse describes five possible types of columns. A choice has been made to further research the bundled type. This type is created by laminating a total of seven extruded borosilicate elements. Six of these are solid rods with a diameter of 22mm, and one is a star-shaped center profile with indents that almost perfectly fit the rods that are laminated around this profile.

Elements

The elements used are extruded borosilicate profiles made by schott. The use of these elements comes with a few aspects that require to be researched during my thesis in order to apply them in a structurally safe way. These aspects are eccentricities, production margins and size limitation. This means that the elements are not 100% straight, have margins of up to 2mm which causes problems when trying to apply a post-tensioning system, and are delivered in sizes of only 1500mm which is less than the proposed column design.

Case

As case study location where this column will be placed the ABT office in Velp was chosen. The reason for this is that ABT is working together with the Delft University of Technology to realise this column. Because of this they have already conducted research where this column will be realised and thus have access to accurate data regardering load cases and the design height.

The imposed load has an Ultimate Limit State of 112 kN, we assume a buckling safety factor of 4 and the design height of the column is 2900mm.

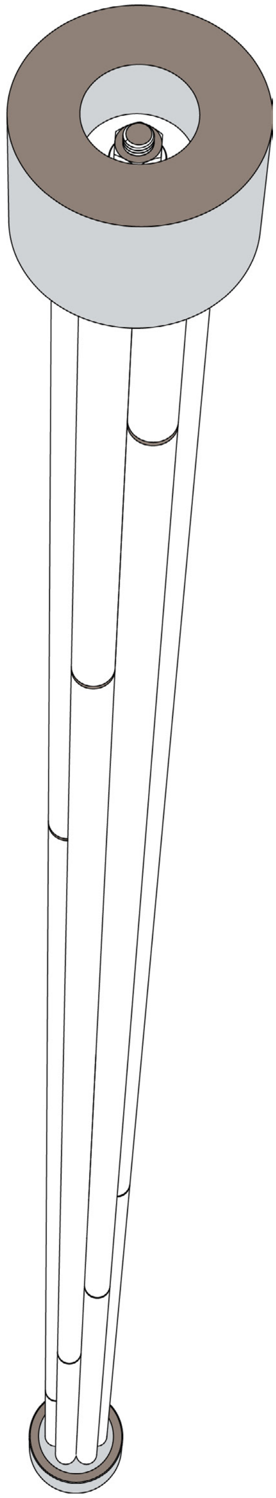
Post-tension

Using the extruded profiles made by schott we have a 17mm wide gap in the center of the column and we are going to use this to apply prestress to the column. This prestress aims to delay initial cracking of the column and counter the buckling movement by relieving tensile stresses.

The expected behavior of the column after applying prestress is partially to increase the load bearing capacity of the column, but the magnitude of this effect is to be proven in destructive testing. A key aspect that this post-tensioning also thrives to achieve is an increase in the safe failure behavior of the column. Glass is a brittle material and fails in an unexpected and explosive manner. By introducing the post-tensioning element, the moment of failure can be stretched-out over a longer period of time rather than exploding. This is done by relieving the tensile stresses using the steel and by producing counter movement as the tendon is under tension. The expected behavior because of this is a more plastic failure behavior, which, if successful, produces a structurally safe column.

Connection details

A final part of this research is the conceptual design of the connection details for the column. The structural behavior is highly dependable on the connection details, whether this is a higned or a rigid connection. For this research both of these types will be researched and proposed.



Research

The research and design of my thesis is split into two domains. The first, and main, part of my thesis consist of a design by research type of research. The latter part of my thesis is following a research by design strategy. Each of these phases has its own corresponding research questions.

Design by Research

Designing the bundled column comes with several problems and issues that need to be answered in order for the column to work. The issues that arise during, or leading up to, the production of the column are investigated, alternatives are designed, choices are made and physical tests are carried out to determine the best option. This option will then be added into the column design for further development. This described method is what the 'design by research' chapter is all about. Issues that are resolved like this are the method of lamination, the split lamination scheme, the head-to-head glass connections that arise from the lamination finally and the design of the post-tensioning tendon. The focus of this phase is exploring and increasing the mechanical behavior of the column.

Research by Design

This part of my graduation is mainly the final stage of the research. Assuming that the result of the previous stage is a complete column of the bundled type with post-tensioning system included that has been developed and tested. This part of the research uses that column as a basis and consists of the design of other aspects that come to mind when designing a load bearing column. During this phase two type of connection details are designed and proposed as viable connection details for the glass column. One of these will be a fully hinged connection, and one will be a clamped connection. Another aspect that is researched is the optimization of the glass elements in the column design. The steel heads that are used to connect that column and to test it in the compression bench will be calculated to see if this can also be made out of glass for future reference. The PVC interlayer used in the post-tensioning will be analysed and checked, and a transparent alternative will be presented. In conclusion this part of the research produces aspects that are not needed for the destructive tests to prove the behavior of the column, but rather design additions for the column once it can be installed for real. Increasing the architectural value of the column is the main focus during this stage.

Design questions

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

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 or do we need to increase the cross section?"
"Does the column show (more) ductile failure behavior after prestress is applied?"

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?"

Planning

My research design covers everything from the literature studies phase, to the conclusions, discussion and recommendations in consecutive order. This means that leading up to the P2 presentation the literature studies is the main focus. Design by Research has the main focus leading upto P3, and the Research by Design joins this track leading up to P4. Once all these phases are done the remaining weeks between P4 and P5 are used to finalize remaining issues, process everything in report form and finally document conslusions and recommendations, thus each thesis part has it's research method.

Reflection on planning

Looking at the time reserved for each graduation phase as scheduled by the Delft University of Technology, 'Part 1' and 'Part 2' of my research design take up most of the time. My own planning does not have very hard deadlines and parts can cross over into each other, but do make up suggested finishing times of each part.

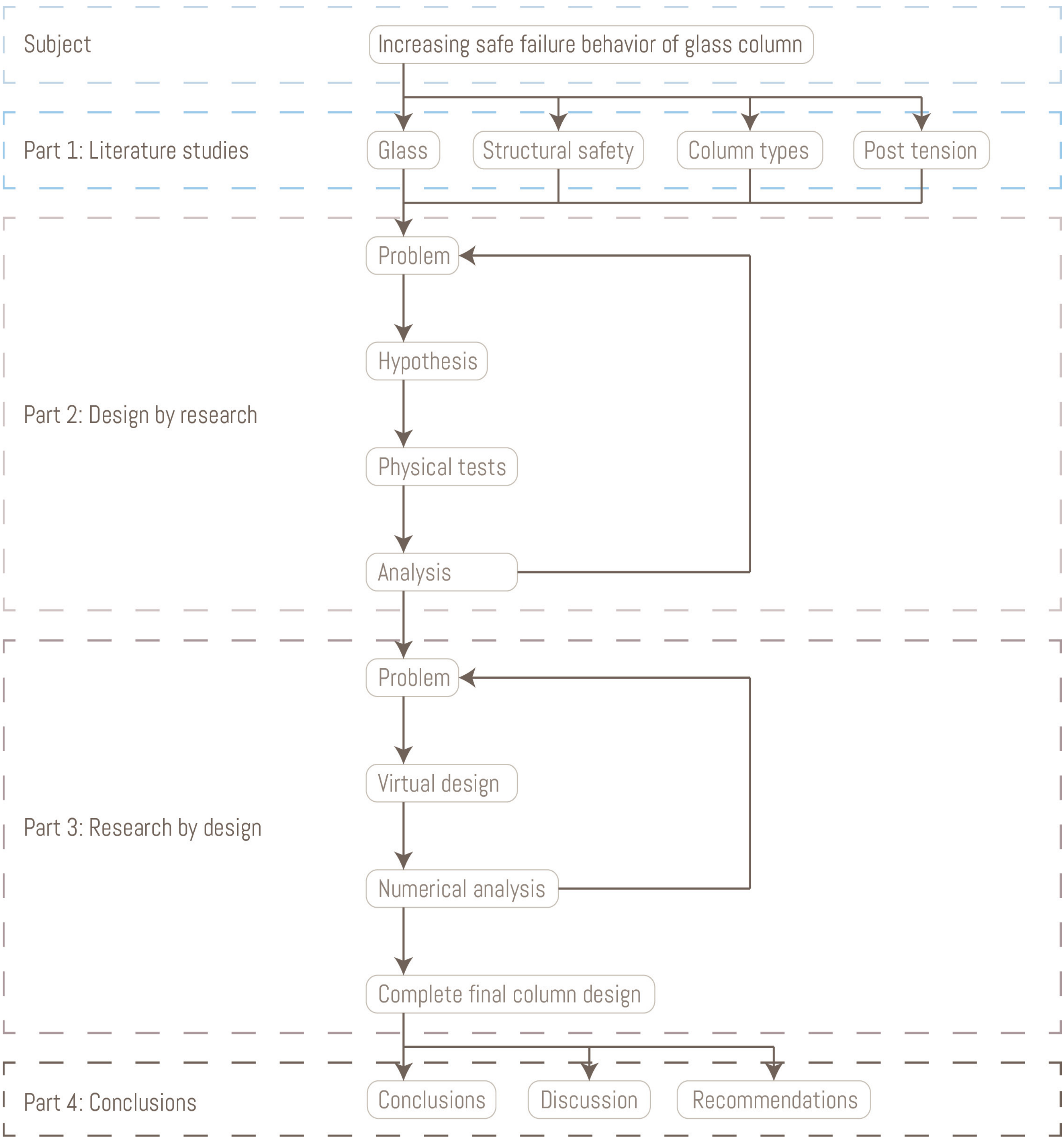
The literature studies were an intense period of time as reading is not my personal strongest point. At the P2 I was content with the amount of research performed however, even though afterwards more literature studies were required. During the first phases of my graduation the final focus of my research shifted between sub-domains of the greater subject. This led to more required reading on subjects such as post-tensioning and steel strengths with according torque moments and reactive normal forces these values create.

Part 2 mainly focuses around the research leading up to reallife physical tests as these tests require availability of material, test equipment and coordination with more people. At the moment of the P3 presentations all boundary constraints have been designed, but some are yet to be produced and tested. This has not led to delays on my personal planning as during free moments I have already been working on Part 3 issues. During this period I have already focused on how connection details should be designed and could potentially look.

At the P4 presentation, all physical columns have been created and destructively tested at the Faculty of Civil Engineering. Alongside the production of the columns, time has been put in to realise the research by design phase. Connection details have been designed and, after discussion with my mentors, revised. Also an entire chapter has been devoted to the pursuit of an all glass coluumn. In our design metal parts have been intergrated, but could these materials be replaced with transparent elements? Alternatives have been found for the aluminum, steel and lead elements. Also the PVC that served as protection has been matched with a transparent alternative. The only elements that did not meet an alternative was the post-tensioning tendon as transparent materials generally always lack the ability to deal with great tensile forces at low deformations.

The final stretch leading up to the fifth and final presentation of my graduation track involves further increase of the architectural value for the column. Initial connection details were designed but require some more attention to really finish them into a whole. General conclusion still have to be drawn as some final physical tests data still has to be processed. Recommendations for further research have to be formulated and a discussion on the method and results of my own research has to be written.

Overall, I am content with the way I have been following my own planning. In the first months it has served me as reminder to finish up on phases I should no longer be focusing on and to keep me on track. Between P3 and P4 things were less strict, and deadlines were more fluid. But designing my planning did make me realise there was still an entire design part of the 'Design by Research' chapter. So during the extended period where I was still working on producing the physical prototypes, I made sure I would use my sparetime to focus on the phase I was 'should' have been. So the planning served as a reminder of what there was left for me to do (which most of the time meant: 'plenty').


Subject
Increasing safe failure behavior of glass column
Part 1: Literature studies
Glass
Structural safety
Column types
Post tension
Part 2: Design by research
Problem
Hypothesis
Physical tests
Analysis
Part 3: Research by design
Problem
Virtual design
Numerical analysis
Complete final column design
Part 4: Conclusions
Conclusions
Discussion
Recommendations

Reflection on design questions

In the research design chapter, or in this document under the titel 'Design Questions' we have summed up a total of eight design questions we wanted to answer during my graduation thesis. Have we gotten an adequate answer to all of these questions however? I proposed five questions with a focus in the 'Design by Research' phase, and three more and the final phase.

Did we manage to answer them all to our own satisfaction and did my research manage to have a positive influence on the general ongoing research into proving glass to be a safe structural material?

'Design by Research'

"How to produce a 2900mm long column out of 1500mm long elements?" A design has been proposed and physically built on a 1:1 scale after which it has been destructively tested. The column showed reliable and structurally consistent behavior and we can assume that split lamination is an effective way to achieve this.

"What is the optimal design of the head-to-head glass connections arising from the lamination of the rods?" Small specimens have been produced and tested to research the influence of the small irregularities arising from the split lamination of the column. Four alternatives have been tested (three times each for scientific validation) and showed consistent behavior. Using and aluminum disc to prevent peakstresses in the glass turned out to be the best option at about 85% monolithic behavior.

"How can we apply prestress to the column is the safest way, assuming large eccentricities and margins in the glass elements?" During initial checks of the glass elements, the amount of deformations and eccentricities were of a shock to me. The space available for a post-tensioning tendon measures 17mm, but showed +/- 2mm formations. Because of this a lot of margin was required in order to be able to apply this tendon. Four alternatives were researched and a most ideal solution was found and applied to the final columns.

"Can we reach the proposed design load, including a safety factor of four with a column this slender or do we need to increase the cross section?" Using the current cross section for the coluumn (greater cross sections are not yet possible with this method) achieving the design height, load and safety factor will not be possible. The slenderness causes low critical buckling forces and a safety factor of 4 simply is way too high. In order to achieve structural intergrity we need to come up with a solution which can lower the safety factor down to 2, post-tensioning shows the most potential.

"Does the column show (more) ductile failure behavior after prestress is applied?" The reason for a safety factor of 4 is the explosive failure of glass. If we can make the failing mechanism more ductile, it becomes a visible failure, which means its structurally safe because there is time to escape or replace the element. A prestressed column appears to show more ductile failure behavior and appears to be a more elastic structural member.

'Research by Design'

"How can the connection details for a glass column look?" The structural behavior of a load bearing column is highly dependent on the type of supports. For a column you have two options for a support, a hinge or a clamp. Designs for both of the conditions have been proposed and shown context. These elements have been designed to be steel elements rather than glass, to not take away attention from the column, but rather show the observer that the glass can handle to forces just as well as the steel, increasing the feeling of structural safety amongst observers.

"How many elements that were previously designed in aluminum or steel can be replaced with glass counterparts?" The use of steel and aluminum elements in our column is to achieve a symbiotic relationship between glass and steel, proving to all people that see the column that we can safety design and apply structural elements using glass. But what if there is a commissioning party that does want these elements to be transparent? Alternatives have been found for all materials used in the column, with the exception of the post-tensioning tendon and bolts. All materials have been researched and presented in my thesis. The structural behavior has been proven using numerical calculations.

"How can we optimize the production process of the column to increase accuracy and transparency?" The way I have been producing the columns that were up for physical testing shows many options for improvement. The glass is of great quality, but as a result of the horizontal extrusion process the leements show significant eccentricities, if we can obtain the elements through vertical extrusion they will be of much more consistent quality. The measuring and cutting is done by hand and thus inconsistent, using a waterjetcutter with laser measurement will provide a 100% reliable and clean element. The laminating is done by hand an thus results in inconsistent adhesive layer thickness, using a foil or tape with rather than a liquid adhesive will greatly increase transparency and accuracy.

Conclusion

Looking at all of the above research questions I think I answered them all as well as I could with the time I available. Producing the elements was more time consuming than I would have expected, but the test results were worth it. I am convinced by the researched we have been conducting that we can apply this design as a load bearing structural elements within only a few years. Of course some more testing should be done to even out any insecurities to ensure structural integrity, but for now it is definitely looking promising.

Conclusion

Glass is known to many people as an unsafe material, especially in structural applications. Over the past few years several pedestrian bridges have been realised with transparent footways and many tourist attractions such as the Eiffel Tower have glass floors through which people can look deep down. Many people are affraid the glass will break because they do not know the strength of this glass. Our research is also intended to deepen the trust people have in glass. A complete column has been designed with a great percentage of glass. It has shown to be a structurally reliable compressive member and should be able to be applied in a reallife case study within a years.

Over the past 8 months I have learned a lot about glass, even though I thought I knew a lot already. Using a design&build approach I have encountered many aspects that would not show up on paper, but do so in real life. I can confidentally say that I feel I have dealt with these situations appropriately and thorough with a hands-on approach and I am very thankful for the opportunity to work on this research given to me by the Delft University of Technology.