LOAD-BEARING GLASS COLUMNS
THE STACKED COLUMN

PART 1 - LITERATURE OVERVIEW

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Proudly I present my graduation thesis which I have enjoyed working on for approximately one year. The subject of this graduation thesis is an innovative structural element: load bearing glass columns. As part of the academic curriculum at Eindhoven University of Technology, I worked on another experimental research project about an innovative flexible formwork system. During this research project the innovative nature of the subject fascinated me and to do experimental research and finding explanations for the events observed during the experiments appealed to me. To do an experimental research on an innovative structural system for my graduation project was a chance to work at a more extensive research project.

The use of glass as a structural material always fascinated me. Glass is a material which appeals to me and a lot of architects and structural designers because of its contradicting properties: for instance the possibilities as a structural material, although it glass is transparent. My interest on this subject was even more triggered by an excursion arranged by study association KOers in March 2012. An experimental research project in structural glass was therefore an obvious choice for my graduation project.

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Last but not least I would like to thank my friends and family, especially my parents Jan van Heugten and Anita van Heugten-Smits and my girlfriend Nicole Manders for their encouraging talks,, motivation and stimulation during my graduation project and the entire period of my study.

Roy van Heugten
Neerkant, oktober 2013
SUMMARY

Glass is the oldest man-made material and it can look back on a history spanning over 7 millenia. However it wasn’t until the Middle Ages that glass started to influence buildings. The need to allow daylight to penetrate to the interior of buildings, while protecting it from the outside weather conditions, resulted in stained glass windows. The ongoing search to maximize the transparency of the façades resulted in larger glass windows. The concrete and steel load-bearing systems gradually became smaller and smaller which eventually resulted in all glass façades. Glass, in this application, can therefore be characterized as a building skin material.

At the same time designers explored the load-bearing capacity of glass. The first use of glass as a structural material dates back to the 19th century palm- and greenhouses in England. In these dome like structures out of glass and steel, the glass panels became an integral part of the structural system. Subsequently architects and designers experimented with all kinds of load-bearing glass building components, from tertiary structures, like handrails and balustrades, to primary structures like beams, walls and columns. Nowadays all structural members can be created out of glass and therefore it is possible to design and build a structure entirely out of glass.

Although it is possible to design and build all structural members out of glass, the glass column is still in its early phases of design compared to the other structural elements. Sometimes it is not really clear whether a “column” is just a small piece of a wall, or a fin in a façade or a free-standing column. Therefore different building projects are analysed with structural elements which can be categorized into three groups: “flat walls”, “configured walls” and “columns”.

The first category is characterized by connecting flat glass panels in the same orientation together to serve as a wall, ranging from rather bulky, solid walls with a lot of different glass panels to slender walls of two or three glass panels.

“Configured walls” are made of curved panels or by connecting flat glass panels (i.e. fins) in a perpendicular orientation to the façade. The walls are configured in this manner to increase the stiffness of the walls and therefore the load-bearing capacity, because the buckling capacity of these configured walls is substantially larger.

Thirdly the structural elements are disconnected from walls and become free-standing structures: columns. These columns can take the shape of a box, or a cross, or all kinds of other cross-sections.

Through the analysis of different projects with glass walls and glass columns, and thus the evolution of the glass column, some aspects and demands which define glass columns came to light: the structural element is only loaded in compression, so it does not contribute to the stability of a design. Furthermore the structural element is freestanding and therefore not part of the façade (which is the case with fins). The width and the depth of the structural element should approximately be the same, which results in a more or less square cross section (i.e. no rectangular cross sections, which is the case with fins or walls). Moreover the width and the depth of the structural element should be substantially smaller compared to the length of it.

Now that the definition of the glass column is clear, it is useful to analyze how glass columns can be designed and build. The glass industry can provide different kind of glass elements and these can all used to design and build glass columns. Therefore glass columns can be divided into four different categories, each with its own specific appearance and points of attention:
Columns made of glass panels
Glass panels can be used to construct solid columns or profiled columns (e.g. cruciform, H-profiles, boxes). Profiled columns will usually be more transparent than solid columns, but the transparency depends largely on the configuration of the panels. When a solid column is configured by placing glass panels behind each other the column retains some of its transparency. When a solid column is configured by stacking glass panels however, the column becomes entirely translucent. Nevertheless the architectural possibilities of this latter concept are virtually endless by variations in the size and shape and by rotation and/or translation of the individual glass panels. Points of attention for the solid columns are the tolerances on thickness and flatness of the individual panels and how the panels are connected and stabilized. For the profiled columns the connection of the individual panels is also critical and some kind of safety-concept should be designed so that, in the case of failure of one panel, the rest of the column remains intact.

Columns made of glass cylinders
The appearance of columns made out of cylinders is different because cylinders plays with light in another way: the columns will be quite transparent, but they will distort the view through the column substantially. A critical point is the safety concept of the columns: when one panel breaks, this cannot lead to ultimate failure of the column so the cylinder must be laminated in some way.

Columns made of solid glass rods
Solid glass rods are another glass element which can be used for a glass column. Solid glass rods needs to be bundled to serve as a column, and will distort the view through the column extensively. One point of attention for this type of column is how to bundle the individual glass rods.

Columns made of cast glass
If the above described configurations are unsatisfactory for the designer/architect, they can make use of the fact that glass can be melted. Glass is liquid during the production process, which makes it possible to be cast in a mould of any shape. Cast glass hasn’t been used a lot as a building material so lots of questions remain regarding the production process, for example: ‘to what dimensions can glass be cast in a mould?’ and ‘What are the load-bearing capacities of cast glass?’. Therefore the production process is the most important point of attention for this type of columns.

In general, one of the most interesting qualities of glass, and thus also of glass columns, is the way glass plays with light. How glass interacts with light depends on the shape of the column and of the parts of which the column is assembled. Flat glass panels interact different with light than glass cylinders or solid glass rods. And by using the different glass elements (panels, cylinders, rods) all kinds of shapes and appearances of glass columns are possible, which make the architectural possibilities of glass columns virtually endless. From all these configurations the concept of the stacked column is selected for further research, first of all because knowledge on this type of column is less developed. This concept might also be an ideal way to make use of the high (theoretical) compression strength of glass: the loads can be introduced in the center of the glass panels, rather than on the edges. And because the strength of the center is substantially larger than the strength of the edges of glass panels, the load-bearing capacity of a stacked column is expected to be relatively large compared to the other concepts for glass columns. Furthermore the architectural possibilities by means of waterjet abrasive cutting techniques are virtually endless and therefore columns of any shape and appearance belong to the possibilities.
LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

_Latin capital letters:_
- C: Spring stiffness
- \( C_{\text{glass}} \): Spring stiffness of glass
- \( C_{\text{intermediary}} \): Spring stiffness of the intermediary
- \( C_{\text{tot}} \): Total spring stiffness
- E: Young’s modulus
- F: Force
- \( F_1 \): Initial crack load
- \( F_f \): Friction force
- \( F_{k,1} \): Characteristic initial crack load
- \( F_{k,2} \): Characteristic second crack load
- \( F_{k,3} \): Characteristic third crack load
- \( F_{k,\text{ad}} \): Characteristic load for a certain axial deformation
- \( F_{k,u} \): Characteristic ultimate failure load
- L: Original length
- \( L_{c,1} \): Initial crack length
- \( V_x \): Coefficient of variation of X
- \( \bar{X} \): Sample mean
- \( X_k \): Characteristic value of a material property

_Latin lower case letters:_
- g: Gravitational acceleration
- \( k_n \): Characteristic fractile factor
- m: Mass
- \( m_x \): Mean of n sample results
- \( m_{x,1} \): Mean initial crack load
- \( m_{x,2} \): Mean second crack load
- \( m_{x,3} \): Mean third crack load
- \( m_{x,\text{axial,add}} \): Mean load for a certain additional axial deformation
- \( m_{x,\text{axial,ini}} \): Mean load for a certain initial axial deformation
- \( m_{x,u} \): Mean ultimate failure load
- \( s_x \): Sample standard deviation
- \( s_{x,1} \): Standard deviation initial crack
- \( s_{x,2} \): Standard deviation second crack
- \( s_{x,3} \): Standard deviation third crack
- \( s_{x,\text{axial,add}} \): Standard deviation for a certain additional axial deformation
- \( s_{x,\text{axial,ini}} \): Standard deviation for a certain initial axial deformation
- \( s_{x,u} \): Standard deviation ultimate failure
**Greek capital letters**

- $\Delta L$: Elongation/shortening
- $\Delta L_{\text{axial}}$: Axial deformation
- $\Delta L_{k,\text{axial,add}}$: Characteristic value of the additional axial deformation
- $\Delta L_{k,\text{axial,ini}}$: Characteristic value of the initial axial deformation
- $\Delta L_{\text{transverse}}$: Transverse deformation

**Greek lower case letters:**

- $\varepsilon$: Strain
- $\eta_k$: Characteristic value of the conversion factor
- $\mu$: Coefficient of static friction
- $\nu$: Poisson Ratio
- $\sigma$: Stress
- $\sigma_{k,1}$: Characteristic initial crack stress
- $\sigma_{k,2}$: Characteristic second crack stress
- $\sigma_{k,3}$: Characteristic third crack stress
- $\sigma_{k,\text{ad}}$: Characteristic stress for a certain axial deformation
- $\sigma_{k,u}$: Characteristic ultimate failure stress
- $\phi$: Angle of inclination

**Abbreviations**

- 468MP: 3M adhesive transfer tape 468MP
- A5010: Akemi Akepox 5010
- AA: Anaerobic
- AC: Acrylic/Acrylate
- AD821: Delo Duopox AD821
- AF: Acrylic film
- AFTC: Acrylic Foam Tape Company
- CA: Cyanoacrylates
- CTM: Compression testing machine
- DP610: Scotch-Weld DP610
- EP: Epoxy
- IM: Imides
- P4302: Delo Photobond 4302
- P4468: Delo Photobond 4468
- PA-6: Polyamide
- PE: Polyester
- PH: Phenolic
- POM-C: Polyoxymethylene
- PU: Polyurethane
- PVA: Polyvinylacetate
- SCALP: Scattered light polariscope
- SI: Silicone
- ST8502: AFTC Silvertape 8502
- THM: Thermoplastic hot melt
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1  PREFACE

1.1 Motivation of the graduation project

“Glass is one of the true marvels discovered by men. The mere heating and cooling of ever-present silica allows for a transformation and opportunity which is unparalleled. [...] Glass and light are a one, without the other cannot shimmer, shine, reflect or capture. If architecture is gravity, then glass is the illusionist allowing light(ness) and interaction. We have been pushing the boundaries of glass throughout the centuries. And like the glass in the Gothic Cathedrals it tells a story for those who wish to listen and observe. The opportunities to tell this story as an architect are endless: etching, coloring, sandblasting, deforming of glass, to name just a few make it one of the most versatile materials. This richness in treatment and effect make it still the favorite in the development of our contemporary world.”

Erick van Egeraat
Challenging Glass 3 (2012)

As described in the quote above, the opportunities with glass as a building material are virtually endless. Not only opportunities with respect to the appearance of glass, but in the past few decades the load-bearing capacities of glass are explored as well. Glass is not only used as an opening in a structure but it becomes an integral part of architecture. What drives architects to use glass in their building designs? The fact that glass is used so extensively in the building industry is a result of three important properties of glass.

Strength

The theoretical compressive strength of glass makes it a very promising material: the generally accepted value is 1000 N/mm², which is more than four times the capacity of ‘normal’ steel (S235). However, the tensile strength is respectively low and when glass fails, it fails without a warning. This brittle failure should be avoided in a safe design and in order to develop load-bearing structures in glass a lot of knowledge about the material and a lot of attention to the details of the design is needed.

Aesthetics

Glass is one of a few materials which can be present and non-present at the same time. Glass is transparent so one could look right through it, but it can still form a barrier from wind or rain for instance. Or it can serve other functions like bearing loads. Although glass is transparent, it is not invisible: like Erick van Egeraat mentions: “it shimmers, shines, reflects and captures” and therefore glass plays with light. This property of glass fascinates architects from all over the world.

Sustainability

Glass is one of the world’s most recycled materials: it can be re-melted over and over again without any change in properties or loss of quality. Furthermore it is non-reactive with most elements and chemicals so it does not need protection from corrosion for instance. This and the fact that it is easily cleanable make it a material which results in low-maintenance costs for the glass building component.
These properties of glass make it one of the most favorite materials in contemporary architecture, more and more as a structural element. All structural elements have been built with glass as a material, only the load-bearing glass column proves to be challenging. Columns are a well-discussed topic in the world of architecture and structural engineering because of the contradicting wishes and desires between architects and structural designers. In general architects and clients do not like columns: they stand in the way and they block the view. If it is impossible to reduce them in number, architects ask them to be made as small as possible. Structural engineers, on the other hand, love columns: they reduce the span of beams and floors and make structures less complicated.

To overcome these contradicting wishes and desires with respect to columns, two solutions are available: columns could be made less present, or more attractive. Both these solutions are possible when glass is used for the material of the column.
1.2 Problem definition and research objectives

Because of its high compressive strength, glass is an ideal material for compression members like columns. Glass columns are already incorporated in a handful of realized building projects, but a lot of aspects with respect to glass columns are still unknown. There are a lot of different types of aspects involved. What kind of glass is used? What is the shape of the column? How is this shape assembled? What kind of glass products are used to assemble the column? How are these glass products connected to each other? How is the entire column connected to the rest of the structure?

The problem definition is formulated as follows: the knowledge of the structural behaviour of glass columns is insufficiently developed.

To see whether or not glass columns are structurally feasible and to contribute to the development of the knowledge on glass columns the objectives of this graduation project are:

- give insight in the possible configurations and points of attention of glass columns
- conduct experimental research into the load-bearing capacities of glass columns
- conduct numerical research into the load-bearing capacities of glass columns
1.3 **Methodology and outline of the graduation project**

This graduation project consists of 4 parts (fig. 1.1):

**Part 1: Literature overview**

Glass is a material which is not discussed as extensively as materials like wood, steel, concrete etc. in the academic curriculum at the University of Technology Eindhoven. Therefore first of all research is conducted into the material glass in this part of the graduation project by looking at the way glass is used as a building material and more importantly as a load-bearing material. Some projects with load-bearing elements in glass are analysed and by doing so the evolution of the column and the points of attention with glass as a load-bearing material become clear. With this knowledge some principle configurations for glass are developed and the possibilities, impossibilities and points of attention for the different configurations are described. One principle shape is selected for further research and this will be done in part 2 and 3.

**Part 2: The stacked column**

In this part some research is conducted into the stacked column. Different points of attention with respect to the load-bearing capacity of this kind of columns are investigated by experimental research and numerical research. The results of the two types of research are then compared and combined and ultimately the feasibility of this type of columns can be evaluated.
PART 1: LITERATURE OVERVIEW
Chapter 2:

GLASS AS A BUILDING MATERIAL
2 GLASS AS A BUILDING MATERIAL
The material glass has been used as a building material for ages. It has been used in two substantially different applications. First of all it was mainly used as a building skin material, but later on designers explored the load-bearing capacity of glass and all kinds of building components in glass were developed.

2.1 Glass as a building skin material
As the oldest man-made material, glass can look back on a history spanning over 7 millennia. Egypt has provided the oldest glass found to date in the form of glass beads and vessels dated at about 5.000 BC (fig. 2.1 and 2.2). The Egyptian art of the production of glass is transferred via Alexandria to classic Greece and the Roman Empire. During the Roman Empire glass was introduced in buildings in the form of the well-known mosaic floors, but the glass wasn’t transparent like we nowadays are familiar with. Only after the invention of the blowing iron in the 1st century BC the production of glass, with a reasonable transparency, became feasible. [1, 2]

Glass really started to influence buildings in the need to allow daylight to penetrate to the interior of buildings, while protecting it from the outside weather conditions. The early glass making techniques of the Middle Ages placed limitations on the uses of glass, on the smoothness, imperfections and discolorations. Furthermore one could only obtain pieces of a very small size, demanding a very dense supporting structure. The framework was therefore an important part of the window design and the aesthetic potential of this framework was exploited. These aspects are characteristic for the stained glass windows in gothic cathedrals (fig. 2.3). [1, 3]

Glass architecture as such first began with the English palm houses and greenhouses of the 19th century. Up until this time window glass was still formed by hand-blowing. Initially hollow vessels were manufactured but later on cylinders were used and were cut open and flattened out. The most prominent example of this glass architecture was the Crystal Palace (fig. 2.4), designed by Sir Joseph Paxton for the Great Exhibition of 1851 in London. The 270.000 panes of glass of the “Palace of Industry for all Nations” were each 1220 mm long, 254 mm wide and 2 mm thick and were all hand-blown! [1]
Because of the invention of a variety of industrial production techniques by Nicolaus de Nehou (cast glass), Emile Fourcault, Eduard Libbey and Michael Owens (all drawn glass), the glass production became easier and started to be widely used. These techniques were developed into a continuous production process and the large-scale use of clear, transparent, flat glass became feasible. However the surface of the cast glass had to be ground and polished first. [1]

Glass architecture received a new impulse with the “Neues Bauen”-movement of the 1920’s. This movement saw the “liberated wall” as a possibility of bringing light, air and sunshine into the buildings. The concrete skeleton structure and the reduced steel framework structure enabled large areas of glazing. For the first time glass was not merely used as a window, but to a great extent also as a filling element of the façade structure. The fully glazed workshop wing of the Bauhaus in Dessau (fig. 2.5) by Walter Gropius is a fundamental example of these façade structures. Another example was the competition design for a tall office building on Berlin’s Friedrichstrasse (fig. 2.6) by Ludwig Mies van der Rohe in 1921. However this design was unnoticed by the jury, it became the prototype for future tall office buildings in framework construction with fully glazed facades. [1, 4, 5]

It was not until over 30 years later that such tall buildings became a reality. By that time air-conditioning was invented and the additional artificial fresh-air supply, air-conditioning and heating of buildings, was regarded as progression rather than a necessary evil. Around the same period the Pilkington Brothers put an end to the standard production techniques as mentioned above with the invention of the float glass technique (fig. 2.7). This technique allows the production of flat glass in a quality superior to that of drawn glass and equal to that of ground and polished cast glass. This makes the manufacturing process more rational and skyscrapers became common practice. [1]

Because of the global energy crisis of the 1970’s the glass industry tried to develop energy-saving products which would reduce both the heating and cooling loads of buildings. Another task to be tackled was the “sick building syndrome” caused by air-conditioning. The result was the development of new glass façades which attempted to achieve an intelligent combination of all the elements of thermal insulation, shading, natural lighting and natural ventilation. [1, 4]
The idea of being able to take down the barrier between inside and outside fascinated architects and they wanted to maximize the transparency of the façades even more. Linearly supported glass windows were substituted by point-supported glass façade-elements and the steel or concrete framework were replaced by cable trusses. The glass façades of the greenhouses at Parc La Vilette (fig. 2.8) in Paris (1980) became a milestone in the development of structural glass façades. Here, glass curtain walls were realized with one glass pane being attached to the next. Cable trusses support the facade for wind loading and the glass supports are sophisticated glass fixings fastened only at the four corners to ensure a maximum of transparency. [4, 5, 6]

In 1988 a step towards an even more transparent façade was made with the development of the cable-net principle for the Kempinski Hotel in Munich (fig. 2.9). A single-layer cable net is pre-stressed in both directions and the glass panes are fastened with point-fixings at the nodes of the cable net (fig. 2.10). Although this system shows great deformations under wind load, the deformations may be controlled with the pre-stress of the cables and have to be carefully observed during the design process. [5]

With the realization of the Kempinski Hotel a highly minimized and extremely transparent façade-system is developed. But still the main load-bearing elements are made of another material than glass: vertical steel cables for the dead load of the façade and horizontal steel cables for the wind loads. In the past decades innovations in glass technology are focused on glass being used as a structural, load-bearing element rather than merely a filling element. This will be discussed in the next paragraph.
2.2 Glass as a load-bearing material

Glass has been used to enclose space and give shelter for ages now, but it was merely used as an infill-material rather than a load-bearing material. Nevertheless the first use of glass as a structural material dates back to the 19th century palm- and greenhouses in England (fig. 2.11 and 2.12). To maximize the use of sunlight, architects designed freestanding enclosures with domed and folded glazed roofs. The stability of these slim cast iron structures was largely achieved by the bracing provided through the small glass shingles. The skeleton forms a structural and functional unity with the glass skin. Because of the shape of these shell structures tensile stresses in glass were avoided and the glass was able to cope with the acting loads on the structure. The roots of modern structural use of glass reach back to these buildings, which have lost none of its fascination to this day. [7, 8]

With the “Neues Bauen”-movement of the 1920’s, the skeleton structure was introduced (fig. 2.13), which led to the separation of the skin from the load-bearing structure. Therefore glass had become a mere covering-material and had almost lost its structural significance. Engineers tried to maximize the transparency of the façade by reducing the load-bearing framework that supported the glass panes, as described in the previous chapter. [7]

Today, glass has regained its significance as a structural building material thanks to the ongoing search for enhanced transparency. Small scale experiments and experiments with temporary buildings led to the use of glass as load-bearing structures in different appearances. Architects and designers first experimented with tertiary glass structures like handrails and balustrades. Applications like these are used everywhere nowadays. Progressively, architects used glass for secondary structures like steps of stairs, roofs, walkways and floors. The next phase of glass as a load-bearing material is the use in primary structures like beams, walls and columns.

The use of glass beams started with glass fins or mullions in façades. Architect I.M. Pei was one of the first to apply glass fins in his design for Terminal 6 at JFK airport back in 1970 (fig. 2.14). He created an all-glass façade with unprecedented use of glass mullions instead of the typical metal ones. [9] After that glass fins were used in a horizontal position and as a result glass beams were born.
One of the first uses of glass walls was in a temporary building of Benthem Crouwel in 1982 (fig. 2.15). The experimental glass house was designed for the competition “Unusual Living” and build in Almere. Three glass walls and one sandwich panel of plywood and polyurethane foam carry the steel roof. The glass walls are stiffened by 15mm glass stiffeners to cope with the wind loads. [1]

The glass column is still in its early phases of design compared to the other structural elements. Nevertheless few examples of structural glass columns are known. In the town hall of Saint-Germain-en-Laye (France) cruciform-shaped glass columns are used to carry the roof of the central glass patio (fig. 2.16). In case of failure of one or even all of the columns, a structural steel tension ring in the roof will prevent the roof from collapsing. This design dates back from 1994 and after that only a handful of other projects with glass columns are built.

Nowadays all structural members can be created out of glass and examples of these realized building components are mentioned above. Therefore it is possible to design and build a structure entirely out of glass and the most prominent example must be the Apple Glass Cube in New York (fig. 2.17). Apple is well-known for its use of glass façades, stairs and stores and evidently contributes to the research and development in glass-construction. For the glass cube in New York only the connections are made out of a material other than glass!
Chapter 3:
GLASS AS A LOAD-BEARING COLUMN
3 GLASS AS A LOAD-BEARING COLUMN

3.1 Evolution of the glass column
Sometimes it is not really clear whether a “column” is just a small piece of a wall, or a fin or a free-standing column. The definition of the column, which will be the subject of this research, needs to be clear and therefore it is wise to take a look at the historic evolution from a wall to a column. Or to quote the words of famous architect Louis Kahn: “Consider the momentous event in architecture when the wall parted and the column became.” This will be done by analyzing different projects with load-bearing walls, fins and columns (fig. 3.1).
3.1.1 Glass body of laminated glass panels
Project: Laminata Leerdam
Place: Leerdam, the Netherlands
Year: 2001 (realized)
Architect: Kruunenberg van der Erve Architecten
Structural design: ABT (Rob Nijssse)

Introduction
Leerdam is known as the glass capital of Holland and the Leerdam housing corporation CWL
(Centraal Woningbeheer Lingesteden) wanted to mark their 40th anniversary with something
unusual. They wanted to build a glass house which would be both experimental and functional. The
design of van der Erven/Kruunenberg won out of a total of 160 design-plans (fig. 3.2 and 3.3).
[10, 11]

The concept of the house was indeed experimental: a glass body is created by an endless succession
of vertical flat glass sheets. The glass panes are cut in the longitudinal direction and are pulled apart
(fig. 3.4). This results in two smaller glass bodies with a complementary space in between. The solid
bodies are cut out to make room for the bedrooms on one side and a hallway on the other. The
complementary space houses the entrance, living area and patio (fig. 3.5). [12, 13]

Laminated body of glass
Because laminated glass on this scale is a prototype, extensive research was carried out by the
Netherlands Organization for Applied Scientific Research (TNO) to thoroughly investigate its
suitability as a primary building material. Although the glass itself is naturally brittle, this inflexibility
is countered by the use of special two-component silicon glue that is UV-resistant and permanently
flexible. Therefore a certain amount of movement is preserved between each sheet of glass to
provide flexibility as a whole. As for strength, although a single sheet is easily shattered by the
impact of an object, the total laminated glass structure is relatively strong. [13, 14]
Structural design and connections
The solid walls, consisting of about 10,000 glass plates, each 10mm thick, rest on one end on the concrete understructure which forms the basement. The glass wall is just sitting upon the foundation (fig. 3.6). Because of the weight of the glass no additional anchoring or stability connection was necessary. These laminated walls, which have a variable thickness of 200 to 600 mm, carry a wooden roof with big glass parts in it. The wooden roof sits at one end on the glass wall with rubber as an intermediary to distribute the forces and to avoid stress concentrations. Small aluminum elements which are glued into the glass walls provide the connection. At the other end, above the corridor, the roof sits on individual glass beams which are clamped in the body of the glass (fig. 3.6). At every 1,20 m glass plates stick out of the body of the glass and aluminum profiles, which are glued against these glass beams provide the connection with the roof (fig. 3.7). [12, 13, 15]

Stability
In this project the stabilizing load-bearing system clearly consists of glass walls. Wind from the y-direction is transferred via the façade partly to the roof and partly direct to the foundation. The roof transfers the forces to the two main glass bodies, where four major glass walls over the full length transfer the forces to the foundation (fig. 3.7).

Portals in the two main bodies (at a distance of 1,20 m from each other) take up the wind loads from the x-direction (fig. 3.7). The beams are clamped into the walls and therefore a portal is created. At the ends of the main bodies glass walls are situated instead of portals. The four walls in the complementary space will also take account for the wind loads in this direction.
Relevance with respect to glass columns

Although the load-bearing system and the stability is achieved with glass walls, these glass walls are the first step towards glass columns. In this project the entire wall is made out of pieces of laminated glass, but this same technique could be used to serve as a column. The only difference would be the dimensions of the building component.

Very often glass is used to acquire a certain amount of transparency but in this case the walls are not transparent anymore. The observer only sees the end faces of the glass panes, resulting in a highly translucent or opaque view (fig. 3.8). The principle of placing glass panels behind each other to acquire solid walls can be used to make walls more attractive. As described previously glass plays with light. And how glass plays with light depends on the shape and dimensions of the glass wall. This is clearly visible in the Laminata house, because the thickness of the walls ranges from 200 mm to 600 mm. This results in a playful composition of color and light. This makes the principle of laminating glass an interesting option to make walls more attractive and could be adapted to be used as a column.
3.1.2 Glass wall of laminated glass panels

Project: Mi Casa Es Su Casa
Place: Leerdam, the Netherlands
Year: 1995 (design)
Architect: Robert Winkel and Marco Henssen
Structural design: ABT (Rob Nijsse)

Introduction

For the same competition in Leerdam Robert Winkel and Marco Henssen designed a similar building in parallel to the Laminata House. Where, in the case of the Laminata House, the total body was made out of laminated panels of glass, the design of Winkel and Henssen involved only four panels made of 6 x15 mm glass panels, laminated in the longitudinal direction (fig. 3.9 and 3.10). [12]

In the architectural concept the floor and the roof are the backbone of the dwelling. These building components enclose the space where the people can live and everything is possible within these boundaries. Between these boundaries are no walls, only climate-screens of glass. Subsequently there are different climatologic spaces: the outer spatial layer, along the façade of single glass, is a multi-functional half-climate zone. This zone acts as a buffer against the winter cold or the summer heat and traffic noise is reduced. The second zone is the actual house where the living area is situated. This zone is separated from the façade by cupboards and screens. Finally, in the center of the building a translucent core houses the bathroom area (fig. 3.11). [12, 16]

Structural design and connections

The four laminated glass panels of 2,5 x 2,5 m toughened glass embody the main building structure and carry steel beams and a wooden roof. Because of the low dead-weight of the roof and the large surface area on the glass walls the stresses in these walls are small. The stresses in this connection detail are transferred from the steel beam via an intermediary material made of...
neoprene rubber and a strip of aluminum to the glass (fig. 3.12). At the base of the glass panels a connection is created by a recess in the top layer of the concrete. Steel angular profiles around the edges and a neoprene rubber between the glass and the steel transfer the forces gradually to the foundation (fig. 3.12). Because of the weight of the wall no bolted connections of any kind are necessary. [12, 17]

**Stability**

The four glass panels also provide stability and take up the horizontal forces evoked by the wind. Two walls take account for the wind in one direction, and two for the other (fig. 3.13). The glass walls in the façade are secondary elements and span from floor to roof to take up the wind loads. The wind loads are transferred through the roof to the main glass panels and therefore diaphragm-action in the roof is necessary. [12, 17]

**Relevance with respect to glass columns**

This project serves as an intermediary step between the glass body as seen in the Laminata House and a glass column. In this example the glass walls are indeed transparent because of the longitudinal lamination and the limited thickness of 90mm. The largest area of the wall is transparent because the viewers look at the surface of the glass panes. Still the end faces of the wall are translucent or opaque. This effect will also occur with columns, which will be even more visible due to the limited dimensions of a column (fig. 3.14). Two faces will be transparent and the two perpendicular faces will be translucent. Architects could use this contradictory effect of the glass column to their benefits.
### 3.1.3 Glass wall of a single laminated glass panel

**Project:** Temple de L’Amour II  
**Place:** Noyers/Avallon, France  
**Year:** 2001 (realized)  
**Architect:** Kraaijvanger Urbis (Dirk Jan Postel)  
**Structural design:** ABT (Rob Nijssse)

#### Introduction

The previous examples showed glass walls made out of series of glass panes laminated together. In Talus du Temple (also known as Temple de L’Amour II) only one (laminated) glass pane forms the glass wall (fig. 3.15). The design sits on a rather unusual building site. The owner of the site in Noyers/Avallon discovered a vault that was originally built as an explosion chamber to destroy a bridge. An 18th-century tower on the site has become the basis of a small summer residence. Above the tower architect Dirk Jan Postel designed four glass walls all around to carry the roof, inspired by the 360° view of the surrounding countryside. According to Dirk Jan Postel the aim of the design “was to express the magic of the roof floating on nothing.” Besides the glass pavilion, the complex also includes one bedroom, a living room and a kitchen. [18]
Structural design and connections
The room measures approximately 5x5 meter and the internal height is 2.3 meter. The walls are made of laminated toughened glass panels, each 2x10 mm thick. The cantilevered roof is a wooden box clad by copper plates, weighing ca. 2,000 kg. The large fixed glass parts are connected by bolts to a steel angle mounted on the ground/top of the landing or on the roof (fig. 3.16 and 3.18). The smaller glass panels are fixed to the roof with the same type of connection. The bottom sides of the glass panels are connected to steel angles, which are mounted on the stone wall with a structural silicone joint (fig. 3.18). [12, 19]

Stability
Besides carrying the weight of the roof, the glass panels also provide stability for the structure. Lateral stability (wind from y-direction) is provided by four full height laminated glass panels, while 4 small side-panels contribute to the rotation stability. Four smaller side-panels provide the stability for wind from the x-direction along with the stone walls (fig. 3.17). A finite-element-model provided information about the worst-case scenarios for the stabilizing glass walls: one with a tensile diagonal in the glass, the other with a compression diagonal. If these constructions succeed (and they did), all intermediate stress distribution can be handled as well. [12, 19]
Relevance with respect to glass columns

Contrary to the Laminata house and Mi Casa Es Su Casa in Leerdam the glass walls consist in this case of a ‘single’ (laminated) pane of glass (fig. 3.19). Consequently the thickness of the walls reduces from 90/600 mm to 20mm. Obviously the transparency increases dramatically, which is also due to the view on the surface of the glass, rather than the view on the end-faces of the glass. Because of the reduced thickness of the glass walls the load-carrying capacity is limited however, which makes this concept only usable for small one-story pavilions etc. Furthermore glass columns with only one glass pane are extremely sensitive to buckling and the load-bearing capacity is therefore too low to apply this concept successfully as a column. Different options exist to increase the bending stiffness of the glass wall of a single laminated glass panel. First of all the shape can be modified into a three-dimensional shape. A flat panel of glass has little bending stiffness but when the panel is curved the bending stiffness increases dramatically. This option is used in the next project, Museum aan de Stroom in Antwerp.
3.1.4 Three-dimensional glass wall

Project: Museum aan de Stroom
Place: Antwerp, Belgium
Year: 2010 (realized)
Architect: Dirk Jan Postel
Structural design: ABT (Rob Nijsse) (corrugated glass panels)

Introduction
In Antwerp at ‘het Eilandje’ the 60m high Museum aan de Stroom (Museum on the stream) has been developed. This museum is designed by Neutelings Riedijk Architects and in this project alternatively closed, massive boxes and glass galleries are stacked one on top of the other (fig. 3.20). The floors are not stacked directly on top of each other but are rotated 90 degrees with respect to each other. The room between the stacked boxes consists of a 5,5 m high gallery which spirals upwards around the core. [20]

Structural design
The structural design consists of a central concrete core of 12 x 12m and the boxes cantilever out from this structure by the use of steel trusses (fig. 3.21). The architects wanted to cover the gallery with glass and they did not want any visual structural elements. With the glass-façade of the Casa da Musica in Porto in mind they tried to realize this ideal image (i.e. only glass and no steel columns or beams) with corrugated glass panels (S-shaped glass panels) (fig. 3.22). The glass panels are not part of the main structural design, but in the corners the bottom panels do carry the weight of the upper panels. [21]
Façade-panels
If one used straight panels, the glass would have been enormously thick because of the free span of 5.5 m. Since the corrugated glass is so much stronger in bending, they were able to use 12 mm thick float-glass panels to take up the wind load. The presence of visitors close to the façade led to the demand that the glass should be laminated to avoid falling through in case of an accident. Therefore 2 times 8 mm float glass was used for the façade-panels. These glass panels are loaded in bending by the wind, but they are not loaded in compression by the boxes because they cantilever out from the concrete core. However, at the corners of the building, the height of the gallery is doubled and the façade-panels need to span 11m. This is too much for only one panel and therefore two panels of 5,5m are stacked on top of each other. At the horizontal joint between the panels a steel, horizontal tube is used which spans between the concrete boxes (fig. 3.23). This tube takes account for the wind load, so the glass panes only have to span 5,5 m. The steel tube does not account for the vertical loads due to the dead-weight of the panels so the bottom panel is loaded in compression. At first the structural engineers wanted to stack the panels directly on top of each other with use of an elastic interlayer. The compressive stresses due to this principle are minimal, but the question remains what happens when the bottom panel fails and how to replace it. Therefore it was decided to add a steel horizontal ‘strip’ that was strong enough to carry the weight of the top panel, when the lower one collapsed, but slender enough to be incorporated within the connection detail (fig. 3.24 and 3.25). [20,22,23]
Relevance with respect to glass columns

The main reason to use the corrugated glass panels (fig. 3.26) was the increased stiffness in the plane of the façade-panels to be used as a simply-supported wind-beam. But the increase in stiffness also has beneficial effects for corrugated panels used in compression: the buckling load of the panels is substantially higher because of the increased stiffness of the S-shaped panels, compared to the flat panels in the previous example. And due to the increase in material and increase in the surface-area of the top edge the glass panels can also take higher loads in compression.

In this example the bending stiffness of the walls of a single laminated glass pane was increased by curving the panels. Another option is to place fins behind the glass panel, this option is used for the next project: the Apple Glass Cube.
3.1.5 Glass wall with fins or glass columns?

**Project:** Apple Glass Cube  
**Place:** New York, United States of America  
**Year:** 2005 (realized) and 2011 (realized)  
**Architect:** Bohlin Cywinski Jackson  
**Structural design:** Eckersley O’Callahan

**Introduction**

For the entrance of the 5th avenue Apple store Bohlin Cywinski Jackson designed a 10x10x10 meter self-supporting all glass structure, which houses a central glass elevator and some glass stairs. The first Apple glass cube was built in 2005 (fig. 3.27). The initial concept for all the new stores was to create a structure that would allow maximum transparency through the space and not defer customers views of the products displayed. At the same time the importance of design to Apple led them to strongly want a series of structures that were not only functional but also magical: structures that had a major ‘wow’ factor and would grab the fascination of the customers in the store environment itself. Clearly these magical structures would be complemented with very highly refined architectural design and finishes. [24]

**Structural design Apple Glass Cube 1.0**

The 10x10x10 meter self-supporting all glass structure had laminated glass columns which also were used as fins to take wind loads. Each of the façades consisted of eighteen laminated glass panels, stretching the capabilities of glass processing technology in size and also in quality. The fins are located at the connection of two façade-elements and therefore five columns per elevation were used. Upon these glass columns a glass beam roof grid is situated. The grid is based on a lamellar principle (fig. 3.28) which was made up out of 25 roof beams of 3,3m and 10 beams of 1,6m. The roof itself is made out of 35 glass plates. [25]
Connections
Due to the lamellar structure of the roof beams moment connections can be avoided. In each end of these beams a thin stainless steel shoe insert is laminated that allowed the post connection of a fin plate. The fin plate is connected to the vertical legs of a u-shaped profile that loops over the supporting beam, transferring the load in bearing (fig. 3.29). This had the advantage of eliminating the need for bearing holes in the middle of the supporting beams where moment is greatest. [26]

The fitting from the fin to the wall panels allows restraint to the fin and transfers direct loads such as wind (fig. 3.30 top). The fitting also provides shear transfer within the plane of the façade so that the walls act as a shear wall to give lateral stability. Throughout my personal analysis of the details I think that the façade-panels are simply stacked on top of each other so this connection detail does not transfer the forces of the deadweight of the façade to the fin. However in case of breakage of one of the panels, the deadweight of the panels is transferred temporarily via this detail to the fins. Fittings on the horizontal joint of the façade panels make sure the forces due to the deadweight under normal conditions are transferred from one to the other façade-panel and also complete the shear transfer action (fig. 3.30 bottom). [26]

Stability
To transfer the wind loads, the façade transfers the force to the fins which moves it to the base fitting and up to the roof plane. At the roof plane it is transferred thought the beams and roof panels into the adjacent wall, and back down to the plaza (fig. 3.31). [26]
Structural design Apple Glass Cube 2.0

In 2011 the existing glass cube has been replaced with a new, even more transparent glass cube (fig. 3.32). Five years of experience laminating all sorts of glass, different interlayers, extra jumbo sizes and extra thick laminations provide the basis for the engineering and fabrication of the Cube 2.0. Each façade could now be build up out of only three panels in contrast to the eighteen panels needed for the first cube. Each façade-panel was 3,280m wide and 10,3m high. Subsequently the amount of columns, roof beams and roof panes decreased dramatically resulting in a far more transparent structure compared to the first glass cube (fig. 3.35). [25]

Connections
The other significant development was the fitting itself. A fabrication technique of laminating metal within the glass (fig. 3.33 and 3.34) was developed and used in the connection of the façade panels to the glass fins. Within each of the façade panels six inserts were laminated: three on each side. These inserts could be used as the primary connection between the panels and the fins. The fins also have a laminated insert at the junction where the panels and the fins are connected. The result of this is that all the fittings are laminated within the glass with no metal exposed at the surface of the glass.

A detail was developed that hollowed out the insert allowing a metal tab to rotate into the insert from having been aligned with the vertical joint. The rotation could be done through the joint itself and then once secured could be covered with a silicone glue to protect the mechanics of the connection. This detail resulted in no visible fittings protruding from the face on any side of the cube which resulted in a purely glazed surface. [25, 26]
Stability
The structure of the cube is similar in nature to the first version in that the overall stability of the structure is maintained by the in-plane stiffness of the sidewalls.

Relevance with respect to glass columns
In the previous examples the load-bearing system was clearly built up of glass walls. In the case of the Apple Glass Cube the structural system is not as clear any more. The façade carries a part of the roof and the fins carry the glass beams and also a part of the roof. The fins interact also with the façade and therefore the question remains whether ‘the fins’ are the columns or ‘the façade in combination with the fins’ are the columns (with a T-shape) (fig. 3.36). Furthermore the corners of the façade can be seen as angular columns. Throughout my personal analysis of the details and connections I think that the fins should be regarded as the main columns, but these fins are (at one end) stabilized by the façade, which reduces the buckling length of the fin at one end. The façade therefore clearly contributes to the load-bearing capacity of the fins. From this example it is evident that the distinction between walls and columns is not clear any more due to the interaction of both.
3.1.6 Glass walls or glass columns?
Project: The Rheinbach Pavilion
Place: Rheinbach, Germany
Year: 2000 (realized)
Architect: Marquardt & Hieber
Structural design: Ingenieurbüro Ludwig und Weiler

Introduction
The Rheinbach Pavilion is a one-storey pavilion which was erected by the local glass school (fig. 3.37). It is also known as the ‘Hans-Schmitz-Haus’ named after the former VEGLA (Vereinigte Glaswerke) marketing director. Like in the Temple de L’Amour the glass carries a cantilevered steel roof. Where Temple de L’Amour used glass walls, the Rheinbach Pavilion uses (huge) glass ‘columns’. Therefore it is the first building where all vertical and horizontal loads are carried by columns made entirely of glass. [5, 27]

Structural design and connections
The dimensions of the pavilion are considerable: the roof measures 32.5 x 15m and consists of a grillage of IPE 360 profiles. The roof cantilevers out 5m on all sides thus protecting the showcases and exhibitions from summer overheating. The 28 ton roof appears to float above the pavilion, because it sits on top of six large, all glass columns of 3.8 x 1.25 m. The columns consist of two outer panes of 10 mm heat strengthened glass and an inner pane of 19 mm thermally pre-tensioned glass. The stiff grid roof of the pavilion is able to transfer loads to remaining glass columns if some columns fail: up to 40 percent of the load-bearing panels may be destroyed without the roof collapsing!
Special attention was given to the force introduction point. Due to the existing tolerances special pin connectors were used (fig. 3.39). To insure a direct contact to all three glass layers the holes of the outer layers are larger and filled with center rings. The remaining gap between glass and aluminum was programmatic 1 mm and filled with a specific mortar. [27, 28, 29]

**Stability**

This pavilion is the first building where all vertical and horizontal loads are carried by glass columns (fig. 3.38). Therefore the columns provide the stability of the building in both directions. The glass panes are fixed with bolted connections to the roof and the foundation. The bolted connections can be loaded in tension, resulting in a moment-resistant connection of the total glass column in the direction of the glass panes. Due to the large dead weight of the roof the glass is mostly under compression however. [29,30]

**Relevance with respect to glass columns**

In the previous example one could see the debate whether the structural system consisted of ‘fins’ as columns, or T-shaped columns of the ‘fins in combination with the façade’. In the literature about this project the load-bearing system is described as glass columns (fig. 3.40), but are columns with dimensions of 3,8 x 1,25 m really columns? In my opinion the stabilizing system consist of glass walls rather than columns. By my definition the cross section of columns have smaller dimensions and the width and depth of columns are approximately the same, resulting in a cross section of a square rather than a rectangle. Furthermore the length of the columns is substantially larger compared to the width and the depth. Although this is an inspiring building with load-bearing glass, glass columns in my definition are of another kind. These columns will be described in the next example.
3.1.7 Glass columns

Project: Town Hall
Place: Saint-Germain-en-Laye, France
Year: 2000 (realized)
Architect: Brunet Saunier Architecture
Structural design: unknown

Introduction
In St-Germain-en-Laye near Paris the first building with glass columns (by my definition) was constructed. Cruciform glass columns with a cross section of limited dimensions support a glass roof (fig. 3.41). The architects J. Brunet and E. Saunier designed a central glass patio for the new Administrative Center of the local town hall. The design comprised of a 700 m² glass roof, an inverted cone of bent glass and glass columns. [12, 31]

Structural design and connections
The glass roof measures 24 x 24m and consists of steel IPE beams. The roof is supported by eight cross shaped columns of 220 x 220mm. The columns, with a height of 3,2m, are made up of three layers of laminated heat treated glass. The central panel is 15mm thick and is protected by two outer panes with a thickness of 10mm (fig. 3.43). To ensure this protection the structural inner layer of glass is recessed from the edges of the adjacent panels. In one direction all three of the glass panes are continuous and the panes in the opposite direction are split up and glued to the other panes. The ends of the columns were set in steel shoes (fig. 3.42). The load-introduction is via an intermediary material with a high density to the inner, load-bearing glass panes and the other panels sit on top of a neoprene strips. [12, 32]
Stability
The columns are only loaded in compression and don’t contribute to the stability of the building. When columns contribute to the stability they need to be loaded in bending, which is wise to avoid for glass columns. Special care in the details is taken to avoid bending to be transferred to the columns. If one or more of the columns collapse the structural system in the roof, with a tension ring around the patio would prevent the roof from collapsing as a whole. The maximum loading which can occur is calculated to be 69 kN, but a full scale test proved that the ultimate load for the columns is 430 kN. [12, 32]

Relevance with respect to glass columns
This project is the first with glass columns which fulfill the definition of columns as I described previously (fig. 3.44). But one could argue whether this column is the ultimate example or not. The choice for the use of glass columns could be based on different aspects, but one of the reasons is the transparent nature of glass. Due to the shape of a cruciform a lot of glass-edges are visible, which form a black line. Furthermore due to the view through multiple layers of glass the colour becomes greener and greener. As with all prototypes lots of improvements could be made, to make glass columns even more spectacular.
3.2 Conclusion
From this overview of the evolution of glass columns (fig. 3.45) a lot of insight has been given with respect to dealing with glass as a structural material. Connections with other building components need a lot of attention and the brittle behaviour of glass is an aspect which needs to be dealt with. However the continuous developments in the glass industry and the amount of buildings where glass is used structurally contribute to the knowledge of glass as a building material.

The different projects with glass fins or glass walls also showed some aspects which could be interesting for the use of glass columns. For instance the placing glass panels in a row like the Laminata House and Mi Casa Es Su Casa could be used and adopted for columns.

The reason of the research into the evolution of glass columns was to define glass ‘columns’ which will be the focus of further research. In this paragraph a couple of aspects and demands which define glass columns came to light:

- The structural element is only loaded in compression, so it does not contribute to the stability of a design.
- The structural element is freestanding and therefore not part of the façade (which is the case with fins).
- The width and the depth of the structural element are approximately the same, which results in a more or less square cross section (i.e. no rectangular cross sections, which is the case with fins or walls).
- The length of the structural element is substantially larger compared to the width and the depth.

Glass columns which fulfill these requirements are already build and one example for the town hall in Saint-Germain-en-Laye is described in the previous paragraph. However this prototype could be improved and one of the most important aspects of the column is its shape. In the next chapter different configurations of columns are described, compared and evaluated.
Chapter 4:
CONFIGURATIONS OF GLASS COLUMNS
4 CONFIGURATIONS OF GLASS COLUMNS

The cruciform shaped columns for the project in Saint-Germain-en-Laye are one of many possible configurations of glass columns. These columns are constructed out of flat glass panels, but there are more possibilities. The glass industry can provide different kinds of glass elements and the possibilities can be divided in four different categories (fig. 4.1):

1. Columns made of glass panels
   - Solid columns made of glass panels
   - Profiled columns made of glass panels
     (cruciform, H-profile, boxes, tubes etc.)

2. Columns made of glass cylinders

3. Columns made of solid glass rods

4. Columns made of cast glass

In the succeeding paragraphs these different categories of glass columns will be described and compared and relevant projects will be analysed.
4.1 Columns made of glass panels
Glass panels can be used to make columns in different ways: they can simply be placed in a row, which results in solid columns, or with a different arrangement of the glass panes profiled columns could be constructed.

4.1.1 Solid columns made of glass panels
As described in the Laminata-house and the ‘Mi Casa Es Su Casa’-project glass panes can be placed in a row to construct glass walls (fig. 4.2 and 4.3). This same principle can be used for glass columns. As we have seen before two faces of the column will be transparent and the two faces in the opposite direction will be translucent. This effect however depends on the dimensions of the column and the type of glass. If the dimensions become larger and larger, the view through the ‘transparent’ face becomes greener and greener, and therefore a big part of the transparency is lost. This effect could be counteracted with use of a special type of glass. Ordinary glass appears colorless when it is thin, but it has a green tint which becomes visible when one looks through thick or multiple panes of glass. This green tint is a result of iron-impurities and therefore the glass industry developed special low-iron glass, which is truly colorless. Aspects of placing glass panels in a row are previously described in the two projects mentioned above. Glass columns could also be created by stacking glass panels and this will be the focus of this paragraph.

Of course when glass is stacked in this way it loses some of it is transparency (fig. 4.4), but transparency is not the only reason to choose the material glass for columns. Architects often like to use glass, not only because it is transparent, but because glass ‘plays with light’. Glass is never truly transparent: glass will always shimmer, shine, reflect or distort light depending on the time of day and the surrounding light. This is what makes glass an interesting material. Furthermore when glass is stacked all kind of shapes can be achieved by differences in the individual glass panes, or by translating or rotating the glass panes with respect to each other. This concept leads to endless possibilities and this effect has been used in different sculptures.
De Glazen Engel (Archangel Michael)

Place: Zwolle, the Netherlands
Year: 2010 (realized)
Artist: Herman Lamers
Engineering: ABT (Rob Nijsse)

The Dutch artist Herman Lamers designed a modern version of the archangel Michael which is placed on the market square in Zwolle (fig. 4.5 and 4.6). He decided that a three meter high glass angel would be the perfect way to depict a modern Michael.

After studying numerous methods he decided to make the angel by stacking glass panels. For the structure approximately 370 glass panels of 8 mm glass were used. With a computer generated image of the angel the glass producer could cut out the correct shape of all the cross sections from a rectangular sheet of glass. To connect the panels on top of each other 3M double sided tape was used. This type of tape is resistant to the outside conditions like rain and frost etc. and its thickness is large enough to counteract the variation in thickness of the individual glass sheets.

Transparent tubes are incorporated in the sculpture to ensure the exact location of the glass panes on top of each other but also to provide additional strength to the structure. The transparent tubes are incorporated in the legs, the body and the wings.

The panels which were left over after cutting out the shape of the archangel are also stacked on top of each other, resulting in a angel inside a glass box (fig. 4.7). Two statues of the glass archangel, a positive and a negative, for the prize of one. [25, 33]
The National Police Memorial
Place: London, United Kingdom
Year: 2005 (realized)
Architect: Foster + Partners
Artist: Per Arnoldi
Engineering: Arup

Foster and Partners designed this memorial in association with the Danish artist Per Arnoldi. The memorial consists of two distinct elements. A dark stone wall displays a book listing the names of police officers killed on duty. Alongside this dark wall stands a wall of glass (fig. 4.8) which will be illuminated with blue light, representing the blue lamp once displayed outside every police station in Britain. The glass wall is 7m high, 3.1m wide and 0.5m deep and consists of ca. 550 layers of 12mm float glass, weighing about 27 tons.

The glass panels are stacked on top of each other without any interlayers (fig. 4.9). The ‘dry stack’ is stabilized by a total of five high strength steel tension rods with a nominal diameter of 31.75 mm. (17.4 ph H1150 Stainless Steel) The top 20 layers are made of laminated tempered panels and are glued together, which have a pure aesthetic function of concealing the connection of the tension rods. The top 2 structural panels are also made from tempered glass to withstand the bending force due to the clamping force introduced by the steel rods.

The top connection comprises a stainless steel disc (diameter = 200mm), with a recess to the bottom side. An intermediary material of vulcanised fibre prevents glass to metal contact. The baseplate is also made of stainless steel and provides a smooth and level base for the glass wall. Three single spherical leveling points on the bottom of the base plate ensure a totally level installation.

A compression test on a small-scale prototype of 400mm x 500mm x 1000mm proved the ultimate load to be approximately 590 kN. Failure occurred on the top panels due to plastic deformation of the fixing plate. Experiments on the full scale structure proved the ultimate load to be lower because of the axial flexibility of the 7m high stack. [34,35]
The Pompano Park water feature

Place: Florida, United States of America
Year: 2006 (realized)
Architect: Carey Jones
Engineering: Malishev Wilson

Architect Carey Jones designed this inspiring glass water feature for the Casino in Pompano Park (fig. 4.10). Nine 3.5m high columns of stacked glass are built out of 10 mm thick annealed glass sheets. The columns support a series of laminated glass bridge-elements carrying a thin layer of water. The water is transported through a stainless steel pipe in the center of the glass columns (fig. 4.11) and then spread across the top to the edges where it cascades down into an artificial pool. In total 14 types of sheets with a typical geometry where used and by rotating these sheets the organic shape of the column could be achieved with a minimum amount of individual shapes of glass (fig. 4.12). Overall 3150 pieces of glass were used resulting in a structure with a total weight of 55 tons.

These columns are also stacked on top of each other without any intermediary material. Throughout my personal analysis of the pictures and figures I think the structure is stabilized with use of steel tension rods. Around the central stainless steel pipe 4 holes are visible in the figures so I think each column is pre-stressed with four tension rods.

One very important aspect of the stacked glass features is the variation in glass thickness and flatness across the sheet. Heavy variations in the thickness may create stress concentration in points of contact between the different glass panes and cause them to fail. Toughened glass needs more attention for stacked structures because of its uneven surface due to the roller waves introduced.
during the toughening process. Measurements during a factory visit at St. Gobain provided the knowledge that 10mm thick glass tends to be 0,35mm thinner along the short edge of the glass. The thickness becomes consistent at about 250-300mm away from the edge and therefore the edges of the glass plates should be cut off by the same amount to avoid unnecessary stress concentrations in the structure.

Another important aspect is the shear capacity of the stacked glass if subjected to horizontal loadings and even more the effect of the present water on the shear capacity. The initial intuition of the engineers of Malishev Wilson was that the presence of water could only reduce the coefficient of friction. Actually the opposite was true! Experiments by the Imperial College of London and the research of Malishev Wilson proved that the presence of water in the contact interface induced by capillary effect produces friction forces due to the liquid tension of water. Consequently the coefficient of friction increases with respect to the values obtained for dry contact. Based on these researches it could be concluded that it would be safe, for design purposes, to assume that the value of the frictions would be at least as high as at a dry condition.

Furthermore the total structure of the water features was calculated with a finite element analysis program (Strand7) to define the stresses and deformations of the glass (fig. 4.13). A summary of the results is presented here:

Maximum bending stress of the bridging element – 28,8 N/mm² (allowable 73,1 N/mm²);
Maximum stress under fail safe conditions – 88,8 N/mm² (allowable 93,1 N/mm²);
Maximum stress in stacked glass – 14,2 N/mm² (allowable 20,0 N/mm²);
Maximum deflections at mid-span of the bridging element – 8,1mm (allowable 19,1 mm). [36]
The Glass Sphinx
Place: Venlo, the Netherlands
Year: 2013 (under construction)
Artist: Fons Schobbers
Engineering: Witteveen+Bos Consulting Engineers & Scheuten Absoluut Glastechniek

When the Dutch city Venlo celebrated its 650th anniversary in 1993 the Venlo-based glass company Scheuten offered the city a massive stacked sculpture designed by Fons Schobbers. Almost twenty years later Scheuten offered the city a larger-than-life version of the statue. With a height of 6 meters and a weight of well over 100.000 kilograms, the Glass Sphinx is a giant copy of the original (fig. 4.14 and 4.15).

Because of its size, the use of normal glass would result in an almost opaque sculpture. Therefore a transition glass is used, which is obtained when a float line oven is switching from normal glass to extra clear low iron glass. The transition glass is almost color neutral which also is structurally beneficial because a lighter glass will lead to lower thermal stresses.

The sculpture is build up out of 600 layers of glass with a nominal thickness of 10mm. Because of its size each layer is segmented and consists of 6 to 16 individual sheets. An adhesive tape (AFTC Silver Tape 8502) is used for stabilizing this structure as the asymmetric shape makes it practically impossible to make use of tension rods. During curing, the adhesive slightly expands and therefore filling possible small gaps caused by deviations in glass thickness.

The sculpture will sit on top of a pile supported concrete block foundation covered in unpolished black stone slabs, that cantilevers out of the dike by approximately 0,5 m. The use of black stone makes the issue of thermal movements between foundation and sculpture more important and therefore the connection of the broader leg to the foundation is designed as a sliding joint, with use of Teflon strips.
With an explorative Finite Element analysis the feasibility of the structure was studied. Three different models were analysed: a solid model, a layered model and a solid hollow model (fig. 4.16). The first model served to gain a quick insight in the structural behaviour and order of magnitude of the stresses. The second model was used to investigate the effect of the soft interlayer. To reduce the overall weight and to make the weight distribution more balanced between the legs a third model was analysed.

Wind loading was applied to all models. The stresses due to wind loading remain extremely low. Well beneath 1,0 N/mm². In the layered model, the stresses were furthermore significantly lower than in the other two models. This is caused by the soft adhesive interlayer which is able to redistribute the stresses.

Uneven settlements may cause more severe stresses. The maximum tensile stress per length is for both solid model approximately 2,8 N/mm² per mm of settlement. The layered model again shows significantly lower stresses: 0,9 N/mm² per mm of settlement. Assuming an allowable permanent stress of 8,0 N/mm² the maximum allowable uneven settlement ranges from 2,8 to 8,8 mm. With a sound foundation design such uneven settlements can be avoided.

Furthermore a temperature load analysis is made on the entirely solid model. A rather extreme situation is modeled as a starting point, where the temperature in the object rises from -20°C to +80°C in a period of 8 hours. Even after 8 hours only the outer 20 cm of the sculpture has risen above 0°C. The rest of the structure remains at -20°C (fig. 4.17 - left). The corresponding maximum stress is 23 N/mm², which is relatively high (fig. 4.17 - right). In reality however the core temperature will never come close to -20°C but will rather have one close to the local annual average of about +10°C. Furthermore the real sculpture will be more flexible due to the segmentations and layers and the maximum stress due to temperature load will be substantially lower. All in all, there seems to be no reason to expect thermal breakages. [25, 37]
CONCLUSION
The sculptures discussed above prove that stacked glass could be used as free-standing structures and this concept could be used for load-bearing glass columns. With this concept the architectural possibilities for the shape of the column are endless, however there are different aspects which need to be taken into account.

First of all the tolerances in thickness and flatness of the glass panes (fig. 4.18). An uneven surface may create stress concentration in points of contact between the different glass panes and cause them to fail. In [35] Jan Wurm presented his findings on the tolerances of the thickness and flatness for stacked glass structures. He discussed 3 types of irregularities: thickness, local/overall bow and roller waves.

The tolerances on thickness given in BS EN 572-2:2004 appear typically in a float glass cut across the ribbon. In an example Wurm proves that these tolerances lead to stresses which exceed the allowable stresses of tempered glass and thus is critical for the concept of stacking. In order to avoid these tolerances, glass from the center of the sheets needs to be used, where the deviations from the nominal thickness are smaller by a factor of 10.

The tolerances on the local and overall bow (for heat treated glass) seem to be less critical. The local bow with a maximum of 0,5 mm/300mm (EN 12150-1:2000) is only locally present and the probability of this variation occurring on the exact same location in the stack is low. The overall bow is typically limited by industry standards to 0,1% of the long edge and the dead-load of the panels will level itself when stacked up, therefore avoiding any stress concentrations.

Roller waves, introduced during the toughening process, can vary ca. between 0,01mm and 0,3mm. The effects of the roller waves prove to be quite substantial and need to be minimized as much as possible. For this reason toughened glass is less suitable for dry stacked structures.
Secondly the stabilizing strategy of the stacked panels is important. There are three basic possibilities: connection of the individual sheets with some kind of interlayer; stabilizing the dry structure by superimposed loads or making a mechanical connection (fig. 4.19).

For the interlayer all kinds of glue, tape, laminating foils etc. could be chosen. A positive effect of this interlayer is that it could distribute the load over a greater surface avoiding stress concentrations imposed by the variations in thickness and flatness of the glass panels. A negative effect is the flow of the interlayer. With thick interlayers like resin, PVB etc. and even with thin compressible layers the flow of the interlayers under compression loads has to be carefully considered. The degradation of the interlayer over time is another unwanted effect and needs to be accounted for. Stacks with laminated and bonded stack-joints require therefore high safety factors, resulting in bulky structures. When columns are used outdoors other aspects like the resistance of the interlayer against sun (UV-radiation), rain, frost, salt corrosion etc. become important too.

Superimposed loads can be introduced by additional dead-load (e.g. by heavy objects placed on top of the stack) or by post-tensioning the stack with use of tension rods. Post tensioning introduces compression forces in the glass columns which reduces the capacity for the additional compression forces in the load-bearing column. Furthermore, if the stacked structure is used as a column, heavy objects placed on top of the stack are naturally present. Calculations are necessary to prove that the minimal compression force needed to stabilize the structure is always present.

A third option is to provide a mechanical connection. Holes could be drilled in each of the glass panes through which a mechanical connection can be made. These mechanical connections do not necessarily have to be made with use of the well-known steel connections (e.g. steel bolts or screws). It is also possible to place glass rods through these holes to make the connection.
4.1.2 Profiled columns made of glass panels

Flat panels of glass could be used to construct solid glass columns, but they can also be used to build profiled columns like we know from the steel industry: angular profiles, U-profiles, H-profiles, I-profiles, cruciform-profiles, box-profiles and all kind of intermediate profiled columns can be manufactured. The main reason to do this is to increase the bending stiffness with use of the same amount of material.

For the earlier described project in Saint-Germain-en-Laye, cruciform-shaped columns were used (fig. 4.20). This was the first time load-bearing columns of glass where designed and constructed, and after this project two more projects made use of this kind of columns: a coffee-house in Göppingen (Germany) and the Danfoss office building in Nordborg (Denmark).
COFFEE-HOUSE IN GÖPPINGEN
Place: Göppingen, Germany
Year: 2006 (realized)
Architect: Mario Hägele Freier Architekt and Attila Acs, Stuttgart
Structural design: Adrian Pocanschi and Marios C. Phocas

Introduction
Mario Hägele designed a three-sided glass building as part of the transformation of the inner city of Göppingen (fig. 4.21 and 4.22). To give an impulse to the pedestrian zone, also in the cold seasons, the glazed bar should act like a magnet for the pedestrians. Accordingly, maximum transparency was an important part of design and therefore two cruciform-shaped glass columns were used for the load-bearing system of the small coffee-house (fig. 4.23).

Structural design and connections
The structural design of the building consists of three main elements: a reinforced concrete core, the roof, and two glass supports. The concrete core is prefabricated in special red, decorative concrete and mounted in one piece to the foundation with use of steel plates and anchors which were encased in the concrete. The roof, with a surface area of 5,0m x 9,0m, consists of a grid structure of steel IPE160 and HEB160 profiles. The roof is prefabricated in three pieces, bolted together at the site and subsequently mounted in one piece. The roof is carried by the concrete core and the two glass columns, but when one or both the columns fail the roof does not collapse but cantilevers out from the central core.
The 3m high glass columns are similar to the glass columns of the town hall in Saint-Germain-en-Laye. In Göppingen the panels of the columns also consist of three layers of glass: two outer panes of 5mm heat-strengthened glass and a central pane of 12mm connected with a PVB foil. There is one big difference between the two cruciform cross sections. In Saint-Germain-en-Laye all three the glass panes of the central panel (the sword) are uninterrupted and one wing on each side is connected to the outer ‘safety-panels’. The central structural panel of the wing is not directly connected to the structural panel of the sword (fig. 4.24). In Göppingen a recess is made in the safety panels of the sword where the structural panel of the wing fits into. Therefore the structural panels are directly connected to each other with a silicone-glue.

The glass columns are connected at the head and foot with steel shoes (fig. 4.25). During the manufacturing the steel shoe was put over the glass column and the gaps between the glass and the wall of the steel shoe are filled with some kind of resin (HILTI-Hy-50) through holes in the endplate of the shoe. The load-introduction to the structural panels is achieved with neoprene strips underneath the safety-panels and the wings. The load is therefore only introduced in the structural panel of the sword. The structural panels of the wings stabilize the sword. To make sure no bending is introduced these columns are placed on protruding pieces of steel which act as a hinge and centers the load introduction. [38]
DANFOSS HEADQUARTERS
Place: Nordborg, Denmark
Year: 2010 (realized)
Architect: Schmidt Hammer Lassen Architects
Structural design: Anne Bagger

Introduction
The Danfoss’s headquarters in Nordborg has undergone a major façade renovation as well as a refurbishment and extension of both the reception and the executive and board facilities. Schmidt Hammer Lassen Architects designed the reception building in front of an existing office block (fig. 4.26). The architectural concept was to create a portal structure that covers both the reception area and a small circular auditorium (fig. 4.27).

Structural design and connections
To reduce the structural span of the portal and to keep the depth of the roof low, two rows of columns support the structure. In order to achieve maximum transparency glass columns were designed to support the roof. Circular glass columns were initially considered but tubular sections were not available in the desired shape and length, especially not laminated. Eventually cruciform glass columns made up from multiple-layer laminated glass were used (fig. 4.28).
The glass columns are approximately 5.5 m tall with a cruciform section of 449×449 mm. Each section of the cross is made up from 3 layers of 12 mm low iron float glass with 1,52 mm PVB laminates. Two opposing wings were glued to each side to the one continuous glass plate with a hard adhesive, and the 5 mm gaps on each side of the noncontinuous arms were filled with a clear silicone, resembling the cross-section of the columns for the coffee-house in Göppingen (fig. 4.29).

At both ends of the column great care was taken to ensure that no bending was transferred to the column. The ends of the columns were set in steel shoes inlaid with 10 mm thick neoprene strips, and the steel shoe connections to the floor and roof were detailed so that the column was unrestrained from rotation. [39]

CONCLUSION
In the latter two projects different improvements are made with respect to the cruciform columns for the town hall in Saint-Germain-en-Laye. First of all the arrangement of the glass panes (fig. 4.30): the structural panels of the columns in Saint-Germain-en-Laye are not connected directly to each other. The safety-panels of the sword are in between the structural panels of the sword and the structural panels of the wings. When one safety-panel of the sword breaks it the structural panels are connected discontinuously. In the coffee-house in Göppingen and the Danfoss Headquarters the designers did account for this event and made sure the structural panels where connected directly to each other. The end-results of Göppingen and Danfoss differ a little bit and I think the Danfoss-solution is a little bit better because it is easier to align the glass panes.

A second improvement of the cruciform columns is the transparency. The columns for the Danfoss Headquarters are made of low-iron glass. This results in truly colorless glass columns, where in Saint-Germain-en-Laye and Göppingen the green tint of normal glass is clearly visible.
GLASS COLUMNS WITH OTHER PROFILED CROSS SECTIONS
As described before the main reason to use profiled cross sections is to increase the bending stiffness of a column with the same amount of material. The cruciform shape indeed has a higher bending stiffness compared to a solid column with the same amount of material, but the cross-shape is not the most ideal configuration (fig. 4.31). H-profiles are one of the most efficient configurations and these profiles have been made out of rolled steel, extruded aluminum, poured concrete, or composed out of wood. One negative aspect of the H-profile is the difference in bending stiffness in the two main directions perpendicular to the axial axis of the component. For beams this aspect is actually positive because beams are mainly loaded in one of these directions. Columns are loaded axially and can buckle in both these directions and therefore this aspect is important. For columns it is beneficial to use a profiled cross section with the same bending stiffness in both directions. A box-shaped cross sections satisfies this demand. Glass panels could also be curved before they are being assembled into a profiled column. In this way other configurations like tubular columns are also possible. Eline Ouwerkerk did some research on different cross sections for her graduation project in 2011 [40].
Experiment 1:
Eline Ouwerkerk composed different cross sectional configurations with three or four glass plates of 1000 mm long, 100 mm wide and 8 mm thick (fig. 4.32). Five different configurations were made and glued together with Araldite 2000 Plus 2013, which is a very strong two-component glue based on epoxy resin. These five configurations where subjected to compression tests until failure occurred (fig. 4.33). In table 4.1 the ultimate load, ultimate stress and failure mode are shown. It is quite difficult to draw conclusions from these experiments, because only one specimen of each configuration was tested. The main conclusions Eline Ouwerkerk drew from these experiments are:

- For all cases the ultimate load was substantially lower than the theoretical failure load by buckling, which results from imperfections in the material itself and the assemblage.
- The failure modes were gradual crack growth, buckling and torsional buckling.
- The double web-profile (configuration 2) has the highest ultimate load of 145,3 kN. The H-profile (configuration 3) failed at an ultimate load of 121,9 kN, but this profile consists of only 3 glass plates. The stresses in the H-profile where therefore 50,8 N/mm² against 45,4 N/mm² for the double web-profile.

As a result of these experiments a few parameters can be pointed out which seem to have an influence on the initial fracture and therefore the loading capacity of the glass columns:

- Slight differences in vertical position of the individual glass plates within a configuration
- Properties of the glued joints
- Quality of the edges of the glass

Slight differences in vertical position lead to stress concentrations in protruding panels, because the load is introduced in this panel only and not in all the panels as it should be. If the glued joint has a certain amount of flexibility these protruding panels can slide along the other panels and as a result the forces can be redistributed to all the panels, avoiding stress concentrations. Stiff glues prevent the panels from sliding along each other thus resulting in stress concentrations. Material properties of the glue therefore determine to what extent the forces can be redistributed over the panels.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf.</td>
<td>Ultimate load [kN]</td>
<td>Ultimate stress [N/mm²]</td>
</tr>
<tr>
<td>1.</td>
<td>111,6</td>
<td>34,9</td>
</tr>
<tr>
<td>2.</td>
<td>145,3</td>
<td>45,4</td>
</tr>
<tr>
<td>3.</td>
<td>121,9</td>
<td>50,8</td>
</tr>
<tr>
<td>4.</td>
<td>128,0</td>
<td>40,0</td>
</tr>
<tr>
<td>5.</td>
<td>83,2</td>
<td>26,0</td>
</tr>
</tbody>
</table>
FEM analysis:
To get more insight in the effects of the first two parameters, these are analysed with use of a Finite Element Model. For this analysis the two parameters are studied for an H-profiled column only, because this configuration proved to have the highest ultimate load in experiment 1.

The first parameter is modelled by increasing the differences in vertical position of the individual glass plates. This changes the material properties of the felt next to the protruding glass plate(s), because the felt is compressed more and more, resulting in a higher stiffness of the felt. Increased stiffness of the felt simulates that the protruding glass plates are loaded higher from the beginning than the non-protruding glass plates. Results from this model indicate that tensile stresses occur (in the direction perpendicular to the direction of the loading) due to a difference in the vertical position of the glass plates (fig. 4.34). No tensile stresses occur when the difference in vertical position is 0 and these tensile stresses reach the characteristic tensile strength of glass (8 N/mm²) at an applied displacement of 20 mm for a difference in vertical position of the glass plates of 2.0 mm. The location of the tensile peak stress in the model coincides with the origin of the initial crack in the tested H-profile column in the first experiment. This also holds true for the stress values.

The second parameter is studied by comparing an adhesive with very high Young’s modulus (i.e. 2550 N/mm²) and an adhesive with very low Young’s modulus (i.e. 1.6 N/mm²) (fig. 4.34 and 4.35). Reducing the stiffness of the adhesive results in lower tensile stresses. The stresses are distributed more evenly over the column, which reduces the peak stresses.
Experiment II-A Glue stiffness
For experiment II-A the influence of the glue stiffness, as previously analysed with the Finite Element Model, is investigated with laboratory tests.

Experiment I is repeated for an H-profiled column with a more flexible glue (Hercuseal). From these tests it can be concluded that the prototypes assembled with Hercuseal resulted in a higher load-bearing capacity that the prototype assembled with Araldite (fig. 4.36). The maximum stress value in the columns is on average 58.3% higher than the stress value in the Araldite bonded columns.

From the cracking pattern it can be concluded that the adhesive with a lower Young’s modulus is able to distribute the stresses over a bigger area. The column bonded with Hercuseal breaks very abruptly with cracks over the whole section, which leads to total failure. The column bonded with Araldite shows local cracks, which after a while lead to total failure.
Experiment II-B:
For experiments II-B three different load introduction-systems are investigated (table 4.2 and fig. 4.37 – 4.40):

For the first experiment three different interlayer materials between the glass column and the steel test bench are evaluated. Lead, aluminum and felt are used because these materials have a lower hardness than glass, to gradually introduce the forces.

In the second experiment the connection system is fastened to the surfaces of the glass. The compressive forces are transferred via shear forces which are distributed over a larger surface. Peak stresses in the glass edges are therefore avoided.

For the third load introduction-system the glass column is cast in a steel shoe with polyurethane rubber. In this way the forces are transferred by a combination of compression and shear, which also avoids peak stresses.

From these experiments it can be concluded that the system where the compression forces are transmitted by means of shear forces is the most promising system. It is assumed, by applying this design, that peak stresses at the edges due to fine imperfections are avoided and a difference in vertical position between the glass plates does not limit the structural strength of the column.

<table>
<thead>
<tr>
<th>specimen</th>
<th>Ultimate load [kN]</th>
<th>Ultimate stress [N/mm²]</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felt</td>
<td>173.8</td>
<td>72.4</td>
<td>100</td>
</tr>
<tr>
<td>Lead</td>
<td>80.1</td>
<td>33.4</td>
<td>46</td>
</tr>
<tr>
<td>Aluminum (99%)</td>
<td>49.0</td>
<td>20.4</td>
<td>28</td>
</tr>
<tr>
<td>Glued sides</td>
<td>204.3</td>
<td>85.1</td>
<td>118</td>
</tr>
<tr>
<td>Glued sides</td>
<td>222.0</td>
<td>92.5</td>
<td>128</td>
</tr>
<tr>
<td>Cast rubber</td>
<td>34.7</td>
<td>14.5</td>
<td>20</td>
</tr>
<tr>
<td>Cast rubber felt</td>
<td>53.1</td>
<td>22.1</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 4.2: Load introduction-systems

![Graph showing the load introduction systems](4.37)

![Images of the load introduction systems](4.38 4.39 4.40)
CONCLUSION

In this paragraph lots of other configurations for glass columns were shown. Only cruciform load-bearing columns are used in building projects until now, but for instance H-profiles also have advantageous properties and prove to have higher load-bearing capacity than other profiled columns.

Furthermore some insight has been given in the connections of the individual glass panes to each other in a configuration. When glass panes are assembled into a profiled configuration differences in vertical position between the individual glass panes are practically inevitable. When a stiff glue between the panes is used this difference cannot be reversed, resulting in protruding edges. In these protruding edges stresses are concentrated because of the load introduction to this individual panel (depending on how the load introduction takes place). When a flexible glue is used the glass panes can slide alongside each other, resulting in an even load introduction surface. The introduced loads are distributed over all the glass panes and stress concentrations are prevented.

The load introduction in glass columns is an important issue and is discussed in this paragraph extensively. Three different load introduction-systems are analysed (fig. 4.41) and to transfer the forces through shear forces proves to be a promising solution. The loads are transferred over a bigger surface which avoids stress concentrations. When the forces are transferred over a larger surface, this means subsequently that a large connection is visible, which subsequently results in a lower transparency of the overall structure.

The profiled columns described in this paragraph were all flat. However, this does not necessarily need to be the case. Glass panels could be bended before glued together to make some kind of configuration. Bended glass has a higher stiffness which could be beneficial for local buckling of the flanges of a configuration. It would also be possible to use curved sheets of glass to make tubular columns, but no research has been conducted on this subject yet.

Profiled columns exist of different panes of glass under different angles which results in a lot of lines and views through multiple panes, multiple edges etc. Especially because of the safety-concept for profiled glass columns. The structural glass panes need to be protected from damage and therefore additional ‘safety-panels’ are laminated to the structural panels. Closed profiles can be protected from damage with just one safety-panel. Protruding parts in the cross section of open profiles need to be flanked with two safety-panels. It is needless to say that these additional panels are not beneficial for transparency of the column either.
Profiled columns made of glass panels
4.2 Columns made of glass cylinders

Glass cylinders exist of one glass pane which is curved and it has no edges except for the top and bottom of the cylinder (fig. 4.42). It is an entirely closed profile and therefore only one safety-panel, or in this case safety tube, is necessary. The closed profile furthermore results in an equal bending stiffness perpendicular to the axial axis of the component, which is ideal when a structural member is used as a column. Laminated glass columns have been used only once in a building project in London.
TOWER PLACE
Place: London, United Kingdom
Year: 2002 (realized)
Architect: Foster and Partners
Structural design: Arup Façade Engineering

Introduction
Foster and Partners designed a public space between two new buildings adjacent to the Tower of London. The two buildings accommodate offices, restaurants and shops and are linked by a large glass-covered atrium. A glass cable-net façade which is over 70 m long spanned between these two buildings and the façade did not reach the ground. The space behind the cable-net is a public space and is accessible at all times. The wind loads from the façade is transferred through “glass needles” – 3,56m long borosilicate tubes – to the steel columns supporting the roof structure (fig. 4.43).

Structural design and connections
The needles consist of a load-bearing inner tube and a protective outer “tube” (fig. 4.43). A number of lamination solutions were proposed. Tests of resin laminations failed because of shrinkage of the resin (fig. 4.45). Another option was the use of PVB-sheeting, but the shrinkage that inevitably occurs during the adhesive process cannot be compensated by the rubbing together of the two tubes. This produces extreme forces that result either in tearing of the adhesive layer or damage to the double tubing system. But if one would separate one of the two tubes at the surface line, the resulting shells can cling to the core tube in the shrinking process. This way, you get a laminated glass tube that is inherently free of forces, in which the core tube accepts the load exerted from the outside, while the two shells perform a protective and supportive function. This latter option is chosen for in this project (fig. 4.46). Within the tube a steel tension cable is inserted to resist the wind suction and steel end components provide the connection of this cable and the connection to the rest of the structure. [41, 42]

The Tower Place in London was the first building project were glass tubes were incorporated in the structure. However glass tubes were previously used as compression elements in sculptures.
TENSEGRITY GLASS SCULPTURE
Place: Stuttgart, Germany
Year: 1996 (realized)
Structural design: Patrick Teuffel and Stefan Gose

Introduction
This tensegrity sculpture (fig. 4.47) was designed as a student project at the University of Stuttgart as a joint project between the faculty of Architecture and Civil Engineering. The aim of this design is to demonstrate the possible application of glass as a load-bearing material. Glass is very strong in compression but weak in tension. For this reason it is preferable to use a structural system, where compression and tension elements are clearly segregated, which is the case in a tensegrity structure. The twelve compression elements consist of glass tubes and the tension elements are made of steel cables.

Structural design and connections
For the compression members different cross sectional profiles were studied using plates, beams or tubes of glass. The use of tubes is more appropriate to avoid buckling problems. At each end of the tubes four, six or eight cables had to be fixed to the joint. Cost and time were the main issues for the design of the joint. For this reason a joint was used, where four steel plates were welded to a strut, which was connected to a base plate of the joint (fig. 4.48). Joints made of cast steel where initially considered, which would have been more elegant, but for cost and time reasons this was not possible. The connection between glass and steel plates are glued using a layer of epoxy resin. This was done to avoid local stress concentrations resulting from the direct contact between steel and glass.
Experiments
The buckling capacity of the glass tubes was determined using numerical methods but the capacity of the connection between and glass was unknown and so experiments were carried out. Based on a calculated serviceability axial load of 20kN and an aimed safety factor of 3.0 the experiments should show a capacity of 60kN. The use of different materials for the layer between the steel plate and the tube were considered:
- Polyurethane
- Epoxy resin

For these experiments tubes with a diameter of 130mm and a thickness of 6mm were used. The specimens were 300mm long (fig. 4.49).

In a first experiment a PU-glue was chosen as it is used in the automobile industry to connect glass and steel. The result was very unsatisfactory although a load of 60KN could be applied to the glass tube. However the glue was too soft and detached after the loads were taken away. Therefore additional experiments were carried out using a 2-component epoxy resin. In this case an axial load of 400kN could be applied to the joint without any failure of the glass or the glue. [43]
FURTHER RESEARCH
Besides these two examples of a tubular glass building component and components for a glass sculpture Fred Veer, amongst others, conducted some research into the development of a tubular glass column. [44, 45, 46] The lamination process, the compressive strength and the end connections where all points of interest in his research.

Lamination process:
One aspect of this research is the lamination process. The columns used in Tower Place London used one core tube, PVB as an intermediary material and two half tube shells that together form the outer “tube”. The shells protect the inner tube against impact damage, but if the load carrying inner tube cracks the outer tube could split apart along the seam resulting in the collapse of the whole structure. This is the reason Fred Veer focused on developing a new kind of resin to laminate two fully intact tubes.

First of all a resin was developed, where exposure to UV light starts the polymerization reaction. The resin only starts to harden when it is exposed to UV light. The shrinkage during polymerization is compensated for by feeding new resin from the top. If the process is conducted at the right speed a solidification front moves up the tube resulting in a void free interlayer between the glass tubes.

Furthermore a custom made low shrinkage and highly adhesive resin was developed. The concept is the same as for the UV light catalyzed resin: carefully control the curing process. Yet this time without the use of UV light. Intensive experimenting with a range of developed resins eventually led to a resin suitable to manufacture columns easily and consistently with close to perfect mechanical and visual results.

These new developments made tubular columns out of two intact tubes possible (fig. 4.50 and 4.51). Both of the glass tubes can be used to carry the load and the resin will slow down and stop cracks. The resin furthermore keeps the fragments of broken glass together after failure resulting in a high post-breakage load-bearing capacity. The damaged glass tubes can still carry loads until the complete cross-section at a particular height delaminates. [44, 46]
Compressive strength:
The compressive strength of borosilicate glass tubes was researched by Fritz-Dieter Doenitz et al [47]. Compressive tests on tubes with dimensions up to 400 mm external diameter and 10mm wall thickness produced strength values of at least 400 N/mm². On test pieces of smaller diameter strength values up to 800 N/mm² were possible without observing any internal failure of the material.

Fred Veer et al also researched the compressive strength of borosilicate glass (table 4.3 and 4.4). In their experiments a nominal initial crack stress as low as 11,8 N/mm² was found (complete failure of this specific specimen occurred at 40,6 N/mm²). This value was found for a 1500 mm tall specimen with an outer tube diameter of 120 mm inner tube diameter of 95 mm and a wall thickness of 5mm. The explanation of this big difference is quite a simple one. Due to the manufacturing process, the ends of the tubes are distorted and are turned inwards a bit. This introduces bending stresses when the column ends are loaded which is highly unfavorable. The tubes in the experiments of Fritz-Dieter Doenitz et al have been very carefully grinded until the ends were completely flat. Bending stresses are avoided this way, and it furthermore allows for a precisely fitting joint piece, which evenly spreads the compressive stresses. In the case of the columns of Fred Veer’s research, a silicone rubber sheet was placed between the glass and the acrylic joint piece. This was however, too soft to avoid peak stresses in the edge of the tubes. The combination of these effects is expected to be the cause of the huge difference in experimental results.

An important fact discovered in all these experiments is that all prototypes have a high post-initial crack strength and therefore a safe failure behaviour. The maximum strength is for all specimens at least twice as high as the initial failure strength [45, 46].

| Table 4.3. Dimensions compression test specimens Fred Veer et al |
|---|---|---|---|
| specimen          | Outer diameter [mm] | Inner diameter [mm] | Wall thickness [mm] | Cavity width [mm] |
| 1200 mm column    | 110                  | 90                   | 5 and 3             | 2                 |
| 1500 mm column    | 120                  | 95                   | 5                   | 2,5               |

| Table 4.4. Results compression tests Fred Veer et al.   |
|---|---|---|---|---|
| Prototype         | Initial failure load [kN] | Ultimate load [kN] | Initial failure stress [N/mm²] | Ultimate stress [N/mm²] |
| 1200 mm column    | 73                        | 146                  | 28,9                          | 57,8                  |
| 1500 mm column    | 61                        | 196                  | 18,0                          | 57,9                  |
|                  | 40                        | 137                  | 11,8                          | 40,6                  |
End connections:
In the experiments of Fred Veer et al attention has been given to the end connections. Two types of joints were used (fig. 4.52):

- Prototypes with the glass edges of the column resting on PMMA sheets.
- Prototypes with PMMA heads/bases adhesively bonded to the inner tube.

PMMA is a material with a significantly lower hardness and Young’s modulus than glass. Therefore it can easily deform and function as a hinged connection between the column and the floor/support. Table 4.5 and 4.6 show the dimensions of the specimens and the average compressive strengths of the various specimens.

The specimens directly supported on a sheet of PMMA have substantially higher initial failure strengths and higher maximum strengths. The reason for the difference in strengths is that the adhesive that is used for the prototypes with glued endings is not properly divided along the circumference and thus has weak and strong spots causing local peak stresses. Glass is sensitive to local peak stresses and thus failure of the glass tubes starts earlier when adhesively bonded on heads/feet are used. However, both types of prototype have a large post-initial crack strength and therefore a safe failure behaviour. [46]

Table 4.5. Dimensions end-connection test specimens

<table>
<thead>
<tr>
<th>specimen</th>
<th>Outer diameter [mm]</th>
<th>Inner diameter [mm]</th>
<th>Wall thickness [mm]</th>
<th>Cavity width [mm]</th>
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<tr>
<td>150 mm column</td>
<td>40</td>
<td>31</td>
<td>1,5</td>
<td>1,5</td>
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</tbody>
</table>

Table 4.6. Results end-connection tests.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Initial failure stress [N/mm²]</th>
<th>Ultimate stress [N/mm²]</th>
</tr>
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<tr>
<td>Plane PMMA</td>
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<td>154</td>
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<td>90</td>
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<td></td>
<td>60</td>
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<tr>
<td>Glued PMMA</td>
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<tr>
<td></td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>
CONCLUSION

For the tubular glass columns it can be concluded that two different lamination processes are available when two tubes (an inner tube and an outer tube) needs to be connected: lamination with resin or a thin PVB-foil (fig. 4.53). When the tubes are connected with a thin PVB-foil one of the two tubes needs to be split in multiple parts or shells, due to the shrinking during the adhesion process. With use of the resin both tubes can be completely intact. A special UV light catalyzed resin or low shrinkage resin needs to be used, to manufacture columns easily and consistently with close to perfect mechanical and visual results.

Furthermore two types of end-connection details are developed: one where the glass edges of the tube rest directly on the substructure (often with an intermediary in between). The other option is to glue the inner tube to the substructure. Another option is the encasement as described for the profiled columns. In the experiments of Fred Veer [46] the first option appeared to have higher initial failure strengths and higher maximum strengths. However all the forces need to be transferred through a small surface area of the glass edges. Dividing the stress over a larger surface area (i.e. the inner/outer surface of the glass tube) will lead to lower stresses in the glass tube. If the inner tube is glued to the substructure, the glue could be applied to a larger surface area. Experiments of this latter option with H-profiled columns led to promising results in Eline Ouwerkerk’s research [40], however the results of Fred Veer’s experiments on this connection-type with tubular elements were not that promising. One big difference between the connections in the two experiments was the surface area at which the glass was glued to the substructure. In Fred Veer’s experiments it was a really small area, compared to the connection in Eline Ouwerkerk’s research. The specimens in Fred Veer’s experiments failed because of local peak stresses in the glue, which was not properly divided along the circumference. To counteract this problem another type of glue and a larger area of appliance of the glue might lead to more favourable results.

The compressive strength of glass tubes is not a well defined value. Different experiments led to large differences in results and the strength values are highly dependent on the connection details which were used in the experiments. Furthermore for appliance as a column slender tubular structures could fail due to Euler buckling. This phenomena is not analysed yet in the experiment, so further research on this topic is necessary.
4.3 Columns made of solid glass rods

Another component the glass industry can provide designers with are solid glass rods. These circular rods have a limited diameter so when they are used for full size columns it is necessary to construct bundles of these rods (fig. 4.54). Bundles of glass rods are not used as columns yet, but glass rods are used as small-scale compression elements in buildings: compression elements in a truss for the Z witserleven office in Amstelveen, and in an undertensioned beam for an entrance building of a parking garage in Haarlem.
ZWITSERLEVEN OFFICE
Place: Amstelveen, the Netherlands
Year: 1996 (realized)
Architect: De Architekten Cie (Pi de Bruijn and Yushi Uehara)
Structural design: ABT (Rob Nijssse)

Introduction
For the new headquarters of the ‘Zwitserleven’ insurance company the Architecten Cie designed an H-shaped building with at the lower level a central entrance corridor, meeting rooms, an auditorium and a restaurant. For the restaurant the architects had a maximum-transparency roof in mind. The span of the restaurant roof was only about 5 meters. Several alternatives were developed for the roof beams but in the end the architect decided that the solution was a truss with glass compression elements (fig. 4.55). [12]

Structural design and connections
As with all trusses in a one-field span the nature of the forces in the diagonals is always either tensile or compressive. Normally all structural members in the truss are of the same material and dimensions despite the location along the truss or the direction of the force. In this case minimized high-quality steel bars were used for the tensile forces and all members in compression were designed in glass. In this way the nature of the internal forces is clearly shown in the design of the truss and a W-shaped truss results in a nice rhythm of steel and glass.
The top member of the truss is a hollow steel pipe with a 120 x 80 x 5 mm cross-section (fig. 4.56). The bottom chord and all diagonal tensile elements were made of steel bars with a diameter of 10 mm. The glass elements were comprised of solid borosilicate rods, 30 mm in diameter. In case of breakage of one of the glass rods the upper steel profile would be strong enough to carry (on its own) the roof with a 1.1 safety factor. In such an emergency the roof would deform significantly but would not come down, so that repairs could be made.

Glass is an ideal material for compression elements, because of its high compressive strength. Furthermore buckling plays an important role for compression elements, so in the calculations special attention was given to this buckling phenomenon. Experiments proved that the capacity of the glass rods was three or four times the necessary capacity. Furthermore to avoid clamping moments the glass diagonals were hinged perfectly. Steel caps were glued to the ends of the glass rods and connected in a central node, consisting of stainless steel disks (fig. 4.57 and 4.58). It is vital to avoid direct contact between glass and steel and therefore neoprene rings and pads were inserted into the stainless steel cap. There is no physical connection between the stainless steel cap and the disks and only by applying the tension-forces in the steel bars the truss becomes stable and forms a unity. [12, 31, 48, 49]
LOAD-BEARING GLASS COLUMNS

RAAKS GLASS CUBE
Place: Haarlem, the Netherlands
Year: 2011 (realized)
Architect: Kraaijvanger Urbis (Hans Goverde)
Structural design: ABT (Rob Nijssse)

Introduction
On the Raaks square in the old city center of Haarlem on top of an underground car park garage a glass entrance building was designed by Kraaijvanger Urbis (fig. 4.59). This glass building acts as a recognizable feature on the square and has a distinct appearance from all four sides: It is an ‘all glass’ cube with dimensions of 7 x 7 x 7 meter which houses some stairs and an elevator. [50]

Structural design and connections
The roof consists of nine heat strengthened glass panels (2,35 x 2,35 m) supported by beams that rest on the glass fins in the façade. The façades also exist of nine panels and are stacked on top of each other for gravity and supported by the glass fins for the wind. The roof beams consist of an undertensioned steel hollow section (80 x 140mm, t = 6mm). This is in some way in contradiction with the wish to make an all glass structure, but the detail where the glass beam meets the glass fins of the façade is a notoriously difficult detail. Therefore a steel hollow section, which is as slender as possible, is chosen. To improve the stiffness an undertensioned beam with a steel cable (d = 8 mm) was designed. An all glass rod with a diameter of 30 mm and a length of 400 mm separates the cable from the beam (fig. 4.60). The glass rod in the undertensioned roof beam is a solid rod made out of borosilicate glass. Again clamping moments are avoided by making a clear hinge in the connection between the glass and the steel elements. Hereby the glass rod is only loaded by pure compression. The stresses in the glass rod are about 15 N/mm² in the ultimate limit state. [25, 51, 52]

Relevance with respect to glass columns
If designers want to use glass columns of story height multiple glass rods should be bundled because the diameter of these glass rods is limited. This concept of bundling glass tubes is worked out for a column in the ABT-office in Velp.

Columns made of solid glass rods
BUNDLED GLASS COLUMN ABT-OFFICE
Place: Velp, the Netherlands
Year: 2000 (design)
Structural design: ABT (Rob Nijsse)

Introduction
As with lots of innovations, pioneers become their own clients creating opportunities to design and construct innovative building components. This is also the case for Rob Nijsse and the bundled glass column for the office of ABT. He designed a glass column to replace a concrete one in the ABT building in Velp. The perfect place for the glass column is near the reception desk between the restaurant and the main building.

Structural design and connections
The glass column that is opted for is the bundled type. The column consists of 7 solid rods round 30 mm, where six outer rods surround one central rod. The borosilicate glass rods are held together by UV-activated glue, which also provides protection against buckling for each rod individually. The total diameter of the column is approximately 90 mm.

Special care is taken to avoid bending. The top detail is shaped like a rolling hinge (fig. 4.61). At the top and bottom of the glass column pads of Polyoxymethylene (POM) provide elasticity and a uniform distributed load-introduction (fig. 4.62).

After the concrete column is replaced for the glass one, it will provide support for a large concrete beam. This beam would be reinforced with an external steel structure. Steel angular profiles are connected to the concrete beam with chemical anchors. The beam would be able to prevent progressive collapse in case of an emergency. The beam is strong enough to carry the total loads, in case the column collapses, although the inherent deformations would be considerable. [12]
CONCLUSION
In this paragraph it became clear that to construct a column, solid glass rods could also be used. When a storey-high column is opted for multiple solid glass rods need to be bundled together. The connection of the individual glass rods to each other is important and is necessary for the column to act as a unity, where the individual rods are prevented from buckling by this connection with the other rods. This connection can be made with glue or a resin, or nowadays progression is made with the production technique of welding glass (fig. 4.63). The glass rods are heated locally and at the points of contact with each other the glass is melted and welded together.

As always the connection of the column with other building components needs a lot of attention. The load introduction into the column is an important aspect in this connection detail. With pads of POM or neoprene stress concentrations are avoided and special care is needed to make sure no individual rods protrude from the other. Otherwise if the protruding part is too large, stress concentrations are inevitable and the stresses are likely to result in failure of the column. The previously described option with adhesives is difficult because of the geometry of the cross-section. An encasement however would be an option with potential, because it can be independent of the geometry of the cross-section.

Bundling of rods

Resin

Welding

4.63
4.4 Columns made of cast glass

As described before, the glass industry can provide different kind of components: flat panels, tubes, solid rods. If these configurations are unsatisfactory for the designer he/she can make use of the fact that glass can be melted and is liquid in the production process. This property makes it possible for glass to be cast into a mould (fig. 4.64). In jewelry and artworks, casting of glass is a well-known production process. For architectural purposes casting glass is used to create glass panels with different kinds of surface textures (fig. 4.65). Furthermore Pilkington Profilit (fig. 4.66) is a well-known product: this is a product with an U-shaped cross-section which is produced by casting of glass. However these products are used as an infill-material, rather than a load-bearing component. Nevertheless this production process could be adapted and used for structural components as well (fig. 4.67). Little to no research is conducted in this aspect of glass columns and a lot of questions remain. To what dimensions can glass be cast into a mould? What are the load-bearing capacities of cast glass? Is the resulting structure still transparent?
Chapter 5:
OVERALL CONCLUSIONS
OVERALL CONCLUSIONS

In the first chapter the contradicting wishes and desires with respect to columns of architects and structural designers became clear. Architects, in general, do not like columns and they want to use as few columns as possible and make them as slender as possible. Structural designers do like columns because they reduce the span of beams and floors and make structures less complicated.

To overcome these contradicting wishes and desires with respect to columns, two solutions are available: columns could be made less present, or more attractive. In chapter two and three the use of glass as a building material, first primarily as an infill material and later on as a structural material, was discussed. The use of glass as a structural material developed from tertiary structures, like handrails and balustrades, to primary structures like beams, walls, and columns. The load-bearing glass column is the least-developed structural element, but in a handful of projects glass columns are implemented in different configurations. In chapter four all kinds of possible configurations of glass columns were discussed, which proved that both solutions (make them less present, or more attractive) are possible with glass columns.

Glass is naturally transparent and therefore distinguishes itself from other materials like wood, steel and concrete etc. This aspect makes it possible for columns to be less present, because in some configurations one can look right through a column of glass. But although glass is transparent, it is not invisible. Glass has the quality that it plays with light: it shimmers, shines, reflects and distorts light. This aspect makes glass columns, in my opinion, also more attractive than for instance steel or concrete ones. The increase in the attention of architects and designers in glass and the applications of glass in buildings, whether it is used as an infill material or a load-bearing material, substantiates my opinion. How glass interacts with light depends on the shape of the column and of the parts of which the column is assembled. Flat glass panes interact different with light than glass cylinders or solid glass rods. And by using the different glass elements (panes, cylinders, rods) all kinds of configurations and appearances of glass columns are possible, which makes the architectural possibilities of glass columns virtually endless. This especially holds true for the stacked glass column, because due to variations in the shape of individual panes or by translating and/or rotating the panes all kinds of configurations become possible.

The goal of this research project is to contribute to the development of the knowledge on glass columns. Some concepts, like the profiled columns made of glass panels or columns made of glass cylinders, have been studied quite a bit before. The knowledge on concepts like the stacked column, the bundled column and the column made of cast glass is less developed. From these three concepts, the stacked column is the most promising concept in order to make use of the high (theoretical) compression strength of glass: the loads can be introduced in the center of the glass panels, rather than on the edges. And because the strength of the center is substantially larger than the strength of the edges, stacked columns will have a relatively high load-bearing capacity. Furthermore the architectural possibilities of the stacked column are virtually endless, by making variations in the shape and/or size of the basic panel and rotations/translations between the panels.

Hardly any research has been conducted into the load-bearing capacity of stacked glass columns. Important aspects for the load-bearing capacity are the connection with other building components (i.e. how loads will be introduced in the columns), the stabilizing-strategy of a stacked column and the brittle failure-behaviour of glass. In ‘part 2 – the stacked column’ special attention is paid to these aspects.
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<td>4.32</td>
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<td>4.33</td>
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<td>4.34</td>
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<td>4.36</td>
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