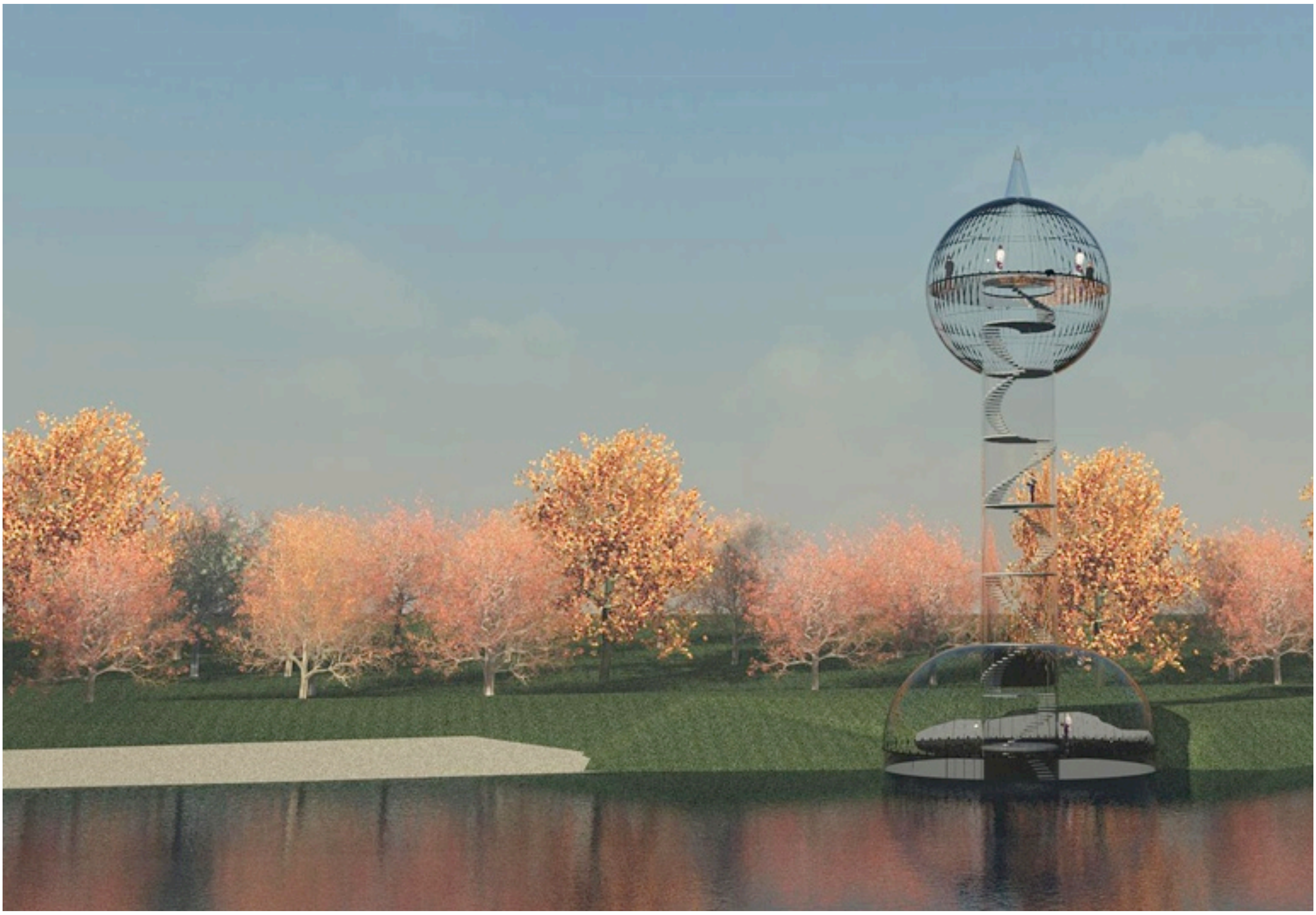
A search for structural applications of transparent plastics in the building industry



M de Graaff

Delft University of Technology

Challenge the future

Noch ist der Traum, völlig ohne unterkonstruktion selbsttragende transparente Hüllen zu bauen, nicht ganz realisierbar – außer in Computeranimationen.

K-tec, thermoforming solutions

Delft University of Technology,
Faculty of Civil Engineering and Geosciences

Master Building Engineering – Structural Design

Pieters Bouwtechniek Delft BV

Delft, june 2012

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Preface

This report is made in completion of the master Building Engineering – Structural Design at the faculty of Civil Engineering at Delft University of Technology. It contains the results of a research into transparent plastics and ability to being used in building structures.

The subject opened a new world for me, as a Civil Engineering student I did not get to know much about plastic materials and their behaviour. It came to me during my internship at Pieters Bouwtechniek when I was involved in the design of a façade for which one of the alternatives was a façade of transparent plastic tubes. When searching for information I found out that it was hard to find the necessary data for making a reliable design. Simultaneously I discovered that a graduation project was open about the behaviour of transparent plastics and their suitability as a building material. My curiosity was provoked. The additional case study made this subject for me an ideal combination between gaining in-depth knowledge and a design assignment.

The result of about a year of hard work is a complete overview of the properties, behaviour and abilities of transparent plastics that will be certainly helpful to further research. I hope that the case study will be inspiring both to the building industry and to the plastics industry and that we will all be able to enjoy the experience of completely transparent buildings in the future.

I would like to thank my graduation committee, prof.ir. R. Nijsse, dr.ir. F. Veer, ir. R. Schipper and ir. R. Doomen for their guidance and support during the process and the attendance of all meetings with great enthusiasm.
Besides there were a lot of other people and companies that helped me out with ideas and by answering my questions, thank you all.

Then I would like to thank Pieters Bouwtechniek Delft for providing me with a good working environment, the necessary facilities, a flexible side job and not to forget: nice company during my master thesis project. It will be a pleasure to keep working for and with you in the future.

Last but not least a word to my family and friends, especially the last months they came on a second place, thank you all for the support.

Mirte de Graaff

Delft, june 2012

Summary

Transparent building appeals to imagination. The availability of glass in all shapes and sizes is continuously increasing; architects thankfully make use of the given opportunities. But glass has also some specific disadvantages, as it's extreme brittleness. Luckily more materials are available that offer the desired transparency; transparent plastics might be a promising addition to the world of transparent building.

The transparent plastics that are considered most suitable for building applications are Acrylic (PMMA) and polycarbonate (PC). In this research the behaviour of these transparent plastics is analysed and it is investigated whether and how the materials can be used in building structures, to further explore the dream of completely transparent buildings.

Transparent plastics
Plastics are polymeric materials; they consist of long chainlike molecules called polymers. The transparent plastics PC and PMMA possess very good mechanical properties as strength and stiffness, compared to other plastics. Thereby the creep and weathering resistance of both materials are relatively high. PMMA already took over the market of large aquarium walls. The material is very clear and can be cast into large blocks. These can be bonded with a special technique to virtually unlimited sizes. PC is often used for (safety) glazing in bus stops, ice hockey boardings and greenhouses as it has a high impact strength and toughness. Because of the limited available production techniques for polycarbonate only thin-walled elements can be made, up to about 15 mm.

Plastics show a complex mechanical behaviour, quite different to conventional building materials. This, with the lack of complete design guidelines, makes the application more complex, especially in structural applications.

Visco-elastic behaviour
Transparent thermoplastics show a mechanical behaviour called visco-elastic behaviour, which causes two phenomena known as creep and relaxation. Creep is the fact that the material keeps deforming when subjected to a constant stress level, relaxation means that stresses will decrease over time when the material is subjected to a constant strain. Additionally the stress-strain relation of thermoplastic is dependent on the temperature. As temperatures rise, the strength will decrease while the toughness increases. The visco-elastic behaviour appears very hard to model precisely; all design values are therefore determined by the analysis and extrapolation of test results.

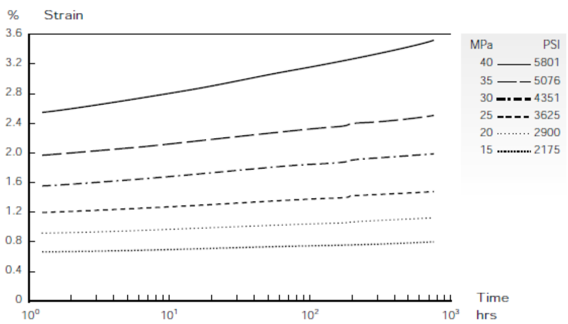

Figure 1: Strain in time for different stresses PC (at 23 °C) (GE Plastics 2004)

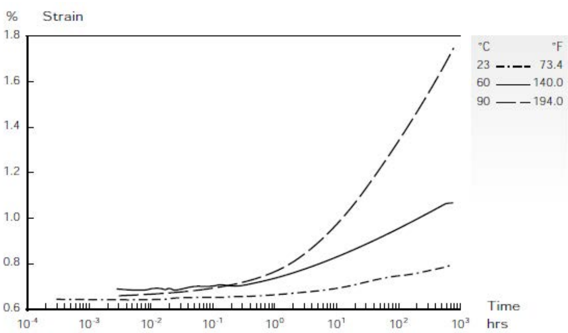

Figure 2: Strain in time for different temperatures PC (at 15 MPa) (GE Plastics 2004)

Failure
The failure of a transparent plastic structure can be caused by configuration failure or material failure. Configuration failure is a stability problem; when slender elements are subjected to compressive loading buckling can occur.

Material failure of the selected transparent plastics can be brittle or ductile depending on the service temperature, strain rate and even thickness of the material. In general acrylic will fail brittle and polycarbonate ductile but circumstances can thus change this behaviour.
A typical plastic material failure is the occurrence of crazing. Sustained tensile stress, above a certain limit value, can cause small hair-cracks perpendicular to the load direction over time. In the early stadium they will be hardly visible and filled with polymeric material. If not cured in time they will propagate and form real cracks.

Design rules
The specific production and properties of transparent plastics will lead to some design rules.
As polycarbonate can only be produced in relatively thin sheets, it is important, when stiffness is desired, to use a stiff shape for the structure. For instance by using ribs, (double) curvature or corrugation. The slender elements are very suitable to resist in-plane stresses.
For acrylic, elements with a large load-bearing capacity can be produced more easily as virtually unlimited sizes are producible. These elements will be most suitable to resist compressive loading, which also eliminates the risk of crazing.
For all designs with transparent plastics, repetition will be a key word. By repeating elements the number of (expensive) moulds can be limited and single elements become cheaper.

Detailing
Much attention should be given to the design of details. For example transparent plastics have a high thermal expansion coefficient compared to other building materials. This could lead to thermal stresses in the connections. Various bonding techniques are available for connecting different plastic elements to each other and to other building materials. Adhesive bonding appears to be the most suitable method as they distribute the stresses over a relatively large surface and can achieve a strength very close to the material strength for all types of loading. A disadvantage is that these kind of bonds are very labour-intensive and have to be executed very securely to actually achieve the reckoned strength.
For acrylic-acrylic connections a special method is the use of polymerizing glue. This can produce almost unnoticeable connections, both mechanical and optical, by forming new polymeric chains between the connected elements.
All conventional structural connections as bolts and screws are also applicable but with a higher risk on stress concentrations. Another possibility distributing the stresses is the method of clamping, which is often used in window frames.

Case study
A design study is performed to get more feeling for the design with thermoplastics. To be able to use the freedom of shape and to explore the limits of the materials an observation tower is designed. An entirely transparent tower, made only from acrylic and polycarbonate.

The observation tower consists of an acrylic tube core structure leading the visitors with acrylic landings and stairs that are cantilevering from the core wall to a polycarbonate sphere structure in which the main observation platform is located. The ground floor is enclosed by a polycarbonate dome structure and below ground surface an observatory room is located where visitors will be able to experience the soil and water life all around.
All applied loads and load cases are determined according to the Eurocode standards.

Design values
The basis of each design value is the regarded material property, which then is divided by a material safety factor and three reduction factors; one to account for the desired service life, one for the maximal service temperature and the last for the environmental conditions during application. Reduction factors are determined from test results found in literature.

Final design
With a combination of hand calculations and 3D computer modelling all structural parts are designed and analysed. For most parts the stiffness is leading in the design, as expected by the low modulus of the materials in relation to the strength.
The deflection at the top of the tower due to wind loads determines the dimensions of the core structure; the stresses will not come near the design stresses for both tension and compression. The same holds for the floors and stairs of acrylic, they all are dimensioned on their maximal deflection.
For the sphere structure peak stresses appeared to occur around the supports, locally material thicknesses had to be raised to keep the stresses within the maximal allowable stresses. Due to the extremely stiff shape of the sphere structure deformations will be low for all load cases, the use of ribs will reduce the risk of buckling.

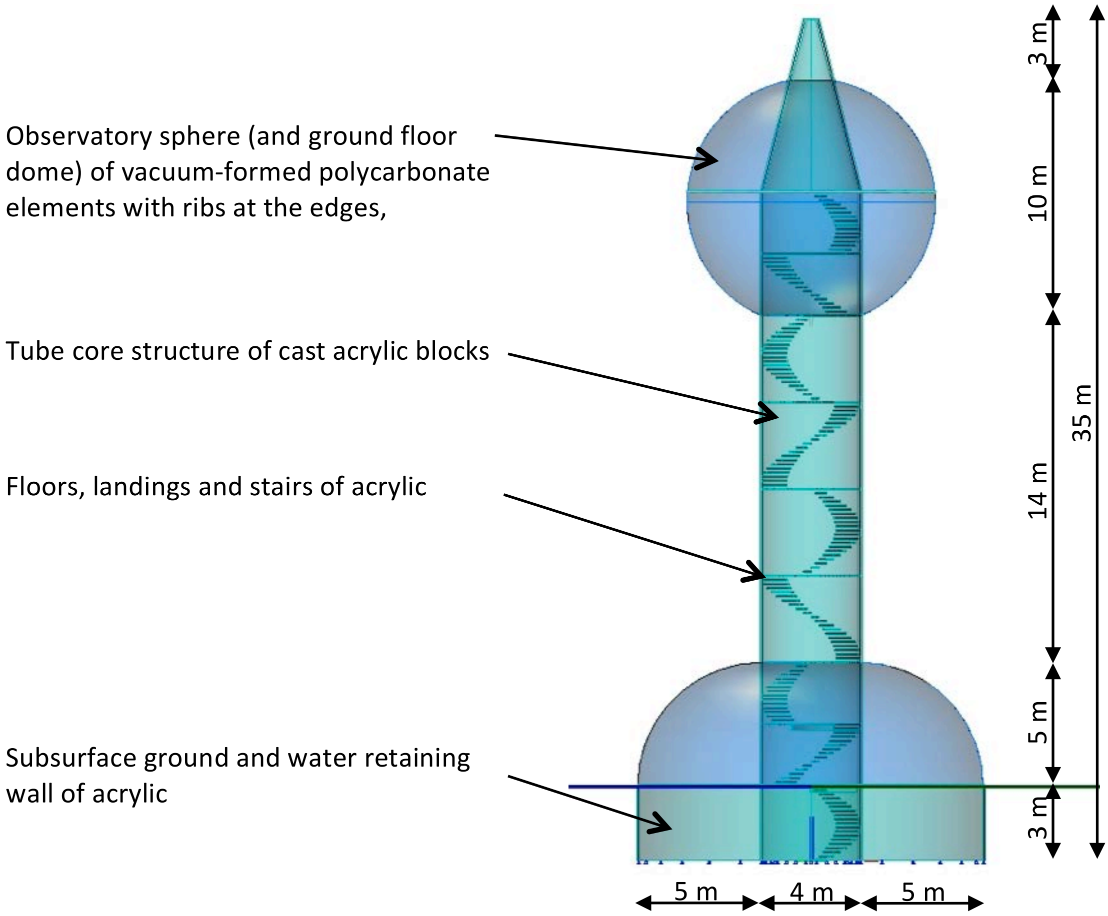

Figure 3: Overall dimensions

The final design is a structure in which the materials are deployed in an efficient way:
- The tubular core structure forms simultaneously a closed façade.
- The core material is brought away from the centre of gravity, forming an efficient and slender structure.
- Stairs, landings and floors could all be designed in transparent plastics as well.

- The use of ribs and double curvature in the polycarbonate shell elements allows for thin wall thicknesses.
- At the vulnerable ground floor level the main structure is protected by the polycarbonate shell elements. The polycarbonate is more vandal proof than acrylic by its high impact resistance and better fire resistance.
- The acrylic core structure will provide enough structural rigidity to keep the tower upright for the required evacuation time of 15 minutes in case of a fire.

The design demonstrates that it is technically possible to design building structures in acrylic and polycarbonate.

Further research
Several aspects of the structure require further research.
- The dynamic behaviour. Preliminary calculations based on the Eurocode standards result in too high accelerations at the top platform. Possibly measures should be taken to increase the stiffness or the damping capacity of the tower.
- The stability of the sphere structure. The relatively small support lengths around the core result at the top in high compressive ring stresses making the shell sensitive to buckling. Research to the specific buckling behaviour of transparent plastics and ribbed shells is necessary to determine the desired safety factor on buckling.
- Standard details. The now proposed details are preliminary designed and need to be investigated further. Testing and 3D modelling will be required to get a detailed image of the load capacity and stress concentrations in the bonds.
- Fire safety. Statements are now based on scarce research results. Tests on full-scale core segments will give more information about the behaviour of thick acrylic blocks when exposed to fire.
- The production process. With help from the plastics industry the borders of production could be stretched. The development of techniques that allow for larger and thicker polycarbonate elements would be promising.

Conclusion
Altogether transparent plastics offer promising possibilities for building design but still a lot will have to be investigated further before they can really be used for load bearing structures.
Building regulations are not yet ready for plastics either, test and research programs will have to be started to prove that polycarbonate and acrylic can be suitable and reliable materials during a long enough design life for building applications.
This will be a trajectory of years but other materials have come that long road before, plastics are just lagging behind which. The development of suitable building products, details and optimal material compositions will certainly progress faster once the plastics industry recognises the opportunities of investing in this new product market.

Transparent plastics will probably never become a threatening substitute for standard glazing applications, but they can be an interesting addition in the world of transparent building. Offering new possibilities in free form design and transparent building without substructures. They may become a worthy colleague to glass in the future.

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1 Introduction

Architects like to explore and stretch the limits of technical possibilities. Building shapes and sizes get more extreme. A great challenge lies with the structural engineers, concerning the realisation of these ideas; the search for new materials and new ways of application to allow for a continuously enlarging freedom of design.

A completely transparent building without additional structural elements is one of the ideas that appeals to imagination. Through the years a lot is undertaken to reach that goal or at least approach the image. The results can be seen in the development of structural glazing, curtain walls with minimal support and even small buildings or pavilions made entirely out of glass. The solution to transparency is obviously sought in glass nowadays.

However the use of glass goes with a lot of difficulties as well. The material is very sensitive to small irregularities and stress concentrations. Glass is very stiff, which is an advantage concerning bending deformations, but this stiffness restricts the possibility of absorbing impact loads. The brittle fracture behaviour is as a result very sudden and still quite unpredictable.
The available size of glass plates is still restricted and because of the low allowable tolerances and the stress sensitivity silicon joints are always necessary between the plates. These will be visible at all times. Thereby the freedom of shape is expanding but double curved glass plates are still very expensive.

Time to search for other solutions to the dream of completely transparent building. A solution might be found in the use of other transparent materials, like the transparent thermoplastics acrylic and polycarbonate. Thermoplastics are lightweight, in general less brittle than glass and can be produced in all kind of shapes and sizes with typical plastic production processes as injection moulding, casting or extrusion.
At this moment plastics can be already found for instance in safety glazing applications, airplane windows and large aquaria in zoos.
In the building industry these are still unusual materials, the occasional applications are mostly confined to facades and skylights. De design experience and material knowledge is lacking and hard to gain as very limited design guidelines and standards are available. Thereby thermoplastics show visco-elastic behaviour, which means that properties as strength, stiffness and strain are as well time as temperature dependant. This behaviour is causing creep and relaxation and makes it difficult to predict long-term deformations and allowable stresses.

Altogether plastics are not yet an obvious answer to transparent building. And will not often be presented to an architect or client as possible building material in the design stage of a building project. But these are materials with a certain potential in creating more design freedom.

In this research the question is asked whether and how these materials can be used in the building industry. In which the favourable properties can be ultimately utilized and the less favourable properties can be eliminated by applying the transparent plastics in a way that suits them best.

Some interesting quotations related to transparent building and the use of plastics

"To date, only the design of acrylic panels in aquaria is well enough understood where their selection can be based alone on finite element analysis (FEA) and an empirically-selected working stress level. This has been feasible because, in this case, the engineer only has to consider in his design a benign environment, a steady loading condition, and an absence of restraint on the weight of the structure allowing him to use a single low-working stress level for acrylic aquaria of any configuration."
(Hydrosight 2012)

"The material properties of plastics can vary widely, but transparent plastics usually have a Young's modulus of approximately 1 to 3 GPa. Additionally, they can show creep and visco-elastic behaviour, which makes them not an obvious choice for main load bearing members in a building structure, as they would require large section dimensions to counteract these effects and limit deformations."
(Bos, Veer and Heidweiller 2006)

In his inaugural lecture (1992) Prof. dr. ir. Mick Eekhout called on his audience to search for the imaginary building material Zappi. This should be as transparent as glass and as strong as steel. The research that followed was mainly focused on glass, for example on reinforced glass. Fred Veer: "We didn't find transparent steel, but glass can now be used as reinforced concrete and is in that position stronger than concrete. A lot more is possible with glass than could be hoped for about 20 years ago. Available sizes keep growing, less support is needed due to smart ways of strengthening glass due to which it can be used structurally. But Zappi is not yet found."
(Integraal 2011)

"In 1962, when this thesis is written, only few examples of the structural application of plastics in the building industry could be mentioned. Most of these were of fairly moderate size and of incidental character. At that time research-programs providing for systematic investigations in this field were almost lacking.
One may wonder, which factors have caused the - initially rather reluctant - acceptance of plastics material by the building industry, since a number of plastics have many characteristics which make them highly suitable as a primary structural material:
- the favourable strength-to-weight ratio
- the good, and sometimes excellent - corrosion resistance
- the low heat conductivity
- the amenity to prefabrication
- the possibility of adaption to aesthetic, psychological and technical demands in relation to colour, surface - texture, form-giving, light transmission, and so on."
(Huyberts 1971)

Plastics offer advantages such as lightness, flexibility in shape and size, impact resistance, ease of processing, transparency, resistance to corrosion etc. A combination of properties that is not available in any other materials.
The ever increasing use of plastics in all kinds of applications means that it is essential for designers and engineers to become familiar with the range of plastics available and the types of performance characteristics to be expected so that these can be used to the best advantage. (Crawford 1998)

1.1 Problem Definition

The wish for transparent building exists but transparency in building still includes the acceptance of structural sealant, mullions and/or spiders obstructing total transparency. Traditionally transparent building implies using glass. The choice for other materials is not obvious because of unfamiliarity and lack of knowledge and applicable building standards. Experience with plastics on large scale outdoor projects is very limited but it is not unthinkable that these materials can offer possibilities that glass can't.

The problem of designing with plastics is the way to work with the unusual characteristics. A lot of properties depend on temperature and duration of the loading. Thereby the material has a significantly lower stiffness then the building materials we are used to. Other characteristics are:

- Under constant load the strain will increase in time (creep).
- When a certain strain is applied the stress will decrease in time (relaxation)
- Strength and stiffness properties depend on time and temperature as well
- Considered should be also the degradation of the mechanical properties with exposure to weathering, sunshine and organic solvents. Periodic inspection will be needed

(Hydrosight 2012)

Another problem is the scepticism of society towards the capability and durability of plastics. Ever since the development of the first plastics these materials are known as cheap and low quality alternatives for natural materials. Over the years a lot has changed and by now it is possible to blend high quality plastics accurately composed for specific purposes. Durability and appearance have improved significantly.
However due to these prejudices and the lack of international standards and unambiguous design information, clients are hesitant to use unfamiliar materials. There is of course a risk of failure.

If the behaviour of transparent plastics is well understood and there is a design guideline available which prescribes how to cope with this behaviour, it should be possible to find interesting applications for this intriguing material.
And when the capabilities of plastics have become clear and design values can be guaranteed it will be as well possible to convince the building industry of the usability of plastics in buildings.

This research will make clear whether it is with good reason that structural applications are rarely seen in the building industry or that the capabilities of plastics are misjudged.

1.2 Research question

The main research question is:

What are the structural possibilities of polycarbonate and acrylic and how can these be used in building design?

The next question to be asked is:

Is it possible to make a structural design for a building or building part in which the favourable properties of polycarbonate and/or acrylic are used in such a way that the limits of the current transparent building can be stretched?

Several sub-questions about both polycarbonate and acrylic should be answered to get a proper answer to the main questions:

- How does the material behave under different loadings?
- What are the strengths and weaknesses of this material and how to cope with these?
- How can connections be made between with the material itself and in combination with other materials?
- What kinds of elements are available today, and how are sizes and shapes restricted by the production process?
- For which building elements should both materials be suitable, bearing in mind the answers on the previous questions?

1.3 Objectives and methodology

Herewith the objectives of the research become:

- *Mapping the properties and behaviour of transparent thermoplastic, which are significant for structural design.*
  Plastics show some deviant behaviour compared to other, more conventional, building materials: viscoelastic behaviour. This implies that the material shows as well viscous as elastic behaviour, which causes the material to creep under sustained stresses and to relax under sustained deformation. Insight in this behaviour will be necessary when designing with transparent plastics. This influences for instance the maximum allowable stresses and the development of the Modulus of Elasticity over time.
  Other properties of importance in building design are for instance thermal, acoustical and optical properties: As the insulation values, thermal expansion and rate of transparency.

- *Determination of design criteria and points of attention for designing with plastics.*
  When the important properties are mapped it will be possible to formulate the design criteria. Which design stresses can be allowed under which circumstances, how should the effect of creep be incorporated? Thereby some points of attention will follow from the properties and production restrictions. The special material properties will require a different design approach.

- *The choice for a suitable design case in which clearly has been done justice to the used materials.*
  What do the properties make clear about polycarbonate and acrylic, and what did others experience? With all gathered information a considerate decision has to be made regarding the design to be computed. A choice can be made to use additionally a conventional material with certain desired properties in a efficient composite structure. This might be necessary when the bearing capacities of plastics appear to be insufficient.

- *Compute one or more application(s) in polycarbonate and/or acrylic and assessing the feasibility.*
  The chosen design case will be worked out structurally to a certain extent, based on the discovered data, guidelines and standards. A point of attention will be the detailing, both the sensitivity to stress concentrations and the high thermal expansion makes could cause problems when using standard details.
  When the design is optimized it will be assessed whether it is realistic to make use of transparent plastics for this specific application.
  Eurocode standards will be used as a guideline to determine allowable deformations, loads and load cases.

- *Drawing conclusions concerning the use of transparent plastics in the building industry*
  The worked out example will give some more insight in the behaviour of a plastic structure or structural part. Based on these results it will be possible to draw conclusions on other applications as well.

- *Break through the traditional pattern of thought: Transparency=glass.*
  The intention of this research is to show that there are situations in which plastics can be a solution to certain design questions concerning transparent building. Show that there is a way to cope with the uncommon properties when these are respected and accepted.
  In the end it will become clear whether that is correct. In that case this might be a step towards breaking the traditional way of thinking in which transparency automatically means glass. And thereby a step closer towards the realisation of transparent dreams which until now seemed impossible!

The first three objectives should be achieved during the literature study that will be performed. This study is meant to get more insight in the materials, the existing knowledge and the current applications. As the material is still quite unfamiliar in building applications it will be difficult to find examples or even the right design data. This makes the literature study to a very important part of this research.

This literature study will be the base for the further research during which a case will be developed and computed. This case should represent the capabilities of the materials and show the strengths and weaknesses.

After this twofold research it will be possible to draw conclusions regarding the use of transparent plastics in the building industry. It should be clear whether it is realistic to apply transparent plastics structurally and which does most justice to the material.

1.4 Limitations

- It should not be a purely material-scientific research as the emphasis lies with structural design. However it is important to understand the material and to find out what the capabilities are with respect to this structural design.
- If necessary some (quite simple) material tests can be executed to get a better insight in the material behaviour. If enough information is available this will not be done, as it is no main goal of the research. This will become clear from the literature study.
- The research is an orientation on the possibilities of transparent plastics and will not directly lead to a usable design guideline. It can possibly be used to develop such a guideline in the future.
- As it concerns an orientating research, the limits of the material will be searched. This might imply that certain current building regulations cannot be met. Depending on the case, these regulations can be ignored for the sake of the research. Not all regulations will be intended for the application of transparent plastics in building and might even be adapted in the future.
- Costs will be handled briefly but it is expected that the kind of projects for which the material is interesting are not the common large-scale projects. For this kind of unique projects, maybe even art, it is difficult to assess the value.
  However material and production costs will be taken into account in making design choices.

2 Plastics

2.1 History

Nowadays plastics are present everywhere in our society, but how did that all start? What are plastics, where do they originate from and how did they manage to get hold of there current position in our society?

A plastic is a type of synthetic polymer, quite similar to natural polymer resins found in animals, trees and other plants (like timber, cotton and silk).
Polymers consist of very long chain-like molecules. Their special configuration of tangled molecules highly determines their properties and behaviour.

Alexander Parkes introduced the first man-made polymer in 1856, this was an organic thermoplastic material derived from cellulose, called Parkesine. This material could be moulded and retained its shape when cooled. It was not a commercial success but despite that an important breakthrough because it led to the development of celluloid in 1870 by Hyatt Manufacturing Company. This material became established as a good replacement for natural materials that were in short supply, as for example ivory. (Crawford 1998)

In 1907, chemist Leo Hendrik Baekland was working on the production of a synthetic varnish when he incidentally discovered the formula for a new synthetic polymer. This new substance, originating form tar coal, was named "Bakelite". Bakelite, once formed, could not be melted again. It was frequently used in the production of high-tech objects including cameras and telephones, because of its favourable properties as an electrical insulator. It was also known as a good substitute for the expensive natural materials jade, marble and amber. By 1909, Baekland was the first one to introduce the term "plastics" for this completely new category of synthetic materials.

Another still very popular plastic is polyvinyl chloride (PVC), a substance now used widely in vinyl siding and water pipes; the first patent was registered already in 1914. Cellophane was also discovered around this period of time. (ACC 2012)

During the early 20th century there was increasing interest in these new synthetic materials. But the popularity of plastics did not really take off until after the First World War. This started with the use of petroleum as a basis for the necessary raw materials, a substance easier to process than coal. Plastics became to serve as substitutes for wood, glass and metal during the hard times of war. Around the start of the Second World War materials such as nylon, polyethylene and as well the transparent plastic acrylic appeared on the market.

In his attempts to find a better automobile safety glass Otto Röhm experimented with polymerization of methyl methacrylate between two layers of glass. Instead of adhering to the glass the *PolyMethylMethAcrylate* interlayer came loose as a perfectly clear solid sheet: the first cast acrylic. Röhm and Haas introduced this Acrylic (or PMMA) commercially in 1933 under the trademark Plexiglas. During the World War II, Plexiglas was already used in submarines, aircrafts and windshields. (Haas 2012)

After World War II, many more plastics were developed, among which also another transparent plastic: polycarbonate. The journal Plastics Technology, October 2005 states: “The modern era of engineering thermoplastics was launched in 1953 when Dr. Hermann Schnell of Bayer AG in Germany and Dr. Daniel W. Fox of GE Plastics in Pittsfield, USA, independently discovered the versatile engineering resin called polycarbonate.”
Mr. Fox was working on a new wire insulating material when during an experiment he ended up with a transparent substance. This was the beginning of GE’s Lexan polycarbonate business. Mr Schnell on the other side was working on aromatic derivatives at the Bayers lab when he discovered PC; this marked the start of the trademark Makrolon. Commercial production for both companies started in 1958. Today polycarbonate is one of the most widely used engineering plastics in the world. (Plastics Technology 2005)

By the 1960s, plastics were widely spread and within everyone's reach due to their inexpensive material costs. Unfortunately many of the early applications for plastics earned them a reputation as being cheap substitutes for natural and luxury materials. It has taken them a long time to overcome this image but slowly the special properties of plastics became appreciated and nowadays a world without plastics would be completely unthinkable. (ACC 2012)

Polymers as building material

In reaction on rapid developments of polymer science and technology, in 1976 Hermann F. Mark and Sheldon M. Atlas wrote about Polymers as Building Materials (Atlas 1976):
They explained the growth of demand for these relatively new engineering materials as follows:

- The basic raw materials for their production are readily available in large quantities and are, in general, inexpensive.
- Intense research activities in many laboratories have resulted in a better understanding of the mechanism of the polymerization reactions by which long chain molecules are formed. This resulted as well in the development of processes suitable for large-scale industrial operations.
- There are many continuous automatic, rapid and inexpensive methods for processing of plastics that give each polymer with attractive properties an almost immediate chance of being converted into useful and saleable consumer goods. Among those processing methods are spinning, casting, blow moulding, injection and compression moulding and vacuum forming.
- The large number of available monomers and the even larger number of polymers and copolymers made from them has provided us with an almost endless spectrum of possible polymer composition, structure and characteristic properties. Developments in molecular engineering have led to a thorough understanding of structure-property relationships. New polymers and copolymers can now even be designed on paper.

Quite soon after the invention of the first plastics, they were started being used in the building industry for certain, mostly out of sight parts as ducts and pipes. Still it was not until recently with the development of fibre reinforced polymers that the building industry started to use plastics more structurally. But the building industry is still very suspicious about the (long term) behaviour and fire resistance of plastics, they are not yet regarded as reliable building materials.

Nowadays a relatively new way of using plastics is growing in popularity; the fibre reinforced polymers. These offer very good material properties, as increased strength and stiffness while maintaining light in weight. The opportunities are high, also in the building industry.

However the presence of fibres or other reinforcing materials highly deteriorates the transparency of a plastic. Only a state of translucency can be achieved which is not sufficient for the applications explored in this research, therefore no further attention is spend on fibre reinforced plastics.

Besides this development of fibre reinforcement, the possibilities of transparent, and thus not fibre reinforced, polymers were as well explored further over the years. Where it started with acrylic windows for submersibles from the 1960's, applications were soon expanded with other types of pressure resistant windows.
In the aerospace and automobile industries weight reduction and a streamlined design are the primary design criteria. In these industries the polymers acrylic and polycarbonate have therefore become more widely used than glass as a glazing material. The ease of forming, lighter weight and higher impact resistance make them excellent materials for this purpose. (Kim 2009)

Quite soon after the invention of acrylic this became the most used material in aquarium design as well, its first structural building application. The availability of virtually unlimited sizes due to the special bonding techniques and additionally to that the excellent optical qualities of acrylic make this material very suitable for these applications. (Engels 2008)
Transparent plastics were never used regularly in other building types than aquaria, partly due to incidents as the 1973 Summerland disaster the upcoming popularity stagnated. This leisure centre, build in 1971 consisted of a street frontage and roof part of acrylic sheeting. A fire here in 1973 killed 50 people. The fire spread very fast, which was mainly blamed on the poor fire resistance of the building materials. Later there appeared to have been more problems as a late arrival of fire safety service, a failing power supply, and inadequate ventilation and locked fire doors.
After this disaster changes in the Building Regulations were made regarding material use in buildings, to improve fire safety. Although material properties have slightly improved since, fire safety is still a big issue in the application of transparent plastics as a building material.

Nowadays large span roof structures for stadiums and greenhouses sometimes use polycarbonate or acrylic sheets as a light weight transparent roof covering material. In some cases large uninterrupted façades are designed in acrylic because of the excellent bonding techniques available. Nevertheless a supporting structure of conventional construction material will always be present in current applications of transparent plastics.

Mr Uwe Gleiter spent his dissertation (2003) on the application of transparent thermoplastics in the building industry. He states: The transparent thermoplastics were already used from the beginning of the 20th century, but mostly as simple plates or windows and all measurements were estimated by experience from the workers.
His work is contributing to a future decent design guideline. With this it will become possible to compute all designs more accurately, and with a certain determined safety. This should improve the reliability of transparent plastics as a building material and will enable the design of more challenging structures consisting of thermoplastics in the future. (Gleiter 2002)

2.2 Structure

The simplest building units for polymers are called ‘monomers’. Joining thousands of monomers to a long chain-like molecule produces the large synthetic polymers. (Crawford 1998)
In scale a simple polymer chain could be compared with a human hair of about a metre length. Chains will normally not exist in completely stretched form but as a tangle. That, in the same scale may have a diameter of several centimetres.
The tangles within a polymeric material are completely interwoven, and are connected by relatively weak bonds that make them move quite easily past each other. This structure determines the behaviour of polymers, it explains for example the low stiffness of the material. (Vegt 1991)

Connections within polymeric material
Various different connections can exist within polymers, as well within the molecules: intramolecular, as between molecules: intermolecular.

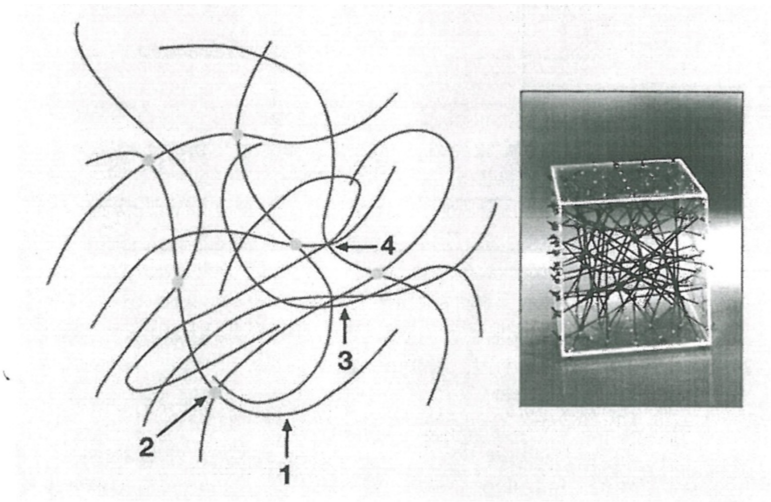


Abbildung 2-1: Bindungskräfte innerhalb eines Polymers [2.6]
1: Chemische Bindungen innerhalb der Polymere
2: Vernetzung des Polymers durch chemische Bindungen
3: Wechselwirkungen zwischen den Molekülen
4: Mechanische Verklammerung verschiedener Moleküle

Figure 4: possible connections (Gleiter 2002)

Intramolecular
This is the primary valence connection between the atoms in the chain-like molecules, which is a strong chemical bond. In some cases atoms of separate polymeric molecules are also bonded to each other by primary connections, this is called chemical cross-linking. An intramolecular bond is based on the electron configuration.
The intramolecular bond that applies to polymers is called the covalent bond; this connection implies that a pair of electrons belongs to two separate atoms in the same time. They can share one or more pairs of electrons making a distinction in single bonds and multiple bonds. The bonds created in this way are much stronger than the secondary bonds between the separate molecules. Numbers 1 and 2 in Figure 2 show possible intramolecular connections. (Gleiter 2002) (Vegt 1991)

Intermolecular
These are the secondary connections between the separate polymer molecules; the physical connections. They do not change the electron structure but are based dipole interaction between molecules.
The strength of the connection depends on the type of interaction that exists. This can be a dipole-dipole bond; atoms or atom groups with an asymmetric charge distribution, so called polar groups, attract each other electrostatically. This is the strongest dipole interaction. It is also possible that such an atom or atom group influences a neighbouring atom creating an induced dipole. Or a neutral atom can become a dipole just because of the electrons moving around the atom core. This causes coincidental fluctuations in the charge distribution and can attract another polar atom or atom group.
The intermolecular forces are very important for polymers as they highly determine the properties. Weak interaction forces for example cause the material to have a low modulus of elasticity.
Number 3 in figure 2 shows this principle.

Mechanical
The last possibility is a bond that actually is not a real bond. When molecules are highly branched they can catch in each other and thereby create a sort of bond. It is understandable that this is the weakest connection that can exist between polymeric molecules.
Number 4 in figure 2 shows this principle

The type of connections that exists between molecules in a certain polymer determines the group of polymers that it belongs to. A lot of properties are group specific and can be derived from the way molecules are connected. More about the subdivision of polymers can be found in paragraph 2.4.

Chain length

The chain length is of great influence on the properties of polymers. Often the chain length is described by the molecular weight, as that is easier to determine and linearly linked to the chain length. As the molecules of a polymer never have the same chain length, the chain length or mass is always a mean value. The mean value can be determined in several ways, for instance with respect to weight (M_w) or to number of chains (M_n). For polymeric materials usually M_w is used, as the longest molecules, with the highest mass, have the largest influence on the properties, not the number of short molecules that is present.

Another way to describe the chain length is defined as degree of polymerization (DP), the number of monomers in a polymer molecule, this is computed by dividing the polymer mass by the mass of a single monomer of which the polymer is composed.

$$DP_n = \frac{\text{Total MW of the polymer}}{\text{MW of the monomer unit}}$$

The mechanical strength of the gained polymers is highly dependent on the size of the chains, as can be seen in the picture below. This can be explained as the longer the chains; the more interaction there will be with other chains and thus the stronger the material. Up to a certain (low) value of DP, the so-called critical value, no strength at all is registered and from then on the mechanical performance rises with a steep slope. At a certain point the curve flattens out. The critical DP value is different for each polymer. (Atlas 1976)

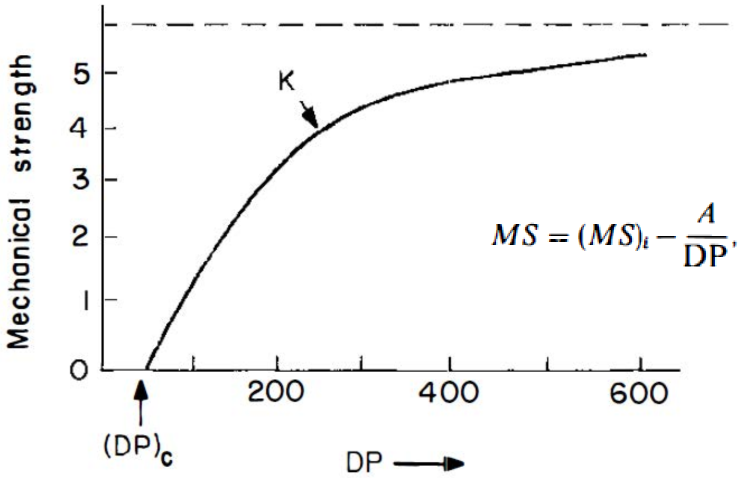


Figure 5: Tensile properties as a function of molecular weight of DP (Atlas 1976)

Where $(MS)_l$ is the mechanical strength of infinitely long chains, MS is the mechanical strength measured for a given DP and A is a constant (Atlas 1976)

The following properties follow from a long chain length:

- Higher strength due to higher secondary bond forces between the molecules and more entangling of the molecules.
- Better toughness because of the lower grade of crystallisation for longer molecules and again, entangling of molecules
- Higher chemical resistance by larger secondary bond forces

Glass transition temperature

The glass transition temperature (T_g) is an important property of a polymer. It marks the phase change between the glassy and rubbery behaviour and determines hereby the service temperatures at which a plastic can be used for certain applications.

For amorphous thermoplastics this brings on the following phases:

- Below Tg: The polymer behaves glassy and is mostly transparent. The Young's modulus is relatively high.
- Above Tg: The polymer acts rubbery, the Young's modulus becomes very low
- Above Tv (melting temperature): The polymer is now a fluid. (Maurik and Dam 2006)

The height of the glass transition temperature depends on the chain flexibility and chain interactions and thereby is related with the chain length, or average molecular weight. (Vegt 1991)
This relation between the glass transition temperature and the molecular weight is described as follows:

$$T_g = T_{g\infty} - \frac{\kappa}{M^{\alpha}}$$

With	κ,α	constants
	$T_{g\infty}$	Glass transition temperature for infinitely long chains

For an increasing molecular mass the glass temperature rises to a certain limit temperature, which is accompanied by a raise of strength and toughness. (Gleiter 2002)

2.3 Production

Polymerization

The process of joining monomers together to form polymer molecules is called polymerization. Monomers are for a large part prepared out of fossil fuels. During the production of coke and tar out of pit coal hydrocarbons arise, compounds that can be used to create polymers.
The same holds for the distillation of petroleum, besides paraffin, petrol and gas oil this process delivers a residue. This residue can, by a chemical cracking process, form a series of hydrocarbons as well. (Vegt 1991)
Other possible monomers are simple derivatives of ethylene, benzene, formaldehyde, phenol, urea and other basic organic chemicals; they are more expensive but also, in general, large-scale industrial products. (Atlas 1976)

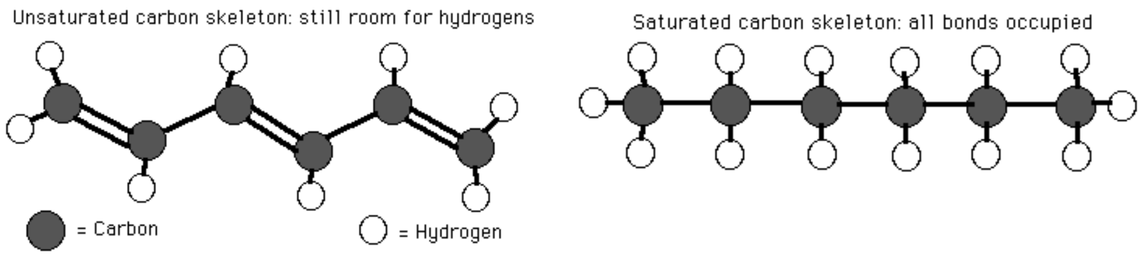


Figure 6: Example unsaturated and saturated molecule

From these hydrocarbons polymers can be build; this process is called polymerization. Unsaturated monomers are the most suitable for polymerization. In that case double bindings are already present between carbon atoms. Long saturated chains can be split in several shorter molecules (as propylene and ethylene) by a cracking process to create these double bindings.
By flipping of the double bindings new covalent connections can be made and that way the long polymer chains will be formed. (Vegt 1991)

Another way of creating polymers is from saturated monomers. For example by condensation of a carbon acid with an alcohol, this will produce in certain combinations a polymer chain while splitting off water molecules. (Vegt 1991)

There are several possible polymerization processes, as polycondensation (step-growth) or chain-growth (addition). Those have in common that the process needs a certain initiator or catalyst to start the chain reaction. The selection of a particular polymerization process is determined by the requirements of the derived polymeric material as this influences largely the properties of the final product. (Magnolis 2006) (Stachiw 2003)
During polymerization, the material can be modified by controlling the process to produce optimal combinations of properties. These modifications include molecular weight control, the forming of chain-interactions, molecular modification, use of specific catalysts and the incorporation of additives.

Additives

The polymer is the pure material that results from the polymerization, but pure polymers are seldomly used. To make a polymer a plastic, additives are used during polymerization. These additives help to improve certain properties, the ease of processing, the mechanical properties or other properties. For example:

- Antistatic agents: Most polymers, being poor conductors, can get statically loaded. Antistatic agents attract moisture to the surface of the plastic, improving the conductivity and reducing the chance on static loading.
- Fillers: Some fillers, short fibres or flakes, improve mechanical properties. Others, called extenders, permit a large volume of plastic to be produced with relatively little polymer resin. This reduces the price of the plastic.
- Coupling agents: These are added to improve the bonding of the plastic to filler material as glass fibres.
- Flame-retardants: Most polymers are flammable; additives containing chlorine, bromine, phosphorous or metallic salts can reduce the ignition temperature and the fire propagation.
- Lubricants: These additives, like wax and calcium, reduce the viscosity of the molten plastic and therewith improve the formability.
- Pigments: Are used to colour plastics
- Plasticisers: These are low molecular weight materials that change the properties and forming characteristics of the plastic. For instance improved flexibility.
- Reinforcement: By adding fibres of glass, carbon and other materials the strength and stiffness properties of polymers are improved
- Stabilisers: Prevent the deterioration of polymers due to environmental factors as heat or UV radiation.

2.4 Subdivision

Plastics can be divided in several types with distinguishing properties. The main categorization used in literature is the division in thermosets, thermoplastics and elastomers: (Crawford 1998)

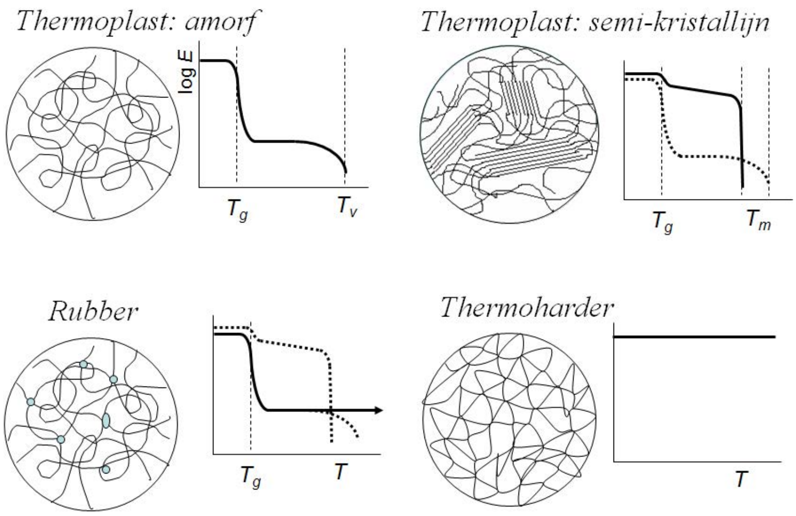


Figure 7: Difference between polymer subtypes

Thermosetting plastics

These kinds of plastics are formed by a chemical reaction that creates cross-links between the chain-like molecules, creating a 3D network of strong chemical bonds, covalent bonds. This reaction takes place during moulding, usually under application of heat and pressure. The resulting product will be rigid when cooled and a close network structure is then formed within the material. The material cannot be melted again by the application of heat; the decomposition temperature will be reached earlier than the melting point, as the covalent bonds will not come loose by the application of heat.

Thermosetting plastics have good mechanical properties due to the strong bonds and the behaviour is not heat sensitive. It is not possible to reshape the material under heat so it has to be processed mechanically, as a result it can only be recycled as a filling material. (Crawford 1998) (Gleiter 2002)

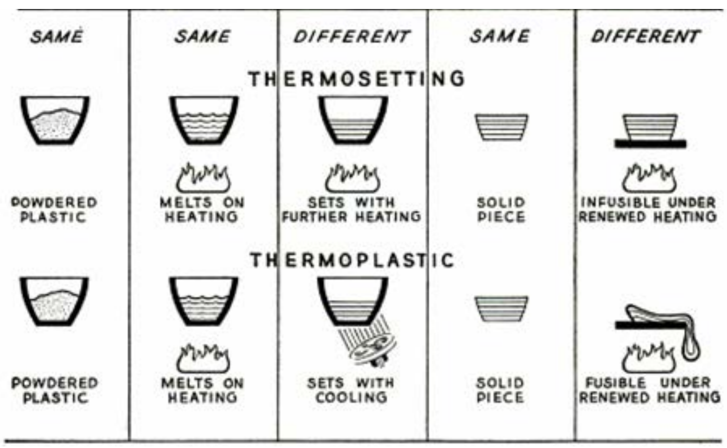


Figure 8: Difference between thermosetting and thermoplastic, journal: Popular Science, jan 1943

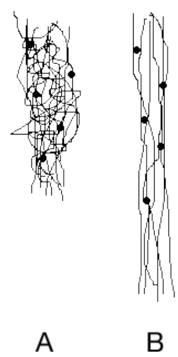


Figure 9: Stretching of elastomers

Thermoplastics

The kinds of polymers that are relevant for this research are thermoplastics. Some sorts offer a very high optical quality; they are less brittle than thermosetting plastics, well formable and in the end recyclable by melting.
In a thermoplastic material the relatively weak dipole forces hold the very long chain-like molecules together. The strength of these physical bonds depends on the distance between molecules. When the material is heated the distance between molecules gets larger due to the increased movement and thus the intermolecular forces are weakened and finally will come loose. The thermoplastic becomes soft and flexible and eventually, at high temperatures it melts viscously.
When the material is allowed to cool it solidifies again. The cycle of softening by heat and solidifying by cooling can be repeated more or less indefinitely. This is a major advantage of thermoplastic materials as it is the basis of most processing methods for these materials and makes recycling possible. (Crawford 1998)
It does have its drawbacks, however, because these weak intermolecular bonds make that the properties of thermoplastics are heat sensitive.

Elastomers

These are rubbery materials that possess large elasticity. They are mostly thermosets but may as well be thermoplastic.
For thermosetting rubbers initially the bonds are weak dipole bonds, and allow for sliding of molecules past one another, the material is then more or less resembling thermoplastics. This can be cured by vulcanising the rubber, a process in which the molecules are anchored together forming a 3D network of chemical cross-links in a similar way to that of thermosets. (Crawford 1998)
The network of elastomers is nevertheless a lot more wide-mesh than of the other types of polymers which explains the large possible deformations, as shown in the figure. (Gleiter 2002) Because of the lasting random position of the molecules and their coiled and twisted nature the rubber molecules will stretch and unwind during deformation and afterwards snap back into shape. (Crawford 1998)
Thermoplastic rubbers exhibit the desirable physical characteristic of rubber but with the ease of processing of thermoplastics as they can be shaped when heated. (Crawford 1998)

2.5 Transparent thermoplastics

Amorphous

A further subdivision within thermoplastics can be made into crystalline and amorphous thermoplastics. The difference lies within their structure; amorphous structures have a random molecular arrangement where as the polymer chains in a crystalline structure are more or less ordered.
The properties of a thermoplastic are highly dependent on this molecular structure. In the search for transparent polymers the outcome will always be an amorphous polymer, the looser structure transmits light so the material appears transparent.
The fact that in practice no thermoplastic structure will be completely crystalline will cause a difference in refractive indices between the two phases. This, combined with the tighter crystalline structure, makes it impossible for a crystalline material to be transparent.
Difference in refractive index is also the reason that most polymer blends are not transparent.

Properties of amorphous materials: They have a wide softening range (period during which the weak secondary bonds are broken down), they are usually transparent, they have a low shrinkage (because no crystallisation (denser packing) takes place during solidification), low chemical resistance (as they are easily penetrated by substances due to the looser structure) and a low fatigue and wear resistance as well. (Crawford 1998)

Material selection

Now that different properties of plastics are explained it is time to get to the material selection. Important in the selection of a suitable building material to bear clearly in mind what is the purpose and function of the product to be designed and in which service environment it will be used. Then the suitability of a range of candidate materials has to be assessed. (Crawford 1998)

Plastics offer a wide spectrum of properties. However, this does not mean that there is sure to be a plastic with the correct combination of properties for every application. Altogether material selection requires an awareness of the general behaviour of plastics as a group as well as a familiarity with the special characteristics of individual plastics. (Crawford 1998)

Generally in material selection the following criteria are of importance: (Crawford 1998)

- Mechanical properties as strength, stiffness, fatigue, toughness and the influence of temperature and time on these properties
- Resistance to weathering and corrosion
- Wear resistance
- Special properties, for example: Thermal, electrical, optical or magnetic properties
- Moulding and/or other methods of fabrication
- Total costs concerning the selected material and the manufacturing process.

With this in mind the transparent thermoplastics most suitable for building applications seem to be polycarbonate and polymethylmethacrylate. They have relatively good mechanical properties as toughness and stiffness, are more impact-resistant than glass and show acceptable behaviour in an outside environment:

- Polymethylmethacrylate (PMMA/acrylic)
  The mechanical properties of PMMA are in the mid range of the transparent plastics. The optical quality is very high; a clear view can be achieved also for relatively high thicknesses. The main advantages lie in the processing area; it can be cast as well as polished. A disadvantage is the brittleness of the material, although the resistance to impact loading is better than for glass.
- Polycarbonate (PC)
  The optical quality of PC is almost as high as of PMMA although it has a slightly grey undertone. The mechanical properties are very good and it also had a high glass transition temperature. The material is not flammable and even self-extinguishing. PC is a tough material with a high elongation to break ratio. A disadvantage of PC is the fact that it cannot be cast, so the achievable thickness is limited. Thereby it cannot be polished either.

(Bos, Veer and Heidweiller 2006)

Other materials with (current) applications in the building industry, from façade panels to ducts are: PVC, ABS, PP, PE-HD and PA6. Most of these have not enough resistance to be applied outside, lack optical quality, less easily processable and/or more expensive than above-mentioned plastics. (Gleiter 2002) (Bos, Veer and Heidweiller 2006) (Solla 2010)

3 Polymethylmethacrylate and Polycarbonate

3.1 Introduction

Polymethylmethacrylate (acrylic)

The term “acrylic” is generally used to describe that group of glass-like thermoplastic resins and resulting derivatives that is made by polymerizing esters of acrylic or methacrylic acid. The most common interpretation of the term is the here meant polymer polymethylmethacrylate.
(Stachiw 2003)

This material has an exceptional optical clarity and resistance to outdoor exposure. It is resistant to alkalis, detergents, oils and dilute acids but is attacked by most solvents. Its peculiar property of total internal reflection is useful in advertising signs and some medical applications. Typical uses include illuminated signs, control panels, dome-lights, (safety) glazing, lighting diffusers, baths, furniture, aquaria, canopies, face guards, nameplates and lenses.
(Crawford 1998) (Gleiter 2002) (Stachiw 2003)

Acrylic is quite brittle when subjected to high tensile stresses, weathering or other disturbing phenomena but because of the low modulus of elasticity it is still well capable of taking impact loads. It will not fail as sudden as glass can do.

The main chain of polymethylmethacrylate consists of carbon atoms only and is saturated (no double bindings), the attached groups are hydrogen atoms, a CH3 group and a COOCH3. (Vegt 1991) The complete structure of acrylic is shown in the following picture

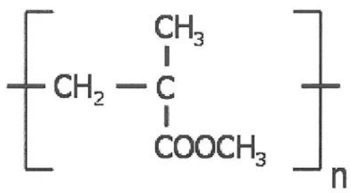


Figure 10: Structure PMMA

Important material properties of PMMA in short (Gleiter 2002) (Stachiw 2003):

- Low density
- High hardness, strength and stiffness
- Scratch resistant and the surface can be well polished
- Water-clear transparency
- High dimensional stability when heated
- Good insulating properties, electrical and thermal
- Resistant to weak acids and caustics as well as un-polar solvents, fat, oil and water
- Good resistance to weathering
- Very good processability
- Maximal service temperature sufficient to use in outside environment
- Risk of crazing
- Flammable
- Brittle behaviour, sensitive to stress concentrations

Polycarbonate

The thermoplastic polycarbonate is based on Bisphenol A (there is also a thermosetting polycarbonate available) and is one of the most versatile and widely used engineering plastics on the market. (Magnolis 2006)

The outstanding feature of polycarbonate is its extreme toughness. It is transparent and has a good temperature resistance but is attacked by alkaline solutions and hydrocarbon solvents. Typical applications include vandal-proof street lamp covers, (safety) glazing, aircraft windows, automotive roofs and windows, multiwall sheet, baby feeding bottles, machine housings and guards, camera parts, electrical components, safety equipment and compact discs.
(Crawford 1998) (Magnolis 2006)

The main chain of polycarbonate molecules consists of unsaturated carbon rings, oxygen and carbon atoms and is saturated. The attached groups are CH3 and an oxygen with an unsaturated binding. This results in the following picture of the polycarbonate structure. (Vegt 1991)

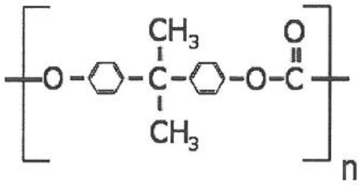


Figure 11: Structure PC

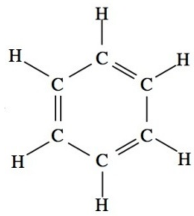


Figure 12: Zoomed-in carbon ring structure (Benzene)

Important material properties for PC in short (Gleiter 2002) (Magnolis 2006)
- Low density
- Outstanding impact strength even at low temperatures
- High hardness, strength, stiffness
- High toughness, not sensitive to brittle failure
- Excellent dimensional stability, also at elevated temperatures
- Outstanding optical properties, water-clear transparency
- Good electrical insulating properties, even when damp
- Easy to colour, transparent, translucent or opaque.
- Good UV stability and weatherability
- Very good flame retardance, even self distinguishing
- High maximal service temperature
- Quite creep resistant
- Processing requires some extra attention
- Resistance to chemicals is limited
- Sensitive to notches and crazing

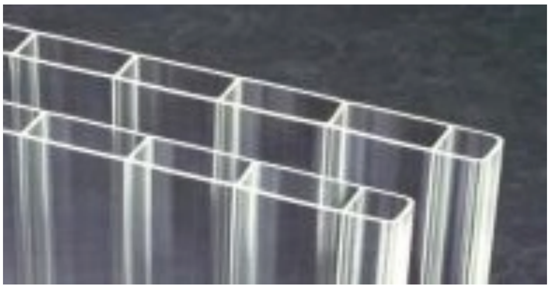


Figure 13: Multiwall polycarbonate sheet

3.2 Fabrication and processing

There are a lot of different ways to create certain shapes of thermoplastic, all with different possibilities and limitations. The chosen process determines the kind of shapes, the dimensions, the tolerances that should be taken into account and it even influences the properties of the resulting material. A conscious choice has to be made. The most important available fabrication processes are described in this chapter.
At first a main shape will be produced with one of the casting, extruding or moulding processes. After this stage a lot of different methods are still available to adapt the product till the desired result is achieved.

Casting- Bulk polymerization

Casting is in principle the easiest way of shaping; a certain mould is filled with a fluid polymer with low viscosity to make sure it fills the complete mould. Then a material-forming reaction takes place, which can be a reaction of different components in a blend, or a reaction initiated by a catalyst. The last phase is the hardening, which takes place either at room temperature or at a prescribed raised temperature.
The difficulty during hardening is the low heat conduction of polymers; heat developed by the reactions can difficultly flow out of the material. This causes a risk on thermal material analysis, therefore in general large thicknesses can better be avoided.

With this method still relatively thick plates and pieces can be made. A disadvantage is the shrinkage that occurs after de-moulding, it causes relatively large tolerances in the dimensions of the resulting product, compared to other processes.
(Vegt 1991) (Stachiw 2003)

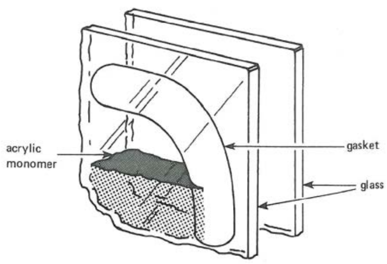


Figure 14: Batch-cell casting

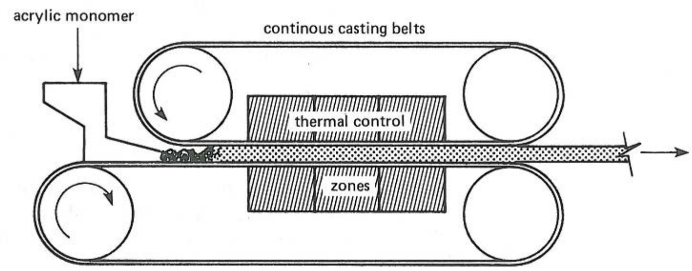


Figure 15: Continuous casting

PMMA
There are only a few thermoplastics that are suitable for casting. Only for these thermoplastics the polymerization can take place during a casting process. As this is only possible when the polymerization process elapses easily, with help of certain catalysts, for PMMA that is the case.

A fluid monomer or monomer-polymer mixture is poured in a mould. Then, as in the previously described casting process, the material forming reaction should take place, in this case the polymerization. The, at room temperature, fluid monomer methylmethacrylate is used to cast in the mould. This way of casting is also called bulk polymerization, there are three ways of bulk casting possible; Batch cell casting, continuous casting and spin casting.

For batch cell casting usually a cell is composed of two pieces of tempered glass separated by a flexible gasket. The cell is filled from one corner with a predetermined quantity of monomer or a monomer-polymer mixture. Polymerization is started by cooling the cell in a water basin, air oven or pressurized autoclave for a specified temperature/time cycle that depends upon the composition and thickness of the material.

Continuous casting resembles extrusion (see explanation in the next phrase) to a certain extent, with the difference that polymerization for casting takes place during the process instead of before. A monomer-polymer mixture is continuously injected between two stainless steel belts, closed at the sides by flexible gaskets. The material proceeds at a constant speed through temperature zones of varying lengths and emerges from the belts as a completely cured sheet. The only size limitation is the belt width. (Stachiw 2003)

Spin casting is used to produce seamless circular acrylic products. Polymer-catalysed and monomer slurry is mixed and placed in the mould. The mould is then rotated to spread the material along the wall of the hollow mould. The material is cooled while still rotating. Because of the presence of the preformed polymer in the mixture, the heat generated by the polymerizing monomer is reduced and more easily dissipated. If the formulations of the preformed polymer and catalysed monomer are similar, a totally clear homogeneous product will be the result.
Extremely large castings, such as clear submarine nosecones and tubular hyperbaric chambers have been produced by this method. In general circular acrylic tubes are made this way as well. (Stachiw 2003)

Extrusion

Extrusion is a continuous process in which material is heated, molten and pushed under pressure through a die to create the desired shape. For instance a sheet, rod or tube profile.
The extrusion process uses pellets or powder of polymer. The material is heated and pressure will be applied until the material is in a molten state and capable of flowing. For extrusion the heating and pressure application are built into a barrel by means of a screw that runs inside its length. This screw takes care of the transport of pellets or powder to the heating zone, and compacts the material on its way towards the die as the screw depth decreases. This as well improves the heat transfer and homogenises the melt. The molten material is extruded through the end of the barrel and into a mould cavity. After leaving the nozzle a spontaneous thickening occurs, the so-called die-swell, this has to be taken into account in the design. Cooling takes place in a water basin or on chilled rollers. (Vegt 1991) (Crawford 1998) (Stachiw 2003)

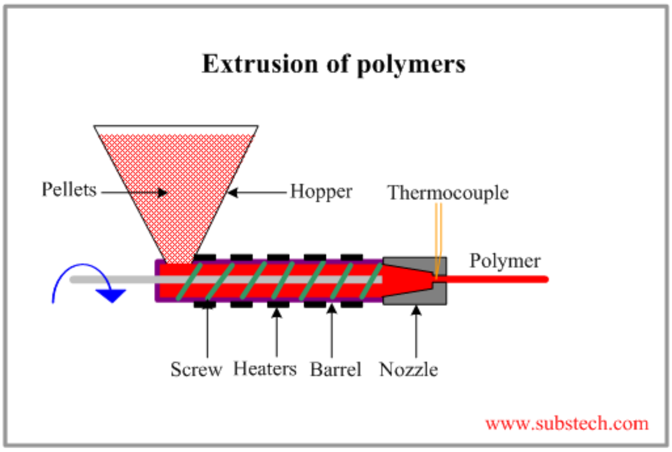


Figure 16: Extrusion process

PMMA
The pellets used for extrusion are usually of lower molecular weight than for casting, meant to reduce the viscosity and thus making the extrusion easier. But as a result the extruded products are generally of low molecular weight as well. The mechanical properties are therefore lower than for bulk-polymerized products. (Stachiw 2003)
Extrusion can leave drawing marks on the surface of the material; the end product has then a lower optical quality. For acrylic though the possibility exists to polish the surface. High quality extrusion machines can produce practically drawing mark free products nowadays. (Stachiw 2003)

PC
For linear or larger parts, extrusion processes are often used for polycarbonate. The melt strength (strength of the material in molten stage) of polycarbonate is not as high as that of a lot other resins, which could induce problems in the extrusion process. To increase the melt strength special branched grades have been developed, with those grades large and complex parts can be readily produced. Since the viscosity and with that the melt strength varies greatly with the temperature care must be taken to minimize the fluctuations in temperature during the process. (Magnolis 2006)
Concerning drawing marks the same principle holds as for acrylic, with the difference that polycarbonate cannot be polished that easily. Therefore high quality extrusion is required to achieve a surface of excellent optical quality.

Moulding

There are several methods that use moulds to produce very precisely shaped products; three different processes are described here.

Injection moulding
This process produces high quality, reproducible, three-dimensional parts and is the most common way of processing thermoplastics. Products are formed by injecting the molten polymer in a cooled die. The heating and cooling is often very difficult; because of the low heat conduction of polymers this can take a while.
To reach all sides of the die a certain injection pressure has to be applied. With this pressure the polymer blend is pushed through a, mostly narrow, opening into the die. To keep the two halves of the mould together under this pressure huge compression forces are required.
The flowing pattern of the polymer in the mould is of utmost importance for the quality of the resulting product. A computer often simulates this flowing process on beforehand. For complicated and/or large shapes multiple injection points will be needed in the mould.
Cooling takes place under pressure, which compensates the largest part of the occurring shrinkage. Product sizes are limited by the cooling down process, too large and thick parts will cause unequal cooling and high residual stresses. Thereby the cycling time will increase, while this will have to be kept low to minimize costs.
The required machinery and moulds for this process are highly advanced and therefore expensive, to make this way of production feasible the production of large series of equal elements is necessary. (Vegt 1991)

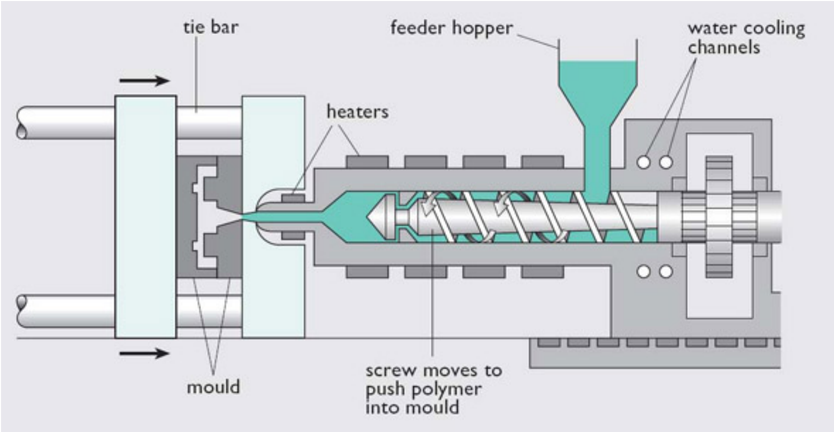


Figure 17: Injection moulding process

PC
When injection-moulding polycarbonate, it is important not to subject the melt to long residence times as this can cause material degradation and as a result a drop in properties. The fastest possible injection speed is desirable due to polycarbonate's fast setup times. However in that case care should be taken to prevent excessive shear stresses to occur, adequate venting is essential.
High mould temperatures are desirable for optimum flow, minimum moulded-in stress and optimal surface appearance. (Magnolis 2006)

PMMA
The same for acrylic. The material used has a relatively low molecular weight, as a suitable rate of plasticisation is required to give a uniform and good quality melt. For PMMA the injection moulding procedure is less common as other, cheaper production methods are available and other plastics are more suitable in thin-walled applications. (Lucite 2001)

Compression moulding
Compression moulding is one of the most common methods used to produce articles from thermosetting plastics. The process can also be used for thermoplastics but this is less common. A charge of partially polymerized material is placed in one half of the heated mould and the upper half is then forced down, forcing the material to squeeze out and take the shape of the mould. Heat and pressure accelerate the polymerization process during the pressing. (Crawford 1998)

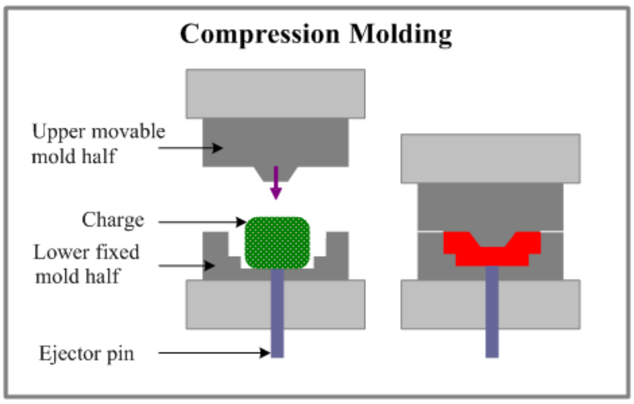


Figure 18: Compression moulding

PMMA
The pellets or powder used are usually of low molecular weight, same story as for extrusion, and therefore the end products are of less quality than casted products.

Blow moulding

This method is used to produce hollow products as bottles and barrels up to large storage drums and containers and is actually an addition to the extrusion process.

Initially a molten tube of plastic is extruded through an annular die. A mould then closes round this tube and is inflated by a jet of gas until it has the shape of the surrounding mould. (Crawford 1998)

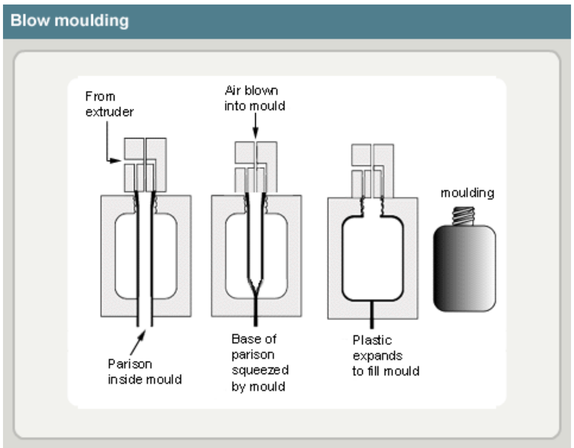


Figure 19: Blow moulding

PC

For large part blow moulding special grades have been developed to increase the melt strength (same as for extrusion) (Magnolis 2006)

Rotational moulding.

Rotational moulding, like blow moulding, is used to produce hollow plastic articles but the principle is quite different. A certain amount of plastic powder is placed in one half of a metal mould. The mould halves are clamped together and heated in an oven. During the heating the mould is rotated. When the material is sufficiently softened and has formed an equally distributed layer inside the mould, the surface will be cooled again to harden the product. (Crawford 1998)

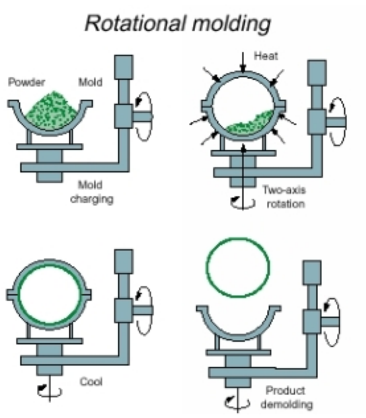


Figure 20: Rotation moulding process

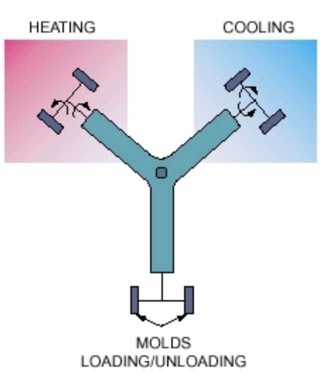


Figure 21: Carousel rotational moulding machine

Processing

Machining
Acrylic is a brittle material. It is therefore necessary that only light machining cuts are taken and feed rates kept slow. Acrylic will soften if heated above 80°C and heat build-up can cause stress. (Perspex 2009a)

Polycarbonate is easy to machine. However, it is important that only light machining cuts are taken and if high speeds are used to achieve good surface quality, it may be necessary to stop the machine periodically to allow the part to cool. Polycarbonate will soften if heated above 130°C and heat build-up due to high friction can cause stress. (Perspex 2009b)

Both Polycarbonate and acrylic have a low thermal conductivity which prevents heat generated by the cutting tool form effectively flowing away from the cutting zone. Therefore sufficient cooling is required, especially when processing thicker sheets. The uses of water or air is recommended during machining. (Stachiw 2003)

Manufacturers formulated guidelines for the equipment that can be used. For instance saw blades with a certain thickness and tooth design and drills with a specified twist drill. Often tools meant for woodworking or metalworking meet these requirements. (Lucite 2001) (GE Plastics 2004) (Stachiw 2003)
Also laser cutting can be used to create complex and intricate shapes, however the cut may look burnt and it may be necessary to carry out an annealing cycle as internal stresses will build up. (Perspex 2009a) (Perspex 2009b)

Milling machines or routers can also be used to shape acrylic or polycarbonate parts, using the same cutters speed as for wood. Routing can be performed dry but the cutter should be kept cool by directing compressed air onto it or with copious quantities of soluble oil.. (Perspex 2009a) (Perspex 2009b) (Lucite 2001)

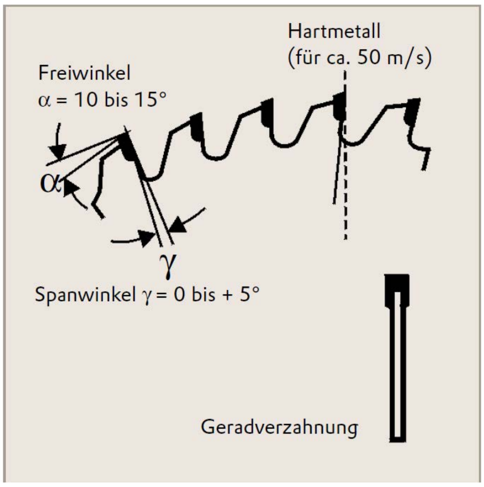


Figure 22: Sawing

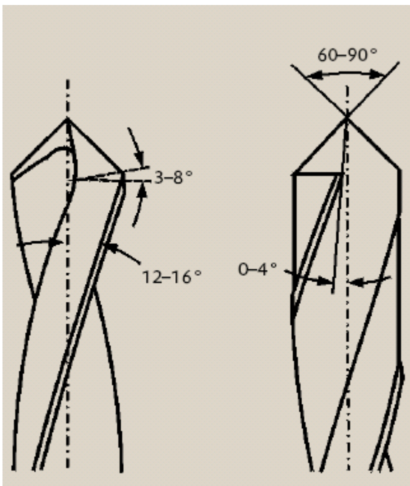


Figure 23: Drilling

Thermoforming
Thermoforming of acrylic and polycarbonate products requires heating the material above its glass transition temperature and applying sufficient pressures and load while hot to obtain the desired shape. While maintaining the application of load the part is cooled and the shape is thereby retained. (Stachiw 2003)

There are several ways to create the desired shape.
Polycarbonate is ideally suited to vacuum forming as it has high extensibility and therefore high definition within the mould. During vacuum forming a heated thermoplastic sheet is forced by vacuum into a cooled mould to produce a simple shaped products. The same counts for extruded acrylic, it has a lower melt strength than cast acrylic and can thereby be drawn by relatively low vacuum forces. Cast acrylic can be vacuum formed if the shapes are quite large and simple in design.

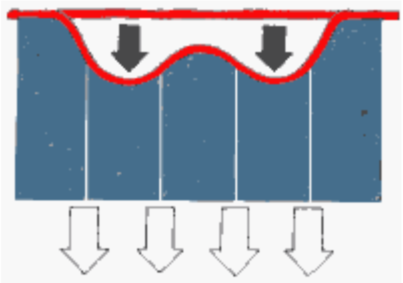


Figure 24: Vacuum moulding

Another option is drape forming, for simple bending it might be sufficient to drape a heated sheet over moulds made out of wood or aluminium and let it cool down at room temperature.
More complex shapes may require the application of more pressure, then the sheets can be pressed in between two matching moulds.

To bend in one direction locally it is possible to hot bend as well acrylic as polycarbonate by heating a narrow line, usually with a hot wire. When the shaping temperature is reached the sheet is bent and clamped or placed in a jig to cool. For sheets thicker than 3 mm for polycarbonate or 5 mm for acrylic double-sided heating is recommended.
As for all operations described heating of the material is quite difficult, partly due to the low thermal conductivity and especially combined with the sensitivity of thermoplastics for high temperatures and long heating.

During these procedures shrinkage will occur, up to 2 % for cast acrylic and up to 5% for extruded elements along the direction of the extrusion. (Perspex 2009a) (Perspex 2009b)

cold bending
Polycarbonate sheets are also suitable for cold line bending, the only forming technique that is not executed at elevated temperatures. All edges need to be smooth, without saw marks or roughness that may initiate a crack along the bend line. The sheet should then be bent at a relatively high speed and 20 to 40 degrees sharper than the desired angle. The thicker the sheet, the larger the radius of the knife required.

Acrylic can be cold bent to a limited radius as well, for instance in single curved glazing. This is no permanent bending, as the sheet is clamped to the bent bearing structure and will for the largest part spring back in its original shape when released. R_{min} = 330 x sheet thickness. Polycarbonate can also be installed this way, with a R_{min}= 200 x sheet thickness. (Evonik 2007)

polishing
After rough machining pieces of acrylic can be sanded by hand or machine to remove scratches, gouges and marks on the surface. The sanding surface should be kept wet with water to minimize generated heat and to prevent clogging of the sandpaper. (Stachiw 2003)

After sanding, the parts might be polished using a mechanically driven buff to remove the fine scratches left. Buffing will cause the acrylic surface to become stressed and it is therefore essential, in applications where the parts come into contact with active solvents or will be bonded, that the samples are hereafter annealed before further use. (Lucite 2001)
For the edges also flame polishing can be used. This is fast and effective but care must be taken not to ignite the surface of the acrylic. Thereby flame polishing can produce highly stressed edges and annealing will be necessary afterwards if bonding will be applied. (Perspex 2009a)

For polycarbonate commercial spray cleaners are available. These sprays contain specially designed waxes and solvents and can be used to polish polycarbonate surfaces. These cleaners leave a glossy, protective layer that is anti-static and dust repelling. (Perspex 2009b)
For polycarbonate prevention is better than repairing, deep scratches cannot be removed.

Annealing

Annealing is a stress relieving procedure, well-known for the application on glass panels. During machining stresses are build up in the material, which can be lowered by annealing the product afterwards. This is as well applied for polycarbonate and acrylic.

Caused by processing and forming internal stresses exist in the material, these stresses cannot be relieved as the plastic is already hardened when released from the process. The high stress rate can cause the following problems:

- Materials will tend to warp and distort
- Physical properties will differ from published data (usually lower)
- Risk on crazing, materials may even crack
- Finished part dimensions may change

Finished parts are placed in an air circulation oven such that air can circulate around them. The oven is heated to a temperature slightly lower than the forming temperature and the parts are held on this temperature for a prescribed amount of time (depending on the thickness of the material). This is followed by slow cooling with a certain maximum cooling rate. In this process residual stresses are released. (RPlastic 2012) (Plastics International 2004)

Available products

There are loads of manufacturers and distributors of polycarbonate and acrylic products, the most common brands are Perspex, Plexiglas and Lucite for acrylic and Lexan and Makrolon for polycarbonate.
The available product sizes in European factories are quite alike, however the American company *Reynolds Polymers* delivers by far the largest cast acrylic elements in a standard program. Maximum standard sizes available, collected from companies Eriks, Bayer, Reynolds and Pyrasied are:

	thickness	width/diameter	length
PMMA			
Cast sheet	3-25 mm	2050 mm	3050 mm
Cast blocks	30-102 mm	2440 mm	3250 mm
Cast tube	3-25 mm	40-2440 mm	2290 mm
Extruded sheet	2-10 mm	2050 mm	3050 mm
Extruded tube	1-5 mm	5-400 mm	2100 mm
PC			
Extruded sheet	1-15 mm	2050 mm	3050 mm
Extruded tube	2-5 mm	10-250 mm	2050 mm

Figure 25: Available product sizes for PMMA & PC

Tolerances vary a little, for extruded parts the length can differ from the given measurements plus or minus 2 mm, the width plus or minus 1 mm and thicknesses above 2,5 mm can deviate about plus or minus 5%.
And for cast acrylic parts the accepted tolerance will be about plus 3 to 4% or minus 6 to 7% for the thicknesses and plus 4 mm to minus 3 mm for length and width.
(Reynolds 2011) (Eriks 2012) (Bayer 2012) (Pyrasied 2010)

Injection moulded parts are always customized and offer a wide range of possible part sizes, but a high repeatability is required as this lowers the mould costs per part. Maximum flow lengths and flow length to thickness ratios (approximately 300) are prescribed, if necessary multiple openings in the mould can be used to create larger or thinner parts. (Vegt 1991) (Bayer 2012)

Different grades of material are available, the delivery program can vary for every grade. Possibilities consist of fire retardant, scratch resistant, UV protective grades and more.
Besides the standard sizes all manufacturers offer the possibility of customised sizes so even more is possible than the above mentioned sizes. Cast acrylic can be thicker but the size is limited by the available mould. Larger surfaces have to be bonded. For extrusion the width is dependent on the size of the machine and thus very expensive to expand but the length is adapted quite easily as long as the extruded part can be leaded and stored.

Conclusion

The possibility of applying casting methods is a huge advantage when using acrylic. This way, combined with the bonding possibilities of acrylic, large, almost limitless elements can be produced. Beside that this method gives for acrylic the best results in terms of material properties, clarity and chemical resistance, due to the long molecular chains.
For polycarbonate injection moulding of 3D parts is the greatest opportunity to get stiff and large enough elements for buildings. Extrusion is the most common used method to produce polycarbonate parts but less suitable for 3D (double curved) parts as a thermoforming procedure is needed additionally. Next to that extrusion of PC is less attractive regarding material properties and appearance.

3.3 Properties

Thermoplastics show some special behaviour, other than conventional building materials. As well the mechanical behaviour as other properties that are of importance in building design are discussed in this chapter.

3.3.1 Mechanical properties

Viscoelastic behaviour

All materials act differently when loaded, two types of behaviour that can be observed are viscous and elastic behaviour:

- Elastic behaviour: The thermoplastic material also shows elastic behaviour under stress, resulting in elastic displacement, which stores energy.
  This behaviour is described by Hooke's law :

  $$\sigma = E * \varepsilon$$

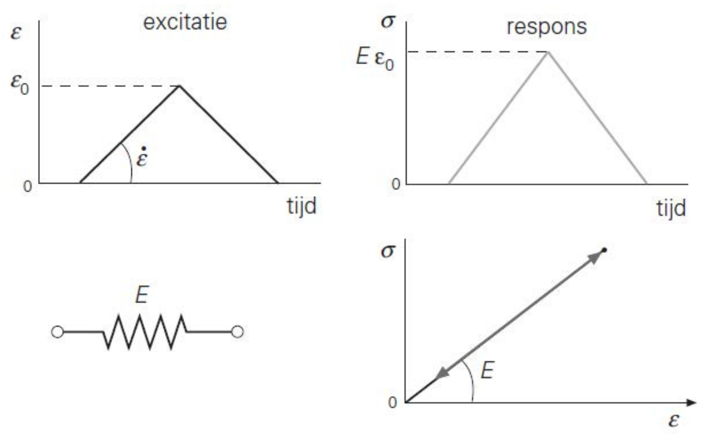
  

  Figure 26: response of elastic material on a constant strain rate (Vegt 1991)

  In the figure the response is shown of an elastic material to a constant strain rate, this shows a constant stress rate as well. And after gradual decrease of the strain, stress and strain become zero again in exactly the same moment.
  Stress and strain are linearly related so a constant strain results in a constant stress and vice versa. Most building materials are considered linear-elastic, which results in straightforward, standard calculations.

- Viscous behaviour: When thermoplastic material is stressed the response will show viscous flow, a process which dissipates energy.
  This behaviour is described by Newton's law:

  $$\sigma = \eta * \dot{\varepsilon}$$

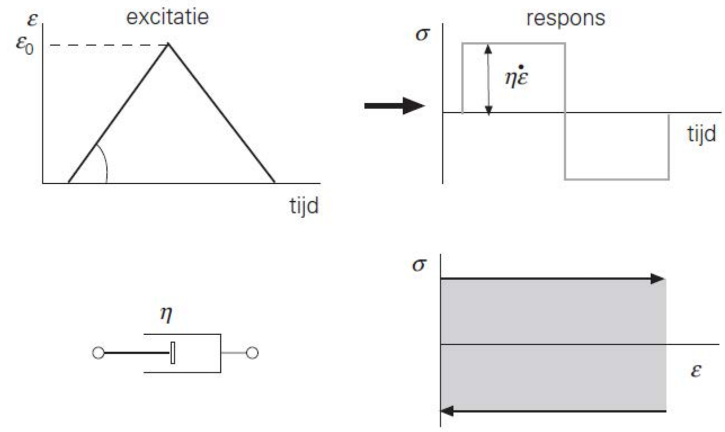


Figure 27: Response of viscous material to a constant strain rate (Vegt 1991)

In this case stress and strain velocity are linearly related, so a constant strain rate results in a constant stress. As a result a constant stress will cause a constant strain rate, when released the final strain level remains as permanent deformation.
A constant strain will only cause a peak stress at the moment of appliance and release and further no stress at all.
(Vegt 1991) (Crawford 1998)

Polymeric materials show a combination of those types of behaviour, the so-called viscoelastic behaviour. In the next figure the response of a viscoelastic material to a constant strain rate is shown. As for an elastic material, the stress builds up steadily, but due to the viscous part this line is not straight anymore. When the strain is gradually lowered again the graph shows that part of the energy is dissipated (the grey surface) and the material is not stress-free anymore when back in starting position. Thereby the response is depending on the magnitude of the strain rate.

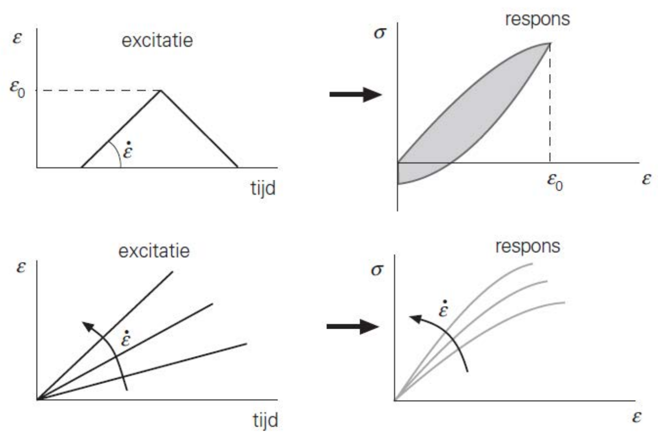


Figure 28: Response of a viscoelastic material to a constant strain rate (Vegt 1991)

Thus when a thermoplastic is stressed it responds by exhibiting viscous flow (which dissipates energy) and by elastic displacement (which stores energy). Therefore the occurring stress in the material is a function of strain and time and may be described as:

$$\sigma = f(\varepsilon, t)$$

This type of response is referred to as non-linear viscoelastic behaviour, but as it is not easy to use for simple analysis it is often reduced to the form:

$$\sigma = \varepsilon * f(t)$$

Which is the base of linear viscoelasticity. The difference between those approaches is shown the figure below.

The behaviour can be explained by the molecular structure of polymers. The tangled polymer chains will be moving past each other when stressed. As they untangle this will partly be immediately but partly slowly when the weak bonds are sliding past each other. When the stress is relieved the chains partly spring back immediately, the rest will stay slightly untangled as the weak molecular bonds did change. When the material is forced back in position, the chains will keep a slight urge to their former, stretched position.

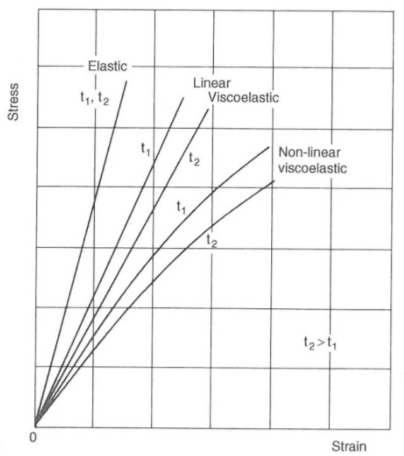


Figure 29: Stress-strain graphs for elastic and (linear and non-linear) viscoelastic behaviour at two points in time (Crawford 1998)

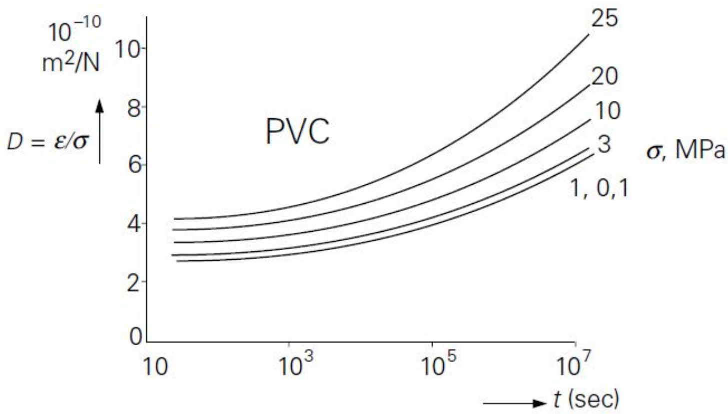


Figure 30: Non-linear behaviour of plastics; change of modulus in time for several stress levels of PVC (Vegt 1991)

For a linear elastic material the modulus as a function of time would be the same for each stress level. In practice for most polymers this is not the case. Figure 30 shows this phenomenon for PVC but the same applies to the behaviour of PMMA and PC.

Conventional building materials exhibit viscoelastic behaviour as well but the viscous part is mostly so small at normal temperatures that they are assumed to behave linear elastically altogether, which simplifies calculations.

Creep

The phenomenon that a material keeps deforming influenced by a constant stress level is called creep. A constant stress will cause an instant raise of stress as for an elastic material, however when time passes the strain will continue to grow, caused by the viscous part of the material. When the stress is released the material will react instantly by the recovery of the elastic part. The last, viscous, part of the build up strain decreases only gradually when time passes. For viscoelastic solids the strain will go back to zero, for fluids a certain strain will be lasting. Glassy polymers are regarded to be polymeric fluids.

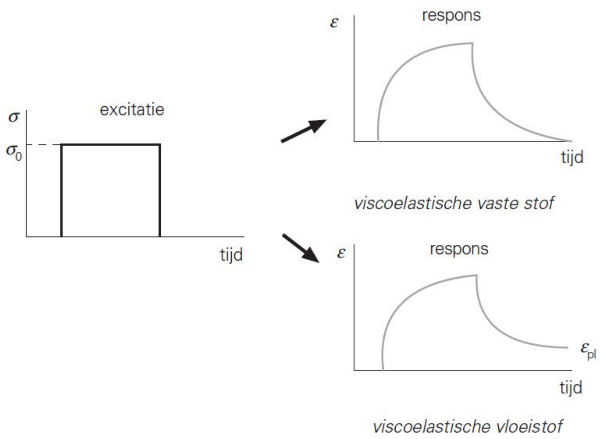


Figure 31: Response of a viscoelastic solid and fluid to a constant stress (Vegt 1991)

Relaxation

For a constant strain the resulting behaviour is shown in the picture below. The stress increases instantly when the strain is applied, which is the initial elastic response. When the strain is released it is visible that the stress gets the opposite direction: the material has to be pushed back in original position. After time the stress decreases again to zero. This phenomenon is called relaxation.

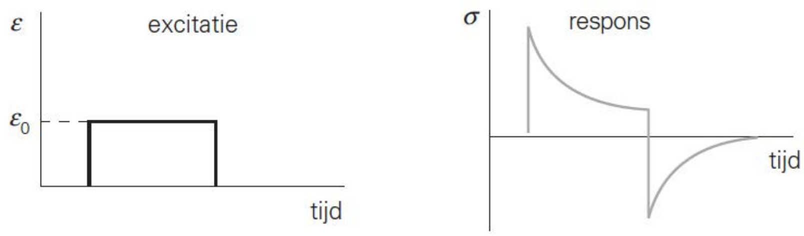


Figure 32: Response of a viscoelastic material to a constant strain (Vegt 1991)

Modelling the viscoelastic behaviour

Where elastic behaviour is modelled as a spring and viscous behaviour as a dashpot, viscoelastic behaviour can be modelled as a combined system. By making combinations as series or parallel connections between dashpots and springs or combinations of those, the basic viscoelastic functions can be found.

Maxwell model

The Maxwell model connects a dashpot and a spring in series as can be seen in the picture, so the stress in both parts will be equal. The total strain will be the sum of the strains in the two elements, so combining the formulas for viscous and elastic behaviour:

$$\dot{\varepsilon} = \dot{\varepsilon_1} + \dot{\varepsilon_2} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta}$$

And:

$$\varepsilon = \varepsilon_1 + \varepsilon_2 = \frac{\sigma}{E} + \frac{\sigma}{\eta} * t$$

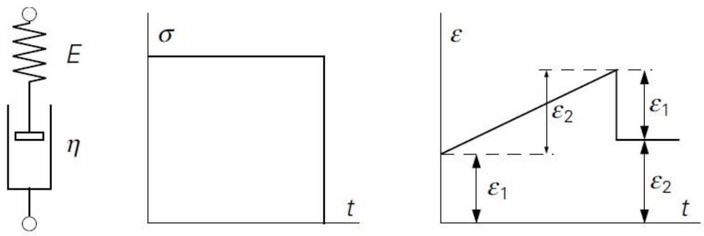


Figure 33: Response of Maxwell model to constant stress – creep (Vegt 1991)

When a constant stress σ_0 is applied, the strain rate remains constant, which is confirmed by the formula:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} = \frac{\sigma_0}{\eta}$$

This indicates a certain grade of creep, although it is a linear increase of strain which is not conform the real viscoelastic behaviour.

When the stress is released, the elastic part recovers immediately but as the strain rate becomes zero when no stress is applied, rest of the strain (the viscous flow) will remain constant. The model roughly describes the behaviour of a polymeric fluid, for which part of the deformation under stress is permanent.

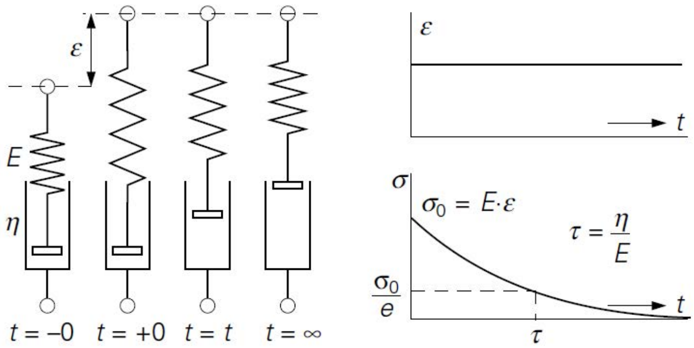


Figure 34: Response of Maxwell model to constant strain – relaxation (Vegt 1991)

When a constant strain is applied, the strain rate is zero.

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} = 0$$

Solving this equation with initial conditions $\sigma = \sigma_0$ at $t = t_0$ results in the following equation which describes the stress in the system.

$\sigma(t) = \sigma_0 * e^{-t/\tau}$ with initial stress $\sigma_0 = E\varepsilon$ and retardation time $\tau = {}^{\eta}/_{E}$

The instant stress σ_0 is the elastic stress, the decrease is caused by the viscous flow of the dashpot which distresses the spring again as shown in the figure. Retardation time τ is the time in which the stress decreases to $1/e$ times the initial value (about 37%).

Kelvin-Voigt model
The Kelvin-Voigt model connects a spring and dashpot in parallel, so the strain in both elements will be equal. Therefore it does not allow for instant deformation, this is prevented by the slowly reacting dashpot. Combining the formulas now results in:

$$\sigma = \sigma_1 + \sigma_2 = E * \varepsilon + \eta * \dot{\varepsilon}$$

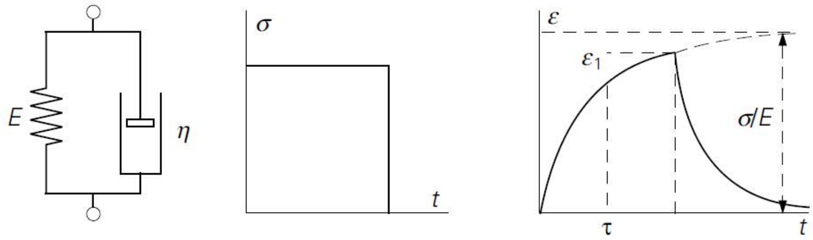


Figure 35: Creep behaviour of the Kelvin-Voigt element (Vegt 1991)

For a constant stress σ_0 this results in:

$$\varepsilon(t) = \frac{\sigma}{E} * (1 - e^{-t/\tau})$$

This indicates an exponential increase in strain from zero up to the value $\frac{\sigma}{E}$ which would have been reached instantly by the spring alone.
After releasing the stress the equation becomes:

$$\sigma = E * \varepsilon + \eta * \dot{\varepsilon} = 0$$

With $\varepsilon = \varepsilon_1$ as a starting point the solution of the differential equation becomes:

$$\varepsilon(t) = \varepsilon * e^{-t/\tau}$$

This indicates an exponential recovery, towards the asymptote $\varepsilon = 0$

Relaxation is not described by the Kelvin-Voigt model, for a constant strain the equation becomes:

$$\sigma = E * \varepsilon$$

So the behaviour is now only elastic and a constant strain will result in a constant stress as well.

Both the Maxwell and the Kelvin-Voigt element are restricted in their reflection of the actual viscoelastic behaviour. The first one does describe the relaxation mechanism but only the irreversible yield. The second one describes creep, although without instant deformation, but no relaxation.
The Maxwell model can be used to illustrate the behaviour of fluid polymers, the Kelvin-Voigt model can be used, slightly expanded, to give an indication of solid polymer behaviour.
For a more realistic view of the viscoelastic behaviour, elements can be combined. For instance a Kelvin-Voigt element and a Maxwell element in series form the Burgers model which combines the behaviour of both elements and shows as well creep as relaxation.

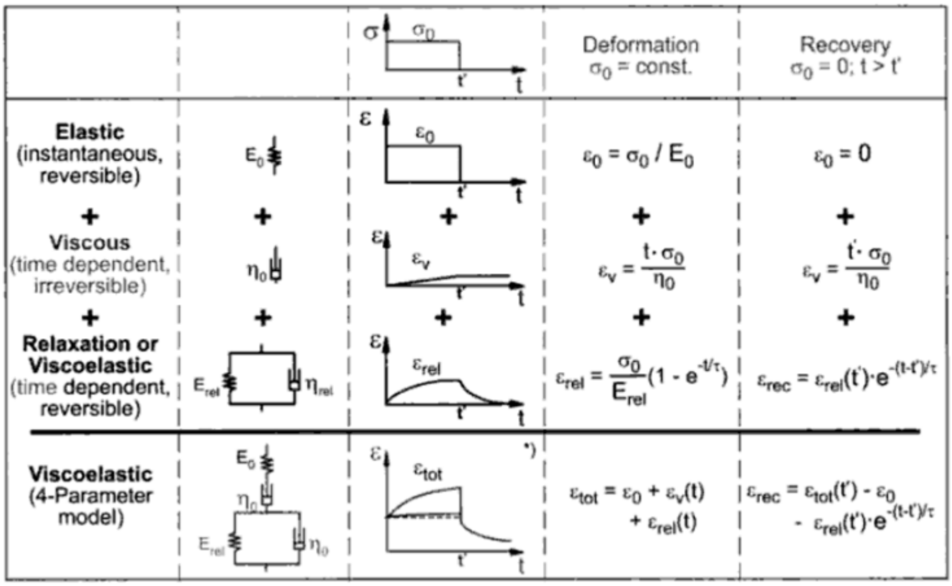


Figure 36: Burgers model [Polymeric materials- G.W. Ehrenstein]

For a quantitative description of polymeric behaviour these simple models are not sufficient. They lack for instance the possibility of simulating processes with more than one relaxation mechanism. By adding more and more elements to the model the simulation becomes better but the mathematics becomes more and more complex as well.

Creep behaviour PMMA and PC

Creep is often a critical concern when designing a structural part in thermoplastics. In practice not the mentioned spring-dashpot models are used to gain the necessary design variables.
Since the process of individual testing over long time periods is not feasible, methods of interpolating and extrapolating data from short-term behaviour are necessary. Another possibility is to combine known values with empirical relations, which together approach the real relations. (GE Plastics 1997)

The different methods available for the determination of the long-term properties of PMMA and PC will be discussed in the paragraphs about computation and guidelines.

Several literature sources show long term testing results for polymethylmethacrylate and polycarbonate.

From the book Kunststoff-Tabellen the following data are obtained:

Kriechmodul (Zugbeanspruchung) von PMMA (hochmolekular) bei 23 °C in MPa

Spannung	Belastungsdauer			
MPa	1 h	100 h	1000 h	10 000 h
10	3200	2900	2500	2000
20	2900	2500	2200	–
30	2500	2000	1700	–
40	2200	1400	1000	–
50	1700	550	–	–

Figure 37: Creep modulus PMMA (Carlowitz 1995)

11	Kriechmodul Zug	1 h	MPa	DIN 53444	2100	2100
12		1000 h	MPa	DIN 53444	1700	1700
13		10 000 h	MPa	DIN 53444	1600	1600

Figure 38: Creep modulus PC (Carlowitz 1995)

The results of tests are usually shown in graphs. As there are too many variables that influence the behaviour to put in one 2D graph, the properties of polymers can be shown by means of isochrones. A bundle of graphs plotted in one figure. Isochrones can be visualised as slices through a three-dimensional stress-strain-time reflection of the thermoplastic behaviour as shown in the figure below.

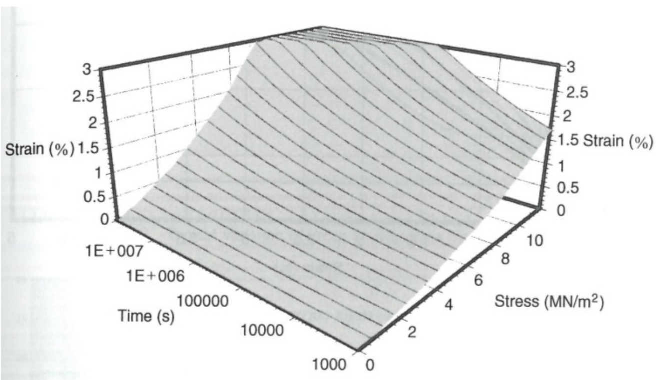
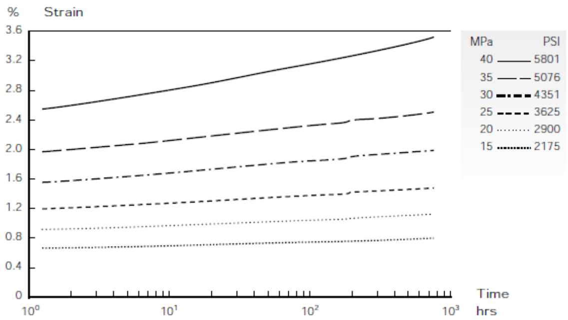


Figure 39: Example stress-strain-time curves (Crawford 1998)

For the creep behaviour of PC and PMMA the graphs will look like this:



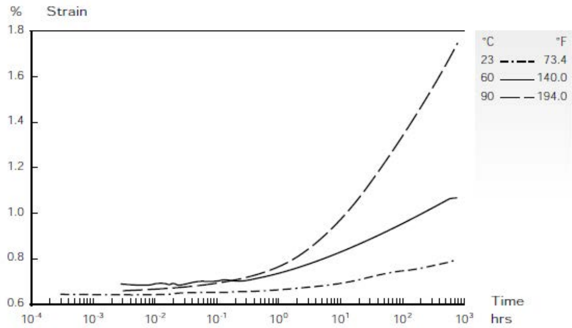


Figure 40: Strain in time for different stresses PC (at 23 °C) (GE Plastics 2004)

Figure 41: Strain in time for different temperatures PC (at 15 MPa) (GE Plastics 2004)

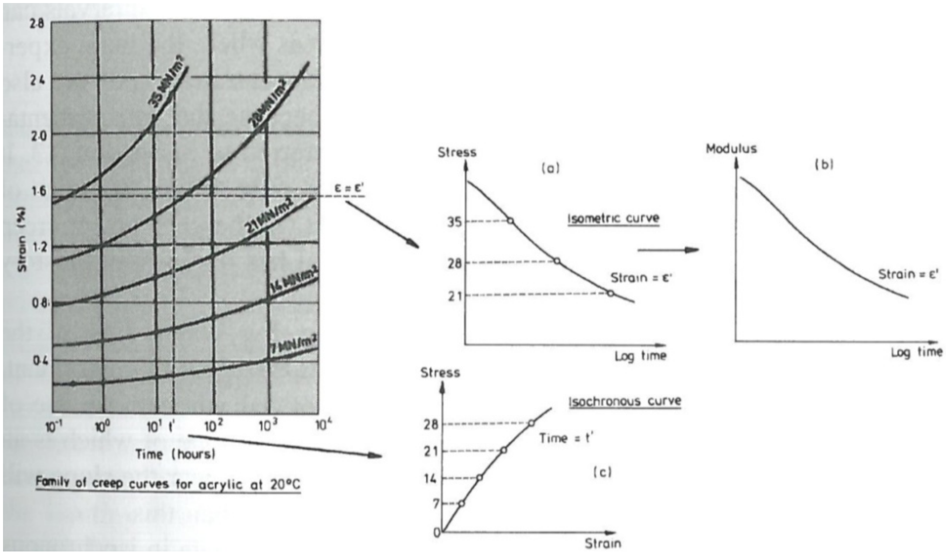


Figure 42: Creep behaviour of PMMA (Crawford 1998)

In the graphs it is visible that the creep rate indeed is depending on time, temperature and load. At a certain low stress level the creep becomes minimal and can even be disregarded in long-term, continuous load applications at room temperature. (GE Plastics 2004)

➔ Relaxation is less relevant in design of building structures. For these applications it is not common to have a fixed deformation whereby the structure is harmed when stresses gradually decrease. Possibly clamped joints will be influenced, the clamping force will gradually decrease in time, something that has to be kept in mind in case this kind of connection is used. The relaxation modulus shows a quite similar course to that of the creep modulus.

Strength and stiffness

The viscoelastic and thermoplastic behaviour results in properties that are time and temperature dependant, and as a result of the viscous part also dependant on the strain rate. When the strain changes rapidly the material responds stiffer than with the same maximum strain applied gradually.

The conventional stress-strain test is frequently used to describe the (short-term) mechanical properties of plastics. However, because of this viscoelastic behaviour the hereby provided material properties and stress-strain curves can only be used for an initial selection of materials and an indication of the behaviour. Design data must be obtained from long-term tests.

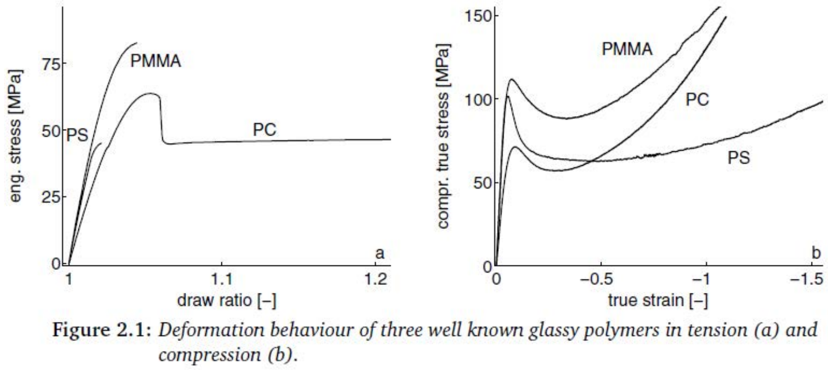
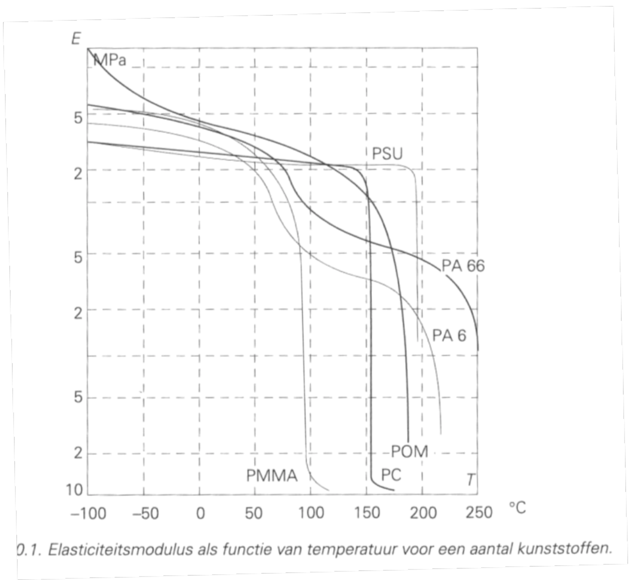


Figure 43: Stress-strain diagram different polymers in tension and compression (short-term) (Melick 2002)

In many respects the stress-strain graph for a plastic is similar to that of a metal. At low strains there is an elastic region with a linear relation between stress and strain. At high strains this relation becomes nonlinear and there will be a permanent element to the strain after yielding. Several plastics are brittle and therefore will break before the yield point is reached.
But as indicated in earlier paragraphs the properties of polymers, in contrast with metals, are strongly time, temperature and load related. To illustrate the temperature influence, figure 44 shows the change of young's modulus in temperature of several polymers. As the temperature increases the material becomes more flexible and the strength decreases. Figure 45 shows the decrease of strength for several polymers during sustained load.



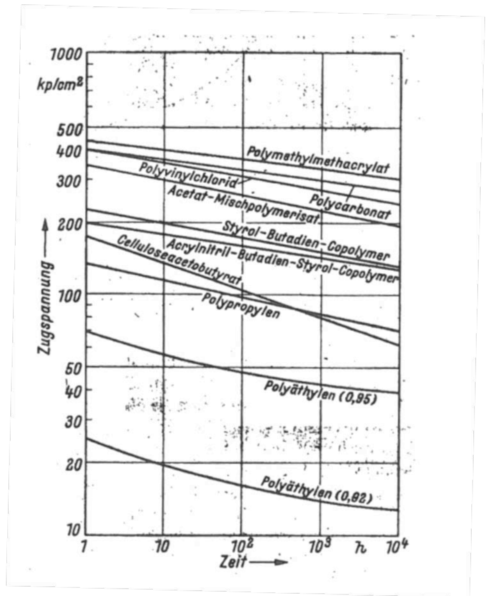


Figure 44: Modulus as function of temperature for several polymers (Vegt 1991)

Figure 45: 2% strain limit strength in time for 20 degrees Celsius determined in tensile tests (Gleiter 2002)

PMMA and PC

Results of long term and temperature testing show the behaviour of both materials clearly.

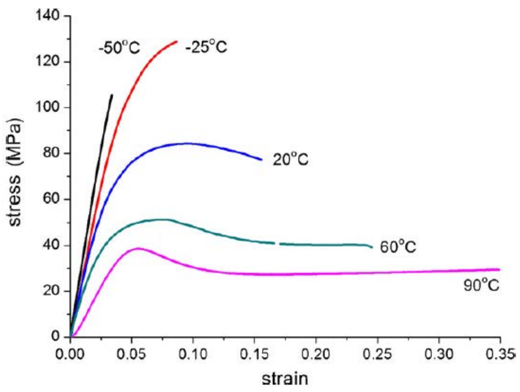


Figure 46: Stress-strain graphs for PMMA (Liu 2008)

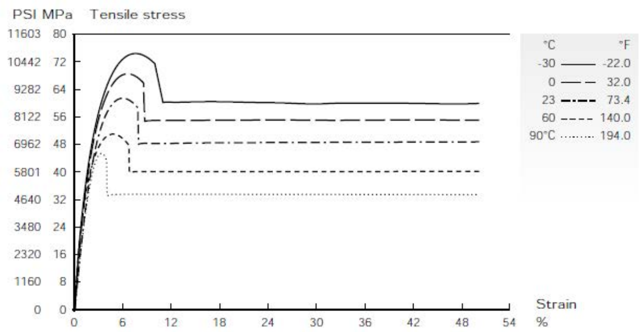


Figure 47: Stress-strain graphs of polycarbonate, Lexan resin 141R (GE Plastics 2004)

PMMA has a brittle fracture behaviour at room temperature, although less extreme and with a higher impact resistance than glass. For higher temperatures, above 60 degrees Celsius, the behaviour becomes ductile, but simultaneously the strength decreases. Polycarbonate on the other hand is very ductile at a wider range of temperatures and can have a failure strain of over 100%. Only the strength of the material decreases with increasing temperatures, although the difference is smaller due to the higher glass transition temperature.

For compression the behaviour is slightly different, the behaviour of acrylic for instance will get ductile as can be seen in the figure below. The modulus is slightly different as well, for perfectly linear elastic materials the behaviour in tension and compression will be equal, but not for the non-linear thermoplastics.

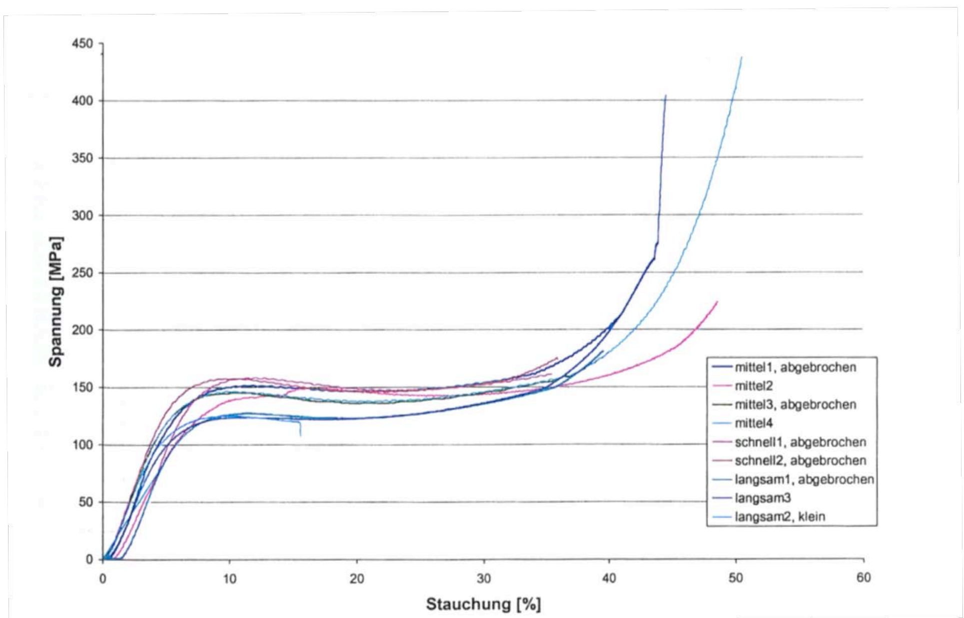


Figure 48: Picture and results of PMMA compression tests (Gleiter 2002)

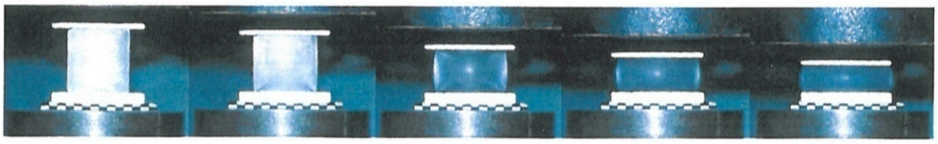


Figure 49: Compression of a PMMA sample (Gleiter 2002)

Very high compression loads can be applied, up to a 90% strain until breaking.

A list of short-term properties of polycarbonate and polymethylmethacrylate at room temperature compared to conventional building materials is included in appendix A.

Strain rate dependence

Both PC and PMMA are also influenced by the strain-rate at which a certain load is applied. When pulling quickly the material reacts stiffer, stronger and more brittle than when it is slowly stretched. This is shown by the following stress-strain curves.

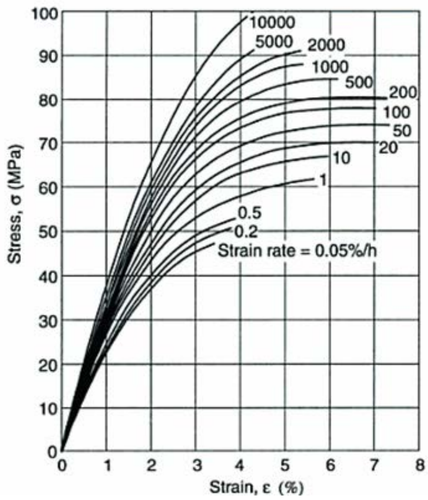


Figure 50: Strain-rate dependence PMMA [polymer processing fundamentals- T. Osswald]

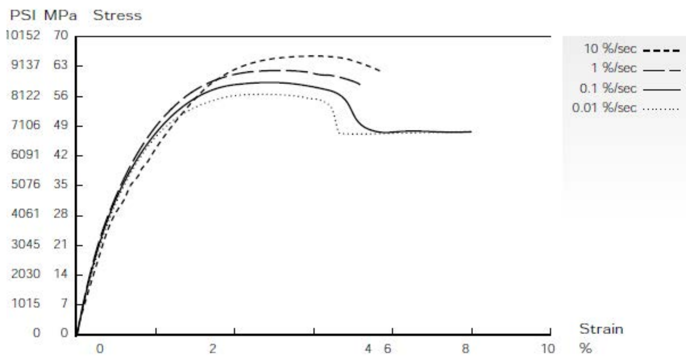


Figure 51: Strain-rate dependence PC (GE Plastics 2004)

PC is less sensible to strain rate differences, especially in the linear elastic part which is confirmed by the shown graphs. (Bos, Veer and Heidweiller 2006)

Conclusion

All properties should be handled with care, as there are a lot of uncertainties. In long term they are influence by physical ageing, which diminishes creep and makes the material stiffer and stronger, but as well more brittle.
Beside that small defects or irregularities in the materials can have a large effect on the moment of failure of a certain part or product.
It is difficult to determine the design properties of PMMA and PC; this depends on the service temperature as well as the load duration and needs to incorporate several safety factors. The available design guidelines are handled in a later paragraph.

3.3.2 Other properties

Not only mechanical properties are of importance. This paragraph handles several other relevant properties.

Fire resistance.

All plastics will burn when exposed to fire but there are large differences in behaviour when the fire source disappears. Some plastics will keep burning, others distinguish by themselves.
The most common way to describe flammability characteristics of plastics is currently the Critical Oxygen Index. This is defined as the minimum concentration of oxygen, expressed as volume per cent, in a mixture of oxygen and nitrogen that will support combustion under test conditions. If this percentage is lower than the amount of oxygen in air (21%) it means that the plastic will keep burning. Plastics with a higher COI than 21% need more oxygen to burn and are self thereby distinguishing in normal air. The figure below shows the COI of several polymers.
The COI can be improved by adding certain additives but this will also influence the clarity of transparent plastics. (Vegt 1991) (Crawford 1998)

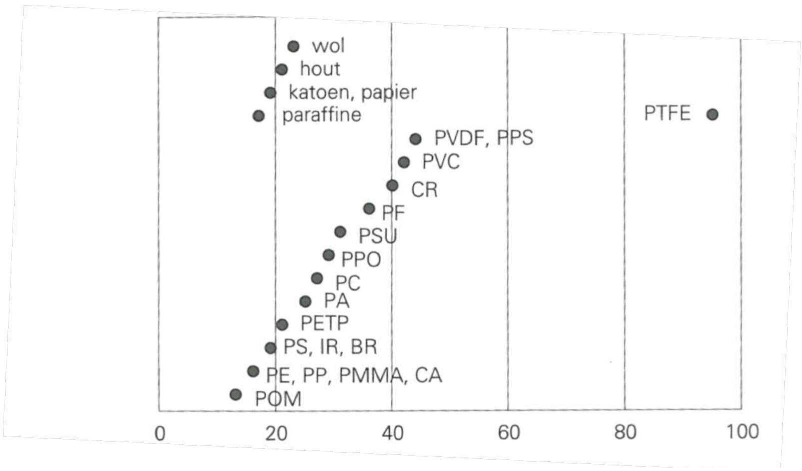


Figure 52: Oxygen index (Vegt 1991)

For the assessment of fire safety of a certain material, more is of importance than only the flammability. For instance the smoke development and the toxicity.

PMMA:
Although PMMA is combustible, it burns slowly, without producing excessive quantities of smoke and does not drip melted plastic. Especially this holds for cast PMMA, extruded PMMA produces more smoke.
In burning PMMA, longer ignition time and more steady burning were observed lower radiative heat flux as for thicker samples. The main products of combustion are H_2O, CO_2 and a small amount of CO, similar to burning other organic materials. (Lucite 2001) (Zeng, Li and Chow 2002)
Tested according to the American standards (ASTM) PMMA has a self-ignition temperature of 455°C and smoke density of 6,4%. (Kim 2009)

The material is generally classified in European fire class E (former class B2), which means it is normally combustible. This has consequences for the application in buildings, according to the Dutch building regulation rules it is not allowed to use this class materials in every part of a building.

- Above 12 meter a fire class of minimal B1 is required, because of the difficult accessibility to fire workers. Propagation of fire above this height should be prevented.

- In public accessible areas the fire class should as well be minimal B1 up to 2,5 m above ground level. For a great deal this rule exists because of the risk on vandalism, if the material is sufficiently protected a design might be approved any way.

There can be exceptions made for specific products if thorough testing does prove the material is save. (DGMR 2011)

PC
By the COI of about 28% polycarbonate is self-extinguishing. The material is classified in European fire class B, s_1, d_0 (former class B1) which means it is hardly combustible with limited smoke generation and no dripping.
Tested according to the American standards (ASTM) PC shows a self-ignition temperature of 554°C and smoke density of 62,8%. (Kim 2009)
The fire resistancy is thus higher, but opposite to that on fire the amount of smoke can be threatening.

Thermal properties

Thermal expansion
The coefficient of thermal expansion of both PC and PMMA is about 7 * 10^{-5} /K and represents the change of length for every relative degree temperature difference. This coefficient is therewith almost 8 times larger than that for glass and almost 6 times larger than the coefficient of steel.
In detailing this is a major point of attention, as there will easily arise stresses in joints between different materials; and stress concentrations can cause cracks.

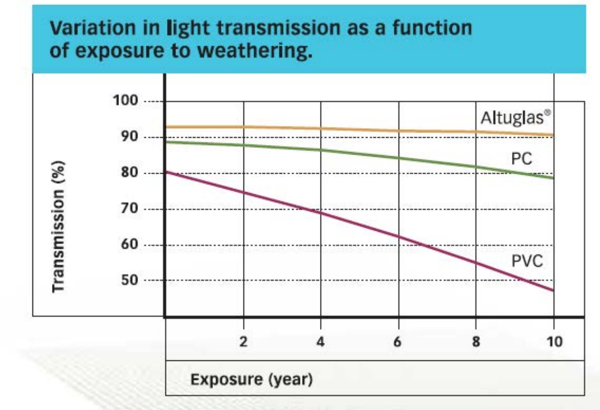
Thermal insulation
Thermal conductivity (k) is the material property that describes the amount of energy flowing through a unit area, in unit time, for one unit temperature difference between the two sides of the surface. For PC and PMMA this value is 0,2 W/mK, comparable with soft wood (0,26 W/mK) and thus quite good compared to glass (1 W/mK).
The heat transmittance (U-factor) is the complete effect of heat transfer consisting of conduction, convection, and radiation. Transparent thermoplastics perform quite good on this aspect, as can be seen in the table below, certainly when the low mass of the material is taken into account. (Kim 2009) (Quinn 2011)

	U-value (W/m2K)			Mass (kg/m2)		
	PMMA	PC	Glass	PMMA	PC	Glass
Single glazing						
5 mm	5,10	5,16	5,74	6,0	6,0	12,5
10 mm	4,49	_	5,60	11,9	_	24,8
Double glazing						
4-5-4 mm	3,12	3,25	3,57	9,5	9,5	19,8
5-15-5 mm	2,55		2,87	11,9		24,8

Figure 53: Heat transmittance and mass

Optical

The transparency of acrylic exceeds that of glass (90%) by a little, for acrylic a light transmittance of 92% is common, for PC this is about 86% (Quinn 2011) The transmittance of visible light is influenced for example by temperature and ageing. (Altuglas 2005) (Lucite 2001)
Both materials offer a very clear view, even with large thicknesses. Acrylic is colourless; polycarbonate has a slightly greyish undertone where glass is slightly greenish.
(Bos, Veer and Heidweiller 2006)
Some additives or protective layers can also cause a slight coloured tone in the plastic.



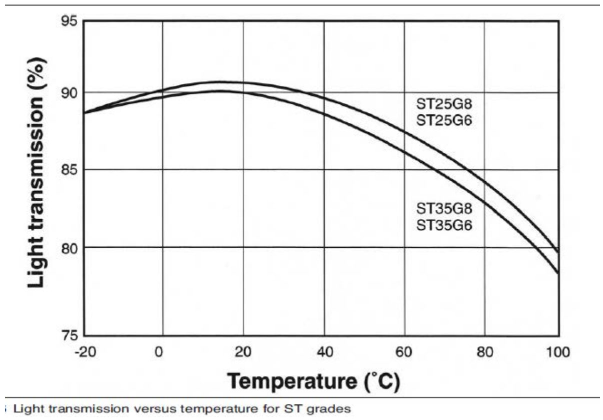
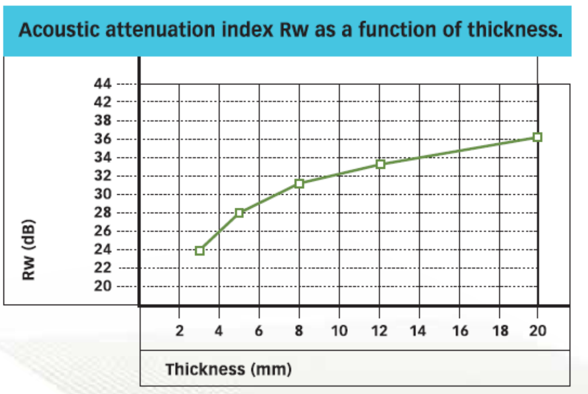


Figure 54: Transparency in time (Altuglas 2005)
***) Altuglas is an Acrylic (Brand)**

Figure 55: Transparency versus temperature (Lucite 2001)

Acoustical

The Sound Reduction Index is used to measure the level of sound insulation provided by a certain structure. Rw is the weighted reduction of sound level for sound that is transmitted through the material, expressed in decibels. Comparative figures for acrylic sheet and glass in a single glazing system are shown in the table below as well as a graph with the relation between sound reduction and material thickness for PMMA. (Lucite 2001)



	Rw (decibels)		Mass (kg/m2)	
Single glazing	PMMA	Glass	PMMA	Glass
4 mm	26	29	4,8	9,9
6 mm	30	31	7,1	14,9
10 mm	32	33	11,9	24,8

Figure 56: Sound Reduction as function of thickness (Altuglas 2005)

Figure 57: Sound Reduction and mass

Durability
Several properties affect the materials durability:

Scratch resistance
An indication for the scratch resistance is the hardness of a material, for instance determined by the Vickers hardness test or the Rockwell hardness test. But there is also a test to measure the resistance of transparent plastics to surface abrasion. The damage is judged by the observed haze after the test. The results are shown in the table below. (Kim 2009)

Table 2.2.1.4 Taber Abrasion Resistance of PC, PMMA, and Glass

Products	% haze
Coated PC (Makrolon AR)	1-2
Coated PMMA (Acrylite AR)	2
PC (Makrolon GP)	35
PMMA (Acrylite FF)	40
Glass	0.5

From "Makrolon AR Product Data," by Sheffield Plastics Inc., 2003, p. 1. "Acrylite AR Technical Data," by Cyro Industries, 1998, p. 2.

Figure 58: Indication for scratch resistance (Kim 2009)

PMMA appears to be slightly more sensitive to scratches than (coated) PC, but on the other hand easier to polish which is a huge advantage. This is also the reason that polycarbonate generally will be covered with a protective coating.

Impact resistance
Impact resistance is the ability of a material to resist fracture under an impact load. Especially polycarbonate has a very high impact strength, caused by its toughness and viscous damping. This makes polycarbonate practically shatter-resistant, providing a high degree of safety and durability. Acrylic has a way lower impact resistance although higher than glass. Special impact modified grades are available with higher impact resistance and less brittle behaviour, this will however affect other material properties, as strength and glass transition temperature.
The impact resistance is depending on a range of variables among which the operating temperature, thickness of the material and the material grade used. For example the relation between impact resistance and temperature for a certain polycarbonate is shown here. This makes it difficult to describe this behaviour with a single value. As an indication and to be able to compare materials some test results are shown in the table.
To relieve fracture problems which can undermine the test results, it is important to avoid factors which cause brittleness such as stress concentrations and low temperatures. (Crawford 1998) (GE Plastics 2004) (Kim 2009)

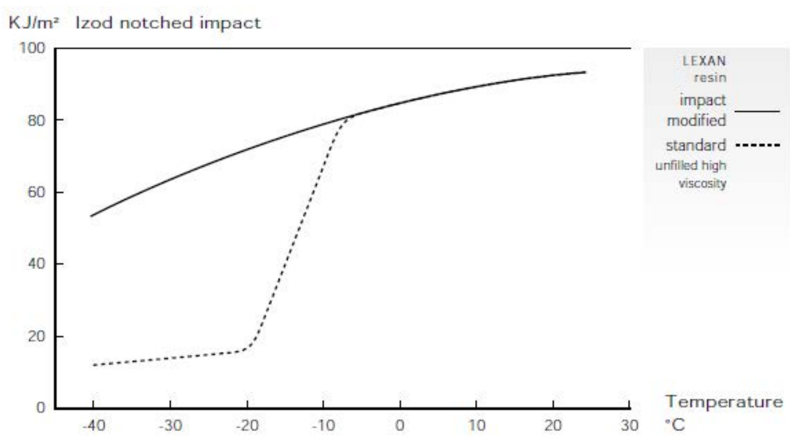


Figure 59: Impact resistance versus temperature (GE Plastics 2004)

Impact properties Izod/Charpy (kJ/m2)	PC	PMMA	PMMA (impact modified)
Impact strength, notched 23 C	90	2,0	5,3
Impact strength, notched -30 C	10	2,0	3,5
Impact strength, unnotched 23 C	195	19	54
Impact strength, unnotched -30 C	195	19	45

Figure 60: Comparison impact resistance PC, PMMA and impact modified PMMA (CES-Database 2012)

Weathering

- Yellowing

UV radiation causes breakdown of the bonds in the polymer chain. The result is deterioration of the physical properties, this is accompanied by yellowing and loss of clarity. The figure shows as well why polycarbonate can only be applied with a UV resistant coating. The dotted line indicates the level of yellowness above which it becomes visible for the human eye. For PMMA the coating makes less difference but for long-term applications it still makes sense. (Crawford 1998) (Vegt 1991) (Kim 2009)

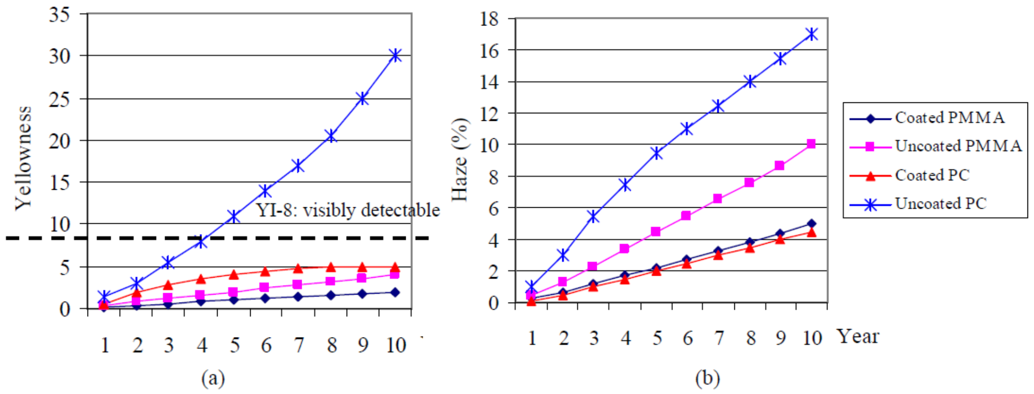


Figure 2.2.1.3 Yellowness Index (a) and Haze of PC and PMMA under UV Exposures
From "Cast and Extruded Sheet Technical Brochure," by Altuglas International, 2001, p. 8. "A New Hard Coat for Automotive Plastics," by Hayes and Bonadies, 2007, p. 25.

Figure 61: Yellowness in time for coated and uncoated PMMA & PC (Kim 2009)

- H2O resistance

Normally water or moist has little influence on the properties of polymers. But when absorbed in significant amounts by a certain plastics it can lower the glass transition temperature, as the water will act as a softening agent. This increases the flexibility but ultimately, when the water is eliminated, it will result in embrittlement. For PC the maximum water absorption is 0,14-0.17 %, for PMMA 0,2-0,4% for 24h of exposure. (Vegt 1991) (Crawford 1998) (CES-Database 2012)

Service life

As there is not yet centuries of experience with outside applications, manufacturers are still cautious in giving long-term guarantees. Guarantees for 10 years are now common for most manufacturers, the guarantee for Makrolon (polycarbonate) is already raised to 15 years and for Plexiglas (acrylic) to 30 years. (Sheffield Plastics 2007) (Evonik 2007) Current applications often appear to suffice a lot longer than expected and beside that material composition and protective coatings are continuously developing. The guaranteed lifetime of plastic might therefore expand further over the years. Guaranties cover as well a certain long-term strength as the lack of crazing and yellowing for the guarantee period in an outside environment.

However it is advisable to create the possibility of replacing damaged elements for applications with a design life of more than 20 years. (Lacasse and Vanier 1999)

Sustainability

Sustainability can be assessed in several ways:
When the embodied energy and CO2 equivalent are observed thermoplastics are not particularly favourable compared to other building materials. When the energy and CO2 per mass are converted to 'per volume' the image looks a lot better, especially for the CO2 footprint.

Tabelle 3-1: Energetische Kennzahlen [3.5]

Material	Primärenergieinhalt (PEI)		CO_2-Äquivalent		Dichte
	[MJ/kg]	[MJ/m³]	[kg CO_2/kg Material]	[kg CO_2/m³ Material]	kg/m³
PMMA	25,3	30.107	2,14	2.547	1190
PC	29,7	35.640	2,51	3.012	1200
Stahl	6,31	49.534	1,65	12.953	7850
Aluminium	69,0	186.300	16,1	42.470	2700
Flachglas	5,0	12.500	1,62	4.050	2500
Fichtenholz	0,32	160	-	-	500

Figure 62: Energy related figures of several building materials (Gleiter 2002)

All thermoplastic materials like PC and PMMA can be recycled excellently. There are several options. The products can be heated and reshaped. Or the material could be completely reground with minimal reduction in resin properties and then used again as starting material in one of the earlier described forming processes. Care must be taken to ensure that the regrind is free from impurities. As the processing temperature for thermoplastics is only about 200-300 degrees Celsius the energy for recycling them is considerably lower than for glass or metals. (Gleiter 2002)
Some quality gets lost however and therefore mostly blends of recycled and virgin material are used. The final option is polymer cracking, also called de-polymerization, this is a process in which the original monomer is recovered. (Altuglas 2005)

Costs

Mr Crawford states in *Plastics Engineering* "It is a popular misconception that plastics are cheap materials. They are not." On a weight basis most plastics are more expensive than steel and only slightly less than aluminium. However, the costs of a material do not only depend on the material costs, fabrication costs and performance costs are at least of equal importance.
Plastics are easily processable, they require way less heat to be (re)formed than for instance metals so this part of the costs may offer particular advantages.

Prices do vary a lot and there are many different transparent grades available with all different prices. Beside that the various processing and forming options highly influence the product price as well.
On average acrylic, as a raw material, is slightly cheaper than polycarbonate, 2,01-2,21 €/kg versus 2,79-3,09 €/kg. In the material properties sheet in attachment II these prices are compared to prices of other building materials. (CES-Database 2012)

3.3.3 Failure modes

Configuration failure: Buckling

Buckling is a common failure mode in building parts under compression, slender parts tend to fail by buckling before they reach the maximum allowable compressive stress.
For beams under bending the buckling mode is called lateral torsional buckling, in that case the lower flange and/or web (depending on the type of beam) will tip over before the maximum allowable bending stress is reached.

The so called critical load can be calculated with Euler's formula:

$$F_k = \frac{\pi^2 EI}{{l_k}^2}$$

In reality a lot of other factors play a role, for instance size effects, out-of-straightness, residual stresses or anisotropy, just using this formula will be too conservative. Therefore empirical formulas and buckling graphs are determined for common used building materials as steel.

For transparent plastics such practical design data are not directly at hand. As the stresses need to be kept low because of creep problems in compression applications, casted sections will not be extremely slender and buckling will probably not be the governing failure mode. However extruded and injection moulded pieces have limited thicknesses and thereby a slender appearance or slender ribs with ability to buckle.
Favourable is that the low modulus of elasticity will ensure that deflections and the ultimate strain are governing in bending applications which induces low stresses after all.

For glass materials research has been done by Mr Luible to determine the buckling curves of glass. Some similarities can be observed. As for glass, PC and PMMA have a lower tensile strength than compressive strength, for glass the computation of the critical load therefore has to be based on the maximum tensile strength.
However the slenderness of glass structures is generally way higher and the ratio between the allowable tensile and compressive strength as well, which makes them more sensitive to buckling. And the low elastic modulus of thermoplastics, certainly in long-term applications, ensures that deflection and ultimate strain are the leading aspect in buckling load computation.
Due to creep it can happen that initially no buckling failure occurs but eventually the modulus decreases that much that the critical load drops below the applied load. (Luible and Crisinel 2004) (Minahen and Knaus 1993)

T.M. Minahen and W.G. Knauss investigated the creep buckling behaviour of viscoelastic structures with PMMA. They used the following geometrically linear (adequate for the allowed displacement levels) model for the numerical part:

$$\delta_c = \alpha(t_c) = \left[\frac{p_0\beta}{1-p_0} + \frac{p_0\beta}{p_0 - r_\infty}\right] exp\lambda\left(\frac{p_0 - r_\infty}{1-p_0}\right) t_c - \frac{p_0\beta}{p_0 - r_\infty}$$

With δ_c = critical deflection midspan,
$\alpha(t_c)$ = thickness normalized response of the structure $\alpha(t) = \frac{A(t)}{h}$ at t=tc
β = normalized initial imperfection $\beta = \frac{B}{h}$
p_0 = normalized load $p(t) = \frac{N(t)}{N_{cr}(0)}$ at t = 0
r_∞ = normalized modulus $r(t) = \frac{E(t)}{E(0)}$ at t=∞

They tested with PMMA specimens at high temperatures to simulate an accelerated creep behaviour and got good results out of it as can be seen in the figure below. Since response $\alpha(t)$is a linear function of initial imperfection β the response to different initial imperfections can be determined by shifting the response curves vertically. The short-term response of the numerical and experimental responses were matched using the initial imperfection of the first mode. This results in excellent agreement between theory and experiment. (Minahen and Knaus 1993)

T. M. MINAHEN and W. G. KNAUSS

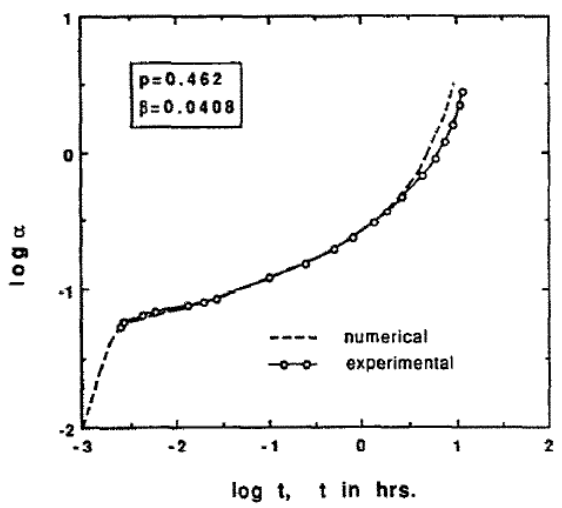


Fig. 11(a). Experimental results.

Figure 63: Numerical and experimantal data compared (Minahen and Knaus 1993)

An easy but limited buckling check can be made by using the creep modulus to calculate Euler's critical load.

$$N_{cr}(t) = \frac{\pi^2 E(t) I}{{l_k}^2}$$

Material failure: Ductile failure/Brittle failure

The two possible modes of material failure are ductile and brittle failure. In a ductile failure the part fails slowly, additional energy is necessary to further spread the damage. Brittle failure is quite the opposite; it is characterized by a sudden and complete failure, which once initiated, propagates without further energy. Brittle failure is regarded as unsafe as it does not pre-warn.
Normally at room temperature acrylic will fail brittle and polycarbonate ductile.
But also ductile materials can fail brittle, ductile-brittle transition will occur from a certain material thickness, temperature, strain-rate or time under load. (Ezrin 1996)
For polycarbonate walls with a thickness above the critical thickness of about 5,5mm at room temperature lose part of its impact strength and may undergo brittle failure during impact. The critical thickness decreases with lowering temperature and molecular weight. (Bayer 2001) (GE Plastics 2004)
A simplified reflection of the relation between brittleness, strain rate and temperature is shown in the figure below. (Bayer 2001)

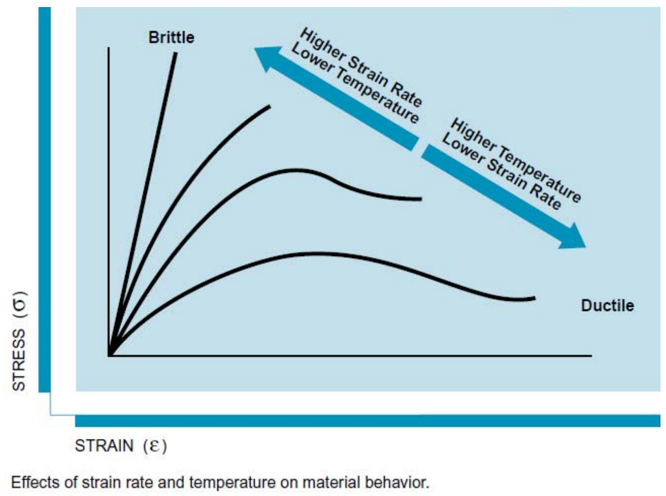


Figure 64: Effects of strain rate and temperature on material behaviour. (Bayer 2001)

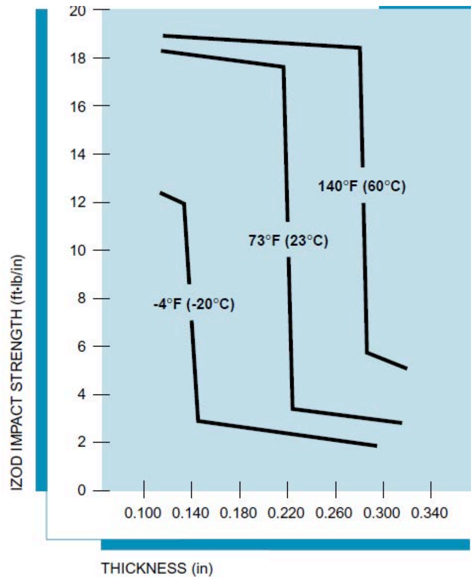


Figure 65: Critical Thickness for polycarbonate walls. (Bayer 2001)

The degree of (initial) irregularities or damage of a certain part has also influence on the failure mode, notches for instance can cause brittle failure in polycarbonate while the temperature and strain rate actually would indicate ductile failure. (Trantina 1994) (Bayer 2001)
The other way round the in general brittle PMMA can obtain ductile failure at temperatures above about 50 degrees Celsius as also can be concluded from the figure in the mechanical properties chapter.

Causes material failure

Which phenomena enhance or even cause failure in thermoplastics? Some of the most important factors in failure are described here.

Crazing
When tensile stress is applied to a glassy polymer that is solid at room temperature, there is a high risk that hairline cracks will occur before fracture. Long before (hair) cracks are fully developed, they are already present and damage the material surface. In this phase the damages are called crazes. They are like cracks as they have a wedged shape and are formed perpendicular to the applied stress. However, they are quite different by the fact that they contain polymeric material, which is stretched in a highly orientated manner parallel to the applied stress direction, sort of bridging the crack. (Vegt 1991) (Crawford 1998)

Crazing reduces the transparency and light transmittance of the material and affects the structural properties. The extreme stress concentrations at the bases of the wedges result in propagation of the crazing with time and under load. In the end crazing can reduce tensile, flexural and impact strengths to virtually zero. (Stachiw 2003)

Crazing is mainly a problem of brittle materials. PC is less susceptible to crazing than PMMA. Surfaces under compression are immune to crazing, as a result they can be subjected to higher strain and stress levels than surfaces under tensile and flexural loadings. (Stachiw 2003)

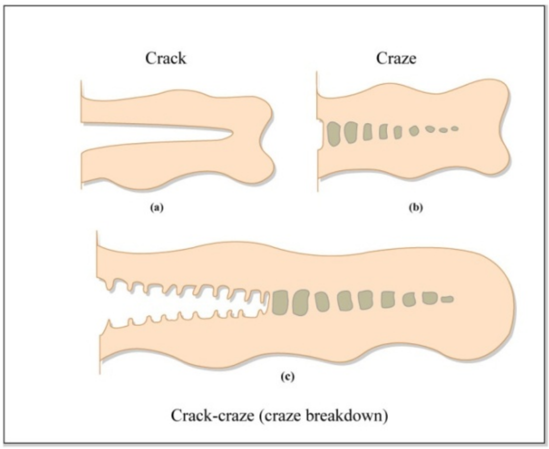


Figure 66: Principles crack and craze (MIT 2012)

A maximum tensile stress level can be determined for which no crazing will occur during a certain life time, of course this is, as all properties of thermoplastics, temperature dependant. Not just structural safety has role in this deformation; often the development of crazing is also aesthetically not desirable. (Lucite 2001)
Manufacturer Lucite states that the onset of crazing for PMMA can be prevented by using these available crazing data and divide them for de desired service life by a safety factor of 1,5 to 2; a tremendous decrease in allowable strength! (Lucite 2001)

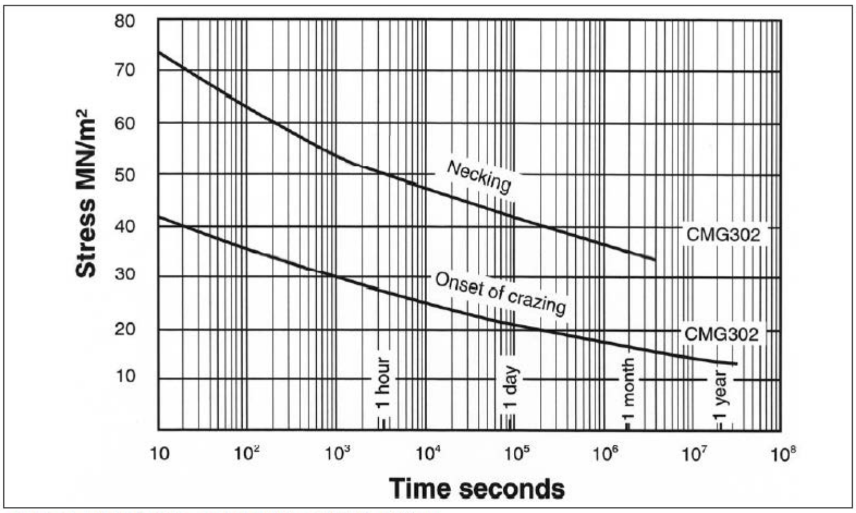


Figure 5 Static fatigue characteristics at 23°C, 65% rh
Figure 67: Allowable stress in time (Lucite 2001)

Environmental stress cracking

Some environmental influences can enhance the degradation of material properties, for example oxygen, acids, UV radiation or temperature. This can cause, among others, discoloration, surface roughness and brittleness. When combined with mechanical stresses this can lead to premature failure by occurring crazing and/or cracks. The stress or the environment would not have lead to failure when applied separately. This phenomenon is called environmental stress cracking.
Safety factors, depending on the planned service environment of a certain structure should prevent environmental stress cracking. (Vegt 1991)

stress concentrations

For any material with (geometrical) discontinuities as deep scratches, flaws or sudden changes in geometry, an increase in stress will be experienced in those areas. This is caused by the re-distribution of forces transmitting through the material around the discontinuity.
Geometrical discontinuities can make a simple uni-axial stress become tri-axial in local areas. This tri-axiality promotes brittleness in the material. Therefore, in practice abrupt changes in section, holes, notches, surface flaws etc in critical, highly stressed areas in a moulding should be avoided.

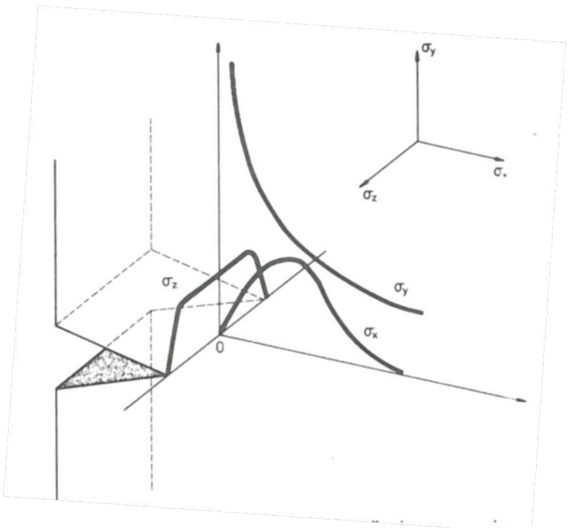


Figure 68: Tri-axial stress developing around crack (Crawford 1998)

Thermal stresses are also a form of stress concentration, in certain applications large temperature differences can occur, for instance between inside and outside of a facade. In that case stresses will exist within the material. The same applies to fixed joints of thermoplastics with other materials, temperature changes cause stresses because of the difference in thermal expansion, this can cause cracks as well. (Crawford 1998)

Fatigue
Failure caused by cyclic or otherwise fluctuating loading is called fatigue. The loading and de-loading process changes the material behaviour over a certain amount of time and causes the material to fail at a much lower stress level than the same material would reach under static loading.
For metals the fatigue process is generally well understood, the cyclic action of the load causes an existing crack-like defect to grow until it is so large that the remainder of the cross-section cannot support the load anymore, resulting in catastrophic crack propagation. The polymer fatigue knowledge is not yet in an advanced stage, the completely different molecule structure means that there will be as well a different crack initiation process. The propagation phase may however be quite similar. (Crawford 1998) (Bayer 2001)

For plastics crack initiation can be caused by machining, which can introduce surface flaws, moulding defects as weld lines or gates and last but certainly not the least; sharp geometrical discontinuities. (Crawford 1998)

To describe the fatigue behaviour is quite complex because of the many factors of influence. Fatigue curves are used to get an indication of the number of cycles to failure for a certain load.
(Bayer 2001)

The higher the stress, the less cycles to failure, the fatigue strength of PMMA can reduce to one fifth of the tensile strength. Ductile materials as PC perform a lot better under cyclic loading. Using thermoplastic grades with high molecular weight has a positive influence on the fatigue failure, due to the increased craze stability as a result of an increase in chain entanglements and a reduction in the number of chain ends. (Ezrin 1996)

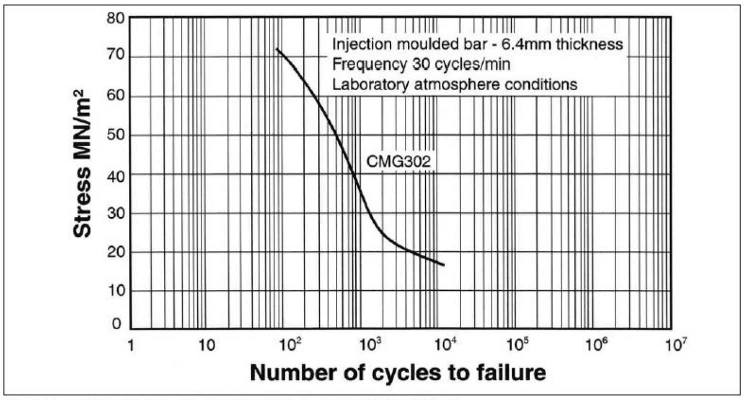


Figure 6 Dynamic fatigue characteristic in flexure at 23°C, 65% rh

Figure 69: Example of fatigue behaviour of acrylic (Lucite 2001)

Creep rupture- cold flow

Creep, or cold flow, has been the most significant factor that often prevented plastics from being used in load-bearing applications. (Ezrin 1996)

Creep causes failure by fracture or rupture when the deformation under static load exceeds what the plastic material and design can withstand. For ductile plastics the final stage of creep usually includes a distinct elongation or yielding just before rupture. In non-ductile materials rupture occurs abruptly without yielding. (Ezrin 1996)

"Measurement of creep rupture is performed in the same manner as for other creep behaviour, except that higher stresses are used and time is measured to failure. Results are usually presented as log stress versus log time to failure, as in the figure." (GE Plastics 1997)

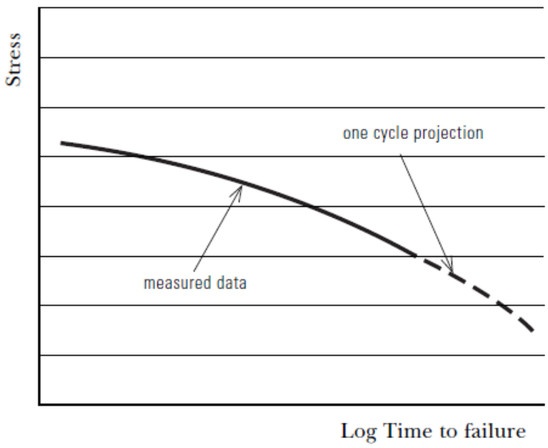


Figure 70: Creep rupture, 1 log (t) extrapolated (GE Plastics 2004)

3.4 Designing with thermoplastics

3.4.1 Smart design

It is not possible to give a general rule on how the geometry of a part should be optimized. For doing this it depends too much on the type of loading and other factors, which can be different for every situation and material. Design limitations imposed by the material properties and the production process have to be kept in mind.
For every situation it can be observed whether strength or stiffness is governing, this indicates where optimization can be found.

Design for stiffness

In general, it can be stated that for cases in which stiffness is governing material should be added where it has the most positive influence on the stiffness of the part. In most cases stiffness will be the leading aspect when designing building parts, as spans are very large with respect to plastics and deflection requirements are quite severe. Therefore it is important to use the material as smart as possible to prevent using an unnecessary amount of material.
Concerning processing it is as well advised to design plastic products with cross-sections, which are as thin as possible. This because thick sections cool very slowly and hence the moulding cycle times are long resulting in uneconomic production. Also, thick sections tend to shrink more and can lead to warpage and distortion.

The part stiffness depends on the moment of Inertia of the parts cross section and on the way the applied forces are transferred. Several options are at hand to increase the moment of inertia without using much more material. The most common features used in plastic design which increase the moment of inertia are the overall shape, ribs or corrugation. The shape of a part can have a positive influence on the flow of forces trough it.

Overall shape
By adjusting the overall shape it is possible to create a stiffer structure. Flat elements will transfer the applied load to the supports by bending and shear only. A single or double curved part will carry applied forces partly by bending and partly by normal forces, the relation between those depends on the present curvature. As a result horizontal forces will arise at the supports which has to be taken into account during further design.
The more load is transferred by normal or in-plane forces (for double curved structures this is called membrane action), the less bending will occur, resulting in less deflection.

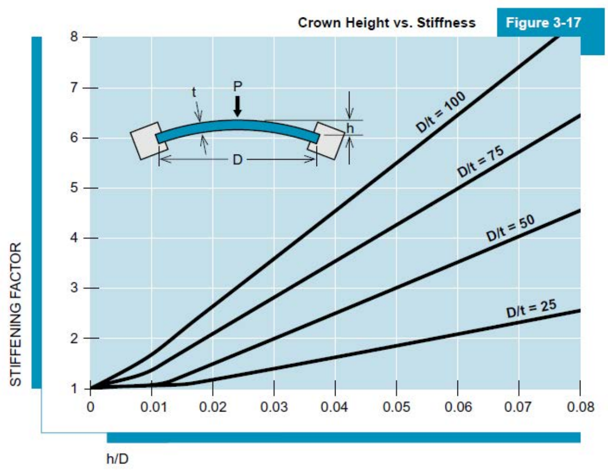


Figure 71: Increase of stiffness for curved plates (Bayer 2001)

The figure shows the effect of crown height on a circular disc, rigidly supported at the perimeter. (Bayer 2001)

Ribs
By adding ribs to a flat element the part stiffness can be economically enlarged without increasing the overall wall thickness.
Design engineers typically follow standard guidelines for rib design. Some of the most common design rules (of thumb) are listed below:

- Rib thicknesses should be 50% – 60% of the nominal wall thickness. Because of the risk on sink marks at the opposite side of the main sheet when using thick ribs.
- Combination of thin and thick ribs should be avoided
- Maximum rib height should not exceed 3 x the nominal wall thickness. To simplify the filling process during moulding and to prevent buckling of the ribs when finished.
- Minimum spacing between ribs should be 2 x the nominal wall thickness for adequate mould cooling
- Ribs that are placed on a part to accommodate bending forces should run perpendicular to the bending moment. For parts under torsion the ribs should be placed diagonally.

(Bayer 2001) (Develop3D 2010) (GE Plastics 1997)

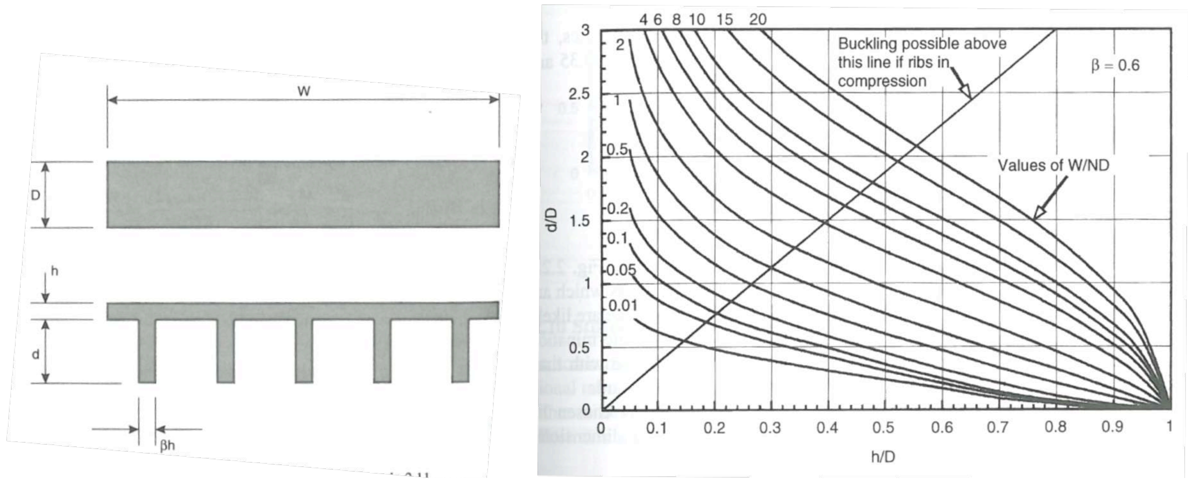


Figure 72: Design of ribbed plates (Crawford 1998)

The figure shows a chart, which indicates permissible combinations of dimensions to be chosen for a rib thickness of 60% of the nominal wall thickness. Also the line above which risk of buckling exists is showed, based on Roark's formula for critical buckling stress . Dimensions below this line are likely to be acceptable for short-term applications, in time the buckling line will move downwards as a result of the decreasing modulus. (Crawford 1998)

Roark's formula: $\sigma_c = \frac{1{,}2*E}{(1-\nu^2)} * \left(\frac{\beta h}{d}\right)^2$ or $\frac{h}{d} = \sqrt{\left(\frac{1-\nu^2}{1{,}2*\beta^2}\right) * \frac{\sigma_c}{E}}$

Corrugation
Corrugation is another way of enlarging the moment of inertia. Actually corrugation is a more effective measure as more material is taken to the outsides of the material cross section, far away from the centre of gravity. Thereby it has no sinking mark problems and less filling problems during the moulding process as its shape is actually a folded one-piece element.

The difficulty with corrugation lies in the appearance, the parts are usually considered unattractive and unpractical as they have both an uneven top and bottom surface. Another disadvantage is that corrugation can only provide stiffness in one direction. (GE Plastics 1997) (Bayer 2001)

Usually buckling problems start to be a concern when the corrugation depth by wall thickness ratio exceeds 10 for short-term loading, and less for long-term loading. The higher this ratio is, the higher the transverse stiffness of the plate and the lower the axial stiffness. (Crawford 1998)

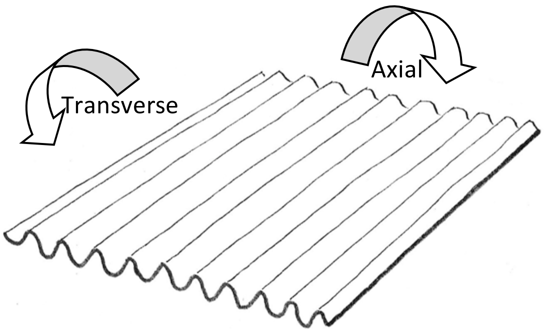


Figure 73: Explanation transverse and axial stiffness

Design for strength

To optimize strength properties in general material should be added in areas with large stresses to create the most uniform stress distribution possible. This way the load is carried by a maximum amount of material which will decrease the occurring stress levels.

Some general design guidelines are as follows

- Sharp corners or notches should be avoided to prevent stress concentrations. The same holds for sharply angled wall intersections, large wall thickness transitions and surface interruptions as holes or inserts, because these stress concentrations cause cracks.
- Situations where the part could be overloaded should be avoided, for example plastic threads have a risk of over-tightening.
- A good margin of safety has to be assured as it is not possible to control all aspects of production and use. Also the worst case scenario for part failure should be considered.
- Processing aspects must be considered, for example weld lines should be avoided or located in the non-stressed locations.

The effect of the first mentioned guideline is confirmed by Uwe Gleiter who developed an optimized profile shape for acrylic while working on his doctoral degree. After testing several common profile shapes in PMMA (with a 4 points bending test conform DIN 1048) he discovered that stress concentrations around the flange-web transition often were the reason of preliminary local failure. This was confirmed by finite element analysis. To provide a better load introduction in these areas the improved I shaped profile has a larger radius in the flange-web transition and more stable, less slender flanges. The result is shown in the figures below where its behaviour in the bending test is compared with solid profiles and a glued I profile. The improved I profile is milled out of a solid 150 by 80 mm profile, the glued I profile is 150 by 150 mm with a 15 mm wall thickness.
(Gleiter 2002)

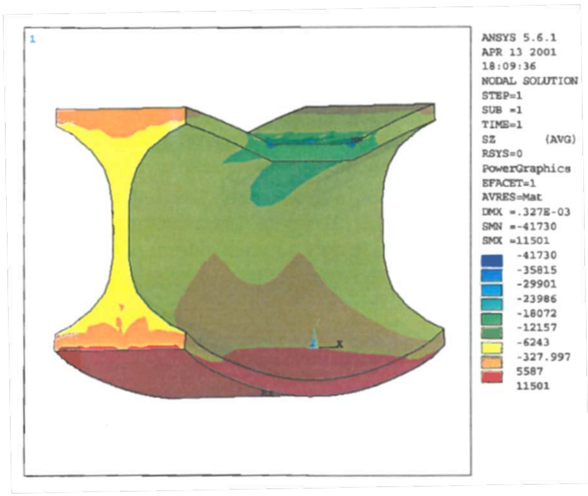


Figure 74: Improved I profile, milled (Gleiter 2002)

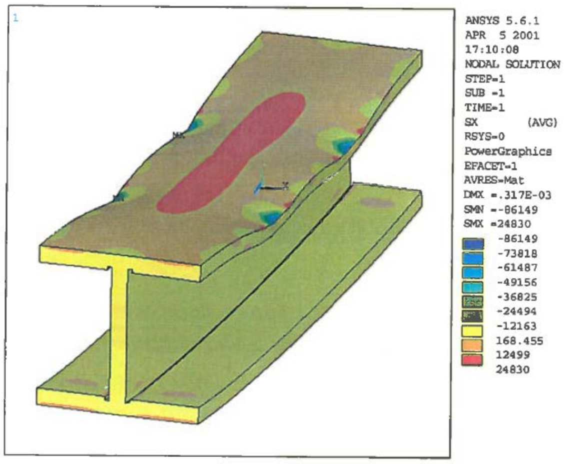


Figure 75: Standard I profile, glued (Gleiter 2002)

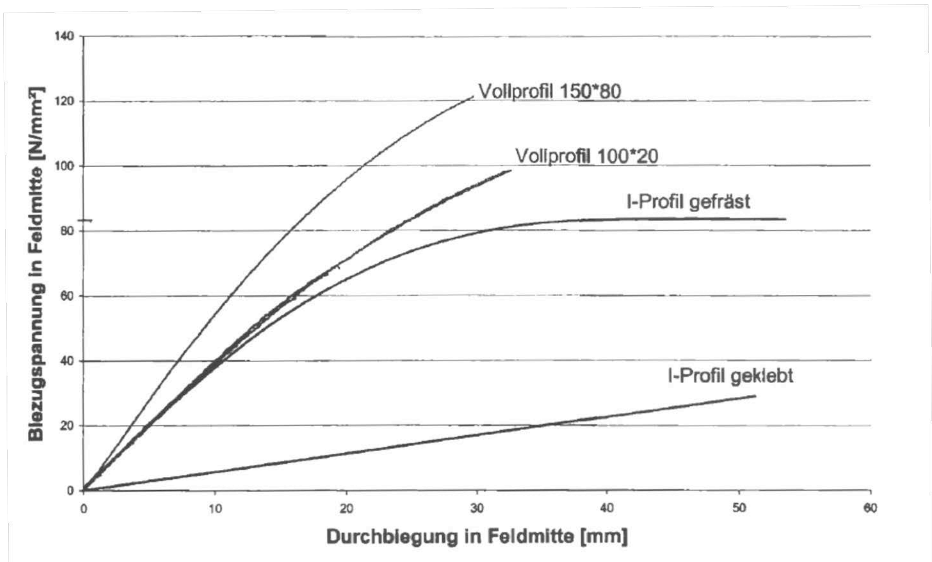


Figure 76: Results of the 4 points bending test for various shaped PMMA profiles (Gleiter 2002)

Linear hand calculations will not be sufficient to identify the areas with the largest stresses and strains but finite element analysis is very suitable to do this job. However the results should still be interpreted with care as the accuracy is dependent among other elements, and the mesh density. (GE Plastics 1997)

Material specific

PC

The polycarbonate material should be used as a relatively thin sheets as the material is provided in the form of extruded or injection moulded parts with a limited thickness. (Huyberts 1971)
To compensate for the low modulus of elasticity and the low thickness the options summed in the "Design for stiffness" part are particularly suitable for polycarbonate.
Measures in one direction can be made by both extrusion and injection moulding. Bidirectional stiffening can only be applied to injection moulded parts.
As these moulds are very expensive, part of the 'smart design' will need to be the use of repetition in the design. This way one or a few moulds can be used to produce a huge amount of elements.
The low modulus combined with thin elements result in large deformations caused by bending moments and an unfavourable behaviour with respect to instability under compressive stresses, which can lead to rippling and buckling. A solution to reduce the occurring deformations and stresses could be found in avoiding bending moments in the sheets and to allow only in plane stresses to occur in the material.

In that case two different solutions are interesting:

1. The material to resist only tensile stresses. With as a disadvantage the risk of creep rupture.
2. The material to resist in plane stresses mainly and the bending moments perpendicular to its plane to be reduced to a minimum by using properly shaped structural forms of sufficient rigidity. Double curved shapes are in this context particularly interesting. (Huyberts 1971)

Altogether polycarbonate would be very suitable for shell structures build up from injection moulded, repetitive parts, optionally stiffened by ribs. As this fits best with the material properties and the available products.

PMMA

Since surfaces under compressive strain are immune to crazing, in that case no precautions have to be taken by the designer to eliminate crazing. Similarly , the effect of weathering is only minor on structures whose surfaces are in compression. As a result, surfaces under compression can be subjected to higher strain and stress levels than surfaces under tensile or flexural loading. As long as buckling does not become critical.
PMMA can be cast to almost unlimited sizes so with this material it is possible to avoid buckling also in large structures when stresses are kept low enough to prevent excessive creep deformation.

Because of the many structural benefits associated with the placement of acrylic plastic under compression, all efforts should be made to design the structure in such a way that the highest stresses on the surfaces will be compressive stresses rather than tensile stresses.

It appears from the long-term test data that under uniaxial compression at room temperature creep becomes excessive only at stress levels exceeding 30 MPa. The presence of a biaxial stress field significantly decreases the magnitude of creep. This is the most efficient if the principal stresses are of equal magnitude in both directions. In that case sagging is prevented, and the volume of the part stays constant. (Stachiw 2003)

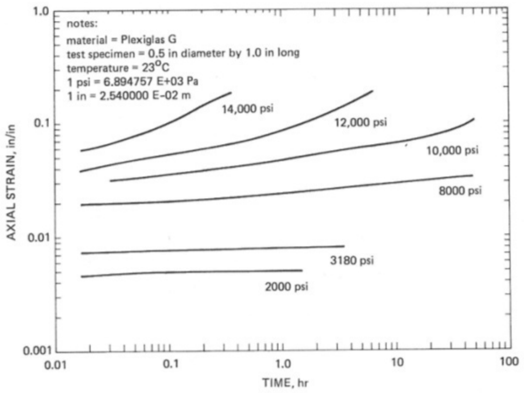


Figure 4.48
Axial strains in cylindrical test specimens of acrylic plastic under long-term sustained uniaxial compression loading in a laboratory environment at room temperature.

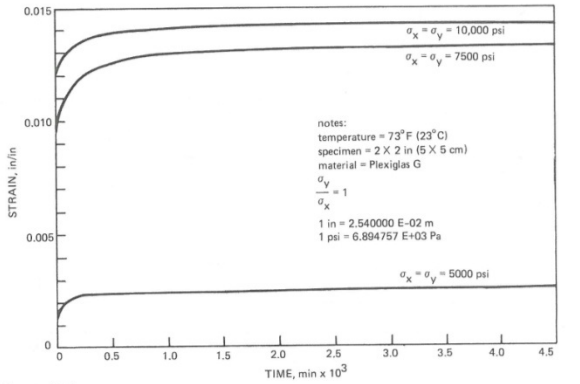


Figure 4.51
Creep of cubical test specimens under long-term sustained biaxial compression loading in a laboratory environment at room temperature. The ratio of biaxial stresses acting along y and x axes is 1.

Figure 77: Strain under sustained uniaxial compression

Figure 78: Strain under sustained biaxial compression (Stachiw 2003)

In the figures above the effect of equal biaxial stress is clearly visible. For a stress level of 10.000 psi (about 69 MPa) the strain increases in 100 hours to more than 10% and keeps going up. This will definitely lead to failure. The biaxial stress field causes for the same stress level only a strain of about 1,4 % which levels out quite quickly, the line appears to become flat within the reach of the graph (75 hours).

Altogether PMMA would be very suitable to be applied in thick cast plates and blocks, resisting compressive forces or combined compressive and bending forces. This way the brittle behaviour of the material is the least restrictive.

3.4.2 Detailing

Adhesive bonding

Adhesive joining relies on the connection between two material surfaces through bonding with an adhesive, various types of adhesive are at hand. The physical strength, and appearance of the joint will vary with the type of adhesive used, and careful consideration should be given to deciding which adhesive is appropriate for a particular application. (Lucite 2001)

The following variables must be considered when selecting adhesive bonding materials:

- Chemical compatibility with the plastic substrate, in terms of material and degradation
- Flexibility/rigidity requirements
- Environmental, temperature and lifetime requirements
- Aesthetic

An important difference can be made in stiff and flexible adhesive joints. The picture below shows the relation between joint thickness and strength for both of these joint types. It can be recognised that stiff joints have an optimal strength for small joint thicknesses whereas the strength of flexible joints is more or less constant with a slight optimum for a several millimetres thick joint. Additionally peak stresses occur at the far ends of a stiff joint through which a larger joint does not automatically means a larger load bearing capacity. For flexible joints the load is more easily spread throughout the joint, a larger joining surface leads to a larger load bearing capacity. (Gleiter 2002)

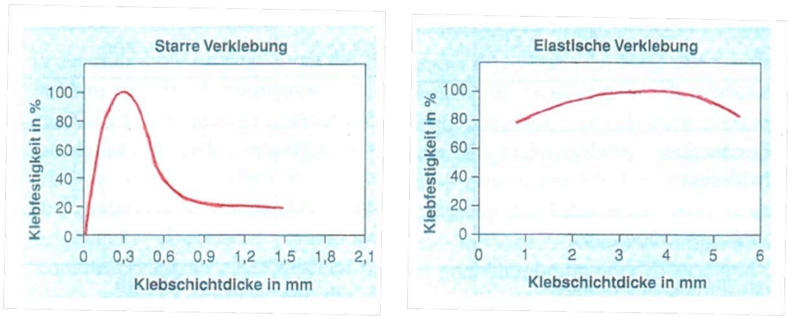


Figure 79: Relation between relative adhesive strength and adhesive thickness for a stiff and a flexible joint (Gleiter 2002)

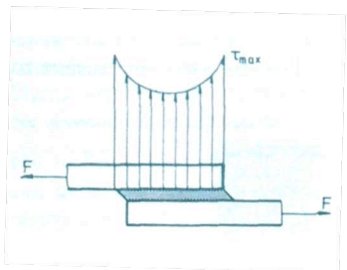


Figure 80: Development of peak stresses for stiff adhesive joints (Gleiter 2002)

Three main types of adhesives can be described:

Adhesive bonding agents

Adhesive bonding systems are among the most versatile options for joining plastic parts to parts of the same or a different plastic or even another material. In general, adhesives produce more consistent and predictable results in joints regarding strength and durability than other joining methods. (Bayer 2001)

If large surfaces have to be connected, it is necessary to use a two component systems for gluing. Other glues will cause trouble in drying as too less air will be able to reach all glue. This same problem occurs for very thick joints. (Gleiter 2002)

For joints with dissimilar materials it is important to use an adhesive with low E-modulus to make sure the connection is flexible enough to absorb thermal movements. For instance silicone based adhesives, these exist in two component and colourless grades as well. (Gleiter 2002)

Strengths up to 40% of the virgin material can be achieved. (Altuglas 2005)

Solvent-based adhesives
The common feature of all solvent type cements is their ability to soften and swell the surfaces of the components to be joined. After pressing the parts together this induces a strong chemical connection.

Mr Uwe Gleiter tested for his dissertation a shear connection between samples PMMA, glued with Acrifix adhesives solvent based glue of Firma Röhm. The tests resulted in an overall average failure stress of 18,8 MPa, finite element analysis for this same average stress shows that there will exist peak stresses of about 44 MPa. (Gleiter 2002)

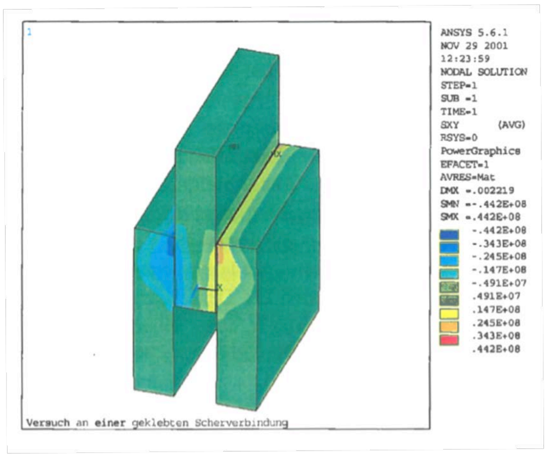


Figure 81: Stress distribution in a glued PMMA samples (Gleiter 2002)

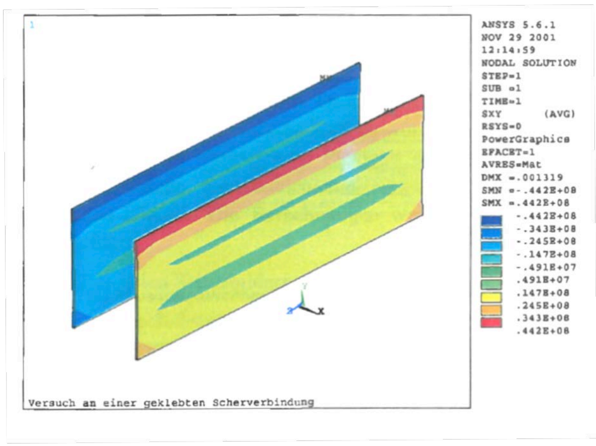


Figure 82: Stress distribution in a glued PMMA samples (Gleiter 2002)

A butt joint with the same adhesive material reached a capacity of about 75% of the virgin material's tensile strength when the material is properly annealed after the joining process. (Gleiter 2002)

For Polycarbonate it is advised by Bayer Corporation to bond with methylene chloride or ethylene dichloride. Methylene chloride's fast evaporation rate helps to prevent solvent-vapour entrapment for simple assemblies.
A thin film of solvent should be applied to only one part. Within a few seconds after applying the solvent, parts have to be clamped together with a pressure between 100 and 500 psi (0,7-3,5 MPa) for about 60 seconds.
Because ultimate bond strength is primarily a function of solvent concentration on the surfaces to be joined, too much evaporation before clamping will result in poor bonding. Therefore the time between application of the solvent and clamping should be carefully controlled. (Bayer 2001)

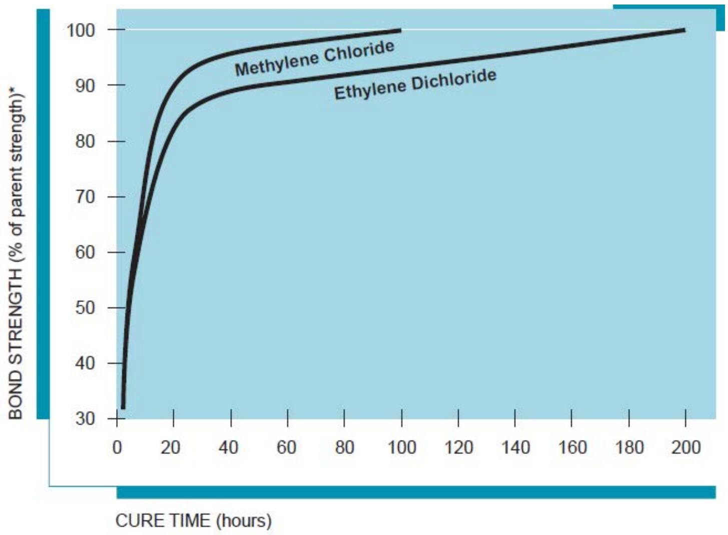


Figure 83: Influence of post curing on bond strength for polycarbonate (Bayer 2001)

Polymerizing glue
This type of connecting only applies to acrylic-acrylic bonds, as for polycarbonate this process, same as for the bulk casting process, is chemically not possible.
To bond acrylic plastic, it is possible to use a specialized chemical bonding agent, a so-called polymerizing glue. This glue consists of a solvent that loosens the molecular bonds of the acrylic sheet. When two pieces of acrylic sheet are treated with this chemical bonding agent and pressed together, the loosened molecules of both pieces of acrylic interweave together, with help of the polymerizing monomer in the glue, and create a strong waterproof connection. (Reynolds 2011)

There are two types of polymerizing glues:

- Un-thickened solvent, a solvent formulation augmented with methyl methacralate (acrylic monomer) and a catalyst that causes the monomer to polymerize. The joint can achieve up to 90% of the tensile strength of the virgin materials being bonded when properly post cured at elevated temperatures.
- Thickened polymerizable cement, a mixture of methacrylate monomer and polymethylmethacrylate resin whose polymerization is as well initiated by a catalyst. Absence of solvent in this mixture allows bonding of wider joint gaps (up to 9 mm) as there is no evaporation of solvent during curing. When properly post cured at 70 degrees Celsius this bond may even equal the tensile strength of the virgin acrylic material.

Bonds deteriorate faster with exposure to outdoor weathering, with the greatest decrease in flexural and tensile strength and the least in compressive yield. The bond will as well yellow slightly quicker than the virgin material and therefore the polymerizing mixture has to be selected carefully. (Stachiw 2003)

Welding

In general welding implies the melting of the welding zone and thereby creating the ability to join two pieces of material together. Welding can be done in several different ways among which hot-plate welding, induction welding and ultrasonic welding, see figures below. The size, shape and function of the part that to be joined define the selection criteria for the welding process. (Bayer 2001) (GE Plastics 2004)

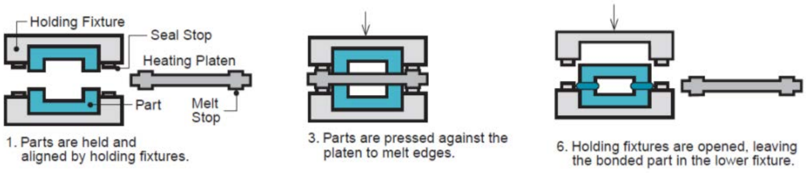


Figure 84: Hot plate welding

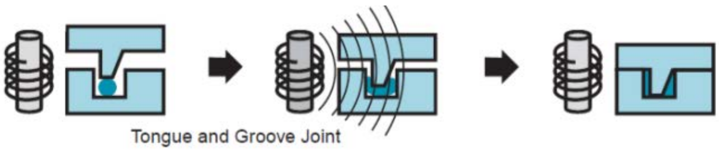


Figure 85: Induction welding

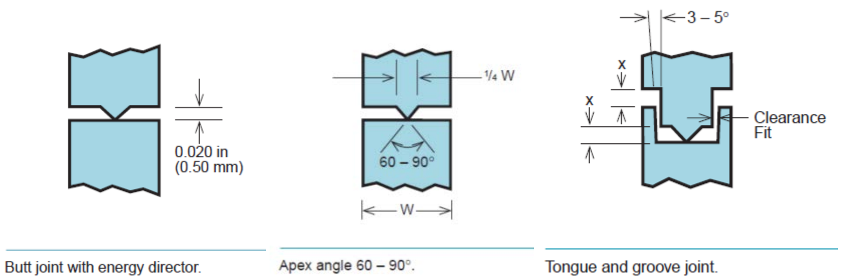


Figure 86: Ultrasonic welding with parts of the same material with energy director tip melting under high frequency vibrations. The molten material creates the bond. (Bayer 2001)

Extruded Polycarbonate and PMMA have a fairly good weldability, all above mentioned welding techniques can be applied. Cast PMMA can only be welded with the use of filler rods, the added material is melted to create the bond. However the operation leaves high internal stresses and an annealing heat-treatment is essential. Thereby welding is primarily used with opaque grades of thermoplastic as the achieved optical quality of welding is not ideal. Under optimal conditions the welded joint can reach a strength of up to 50% of the virgin material. (Gleiter 2002) (Altuglas 2005)

Mechanical fastening

Dowels , screws, bolts and rivets

Each of these joining devices requires drilling of holes in the thermoplastic material. As mentioned earlier the material is very sensitive to irregularities and boring should therefore be executed with specially ground drills to create smooth holes. These techniques are reliable if the brittleness and the low temperature melting point of the materials are taken into account during machining. ‘ (Stachiw 2003)

Major drawbacks of mechanical connections are the creation of stress risers which can serve as crack initiators and the need for elastomeric seals to provide a watertight joint.
An advantage of this way of joining is the fact that components can easily be taken apart periodically for maintenance , inspection or replacement. (Stachiw 2003)
Another point of attention is the fasteners head. The use of tapered heads can cause undesirable tensile stresses in the matching parts, therefore heads with a flat underside should be used combined with flat washers to help distribute the assembly force over larger areas. The minimal distance between the fasteners hole and the edge of the element should be at least the largest of the hole diameter and twice the part’s thickness. (Bayer 2001)

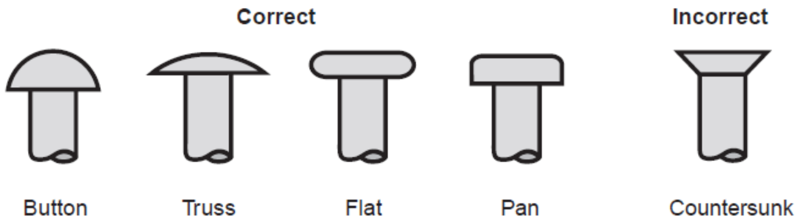


Figure 87: Different fasteners heads (Bayer 2001)

Another way of strengthening the bond is to apply edge attachment materials, adhesive bonded to the acrylic, before riveting or bolting the element to another. In this way the stress can be spread over a larger surface. The bolthole is placed in the bonded attachment instead of the acrylic to prevent stressconcentrations.

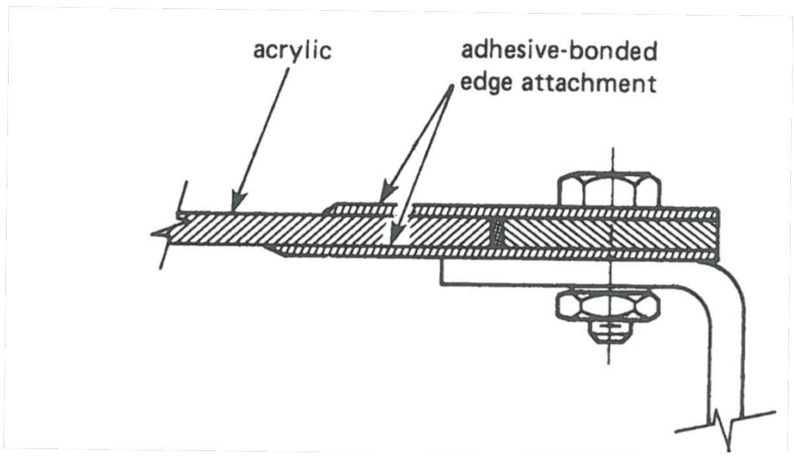


Figure 88: Edge attachment, bonded to acrylic (Stachiw 2003)

As for the capacity of the joints, several factors are governing. For instance the diameter of the hole, thickness of the sheet, distances between sheet edge and hole and between holes themselves etc. Mr Gleiter did tests on both a bolted and a riveted connection. He advises to use only a single row of fasteners for unidirectional loads as the second row will only have limited effect due to the brittle material behaviour. Computation of the capacity of this type connections can be done according to the guidelines of the Büv-Empfehlung (Büv 2010). The ultimate capacity of the rivets was determined to be about 55 MPa based on testing. (Gleiter 2002)

Clamped connections

As drill holes have a negative influence on the material behaviour it is better to install the components intact. In some cases it is possible to use a clamped connection for instance as used in window frames. This way the whole length of the connected surface can be used to bear the applied loads. Disadvantages are the fact that this connection is only practical for sheet elements and that a substructure will always be necessary to attach the clamping device.

Clamp forces have to be distributed over a larger surface area. In this way local stresses concentrations in the part after assembly are prevented, and is the risk of loosening of the fasteners through creep and relaxation minimized. (Gleiter 2002) (GE Plastics 2004) (Bayer 2001)

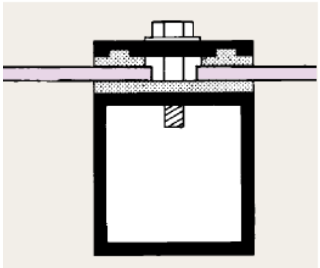


Figure 89: Example of a clamped connection, window frame. (Röhm 2002)

Snap fits

An efficient, inexpensive, quick joining method is the snap fit, a moulded in feature which makes both parts fit together with a click. They have to be designed with great care and precision to avoid excessive (hoop) stress in the assembly. It is a moulded feature and therefore the risk of damage during handling occurs as well.

The degree of interference between parts is critical, too less and the connection will be too loose, too great and assembly becomes difficult and the material gets overstressed. Clearly, this type of assembly method is only realisable when tight manufacturing tolerances can be achieved. The system is not quite suitable to connect dissimilar materials as differences in thermal expansion will affect the precise fitting too much. Injection moulding is the appropriate process to produce these precise features. (Bayer 2001)

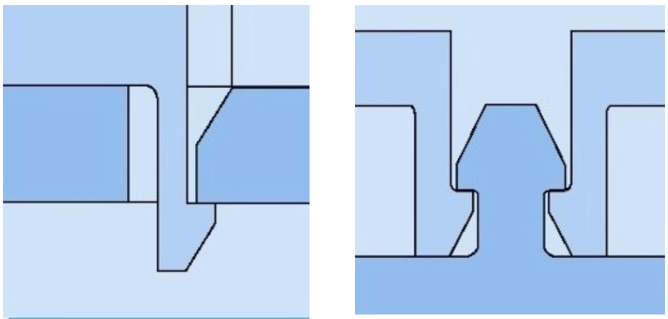


Figure 90: Two possible snap fit joints, a cantilever snap arm and a cylindrical snap fit (MIT 2012)

Material specific

Obviously resulting from the previous paragraph there are various ways to connect different parts together, as well for plastics parts among each other as for plastic parts with other construction materials.
The weak link in a structure is usually the joining mechanism, which means that careful attention must be given to the method used, the structural design, the notch sensitivity and the effects of different thermal expansion.

Polycarbonate-polycarbonate
Especially gluing and clamping are very suitable connections for these kind of materials as they connect a large surface and therefore cause the least stress concentration. Solvent bonding gives the highest bond strength, up to 90% of the material strength is attainable.

Acrylic-acrylic
The most interesting joint type for acrylic is the polymerizing glue adhesive joint. This is a unique feature of designing with acrylic as it creates the possibility to make virtually limitless acrylic elements. The strength of these bonds is as well unequalled as it can reach almost the entire strength of the virgin material.

Thermoplastic-other material
When combining thermoplastics to other materials, the most suitable connections are gluing, clamping and the use of bolts. Point of attention is the difference in thermal expansion that usually exists with other materials. The connection should be able to take strain differences without causing peak stresses. To prevent the parts and the connection from failing. (Gleiter 2002)

The change in shape of a material when it is subjected to a change in temperature is determined by the coefficient of thermal expansion. Normally for isotropic materials this will be the same in all directions. For convenience this is often taken to be the case in plastics but one always needs to bear in mind that the manufacturing method may have introduced anisotropy which will result in different thermal responses in different directions in the material, e.g. extrusion. (Crawford 1998)

The easiest way to allow for deformations is to use clamped connections as in window frames or bolts/rivets or else in elongated holes which are generally used to allow for thermal movements in only one direction only.
In case of gluing, for joints between polymers and other materials only adhesives with very low Young's modulus are suitable for connecting the materials, for instant silicones, to be able to make up for the thermal movements. (Gleiter 2002)

3.4.3 Computation and guidelines

Due to the, earlier described, viscoelastic behaviour of plastics deformations are dependent on factors as time under load and temperature. Therefore, when structural components are designed using PMMA and PC, classical equations are not automatically applicable. The equations, available for the design of springs, beams, plates, etc have all been derived assuming linear elastic behaviour, which incorporates that (Crawford 1998):

- The modulus is constant
- Strains are small
- Strains are independent of loading rate or history
- Strains are immediately reversible
- The material is isotropic
- The material behaves in the same way in tension and compression.

The behaviour of plastics however leads to complex viscoelastic models as shown previously. Although some approaches give very accurate results, as a drawback complicated calculations are necessary, involving Laplace transformations or numerical methods and these are not attractive to designers, because this can be very time consuming.

One method to overcome complex numerical complications is the so called Pseudo Elastic Design Method. In this method experimental data is used, time dependent properties are selected from these data and substituted into the classical equations. It has been found that this approach gives sufficient accuracy in most cases. The chosen modulus value has to take account for external factors as the service life of the component, the service temperature. (Crawford 1998)
The same is stated in the Dutch standard NEN 1778.

This method assumes that the long-term design data are available, but experimental data will have to be used to determine the right values. Experimental data cannot be used directly, safety factors should be incorporated in the determination of certain properties.

Mrs. Kyou-Hee Kim used in her research “Structural Evaluation and Life Cycle Assessment of a Transparent Composite Facade System” a safety factor of 2 according to the Baker’s weighted safety factor to estimate the allowable stress of plastics. (Kim 2009)

To obtain the right design data several guidelines, figures and tables have been examined.

Extrapolation

A common way of determining long-term data is extrapolation. Several experimental results from manufacturers and researchers are at hand to do so. A common adopted rule of thumb is that creep data or creep rupture data should not be extrapolated more than one decade of time, so only one complete step in a log-time graph. This to make sure that the data used will not deviate too much from the real data. As there are only little data available for service times of 10 to 20 years it can be difficult to maintain this rule in building design. (Crawford 1998) (GE Plastics 2004)
GE plastics states in its Design guide that “...engineering judgement must be used concerning the extent of the extrapolation in time. But it is not recommended that the extrapolations exceed a strain limit of 20 % of the yield or ultimate stress value for the material being analyzed and not more than one unit of logarithmic time.” (GE Plastics 1997)

Time-temperature superposition

Another way to obtain long-term data is extrapolating with help from tests in elevated temperatures by the time-temperature superposition principle. The creep behaviour elapses in quite a similar way as the lowering of the modulus for higher temperatures. So actually testing at elevated temperatures is a way of accelerating the creep process. From a series of tests in a limited time range for different temperatures the shifting factor $\alpha_T(T)$ can be determined. The mastercurve is constructed from those combined results and then the graph can be used to determine the modulus for a larger time range. This time-temperature phenomenon does not apply to all thermoplastic materials but usually though for amorphous polymers as PMMA and PC. (Vegt 1991)

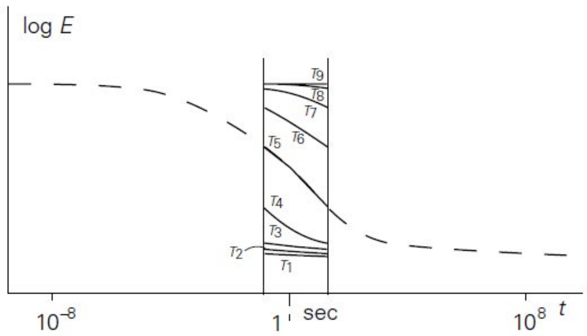


Figure 91: Mastercurve (Vegt 1991)

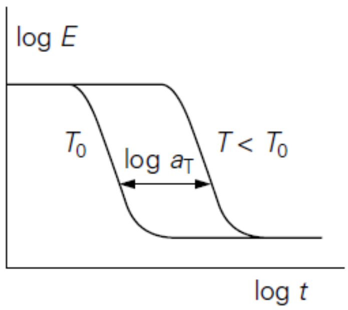


Figure 92: Shiftingfactor (Vegt 1991)

Empirical formulas

To describe creep behaviour often empirical relations are used, for instance the one of Kohlrausch:

$$D(t) = D_0 * e^{(t/t_0)^m}$$

This empirical formula expresses the Creep compliance, the reciprocal of the creep modulus, as a function of time and initial creep compliance. This equation appears very usable to describe the behaviour of a large amount amorphous glassy polymers. *m* Usually is 1/3. With two parameters D_0 and t_0 (which are temperature dependant for the applied polymer) creep can be described quite easily. This equation appears however not sufficient in practice because of the complicated behaviour of plastics: it does not take into account the non-linearity of viscoelastic behaviour, creep and physical ageing. (Vegt 1991)

Another , comparable, available formula is the one of Findley:

$$\frac{1}{E_c} = \frac{1}{E_1} + \left(\frac{1}{E_1} - \frac{1}{E_0}\right) * \left(\frac{t}{t_1}\right)^n$$

With in this case n=1/3 for PC and PMMA. The hereby obtained values are on the safe side of the real values for the long term modulus. (Gleiter 2002)

Guidelines

At least two guidelines are interesting concerning the computation of long-term values and as well in describing methods to determine safety factors. One German guideline about plastic load-bearing building components, which handles fibre reinforced plastics as well, and a European guideline about self-supporting transparent roof structures.

ETAG010 –self-supporting transparent roof kits

The basic formulas used in the ETAG010 guideline to determine the design resistance of transparent plastics is the following:

$R_d = \eta_{dC} * R_k/\gamma_{MR}$ or $R_d = \eta_{dK} * R_k/\gamma_{MR}$ for load bearing capacity – U.L.S.

$C_d = \eta_{dC} * C_k/\gamma_{MC}$ for serviceability – S.L.S.

$\boldsymbol{\eta_{dC}}$ is the material factor depending on the magnification factors for the design situation, for failure caused by deformation
$\boldsymbol{\eta_{dK}}$ is the material factor depending on the reduction factors for failure caused by breaking
$\boldsymbol{R_k}$ is the characteristic resistance for load bearing
$\boldsymbol{C_k}$ is the characteristic resistance for serviceability
$\boldsymbol{\gamma_{MR}}$ is the material safety factor for load bearing,
$\boldsymbol{\gamma_{MC}}$ is the material safety factor for serviceability,

Determination of the material safety factors:

$\gamma_{MR} = \gamma_{Rd} * \gamma_{mK}$ and $\gamma_{MC} = \gamma_{Rd} * \gamma_{mC}$

With:

$\gamma_{mK} = e^{(\alpha_R * \beta_K - k) * v}$ and $\gamma_{mC} = e^{(\alpha_R * \beta_C - k) * v}$

$\boldsymbol{\gamma_{Rd}}$ is the partial safety factor in accordance with the uncertainty of the model used, in this case it can be set to **1,05**
$\boldsymbol{\alpha_R}$ is a weight factor and can be set to **0,8**
$\boldsymbol{\beta_K}$ can be set to 4,2 (U.L.S.)
$\boldsymbol{\beta_C}$ can be set to 2,5 (S.L.S.)
k is the fractile factor and can be taken as **1,645**
v is the variation coefficient based on the standard deviation of the test values, not lower as **0,1**

Determination of the material factors:

Depending on the governing situation for the transparent sheet, deformation or strength, the material-dependent magnification factors (for deformation, S.L.S.) or reduction factors (for breaking strength, U.L.S.) have to be taken into account to determine the material factors.

$\eta_{dC} = 1/(C_t * C_u * C_\theta)$ and $\eta_{dK} = 1/(K_t * K_u * K_\theta)$

C_t and K_t take into account the duration effect for the design values
C_u and K_u are applied to take into account ageing and environmental influences
C_θ and K_θ account for the temperature influences.

In the guideline tables can be found with suitable design values of C_t and K_t for various reference times. Values of C_u and K_u for open-air weathering with normal protection as a UV stabilizing surface layer. And values of C_θ and K_θ for 60/70 degrees Celsius.
For plastics normally used at room temperature these last factors can be taken as 1,0, for other temperatures the value can be derived from the stress-elongation behaviour or the shear modulus curve, with reference temperature T_0=23 °C.
(ETAG010 2002)

Factor/reference time		Polycarbonate (PC)	Polymethyl-methacrylate (PMMA)
K_t C_t	24 h (1 day)	1.20 1.10	1.25 1.20
K_t C_t	650 h (approx. 1 month)	1.25 1.15	1.35 1.25
K_t C_t	2000 h (approx. 3 months)	1.30 1.20	1.40 1.30
K_t C_t	2×10^5 h (approx. 20 years)	1.60 1.50	1.70 1.60

Factor	Polycarbonate (PC)	Polymethyl-methacrylate (PMMA)
K_u C_u	1.10 [2)] 1.10 [2)]	1.05 [2)] 1.05 [2)]

Factor	Polycarbonate (PC)	Polymethyl-methacrylate (PMMA)
K_θ C_θ	1.3 / 70°C 1.2 / 70°C	1.6 / 60°C 1.5 / 60°C

Figure 93: Tables with magnification/reduction factors for PC and PMMA (ETAG010 2002)

BÜV Empfehlung – tragende Kunststoff Bauteile im Bauwesen

The basic formula used to check whether a structure has sufficient capacity in this guideline is the following:

$$E_d(t_\alpha) \leq R_d(t_\alpha) \qquad \text{with} \qquad R_d(t_\alpha) = \frac{R_k}{\gamma_M * A_{mod}}$$

And: $A_{mod} = A_1 + A_2 + A_3$

$\boldsymbol{E_d(t_\alpha)}$ is the effect of the applied load for load duration t_α
$\boldsymbol{R_k}$ is the characteristic property of the material
$\boldsymbol{\gamma_M}$ is the material safety factor
A1 is the factor depending on the load duration
A2 is the environmental influence factor
A3 is the temperature dependency

The modification factors are divided in three categories, A^f_{mod} , A^E_{mod} and A^D_{mod} The first one is applied in the ultimate limit state for properties related to strength and the second one, A^E_{mod} is used for stability control. The last one, A^D_{mod} is meant to be used in the serviceable limit state, for checking of the deformations.

The formula is equal for all properties, just the proper safety and modification factors have to be determined for every situation and material separately.
The factors can be found in tables, unfortunately polycarbonate is not included in this guideline. But as the factors for polycarbonate are less than for PMMA in the Büv Empfehlung it will be safe to use the same values as for PMMA when using this guideline.

For PMMA the following factors are mentioned:

PMMA	**Af** (U.L.S.)	**AE** (Stability)	**AD** (S.L.S.)
A1 (20 years)	2,3	2,5	1,0
A2 (Inside)	1,0	1,0	1,0
A2 (under water)	3,1	N.A.*	1,0
A2 (weathering)	5,4	N.A.*	1,0
A3 (40 degrees C)	1,3	1,2	1,0
A3 (60 degrees C)	2,1	1,5	1,0
N.A.*: information is not yet available			

Figure 94: Modification factors for PMMA

For factor A2 (U.L.S.) the factor for outside application, **5,4** is including temperatures up to 60°C so in that case A3 will be **1,0**. (Gleiter 2002)

For combined stresses the following criterion should be met:

$$\frac{E_{dN}}{R_{dN}} + \frac{E_{dM}}{R_{dM}} + \frac{E_{dV}}{R_{dV}} \leq 1$$

With all **E**-values the effect of applied normal forces, bending moments and shear forces and all **R**-values the computed resistance of the cross-section to normal force, bending moment and shear.

The material safety factor for each loading situation can be determined with the table below, applying to all thermoplastics.

γm	**Strength**	**Local stability**	**Overall stability**	**Joints**
Tension	1,5			
Compression	1,2	1,4	1,2	1,4

Figure 95: Material safety factors for thermoplastics

Other design rules established in this guideline are:

- Failure modes of bolt, screw or rivet connections
- Computation of the capacity of these joints
- Criterion for combined stresses in cylindrical shells
- Transient load factors for multiple layered buildings

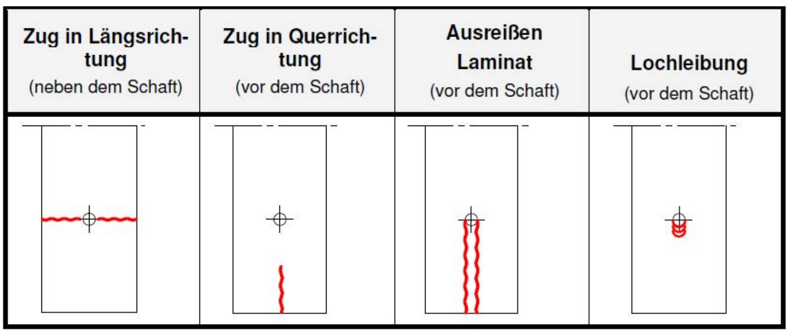


Figure 96: Possible failure mechanisms for a bolted connection (Büv 2010)

This guideline is as well used by Uwe Gleiter for the computation of an acrylic beam structure in his dissertation.
(Gleiter 2002) (Büv 2010)

Comparison of design values for PMMA for a service life of 20 years and inside application.

The methods used are the ones described above and they are compared as well with the design values mentioned in the Handbook of Acrylics (Stachiw 2003). The guideline formulas are used with the values from the Kunststoff-tabellen (Carlowitz 1995) as starting variable and the characteristic values from the material sheet in attachment II.

	PMMA
E-modulus (MPa)	3300
E-modulus (1h) (MPa)	3200
E-modulus (1000h) (MPa)	2100
Char. tensile strength (MPa)	70
Char. Compressive strength (MPa)	110

Figure 97: Used characteristic variables for PMMA

	Max tensile stress	Max compr. stress	Creep modulus
Handbook of Acrylics	10,3	38,6	1630 (3 yr)
Inside application			
ETAG010	27,9	51,9	1558
Büv Empfehlung	20,3	39,9	1100
Under water			
ETAG010	N.A.*	N.A.*	N.A.*
Büv Empfehlung	6,5	12,9	N.A.*
Outside application			
ETAG010	16,5	30,8	1200
Büv Empfehlung	3,8	7,4	N.A.*
N.A.*: information is not yet available			

Figure 98: Comparison of maximum working stresses for the two guidelines

For the ETAG010, computation is difficult as the variation coefficient *v* is not known. This coefficient can be derived from testing results and is not generally supplied by the manufacturers. In the above overview a value of 0,2 is taken for the tensile stress and the imposed lower limit of 0,1 for the compressive stress and modulus. This because (brittle) thermoplastics have a higher chance of unpredictable failure during tensile testing which will probably cause a higher deviation in the testing results.
Another difficulty is the lacking of values for the A_2 factor applicable to the E-modulus calculation in the Büv Empfehlung. The values given for strength application are very conservative and will not give a usable modulus. (356 MPa and 266 MPa respectively)

At the first sight the Büv Empfehlung appears very conservative, but the guideline is meant for all types of plastic bearing structures opposite to the ETAG010 which is only aimed at roof kits (however still self-supporting). Thereby the ETAG010 factors could not be calculated properly due to the missing *v* values.
It is still possible that the outside application for the ETAG010 gives more favourable results than the Büv Empfehlung as it explicitly takes into account that the material has a UV protective coating.
When the in the Handbook of Acrylics mentioned design modulus is extrapolated to 20 years with help of the empirical Findley formula a value of 835 MPa is found which possibly is a usable long-term modulus.

Conclusion

In general all sources offer a preliminary design guideline to determine the allowable design stress, it will be wise to use the most conservative values in this stadium as there are still much uncertainties in the use of these materials as a bearing material. For instance the influence of damage, fatigue, from scratches and notches to holes is very unpredictable and risk full. Therefore it is important to have enough safety build in the computation. A disadvantage is that conservative calculations can cause excessive and unnecessary use of material and thereby increased costs.

Besides the determination of design variables all sources advise to use final element software to investigate the precise flow of forces to avoid unexpected stress concentrations.
A last step in the design process is small scale and full scale testing, this is still advised for all structures, even for the more or less standard roof structures.
From ETAG010: "*Because of the limited available data, the load-bearing behaviour of the translucent parts of a roof kit shall be examined by full-scale tests. In addition, in order to characterise the performance of the sheets themselves, a series of material specific small-scale tests is required..*"

3.5 Transparent plastics as a building material

A lot has become clear about transparent plastics by now, the properties, the possibilities of smart design, ways of joining the components and how to compute maximum workable design stresses.

Will the opportunities weigh up to the disadvantageous properties in the end and will transparent plastics appear to be suitable and maybe even structural building materials? It might be good to have a look at other building materials to get more insight in this matter. To compare general characteristic properties a material comparison sheet can be found in attachment II.
With a density of about 1200 kg/m^3 transparent plastics belong to the light weight building materials, for a light weight material they have a relatively high strength and stiffness as can be seen in the next figure with weight reduced stiffness for various materials. (Vegt 1991) (Gleiter 2002)

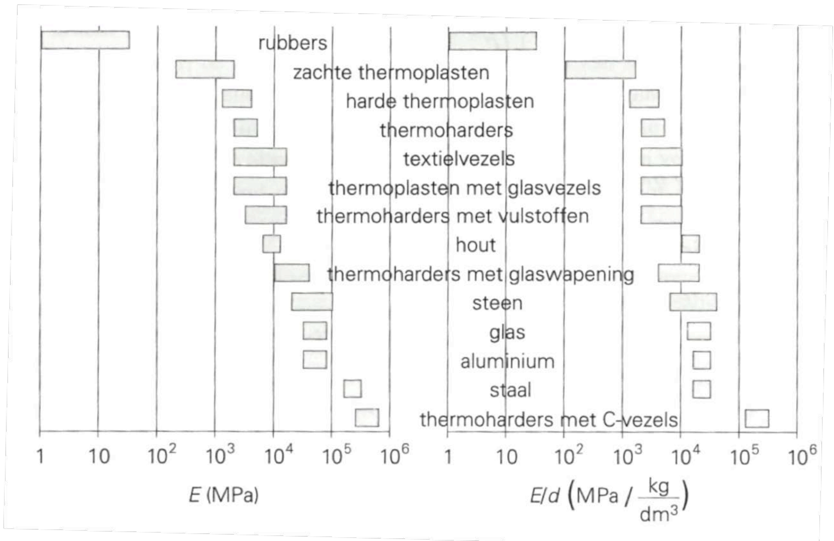


Figure 99: Absolute and weighted modulus of various (building) materials (Vegt 1991)

However the Young's modulus' of plastics are mostly significantly lower than the modulus' of other building materials as steel or concrete. This asks for some special designing but the use in high demand building parts for submersibles, airplanes and cars shows that it is possible.

Another interesting relation is that between ultimate yield strength and modulus of elasticity, the following values are computed:

	Young's modulus	Yield strength	Ratio
Acrylic	3300	65	50,8
Polycarbonate	2300	65	35,4
Soda-lime glass	70000	30	2333,3
Steel	210000	235	893,6
Concrete	20000	2	10000,0
Softwood	9300	40	232,5

Figure 100: Relation between Young's modulus and ultimate strength for various materials

For both transparent plastics concerned this ratio is way lower than for other building materials. This will have results for the design process, deformations will probably be leading in the determination of structural dimensions.

The thermal conductivity of thermoplastics is a lot lower than of a lot other materials as for instance metals and glass and can therefore be quite suitable as insulating outer shell material for buildings as well. (Gleiter 2002)

The most obvious material to compare with transparent thermoplastics will of course be glass. Nowadays transparent parts of buildings will almost without exception be made out of glass.
The only exceptions will be light weight glaze roofing. For instance stadiums or green houses which are often made out of transparent plastics as polycarbonate or acrylic. Impact resistant or high pressure resistant structures from underwater windows and aquaria to bulletproof glazing. And beside that private applications as carports, windshields, light domes etcetera.

The first reaction to PMMA and PC is that it does not appear to be a feasible material for constructing types of transparent bearing structures. Their lower compressive strength, lower Young's modulus, better but for acrylic still low fracture toughness and sensitivity to stress concentration and scratches make them no obvious materials for bearing applications or as replacement for glass in general. However, the good strength-to-weight ratio makes them getting near to several other building materials, the plasticity permits them to tolerate large stress concentrations in compression. In addition the optical quality of these transparent plastics, especially acrylic is unequalled and is in 3D shapes far more inexpensive in comparison to glass. (Stachiw 2003) (Engels 2008)

The low processing temperature of thermoplastics creates the possibility to form even complicated parts relatively economically. This has also negative side effects, as operating temperature can get quite close to the glass transition temperature and how closer it is, how larger the deformations of the material get. A higher temperature can also affect the mechanical properties quite severely. (Gleiter 2002)

Plastics are known for being inexpensive materials but the scarcity of certified manufacturers of for instance cast acrylic sheet leads to extended delivery times and high transportation costs, especially when large elements are desired. This although production is highly industrialized and does not involve extremely costly processes. Straight forward structures therefore can still be made more easy and less expensive in glass. (Engels 2008)

Compared to glass, thermoplastics have a lot of advantages but equally disadvantages, the choice for a certain material will therefore be highly dependent on the individual application.
So altogether, when designing smart, those materials will be more colleagues than rivals. The specific strengths of glass are not by far equalled by transparent thermoplastics but the various possibilities as freedom of shape, special bonding techniques for acrylic and the ductility of polycarbonate will provide opportunities for other, new, ways of transparent building. Thermoplastics can be a helpful companion on the way to a non-supported transparent structure.

As a conclusion it can be said that transparent thermoplastics polycarbonate and polymethylmethacrylate are suitable building materials when certain design rules and limitations are respected.

4 Case study

4.1 Program of requirements

4.1.1 Introduction

To get more insight in the capabilities of transparent plastics and to get a feeling for designing with plastics, it was decided to work out a case-study.
This will be an imaginary project in which it is possible to try out and show the performance of transparent plastics in a structural application.

A few possibilities have been considered:

- Using an existing building as a case and improving this building design by replacement of one or more building parts using transparent plastics.
- Using an extreme as a case study. Stretching the limits, building as high as possible or determining the maximal span of a transparent plastic structure.
- Making a new design based on the found properties and resulting possibilities.

The decision fell on making a new design: An observation tower achieving maximal transparency by the use of the transparent plastics acrylic and polycarbonate. Reasons for this choice:

- Conventional buildings will be less suitable to show the possibilities of transparent plastics. Because of the properties of plastics, glass will still be the most favourable solution to straight facades and standard windows. A special structure will be the way to show the appealing possibilities of plastics.
- Observation towers in the Netherlands have become a sort of art-objects over the years. They are not only meant to be functional in bringing a visitor to a viewpoint, but climbing should be an experience itself. Transparent plastics might be very suitable to create such an object.
- The freedom of design allows for the ultimate use of the transparent plastics. The case actually becomes a ''show-case''. In which smart design with plastics can lead to an interesting transparent landmark.

Three design options have been sketched, they all contain a core structure, an observatory sphere and a subsurface observation room:

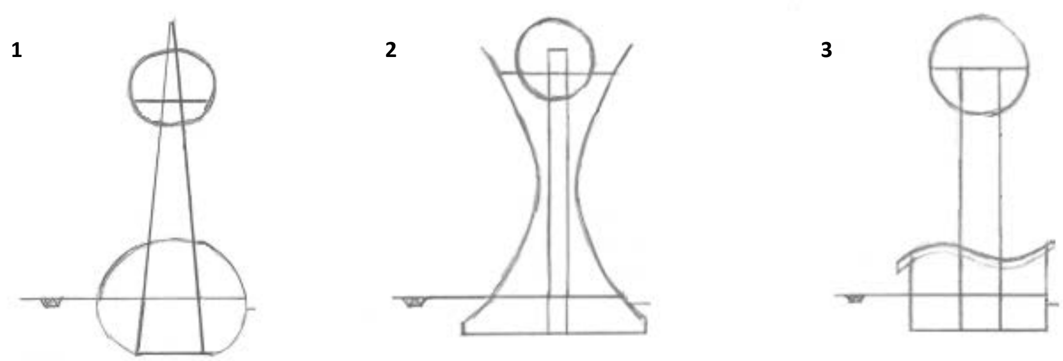


Figure 101: Sketched design options.

In consultation with an architect it was decided to use option 1 for the further design.

This leads to the following project description:

An observation tower designed as a case-study for the application of transparent plastics in building structures. The building will be a public building with a gathering function.

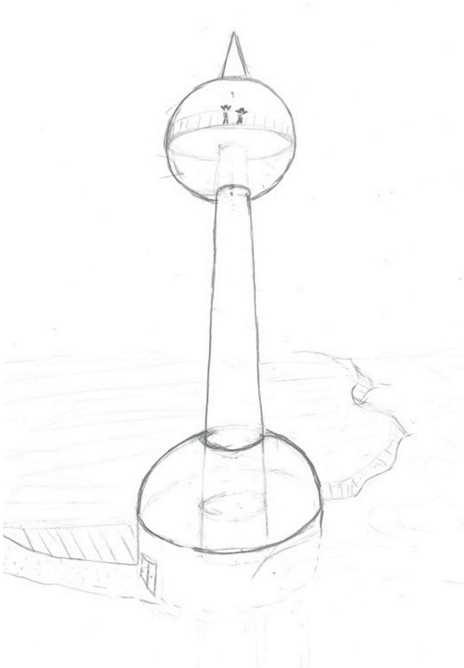


Figure 102: Early sketch

The project consists of an observation tower and visitors centre along one or more of the "Randmeren" , for instance the Veluwemeer. The tower will be as transparent as possible allowing the visitors to have a view around all the way up and down the tower. In the top there will be a spherical observatory room. Below surface there will be an observatory room as well, with transparent walls to teach visitors about the sub surface life in ground and water. A lot of birds and fishes live around this area.
Clearness of the surface water is a spearhead of the Nature Conservancy in the Netherlands; the Veluwemeer already has gained an underwater sight of about 3 meters, which will be further improved. This progress could be made visible for the visitors of this observatory tower.

4.1.2 Determination of basic dimensions

Height

The design height is determined based on the observation of reference projects. For instance:

- Bostoren – 40m high, platform with 17 meter diameter
- Wilhelminatoren, Vaals – 34 meter high
- Several remaining air watchtowers – originally about 140 were built between 1950 and 1960, with heights from 2,5 to 31 meter, with about 18 square meter platforms. (Hillinga 2010)

Figure 103: Pictures of (from left to right) Bostoren, Wilhelminatoren and watchtower Ruinen

View also Appendix B for more examples. In general towers without an elevator exist between 10 meter and 50 meter. It depends on the landscape and the kind of trees present what height is needed to be able to look over a forest. For example a pine forest can achieve a height of 60 meter whereas a birch or chestnut tree will not exceed 30 meter.
As this observation tower should offer a viewpoint over water and land and is not standing in the middle of an old forest, an average height will be sufficient. But as the tower should be a striking landmark a certain prestigious height is desired. The choice is made to make the highest point of the tower at about 30 meter; the platform will be significantly lower, because of the spherical shaped observation room.

Platform size

To determine the desired platform size it is necessary to make an estimation of the number of simultaneous visitors that could be present. As a reference a market research of the Bostoren is used.
This study resulted in an estimated visitors number of 50.000 a year. This number is used to get an indication of the maximal number of people that could visit on one day, and per hour. And thereby to know what size for the observatory deck would be sufficient. (Berkers and Middelkoop 2003)

As an outdoor attraction will attract the most visitors during the summer months, it can be assumed that half of the people will visit within three summer months. That results in about 280 visitors each day, possibly up to 500 visitors on busy day.

For instance the opening hours could be between 9 am and 9 pm. During the opening hours the number of visitors will not be equally spread. State that a maximum number of visitors around 85 visitors per hour is possible. A visit of half an hour to the observation sphere will be satisfactory, so the assumption can be made that ultimately 45 people are present at the main deck in the same time.

A diameter of 10 meters will provide an area of about 75 square meter, divided by 45 people this would give a minimum available surface of 1,7 m^2 per person. That will be sufficient. The 10 meter diameter sphere will fit well in the design, in relation to the core height covering one third of it.

Core diameter

The core should provide enough strength and stiffness but as well enough space to contain the staircases and some free space at the landings. The minimal width of a staircase is 0,8 meter, say 1 meter. As it will be spiral or winding it needs to fit twice into the core diameter. To provide for a meter additional space around or inside it a core diameter of at least 4 meters is desired.

Lower dome

For the image of the tower and the possible repetition of plastic elements the lower dome is designed with the same radius as the sphere over the height, thus 5 meter. The dome is wrapped around the core so the floor radius will be 5 meters plus the core radius of at least 2 meter.

Subsurface room

The diameter of the lower dome structure as well determines the size of the subsurface room. The height of this room is chosen to be 4 meters, well proportioned to the 5 meter height of the lower dome and allowing for a spacious feeling for visitors of the room.

Distance between landings

In the National Building Decree a maximal stair height without interruption of 4 meters is prescribed. As a floor at the level of the dome and sphere support is desired at these locations the distance of 5 meters is divided by 2, resulting in a distance between landings of 2,5 meter.
Rest of the landings, three in total, are positioned at a distance of 3,5 meter, this makes a platform height of 4 times 2,5 added by 4 times 3,5 thus 24 meter above ground floor level. Top of the sphere will be at 29 meter now and thus the total height including the cone on top will be just above the 30 meter that was aimed at.

4.1.3 Main principles

- The observation tower should be as transparent as possible, meaning that all parts will be designed in transparent plastics unless this is proved impossible.
- About 45 people should be able to visit the observation deck at once; about 100 visitors could be in the complete information centre, including the observation deck.
- The tower will be about 30 meters high.
- The observation sphere will have a diameter of 10 meters which provides an area of around 75 square meter, which divided by 45 people gives a minimum surface of 1,7 m^2 per person. That will be sufficient.
- The ground floor of the low level dome will have a radius of 5 meter, and is wrapped around the shaft. Making a ground floor radius of 5 added with the radius of the core.

- Design values will be determined aiming to prevent crazing (and therewith prevent collapsing as well) for at least 20 years. (The concept of crazing is explained in paragraph *3.3.3: Failure modes*). The design factors will be based on the safety factors stated in the available guidelines in combination with several studies on the behaviour in different time, temperature and environment conditions.
- A longer lifetime is at this moment not considered practicable as necessary data are missing to be able to determine design values. Test results are available up to 20 years and in some cases extrapolation is used already. Further extrapolation will possibly lead to large errors and is therefore unreliable. The uncertainties with respect to long term behaviour of thermoplastics, especially in an outdoor environment, are too large to ensure structural rigidity for more than 20 years yet.

- For most parts the stiffness will be leading, because of the low Young's modulus compared to the strength of the material. This requires a (composed) cross-section with a large Moment of Inertia. A result will be that the Section Modulus is large as well so relatively low stresses will occur. This is a favourable situation, as low stresses will result in little creep sensibility.
- As well the wind loads, as the live loads are short-term loads, which means that higher resulting stresses are allowed, as the material is less sensitive to short-term stresses.
- The stability is realized by the core parts connection with the foundation. As these parts work together as one cross-section, the parts do not need to be clamped in the foundation individually. These pinned connections along the cross-section will create a clamped system altogether.
- An important starting point for design with plastics is repetition. The repetition of parts highly influences the feasibility as usually expensive moulds are used for the production. The more elements are produced with one mould, the lower the costs per element.

- Dynamic effects will be handled briefly to be able to make an estimation whether it will lead to problems and needs further research, or not.

- Fatigue of plastics is a very complex problem, which is not examined further. However due to the fluctuating wind and other variable loads fatigue will occur. To compensate for fatigue and possible degradation of material properties over time, conservative assumptions are made regarding to short-term design values as well. A duration of 24 hours is used in the determination, as well for wind loads and snow lads as for the short-term part of the imposed loads.

- For long-term loading the self-weight and part of the imposed floor load will be taken into account.

4.2 Preliminary design

4.2.1 Design choices

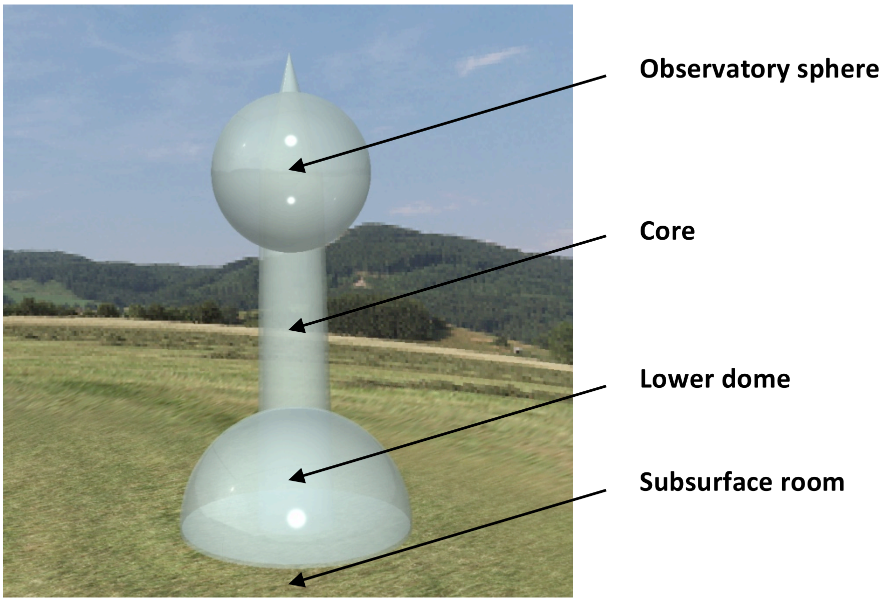


Figure 104: Parts of the building structure

All information gathered results in the following preliminary design choices:

- Acrylic blocks will be used for the bearing structure as only PMMA can be cast to large monolithic blocks, suitable to bear the weight of the platform and providing enough stiffness to resist wind loads. Thereby the blocks can be connected with polymerizing glue, which will create a structure that can be practically regarded as one element. Acrylic behaves favourable under compressive loading.
- The observatory sphere will be assembled of polycarbonate segments that are glued together. This material has better properties concerning, long term behaviour and temperature sensitivity and is less brittle than acrylic. Its UV resistance is not impressive so UV protective coating is required for applications outside. As no especially thick elements are needed for the shell polycarbonate is an excellent material for this application. To provide extra stiffness without using thicker material the possibility exists to use ribbed elements.
- The lower dome structure may be composed with the same elements as the observation sphere, however this can bring up a problem since the curvature differs.
- The polycarbonate is very suitable for the façade as it is more resistant to impact loading and less brittle, thereby its fire-resistance is higher so altogether it will be creating a protective coating for the main structure. So most of the façade will be constructed of polycarbonate.
- The subsurface part of the structure will be composed again of acrylic elements, because of the ground and water pressure it has to resist; the required wall thicknesses will be higher than achievable in polycarbonate.

4.2.2 Loading

4.2.2.1 Applicable loads

Imposed loads

Floors [1)]	3.00 kN/m^2	(ψ=0,25)
Stairs	3.00 kN/m^2	
Roof 0-15° [2)]	1.00 kN/m^2	(ψ=0)
Roof 15-20°	1.00-0.00 kN/m^2	(ψ=0)

[1)] As the building does not have a standard function the imposed load is determined to be 3 kN/m^2, as there will be practically no furnishing, three people of 80kg (2,4kN) and 0,6kN furnishing are taken into account on every square meter, which is way more than expected (1/1,7=0,6 person/m^2). ("bijeenkomstfunctie" approaches its function the nearest but that assumes high concentration gathering of people and some furnishing resulting in a total imposed load of 5kN/m^2). (NEN-EN1991-1-1 2002)

[2)] As the roof is curved outwards to all sides there will be no water accumulation on the roof.

Wind loads

Veluwe/randmeren:	Wind area II, undeveloped
Building height:	30 meter
Maximum impact pressure:	$q_p(z_e)$ = 1,19 kN/m^2

The Wind force factors (overall wind load) used are:

Cylindrical part:	Cf = 0.5
Sphere:	Cf = 0,2
Dome:	Cf = 0.4

The governing wind pressure factors (local values) used are:

Cylincrical part:	Cp = +1,0/ -2,2, ψλ = 0,66, ψλα=1;
Sphere:	Cp = +0,4/-0,6 (same ratio global/local pressure used as for the cylinder, Cf/Cp+ =0,5/1=0,5 as the transition point is reached at about the same angle α)
Dome:	Cp = +0,8/-1,2

Determination of all factors can be found in Appendix D.

Global wind forces can be calculated with the following formula:

$$F_w = c_s c_d \cdot \sum_{elementen} c_f \cdot q_p(z_e) \cdot A_{ref}$$

The structural factor $c_a c_d$ takes into account the effect on wind actions from the non-simultaneous occurrence of peak wind pressures on the surface together with the effect of the vibrations of the structure due to turbulence. Usually a safe assumption for this factor is 1, and as this building consists of three different shaped and sized parts it is hard to compute the factor with the in the Eurocode described procedure. It is chosen to use the safe factor of 1. (NEN-EN1991-1-4 2005)

Snow loads

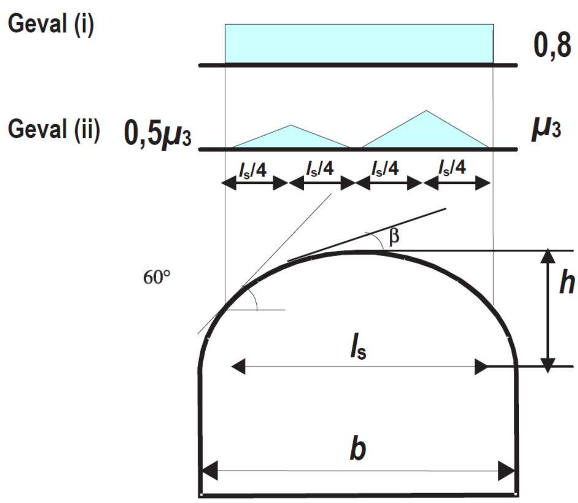


Figure 105: Snow load coefficients for cylindrical roofs. (NEN-EN1991-1-3 2003)

The basic snow load sk is 0,7 kN/m^2.

$$s = \mu_i * sk$$

For cylindrical roofs two different situations have to be concerned, a uniformly distributed load with μ= 0,8 and a redistributed situation as shown in the picture. Then for μ3 the following value applies: (NEN-EN1991-1-3 2003)

$\beta > 60°$, $\mu_3 = 0$

$\beta \leq 60°$, $\mu_3 = 0{,}2 + 10\ h/b$

The maximum value for μ3 is 2,0 which is applicable to both cylindrical roofs as h/b = 5/14 = 0,4 and 5/10 = 2 which makes 4,2 and 2,2 both larger than 2.

Temperature loads

- Can give a difference in air pressure between inside and outside. But as ventilation will have to be applied to reduce warmth and supply fresh air this is not the case here.
- Can cause stresses by differences in temperature between inside and outside and by differences in thermal expansion between different materials.

Temperature load is considered a permanent load in the load combinations.
(NEN-EN1991-1-5 2003)

Situatie	Temperatuur	
	Momentaan °C	Extreem °C
Zomer – buiten niet directe zonbestraling	17	30
Directe zonbestraling – zeer lichte kleur [a] – lichte kleur [b] – donkere kleur [c]	 17 17 17	 50 60 75
Zomer – binnen	17	25
Winter – buiten	4	–25
Winter – binnen	17	20
Constructies in de grond	10	10

[a] Wit, lichtgrijs, geel, crème.
[b] Oker, beige, grijs, groen, lichtblauw.
[c] Zwart, blauw, bruin, rood.

Figure 106: Temperature differences in various weather conditions. (NEN-EN1991-1-5 2003)

Largest temperature differences that can exist:

- Due to the seasonal cycle: -25 degrees in winter and 50 degrees in summer is a difference of 75 degrees. For PC/PMMA, with a thermal expansion coefficient of 0,00007/K, that means a difference between the shrunken and the expanded state of over 5 millimetres per meter.
- Due to the daily cycle: A maximal temperature difference of about 20 degrees can exist between day and night time temperature. This can increase to about 40 degrees for surfaces in direct sunlight.
- Between inside and outside: A maximal difference of about 30 degrees can exist when sun is directly shining on the outside surface and the inside temperature is still quite low from the night.

Ice loads

When the water freezes the crushing can cause an extra load on the walls of the cellar from outside.

This load will probably be less than the soil pressure on the other side of the subsurface room. This is now dominant and causing an asymmetric loading on the subsurface room thus extra loading on the water side will only balance the structure. Yet the ice could damage the surface of the material with scratches or worse.

The risk for surface damage caused by ice is beyond the scope of this research.

4.2.2.2 Load cases

Ultimate limit state

Conform the Eurocode 1 (NEN-EN1991-1-1 2002) the following fundamental load cases need to be concerned, 6.10a and 6.10b for the conventional reliability and consequence class RC2/CC2:

Blijvende en tijdelijke ontwerp-situaties	Blijvende belastingen		Overheersende veranderlijke belasting	Veranderlijke belastingen gelijktijdig met de overheersende	
	Ongunstig	**Gunstig**		**Belangrijkste** (zo nodig)	**Andere**
(verg. 6.10a)	1,35 $G_{kj,sup}$ [a]	0,9 $G_{kj,inf}$			1,5 $\psi_{0,i}\,Q_{k,i}$ (i >1)
(verg. 6.10b)	1,2 $G_{kj,sup}$ [b]	0,9 $G_{kj,inf}$	1,5 $Q_{k,1}$		1,5 $\psi_{0,i}\,Q_{k,i}$ (i >1)

[a] Bij vloeistofdrukken met een fysiek beperkte waarde mag zijn volstaan met 1,2 $G_{kj,sup}$.

[b] Deze waarde is berekend met ξ = 0,89.

Figure 107: Fundamental load cases (NEN-EN1991-1-1 2002)

The national supplement of Eurocode 1 prescribes for the variable load class C a ψ_0 of 0,25 and for wind and snow loads a ψ_0 value of 0. This factor is multiplied with 1,5 for combined load cases. The complete table with momentaneous factors is shown below.

Belasting	ψ_0	ψ_1	ψ_2
Voorgeschreven belastingen in gebouwen, categorie			
Categorie A: woon- en verblijfsruimtes	0,4	0,5	0,3
Categorie B: kantoorruimtes	0,5	0,5	0,3
Categorie C: bijeenkomstruimtes	0,25	0,7	0,6
Categorie D: winkelruimtes	0,4	0,7	0,6
Categorie E: opslagruimtes	1,0	0,9	0,8
Categorie F: verkeersruimte, voertuiggewicht ≤ 30 kN	0,7	0,7	0,6
Categorie G: verkeersruimte, 30 kN < voertuiggewicht ≤ 160 kN	0,7	0,5	0,3
Categorie H: daken	0	0	0
Sneeuwbelasting	0	0,2	0
Windbelasting	0	0,2	0
Temperatuur (geen brand)	0	0,5	0

Figure 108: Ψ-factors, applicable for buildings. (NEN-EN1991-1-1 2002)

As a result the following scheme can be used for the applicable load cases:

	G		Qv	Qw	Qs
U.L.S.		Favourable			
Long term					
1	1,35	0,9	0,38	-	-
Short term					
2	1,2	0,9	1,5	-	-
3	1,2	0,9	0,38	1,5	-
4	1,2	0,9	0,38	-	1,5

Figure 109: Load cases, with:
G = Selfweight of the structure
Qv = Variable floor load (with ψ_0=0,25)
Qw = Wind load (with ψ_0=0)
Qs = Snow load (with ψ_0=0)

Distinction is made between the long term and short-term load cases as different design values should be used for as well stiffness as maximum allowable stresses.

In case the total load on core or foundation is concerned, only two floors need to be calculated with their extreme floor load. Rest of the floors are then loaded momentaneously, with the ψ_0 factor of 0,25 again. In this design study the ground floor and observation floor are loaded extreme as this will generate the most unfavourable situation, these floors having the largest surfaces.

Serviceability limit state

Concerning deformations, for the serviceability limit state the following combinations exist in the Eurocode:

Combinatie	Blijvende belastingen G_d		Veranderlijke belastingen Q_d	
	Ongunstig	Gunstig	Overheersende	Andere
Karakteristiek	$G_{kj,sup}$	$G_{kj,inf}$	$Q_{k,1}$	$\psi_{0,i}Q_{k,i}$
Frequent	$G_{kj,sup}$	$G_{kj,inf}$	$\psi_{1,1}Q_{k,1}$	$\psi_{2,i}Q_{k,i}$
Quasi-blijvend	$G_{kj,sup}$	$G_{kj,inf}$	$\psi_{2,1}Q_{k,1}$	$\psi_{2,i}Q_{k,i}$

Figure 110: Calculation values for load combinations (NEN-EN1991-1-1 2002)

To find a right way to apply them in this case study with creep sensitive thermoplastics the timber regulations, Eurocode 5, are considered. This standard indicates that to calculate the instant deformations the characteristic combination can be used, resulting in the following load cases: (NEN-EN1995-1-1 2011)

Characteristic	G		Qv	Qw	Qs
S.L.S.		Favourable			
Short term					
5	1	1	1	-	-
6	1	1	0,25	1	-

Figure 111: Characteristic load cases.

For plastics as well as timber it is necessary to take into account the creep deformation caused by permanent loads.
As the wind load on the main structure has no permanent effect and self-weight is not influencing the deformation of the core significantly, the characteristic load case is used to determine the horizontal deflection of the tower.

For the long term situation the quasi-permanent load case as described in Eurocode 5 can be used. This case takes into account the part of the load that is assumed to be permanent, indicated by the factor ψ_2. Regarding the situation of an observation tower only visited during day hours it would be too conservative to take ψ_2=0,6 as the part of the load that is permanent so the combination factor ψ_0=0,25 is used as the part of the load that will be taken to be permanent.
Eurocode 5 standard uses a factor k_{def} that incorporates the difference between long- and short-term behaviour. The final deformation is then calculated as the sum of instant deformation and additional creep deformation with the following formula:

$$u_{\mathrm{fin,G}} = u_{\mathrm{inst,G}}\left(1 + k_{\mathrm{def}}\right)$$

$$u_{\mathrm{fin,Q,1}} = u_{\mathrm{inst,Q,1}}\left(1 + \varphi_{2,1} k_{\mathrm{def}}\right)$$

(NEN-EN1995-1-1 2011)

For now the long term and short-term part are separated for easy reference. The momentaneous part of the imposed loads, together with the self-weight will be subjected to the long-term modulus. Rest of the variable load will be subjected to the short-term modulus. Both deformations are then summed to get the final deformation. This results in the following load case:

Quasi-permanent	G		Qv	Qw	Qs
S.L.S.		Favourable			
Long term					
7	1	1	0,25	-	-
Short term					
7	-	-	0,75	-	-

Figure 112: Quasi permanent load case.

The total deformation can be visualised as follows:

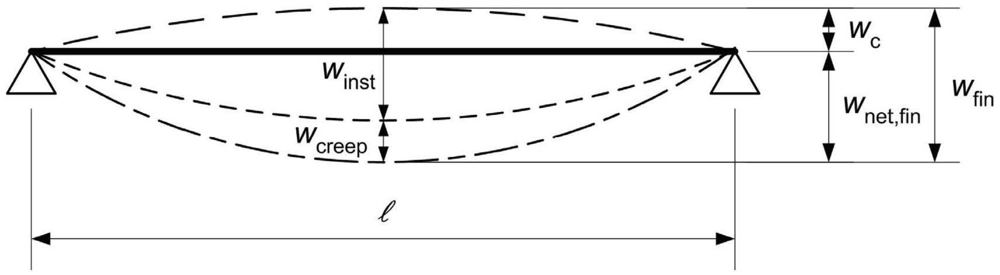


Figure 113: Contributions to deformation. (NEN-EN1995-1-1 2011)

From Eurocode 5 the following criteria are adopted: In case of floor loading the 'instant' deformations from the characteristic load case should remain within 1/300 of the span of the structure. The long-term deformations from the quasi-permanent load case should remain within the 1/250 of the span requirement. When long-term deformation is not an issue the standard 1/250 requirement is sufficient.

To make the long-term load case workable for 3D modelling programs it is rewritten. The short-term modulus of acrylic is 1515/727=2,1 times the long-term modulus. This is done for PMMA as only for the acrylic floors long-term loads, other than self-weight, are present. As the Modulus of Elasticity and the deflection are linearly related it can be stated that:

$$w \cong \frac{G + 0{,}25Q_v}{E_{LT}} + \frac{0{,}75Q_v}{E_{ST}} = \frac{G + 0{,}25Q_v}{E_{LT}} + \frac{0{,}75Q_v}{2{,}1 * E_{LT}} \approx \frac{G + 0{,}6Q_v}{E_{LT}}$$

(NEN-EN1995-1-1 2011)

Now the long-term serviceability load case can be used with the long-term Modulus of Elasticity only, as the ratio between long and short term modulus is incorporated it is only applicable to PMMA elements.
The load case has become:

	G		Qv	Qw	Qs
S.L.S.		Favourable			
Long term					
7	1	1	0,6	-	-

Figure 114: Long term load case.

Extraordinary load case

Ontwerp-situatie	Blijvende belastingen		Overheersende buitengewone of aardbevings-belasting	Veranderlijke belastingen gelijktijdig met de overheersende	
	Ongunstig	Gunstig		Belangrijkste (zo nodig)	Andere
Buitengewoon (Verg. 6.11a/b)	1,0 $G_{kj,sup}$	1,0 $G_{kj,inf}$	1,0 A_d	$\psi_{1,1}$ $Q_{k,1}$ [a]	$\psi_{2,i}$ $Q_{k,i}$ (i >1)
Aardbeving (Verg. 6.12a/b)	1,0 $G_{kj,sup}$	1,0 $G_{kj,inf}$	1,0 A_{ek} of 1,0 A_{Ed}		$\psi_{2,i}$ $Q_{k,i}$ (i >1)

[a] Uitsluitend voor wind op de hoofddraagconstructie; voor overige gevallen $\psi_{2,1}$.

Figure 115: Design values for extraordinary load cases. (NEN-EN1991-1-7 2006)

In case of fire not the entire wind load has to be taken into account. Conform the above scheme the following load case is determined with ψ_1 for wind loads is 0,2 and ψ_2 for the imposed loads is 0,6. (NEN-EN1991-1-7 2006)

	G		Qv	Qw	Qs
Extraordinary		Favourable			
Short term					
8	1	1	0,6	0,2	-

Figure 116: Load case derived from the figure above.

4.2.2.3 Allowable deformations

Floors and roof structures under permanent and variable loads	l/250
Façade elements under only variable load	l/150
Non-structural cladding [1)]	l/50
Horizontal deflection per storey	h/300
Global horizontal deflection	h/500

[1)]Plastics are flexible materials compared to conventional building materials and can handle quite some more deflection without damage. Plexiglas prescribes a design deformation of 1/50 of the span based on aesthetic appearance and economy; *"A deflection of 1/50 of the sheet width (= 2 %) - a permissible value for plastics – is not exceeded, so that aesthetic appearance and economy are guaranteed."* (Röhm 2002)

4.2.3 Fire safety

A difficult aspect of plastics is the generally low fire-resistance of the materials. Especially for the acrylic parts this can be a problem as this material is not self-extinguishing either, contrary to polycarbonate.

Conform the national building code, the observation tower is a ‘building with other function’, which means that no general rules apply concerning the fire-resistance of the building.

gebruiksfunctie	leden van toepassing							
	bezwijken	tijdsduur						bepalingsmethode
artikel	2.9							2.10
lid	1	2	3	4	5	6	7	*
1 woonfunctie								
a woonfunctie van een woonwagen	-	-	-	-	-	-	-	-
b andere woonfunctie	1	2	3	-	-	-	-	*
2 bijeenkomstfunctie								
a bijeenkomstfunctie voor kinderopvang voor kinderen jonger dan 4 jaar of 24-uurs opvang	1	-	-	-	5	6	-	*
b andere bijeenkomstfunctie	1	-	-	4	-	6	-	*
3 celfunctie								
a celfunctie voor dag- en nachtverblijf	1	-	-	-	5	6	-	*
b andere celfunctie	1	-	-	4	-	6	-	*
4 gezondheidszorgfunctie								
1 gedeelte voor aan bed gebonden patienten	1	-	-	-	5	6	-	*
2 ander gedeelte	1	-	-	4	-	6	-	*
5 industriefunctie	1	-	-	4	-	6	-	*
6 kantoorfunctie	1	-	-	4	-	6	-	*
7 logiesfunctie								
a logiesfunctie met een gebruiksoppervlakte van niet meer dan 100m2, niet gelegen in een logiesgebouw	1	-	-	-	-	-	-	*
b andere logiesfunctie	1	-	-	-	5	6	-	*
8 onderwijsfunctie	1	-	-	4	-	6	-	*
9 sportfunctie	1	-	-	4	-	6	-	*
10 winkelfunctie	1	-	-	4	-	6	-	*
11 overige gebruiksfunctie								
a overige gebruiksfunctie voor het personenvervoer	1	-	-	4	-	6	-	*
b overige gebruiksfunctie voor het stallen van motorvoertuigen	1	-	-	4	-	6	-	*
c andere overige gebruiksfunctie	-	-	-	-	-	-	-	-
12 bouwwerk geen gebouw zijnde	-	-	-	-	-	-	7	*

Figure 117: Table from Building Code indicating building types and the applicable regulations. (NEN-EN1991-1-2 2002)

The only applicable rule that remains is: “A building should have a building structure such that the building can be evacuated and searched through within a reasonable amount of time, without risk of collapse.”
The observation tower has to be considered a building because: “A building is a structure, that creates a covered and completely or partly walled space, accessible to people.”
(NEN-EN1991-1-2 2002)

According to a fire expert at the DGMR, normally the building still should have to comply with several rules, as the local fire brigade is allowed to state additional rules.
As the highest floor level is above 5 meters, the basic requirement is 90 minutes of fire-resistance.
For this situation the following statements lead to a realistic fire safety requirement.

- The fire resistance can be reduced to 60 minutes by the fact that not much burnable material is present.
- As only the building itself offers material that can burn and there is no shop, office or anything housed in the building, this 60-minute requirement will in most cases automatically be met.
- Concerning plastics this is slightly different. As the material itself is more flammable than conventional building materials it cannot be ensured that the structure holds for 60 minutes.
- The absence of installations and neighbouring buildings on the other hand reduces the risk of a fire. The only causes of fire can be a deliberately started fire or a forest fire (in that case people will have left the building before the fire has reached the building)

For situations with only one fire compartment there is no added value in fire resistance at all, so no requirements but the safe evacuation exist.

It can be concluded that in this specific case it is acceptable regard the building as lost in case of a fire as long as there is enough time to evacuate the building. As the area of the observation deck is small (about 75 square meters) this is a plausible situation.

The aim is to evacuate within 15 minutes: the applicable requirement for buildings without a special safety staircase. According to the national building decree, the maximal amount of people that can leave the building during the evacuation time can be calculated with the following formula: (Bouwbesluit 2012)

$$P_k = Q_k * (t - \left(\frac{1}{2}n + 1\right))$$

This formula computes the flow capacity in people per minute with;
P_k = number of people that can maximally leave the building
Q_k= The flow capacity of the stairs
t = the time allowed for evacuation
n = The number of storeys, evacuation speed 30 seconds per storey

The flow capacity of stairs with a width of 1 meter will be 45 people per minute according to the building code. The height of 24 meter (location of the observation deck) can be regarded equal to about 8 storeys. For an evacuation time of 15 minutes the evacuation capacity will be 450 people, a number that never will be present at the observation deck and lower levels. (Bouwbesluit 2012)

It can be concluded that if 15 minutes of evacuation time is available, a safe evacuation can be guaranteed.

Core structure

An important question remaining is, will the structure remain upright and safe for 15 minutes in a fire?
The emphasis here is on the acrylic core structure as this is the main structure, which keeps all other parts up. Some research results show more about the behaviour of acrylic when burning.

Interesting research has been performed by Brian T Rhodes from the University of Maryland to the burning rate of PMMA with a Cone Calorie Meter. On the contrary to other available test that often use strip samples, a sample is burnt from one side and the results are therefore expected to be scale independent. The mass loss is registered by this apparatus meaning that the burning speed of solid PMMA can be determined. Most tests show the burning speed of thin strip samples, which is not representative for the behaviour of the acrylic core structure in the observatory tower design. (Rhodes 1994)

The following test set-up was used: a cone heater is used to subject the 25 mm thick PMMA samples to an external radiant heat-flux, which causes the ignition of the material. The height of the external heat flux determines the time of ignition as shown in the graph.

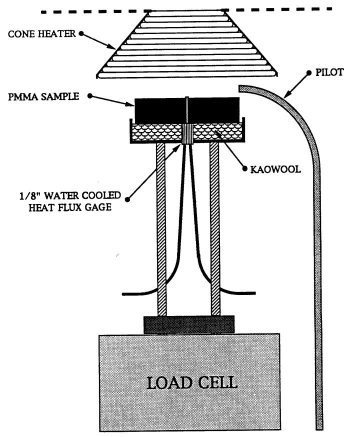


Figure 3.1. Schematic layout of burning rate apparatus

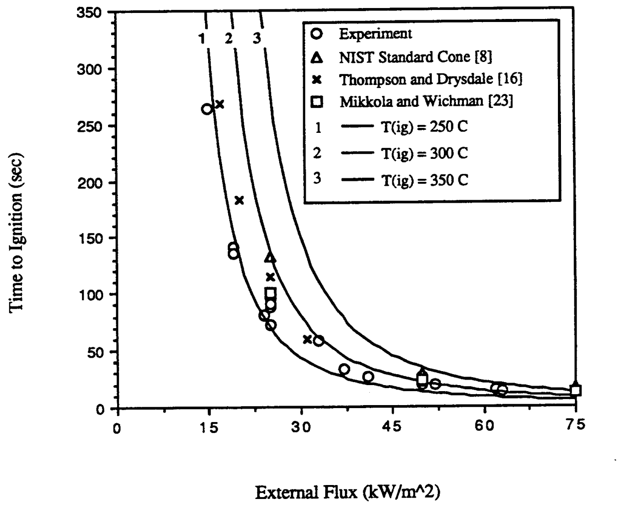
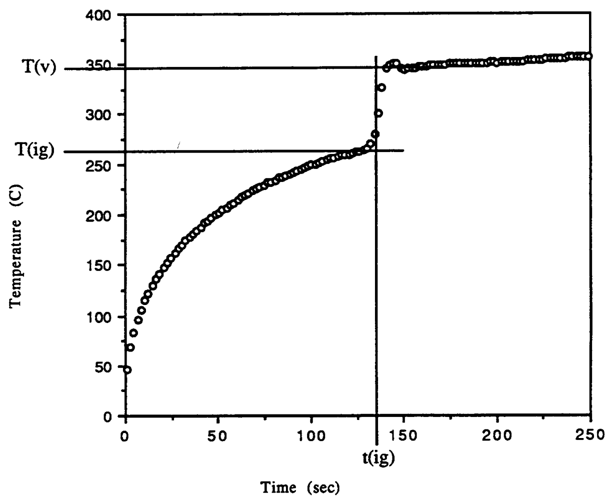


Figure 118: External Heat flux and time to ignition. (Rhodes 1994)

The surface temperature appears to rise from zero to the ignition temperature gradually, then when ignition starts the temperature suddenly rises to a higher level. This is the so called vaporization temperature, at this temperature evaporation of the monomer starts. These temperatures increase slightly for higher heat fluxes as can be seen in the table with test results below.



Test Number	External Flux (kW/m²)	Ignition Temperature (° C)	Vaporization Temperature (° C)
t4	15	250	325
t8	19	265	350
t5	24	280	365
t22	46	345	375
t23	58	355	380

Figure 119: Temperature development during ignition. (Rhodes 1994)

Usually for buildings a fire load of 45 kW/m^2 is taken into account. To imagine the impact; for a fire involving a tank lorry with hazardous substances on a distance of one meter a heat flux of 15 kW/m^2 is considered. (Keemen 2011) The test results for a heat flux of 50 kW/m^2 will be used to get an idea of the behaviour of acrylic during a fire.

The following development of mass loss rate is observed:

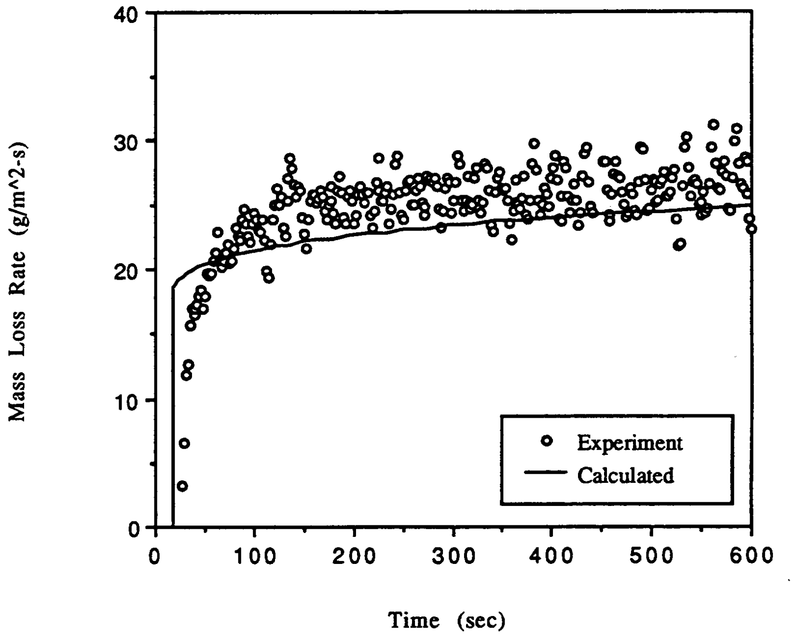


Figure 120: Mass loss rate; experimental data compared to calculated values. (Rhodes 1994)

The test only stopped when the complete sample had burnt, for this sample that happened after 19 minutes and 13 seconds, or 1153 seconds. A peak mass loss rate of 30,05 g/sm^2 was determined. The maximum burning rate in mm/min can be computed from this figure:

$$\beta_0 = \frac{30{,}05 * 10^{-3}}{\rho} * 60 * 10^3 = \frac{30{,}05 * 10^{-3}}{1200} * 60 * 10^3 = 1{,}5\ mm/min$$

In the situation that the evacuation time of 15 minutes is considered this would result in a (probably local) maximum material loss of 15*1,5= 22,5 mm of the core thickness.
The full test report is included in Appendix E.

Not only the burning rate is of importance, the rising temperature will influence the capacity of the core structure as well. The maximum service temperature of PMMA is about 90 °C, but from the literature research it became clear that properties already decrease dramatically above 60 °C. The high thermal insulation of the material is however favourable and might block the heat for the required evacuation time.

A maximum surface temperature of 370 °C is assumed, conform the earlier mentioned test measurements. If the temperature on the other side of the core wall would be zero degrees, a temperature difference between inner and outer side of the wall of 370 °K is reached.
Now the heat flow through the structure can be calculated:

$$\Phi^{\mathrm{p}} = -\lambda \frac{dT}{dx} = -0{,}19 * \frac{370}{0{,}155} = -454\ W/m^2$$

With λ	Thermal conductivity in W/mK
dT	Temperature difference in K
dx	Thickness of the material in m

This is only a relatively small amount of heat and will not cause a dramatic raise of temperature on the other side of the core wall. To put it in a context: The specific heat capacity (c) of PMMA is 1.490 kJ/kgK which means that one kJ is needed to heat one kg of PMMA one degree Kelvin. The density (ρ) of PMMA is 1200 kg/m^3.
So with 454 W/m^2, which is basically 454 J/sm^2, a layer of (454*60)/(1200*1490)=0,015m or 15 mm can be heated only one degree Kelvin per minute. Of course the closer to the fire source, the less material is between the high and low temperature and thus the more heat flow is coming through.

To get more insight in the influence of temperature the penetration depth is calculated.
This can be done based on the following differential equation: (Rhodes 1994)

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2}$$

With T	temperature in K
T	time in s
Y	distance from surface with vaporization temperature
α	Thermal diffusivity λ/ρc

Boundary conditions are used to get the solution for the penetration depth δ, the depth for which holds that $T=T_0$ and dT/dy=0. So the temperature is equal to the initial temperature and the temperature change while moving further from the burning surface is zero. This is the depth to which the influence of the fire reaches after a certain period of time.

Differential equations are solved and lead to the final simplified solution (Rhodes 1994):

$$\delta = \sqrt{\frac{12\,\alpha\,t}{e_4}}$$

With e_4=1,9 for a heat flux of 50 kW/m^2. This results for a duration of 15 minutes or 900 seconds in a penetration depth of:

$$\alpha = \frac{0{,}2}{1200 * 1490} = 1{,}119 * 10^{-7} \quad and \quad \delta = \sqrt{\frac{12 * 1{,}119 * 10^{-7} * 900}{1{,}9}} = 0{,}0252\ m = 25{,}2\ mm$$

The effect of the thermal insulating properties of plastics are now clearly visible, at a distance of 25,2 mm from the burning surface the fire does not even raise the temperature within 15 minutes. (Rhodes 1994)

Thin plates

For burning of thin plates tests are performed for example by Perspex, with vertical PMMA strips, burning rates vary from 28 mm/min for 3mm thick samples and 22 mm/min for 6mm thick samples. It is obvious that the all sided fire around a thin strip has less favour of the thermal insulation capacity.

Other properties are as well mentioned in the literature research and include that cast acrylic produces little or no smoke on combustion and does not continue to smoulder after the fire is extinguished. Thereby cast acrylic does not melt or drip when burning and is thus less likely to propagate a fire compared to extruded acrylic that does melt and drip and produces more smoke as well. This due to the lower molecular mass.

Polycarbonate

Polycarbonates have a better fire safety rating as they are self extinguishing. Therefore the presence of polycarbonate material does not contribute to flame spread. Only a sustained fire load can keep the polycarbonate burning. Burning of thins strips will stop within 30 seconds after the source of fire is released.
The test with a calorimeter and a sustained heat flux gives for one dimensional burning of polycarbonate a slightly lower burning rate, but still quite comparable to acrylic. As illustrated in the table:

Material	*PC*
Peak Rate of Heat Release (kW/m^2)	940
Time to Ignition (seconds)	87
Time of Peak RHR (seconds)	105
Total Heat Released (MJ/m^2/g)	2.24
Avg Mass Loss Rate (10 % to 90 %) (g/m^{2}s)	27.1
Sample left (%)	17.0

Figure 121: Burning specifications for PC. (Banse 2007)

For burning of thin strips the burning rate will be below 25,4 mm/min for strips of 3 mm under sustained fire loading. (Banse 2007)

Ignition temperature and fire propagation

The ignition temperature of PMMA is approximately 350 °C, that of polycarbonate about 500 °C, these plastics can thus be ignited by a cigarette lighter or other flame if tried. Flame temperatures depend on the fuel used but will be mostly around 1000 degrees Celsius. The ignition time will be longer when the heat flux is lower. For example measurements are known of an ignition time of 900 seconds for a heat flux of 9 kW/m^2.
It can be concluded that the risk of fire is low for this observation tower, but it is still relatively easy to cause a deliberately ignited fire. In that case the fire propagation in the structural parts will be slow and as long as the fire is kept out of the staircase the evacuation can be done safely within 15 minutes.

For this situation, adjacent to the open water, it will be easy to provide a facility which makes it possible to pump water rather quickly from the lake or river to use for cooling and extinguishing or just slowing down the fire. Considering the gained information about the burning of acrylic a sprinkler should be installed inside the core to make sure that any fire inside the (flight) staircase would be immediately extinguished. This way a safe evacuation is practically guaranteed. Perhaps sprinkler devices could be cast into the floor discs.
The sprinkler system can thereby bridge the time until the fire fighters arrive, as evacuation should take place immediately. Additionally an automatic alarm installation could be used to make sure that the fire fighters arrive within 15 minutes. In that case the chance that (part) of the building can be saved immensely increases. And the safety of the visitors can be guaranteed as well. (ETC Laboratories 2001)

4.2.4 Determination of design factors

As the two available guidelines that provide design factors contradict with each other and one of them does not even mention the material polycarbonate, the material data are analysed to determine the final design values.

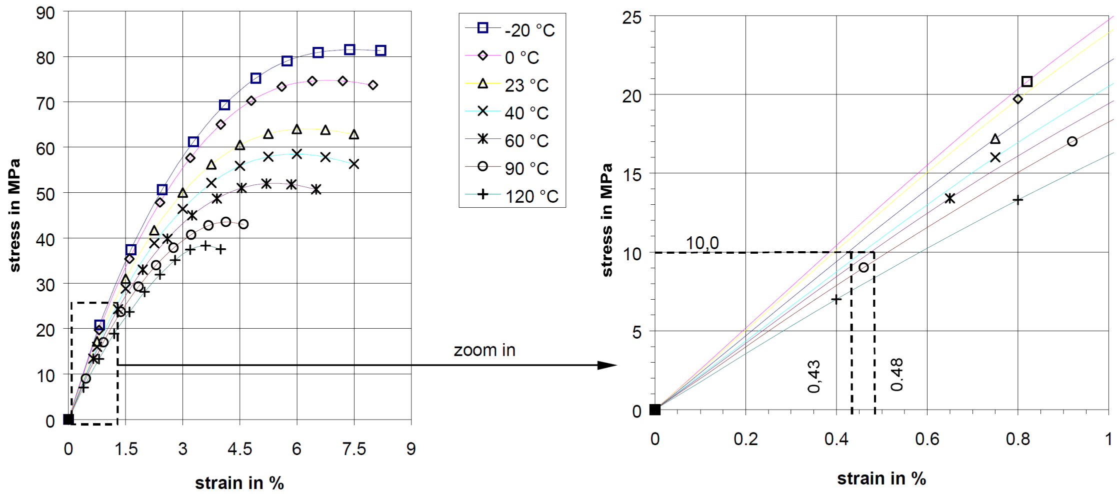
As mentioned in the literature study, both guidelines mention material safety factors to be used beside the reduction factors caused by time, temperature and environment dependence of the properties. These factors at least show some conformity. The ETAG010 makes use of a variation coefficient based on the standard deviation of available figures in computing the material factors. But the results can be easily put together with the use of acceptable variation coefficients (0,1 for compression and 0,15 for tension, where 0,1 is the minimal value). This gives values practically equal to those of the Büv Empfehlung.
More information about these guidelines can be found in paragraph 3.4.3

The material safety factors used are the following:

γm	Strength	Local stability	Overall stability	Joints	S.L.S.
Tension	1,5	1,4	1,2	1,4	1,1
Compression	1,2				

Figure 122: Material safety factors

As stated in both guidelines, the other modification factors are based on test information of the materials. An example is shown in the ETAG010 where the modification factor for polycarbonate use in 60°C is determined from a short time test in stable environment. The strain for a 23°C test is divided by the strain in a 60°C test at the same stress level to determine the design factor.



$$Ct = \varepsilon_{23°C} / \varepsilon_{60°C} = 0,48 / 0,43 = 1,11$$

Figure 123: Determination design factors for temperature influence on PC, short term, stable environment. (ETAG010 2002)

The BÜV guideline turns out to be much more conservative concerning the modification factors than the ETAG010, as mentioned earlier. Checking several graphs and figures in the way as shown above produces values that are approximately the same as the BÜV guideline mentions. Probably tests at low stresses are used for the determination according to ETAG010 as this guideline is only meant for the design of secondary roof plates and not for other (bearing) building parts as the Büv Empfehlung. (Büv 2010) (ETAG010 2002)

To obtain a complete list of design values it is necessary to look over all properties and their change in time, temperature and environment. As well for polycarbonate, for which no usable modification factors are available, as for acrylic, where some factors are missing.
For wind loads, snow loads and the short-term part of the imposed loads, the short-term design values can be used, this results in higher allowed stresses and stiffer behaviour can be taken into account. To determine these values a time span of 24 hours is used, as it would not be fair to use the instant material properties. Wind loads and public last for longer than just a moment, 24 hours was used to make estimation on the safe side.

For the determination of the long-term design values a desired design life of 20 years is used. Long-term test results over a period of more than a couple of years are hardly available and extrapolation of large time steps will not lead to reliable results. Thereby the guarantees of factories producing these plastics often do not exceed 10 years either. It will have to turn out in the future whether these materials can be designed for a common building service life of 50 years as well.

Because of this reduced service life compared to standard buildings, according to the Eurocode the loads on the structure may be reduced with a certain factor. However this will have only significant influence for a service life of only a few years. Therefore the effect is neglected in this case study.

The resulting table with design values is shown here, for more background information the determination procedure is included in appendix F.

Used design values	Material factor		Design values inside				Design values inside - direct sun				Design values outside				Design values under water			
Long term	**PMMA/PC**		**PMMA**		**PC**		**PMMA**		**PC**		**PMMA**		**PC**		**PMMA**		**PC**	
E-modulus Bending (MPa)	1,1		909		1270		727		1212		727		1212		909		1270	
E-modulus Buckling (local/global) (MPa)	1,4	1,2	714	833	998	1164	571	667	952	1111	571	667	952	1111	714	833	998	1164
Max. tensile strength (MPa)	1,5		12,4		20,8		7,7		17,6		2,9		6,5		6,2		9,9	
Max. Compressive strength (MPa)	1,2		24,3		35,5		15,1		30,0		6,5		11,1		13,5		16,9	
Short term	**PMMA/PC**		**PMMA**		**PC**		**PMMA**		**PC**		**PMMA**		**PC**		**PMMA**		**PC**	
E-modulus Bending (MPa)	1,1		1894		1732		1515		1653		1515		1653		1894		1732	
E-modulus Buckling (local/global) (MPa)	1,4	1,2	1488	1736	1361	1587	1190	1389	1299	1515	1190	1389	1299	1515	1488	1736	1361	1587
Max. tensile strength (MPa)	1,5		21,1		25,6		13,1		21,7		5,0		8,0		10,6		12,2	
Max. Compressive strength (MPa)	1,2		41,5		43,7		25,7		37,0		11,2		13,7		23,0		20,8	

Figure 124: Resulting long term and short-term design values for indoor and outdoor environments. (Büv 2010)

4.3 Structural design

4.3.1 Bearing structure

For the bearing structure (core), made of PMMA several variants have been drawn, the initial idea is a core of about 5 meter in diameter, which tapers upwards to about 4 meter. As the spiral staircase will need a minimal width of 0,8 meters, the remaining available structural depth around the staircase will be about 1,5 meter at floor level and about 1 meter on top.
The core can be schematized as a simple cantilever beam, clamped in the foundation. It has to resist bending and compression caused by the wind pressure in horizontal direction and self-weight and other variable loads in vertical direction.

Cast PMMA is quite commonly used for aquarium windows, retaining water of meters depth. The material is therefore available up to very large sizes. Standard block sizes can have a maximal size of 2,8 by 7 meter with a thickness of 102 mm, customized casting can even produce sheets up to 2,8 by 8,4 meter with a thickness of 1220 mm.
Usually the PMMA is cast into sheets and blocks or spin cast into tubes, other shapes are cut and hot formed from these sheets. It is not yet common to cast in other moulds, with material saving shapes or profiles.

4.3.1.1 Design options

Several options are considered; the required dimensions for each option are calculated in the next paragraph (4.3.1.2).

Variant A: PMMA columns in a circle

In an attempt to optimise as well stiffness as transparency the material is brought to the outside of the structure and openings are created for a spectacular view. The column structure creates interesting spaces on the landings where people can walk and stand between the columns to have a look outside. The structure is clear; the way it works can be felt inside the tower, normal forces from permanent and variable loads flowing through the columns to the ground. A tapering is applied upwards as the most stiffness is required close to the ground where the resulting moment from the wind forces is at its maximum. Another advantage is that if the space between the columns is large enough: the structure does not need to be interrupted to create an entrance.

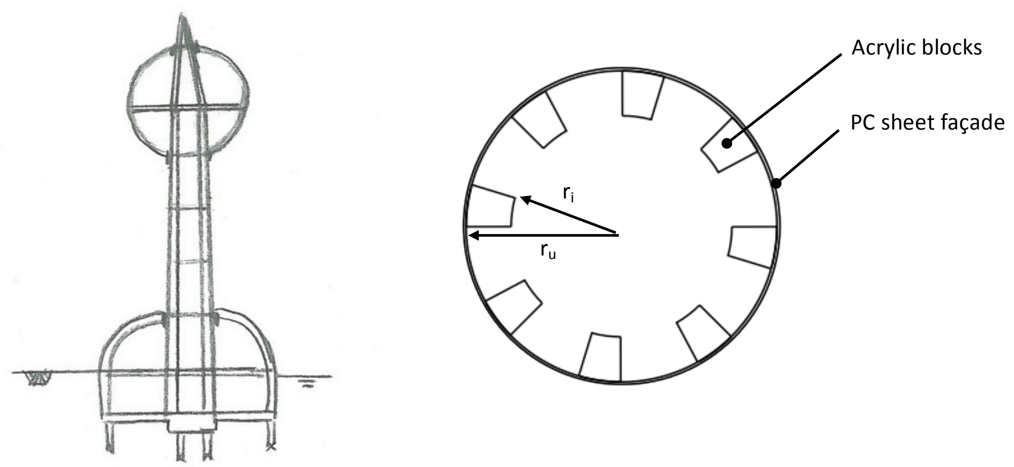


Figure 125: left: Bearing structure with PMMA columns; right: a cross section of the bearing structure (core)

Difficulties for this structure are the way the columns cooperate, to achieve an ultimate Moment of Inertia it is essential that the columns react as one section. If not properly connected this will not happen and the structure will wobble on the wind. PMMA rings can be applied under every landing to pass on the bending moment by shear stress. These rings should also prevent torsional buckling, another threat for this type of structure.
An economic solution has to be found to produce the tapering column parts and an assembly method in which the floors are sort of stacked between the column parts forming a solid whole. The structure has to be closed with facade panels for which a proper, easy and watertight connection should be developed.

Variant B: Star shaped structure

The star shaped structure is solving the problem of making the material working as one section. All core parts are connected in the centre of the cross-section. Additionally the stairs will need to spiral upwards through those elements.
The star shaped core makes sure that the floors of all landings are properly supported; the floor spans are way lower than for the tube shaped core structure. Thereby the stairs as well only need to span between two core parts.

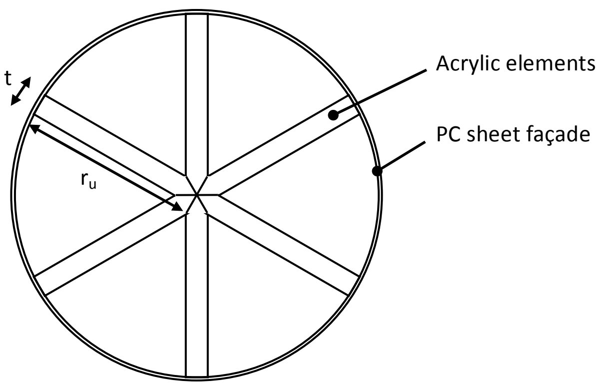


Figure 126: Star shaped bearing structure (cross-section).

Figure 127: Stairs run through structural elements.

Difficult for this structure is the risk of buckling; the floors will reduce the buckling length for buckling of the compression 'flanges'. But the torsional stability is not yet guaranteed.
Another difficulty is assembly, as the stairs are circling upwards through the structure not all elements can be the same. The stairs will cross every element on a different height. The stairs will need to be lifted in later as they are supported by the core parts, but not much space is left for that. And fitting will be tight.
Thereby during assembly the core elements itself are not stable until properly connected in the middle. This connection will be difficult to make.

Variant C: PMMA Tube structure

The tube structure is a common type of section which is equally stiff along all axes of bending and thereby very torsion stable. In this case it is very large scale, as the whole staircase will fit inside. The section can be regarded as one part so there will be no problems of creating a structurally sound connection.

The material is brought ultimately outwards which is favourable for the material use and structure simultaneously closes the facade. The core segments are composed of two half circular parts bonded together on-site.

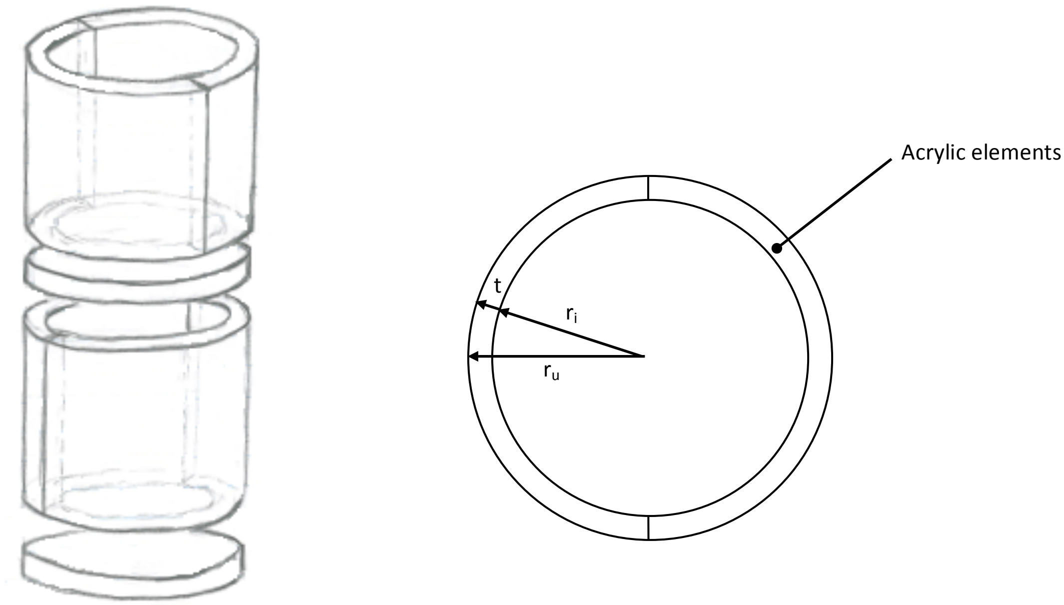


Figure 128: left: Side view of stacked tube structure; right: cross section of the bearing structure (core).

Difficult for this structure will be the larger floor spans. The objective is to make the floors as well in PMMA and the low stiffness will require large floor thicknesses increasing quadratically with the floor span. The material is pushed to the outsides so if the floors are stacked in between the core elements the span will be about the diameter size. As a balance should be found between a slender core and still achieving a certain stiffness without using unnecessary amounts of material, the diameter cannot be very small.
The way the stairs fit into the tube structure will be another point of attention. This can be realised by using a middle tube around which the stairs can spiral. Or the stairs can be integrated in the outer wall, cantilevering or supported by a curved beam between the landings.

4.3.1.2 Core stiffness

To be able to assess the suitability of the various options, the dimensions are determined.
As polymers are quite flexible materials compared to other building materials it is expected that the deformations will be governing for the design. To make an estimation of core dimensions for the various structure types, the necessary moment of Inertia is calculated. The governing situation will be the structures stability under wind loads. After this initial determination of the core dimensions the occurring stresses will be checked.

The assumption is made that an average cylinder diameter for the core of **4,5 meter** will be sufficient. The sphere and dome both have a radius of **5 meter**, of which the dome is wrapped around the core creating a floor diameter of **14,5 meter**.
The height of the tower is 29 meters above ground measured from the top of the observation sphere. However the core ends below floor level, in the subsurface observatory room. The in between connected dome and floor structures will not offer enough support to clamp the core so the actual support will be 4 meter below ground level. This makes a total structural height of **33 meter**.

The wind load factors that are determined in Appendix D are used to calculate the wind forces with the following formula:

$$F_w = c_s c_d \cdot \sum_{elementen} c_f \cdot q_p(z_e) \cdot A_{ref}$$

(NEN-EN1991-1-4 2005)

For circular chimneys, the category most resembling this structure, the factor $c_s c_d$ may assumed to be 1,0 if the chimney is lower than 50 meter or 6,5 times the diameter. As the height of the tower is 33 meter, criterion one is met. The equivalent diameter of the tower (above ground) will be:

$$D_{eq} = \frac{A_{core} + A_{sph} + A_{dome}}{h_{core} + h_{sph} + h_{dome}} = \frac{4{,}5 * 14 + \pi * 5^2 + 4{,}5 * 5 + {}^1\!/_2 * \pi * 5^2}{14 + 10 + 5} = 7{,}0\ m$$

Thus 6,5 times 7 makes 45,5 meter, which is lower than the actual height, so the second criterion is met as well. Thereby the value 1,0 is on the safe side for most situations.

The load factors c_f as determined in appendix D from the Eurocode standards are based on freestanding shapes and appear to be very low. As the three shapes are connected there will be interaction from wind streams and turbulence will occur around the connecting surfaces. The Dutch national supplement indicates that turbulence is not taken into account. The only end-effect-factors available are reduction factors.

Remarkable as well is that the differences between the force factors of cylinders and spheres are very large. Of course a spherical shape is advantageous concerning wind forces, but free-floating spheres do not exist in buildings. As the sphere and dome are connected to the cylindrical core in such a way that it could almost be considered an overall cylindrical structure, it is not imaginable that such distinct transitions of load factors exist.

Thereby the former NEN 6720 standards prescribed higher force factors for cylinders than the ones prescribed in the Eurocode 1. Following the NEN regulations a factor of C_t= 1,0 is found for the cylindrical core (with Re=3,9*10^5), whereby a rough surface even would lead to a C_t of 1,2. Based on these same NEN standards the observatory sphere would have a factor of 0,2, which does resemble Eurocode 1; so the difference between cylinder and sphere is even larger in the NEN standards. (NEN-6702 2007), (NEN-EN1991-1-4 2005)

To take into account these uncertainties and the effects of connecting multiple shapes together it is decided to apply the cylindrical load factors over an extended height.
The wind load factor on the core is continued from the bottom to halfway the observatory sphere of the tower and the forces on the sphere and dome are diminished with the net surface of the continuing cylinder.
It is sensible to apply a slightly conservative wind force when this much uncertainty exists. But the real behaviour of this complex structure would have to be determined during wind tunnel tests on a scale model.

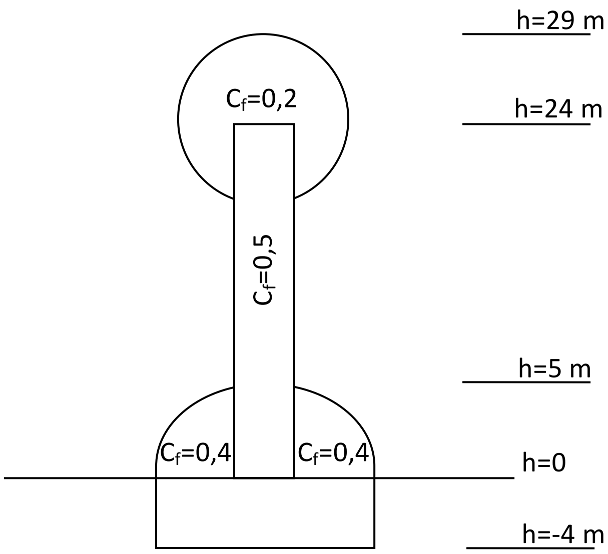


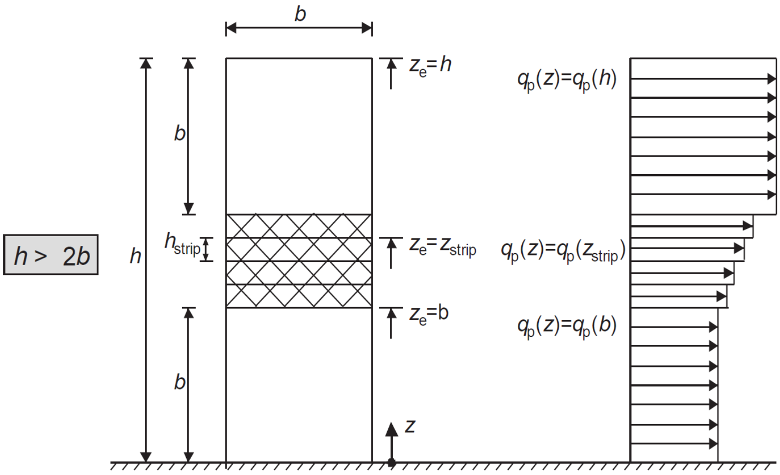
Figure 129: side profile with according wind load factors

The loads on the sphere and on the dome can be regarded as a concentrated load with A_{ref} as the projected surface area. They are thus computed as follows:

Sphere: $F_{sphere} = C_f * q_p(z) * (\pi * r^2 - d * r) = 0{,}2 * \; 1{,}19 * (\pi * 5^2 - 4{,}5 * 5) = 13{,}3 \; kN$
(In the middle line of the sphere)

Dome: $F_{dome} = C_f * q_p(z) * \frac{1}{2} * \; \pi * r^2 = 0{,}4 * 0{,}66 * \frac{1}{2} * \pi * 5^2 = 10{,}4 \; kN$
(at 1/3 of the dome height)

The wind loads on the cylinder are regarded as line loads and determined according to the next figure:



OPMERKING De extreme stuwdruk behoort uniform te zijn aangenomen over elke beschouwde horizontale strook.

Figure 130: Reference height z_e as a function of h and b, and resulting wind load profile. (NEN-EN1991-1-4 2005)

As the cylinder is higher than twice its width (d), the wind load should be divided in two parts with height d and several strips. (NEN-EN1991-1-4 2005) The cylinder is 24 meter high up to the mid of the sphere. In this case the choice is to divide the remaining building part into 4 strips of height (24-2*4,5)/4 = 3,75m

For a diameter of 4,5 meter, the following representative wind pressure forces are found:

ze	qp(ze)	qw (kN/m)
24	1,13	2,5
19,5	1,06	2,4
15,75	0,99	2,2
12	0,9	2,0
8,25	0,8	1,8
4,5	0,63	1,4

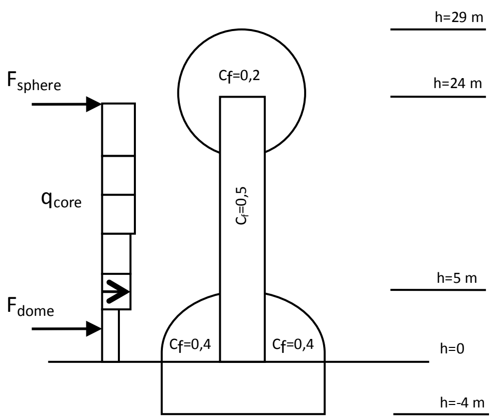


Figure 131: Representative wind pressure forces.

The line loads are converted to concentrated loads in the centre of gravity of the line load by multiplying the wind load with the corresponding surface area and applying the load factor C_f of 0,5. Now all concentrated loads are summed to get the representative shear force at the foundation. All forces are multiplied with the height of the centre of gravity to determine the resulting moment on the foundation.

Wind loads	Cf	r	h	A (m2)	qp(z) kN/m2	h zwpunt (m)	Vrep (kN)	Mrep (kNm)
Sphere	0,2	5	10	56,04	1,19	28	13,34	373,4
Core high	0,5	2,25	4,5	20,25	1,13	25,8	11,44	295,2
Core strip 1	0,5	2,25	3,75	16,875	1,06	21,6	8,94	193,2
Core strip 2	0,5	2,25	3,75	16,875	0,99	17,9	8,35	149,5
Core strip 3	0,5	2,25	3,75	16,875	0,9	14,1	7,59	107,1
Core strip 4	0,5	2,25	3,75	16,875	0,8	10,4	6,75	70,2
Core low	0,5	2,25	4,5	20,25	0,63	6,25	6,38	39,9
Lower dome	0,4	7,25	5	39,27	0,66	5,5	10,37	57,0
						Sum:	73,17	1285,5

Figure 132: Wind loads.

The deformations caused by the wind forces are calculated with the "vergeet-me-nietjes":

$$\varphi = \frac{F * l^2}{2EI} \; and \; w = \frac{F * l^3}{3EI} + \varphi * (h - l)$$

With l as the point of application with respect to the support, 4 meters below surface and h as the total height of the tower, from top to support. The deformations are used to determine the necessary Moment of Inertia.

The following results are obtained:

I (mm4)	3,48E+12
E (N/mm2)	1515
h,tot (m)	33
wmax (mm)	66

Wind loads	h zwpunt (m)	Frep (kN)	w,dir (mm)	ϕ(gr)	w, tot
Sphere	28	13,34	18,51	9,92E-04	23,47
Core high	25,8	11,44	12,42	7,22E-04	17,62
Core strip 1	21,6	8,94	5,70	3,96E-04	10,21
Core strip 2	17,9	8,35	3,03	2,54E-04	6,86
Core strip 3	14,1	7,59	1,35	1,43E-04	4,05
Core strip 4	10,4	6,75	0,48	6,92E-05	2,04
Core low	6,25	6,38	0,10	2,36E-05	0,73
Lower dome	5,5	10,37	0,11	2,97E-05	0,93
				Sum:	65,9

Figure 133: Resulting deformations caused by wind forces.

The same result can be seen in the Technosoft[1)] calculation, to clarify the behaviour of the core structure the loading, the ultimate limit state moment line and the serviceability limit state deformation is shown.

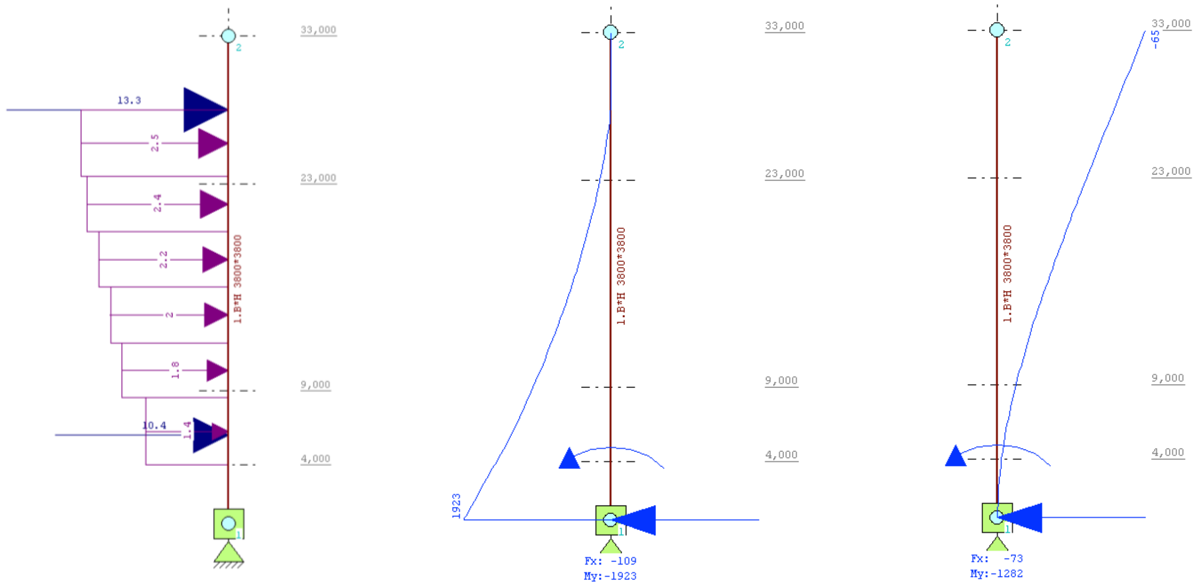


Figure 134: Deformation caused by wind forces as calculated by Technosoft[1)].

Concerning tapering the structure, a small design research in Technosoft[1] learned that the equivalent cross-section (with respect to deformation) for a tapered section with ground radius or width r_g and top radius r_t can be described by:

$$r_{eq} = r_t + 0{,}76(r_g - r_t)$$

For a core with the radius varying between 2,5 and 2 meter this means that the structure reacts to wind pressure as if being a core with radius 2,38 meter. The material use however is only equal to a structure with the average radius of the two, 2,25 meter. This favourable stiffness to material ratio makes a tapering structure very efficient.

For all variants now the necessary equivalent core section can be computed, which allows for a comparison between the different core options. For each option a cross section is determined with the necessary Moment of Inertia, $3{,}48*10^{12}$ and an outer equivalent diameter of 4,5 meter.

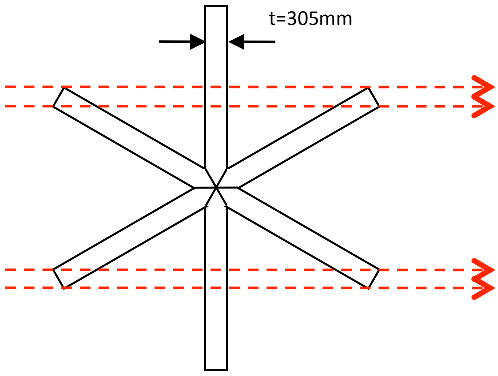
The Moment of Inertia is used to determine the necessary wall thickness and/or inner core diameter. For all variants the modulus is (practically) the same in all directions because of the (rotational) symmetry. For the tube the moment of Inertia is easily calculated with the formula:

$$I_{zz} = \frac{\pi * (r_u^4 - r_i^4)}{4}$$

This same formula is used for the option with acrylic columns, as these are part of a circular cross section and the assumption is made that it is possible to make them act as one section. The columns are placed with three times the width as in-between space and are bounded by the radius of the circle. So the moment of Inertia will be 25% of the total tube moment of inertia. The same principle holds for the surface area.

[1] Technosoft is a software developer.

The star shaped structure of design option B is projected towards the central axis to be able to calculate the moment of inertia and the surface area. This results in a compound cross-section with a central element with width *t* and height *2r* and two neighbouring elements with width *t/sin 30=2t* and average height *2*r*sin 30= r* as shown in the picture.



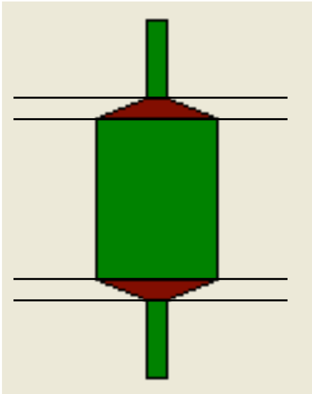


Figure 135: Projected star shaped structure

The results are shown in the next table. The required surface area of the cross section is added, this indicates how much material will be used for the core structure in every option.

	ru (eq)	ri (eq)	t	% of circle	A (m2)	Izz (mm4)
A columns	2250	1675		25	1,77	3,49E+12
B star	2250	-	305		4,12	3,49E+12
C tube	2250	2145	105	100	1,45	3,50E+12

Figure 136: Resulting dimensions for the three design options

To calculate the bending stresses the bending moment is divided by the section modulus. As all core options have a same moment of inertia and the same outer diameter, the section modulus will be the same for all variants. The section modulus of circles and tubes can be calculated with the following formula:

$$W_y = \frac{\pi * (r_u^4 - r_i^4)}{4 * r_u} = \frac{I_{zz}}{r_u} = \frac{3{,}48 * 10^{12}}{2250} = 1{,}55 * 10^9\ mm^3$$

This results in the following stresses:

Wy (mm3)	Md (kNm)	σb,max (N/mm2)
1,55E+09	1928,25	1,24

The resulting shear stresses can be calculated by dividing the horizontal support reaction by the available surface area.

	A (m2)	Shear (kN)	σs,d (N/mm2)
A columns	1,77	109,8	0,055
B star	4,12	109,8	0,024
C tube	1,45	109,8	0,067

The design value for the allowable short term tensile stress for outdoor applications in PMMA is 5 N/mm^2, the shear strength is approximately the same. This suffices for all core options. Apparently the deformation of the core is indeed governing for the design.

Major point of attention will be the way the core is connected with the foundation slab. The connection needs to be able to transfer these forces to the foundation. This will be handled in a later design stage.

4.3.1.3 Design decision

To make a decision on the type of core structure that could be used best in this design, a multi-criteria analysis (MCA) is made.

MCA core structure	**A columns**	**B star**	**C tube**
Structural behaviour	-	+	++
Material use	0	-	+
Transparency	++	0	0
Architectural value	++	+	-
Assembly	-	-	+
Costs	-	-	0
Sum	+	-	+++

Figure 137: Pros and cons for the design options compared.

Decision

In this MCA the tube structure clearly appears to be the best choice. This is the type of structure that will be used. It saves a lot of work and material as it is structure and facade at the same time, that is the decisive factor in deciding for the tube core.

Some adjustments are made to optimize the structure:

- The baring structure (core) is made slightly more slender, with a radius of 2 meter. This reduces the floor spans of the landings and as the tube structure is space efficient, the area necessary for the stairs is still easily available. In the same time a higher slenderness improves the image of the tower.
- The core will be straight instead of tapering. To be able to use uniform elements the tapering is removed. In spite of the material efficiency of a tapered cross-section the choice is made to prefer repetition of elements. Now every 'storey' can be made of two identical half-circle elements and all floors will have the same diameter, thickness and staircase as well.
- The subsurface room height is reduced to 3 meters as water depths will not exceed 2 meters and a ground level - water level difference of one meter seems appropriate. Thereby the room will not easily feel uncomfortably low as the ceiling will be of translucent acrylic.
- The core wall thickness will be raised with 10mm to provide enough buffer for polishing (meant to remove scratches and crazes). The net thickness will be used for the calculations so all requirements can still be met after several polishing cycles.

Calculations for the final core design

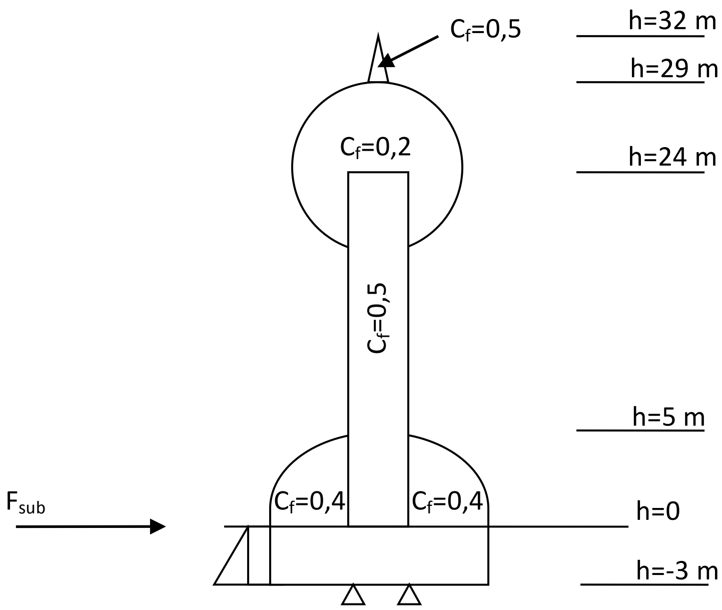


Figure 138: side profile with subsurface load

The wind loads and required Moment of Inertia are calculated again and more accurately for the new core radius.
The top of the structure is as well taken into account, as a tapering cylinder with a height of 3 meter; the radius on top of the sphere will be 0,75 meter. Determined by the intersection point a straight line between the 2m radius of the core on platform level and the top and the top surface of the sphere.

Also the subsurface room is taken into account, the difference in ground and water pressure on both sides will cause a resulting force on the core. The water pressure is assumed constant around the core. The resulting force is approached by the horizontal ground pressure on the subsurface wall added with the horizontal component of the variable load on the ground around the structure. To transfer the complete 'support reaction' at ground level resulting from these forces to the core is a conservative approach. Part of this force will be transported to the foundation by bending of the closed circular 'profile' that the subsurface room forms itself. But as the wall thickness of the subsurface room is relatively thin compared to the diameter, local bending will as well take place, resulting in a transition of part of the forces to the floor and thus to the core.
The occurring situation will be somewhere in between but the slightly conservative (thus safe) estimation is made that all of the possible 'support reaction' is transferred to the core. So 1/3 of the total ground force on the wall and ½ of the total variable load:

$$f_{sub} = \frac{1}{3}\left(\frac{1}{2} * h * \left(h * 0{,}5 * \left(\gamma_g - \gamma_w\right)\right)\right) + \frac{1}{2}(0{,}5 * h * 3) =$$
$$\frac{1}{3}\left(\frac{1}{2} * 3 * (3 * 0{,}5 * 10\right) + \frac{1}{2}(0{,}5 * 3 * 3) = 7{,}5 + 2{,}25 = 9{,}75\ kN/m$$

This makes F_{sub}=*14 *9,75 =* ***136,5 kN*** at ground level, so 3 meters above the support.

In the model of the subsurface room later it will be checked whether this assumption is more or less correct by comparison of the deflection at ground floor level for both computations.

The reduction of the floor height in the subsurface room reduces as well the point of application of all forces on the core with 1 meter, this is adjusted in the excel sheet.

The resulting forces are shown here:

Wind loads	Cf	r	h	A (m2)	qp(z) kN/m2	qw (kN/m)	h zwpunt (m)	Vrep (kN)	Mrep (kNm)
Top	0,5	0,75	3	2,25	1,22		33	1,4	45,3
Sphere	0,2	5	10	58,54	1,19		27	13,9	376,2
Core high	0,5	2	4	16	1,13	2,26	25	9,0	226,0
Core strip 1	0,5	2	4	16	1,07	2,14	21	8,6	179,8
Core strip 2	0,5	2	4	16	1	2,00	17	8,0	136,0
Core strip 3	0,5	2	4	16	0,9	1,80	13	7,2	93,6
Core strip 4	0,5	2	4	16	0,79	1,58	9	6,3	56,9
Core low	0,5	2	4	16	0,6	1,20	5	4,8	24,0
Lower dome	0,4	7	5	39,27	0,66		5	10,4	51,8
Subsurface	1	7	3	42,00			3	136,5	409,5
							Sum:	206,1	1599,0

Figure 139: Resulting forces on the structure

Deformations become as follows:

I (mm4)	3,47E+12
E (N/mm2)	1515
h,tot (m)	35
wmax (mm)	70

Wind loads	h zwpunt (m)	Frep (kN)	w,dir (mm)	th (gr)	w, eind
Top	33	1,37	3,26	1,48E-04	3,56
Sphere	27	13,93	17,39	9,66E-04	25,12
Core high	25	9,04	8,96	5,37E-04	14,33
Core strip 1	21	8,56	5,03	3,59E-04	10,05
Core strip 2	17	8,00	2,49	2,20E-04	6,45
Core strip 3	13	7,20	1,00	1,16E-04	3,55
Core strip 4	9	6,32	0,29	4,87E-05	1,56
Core low	5	4,80	0,04	1,14E-05	0,38
Lower dome	5	10,37	0,08	2,47E-05	0,82
Subsurface	3	136,50	0,24	1,22E-04	4,14
				Sum:	70,0

Figure 140: Calculated deformations

The necessary Modulus of Elasticity is now 3,47 $*10^{12}$, a core section with a wall thickness of 155mm is sufficient. The following properties of the final tube core (with net thickness) are obtained:

	ru	ri	t	A (m2)	Izz (mm4)	Wy (mm3)
C tube	2000	1845	155	1,64	3,47E+12	1,73E+09

The resulting moment and shear force are calculated with a design factor of 1,5 for wind loads and 1,2 for ground pressure as follows from the load combinations. The moment is divided by the Section Modulus and the shear force by the surface area to determine the resulting stresses in the core.

Md (kNm)	σb,d (N/mm2)	Vd (kN)	σs,d (N/mm2)
2275,7	1,31	268,2	0,164

The outside application design stresses for acrylic were determined for short-term loading on 5 MPa tensile stresses and 11 MPa compressive or bending stresses. The core bending by wind implies bending stress but as the profile size is so large it is more realistic to assume pure compression and tension on the outer sides of the profile. Still the stress of 1,31 MPa does not come near the design stress of 5 MPa so it is clear that indeed the deformation in the top was governing.

Later in the research the normal stresses in the core due to self-weight of the total structure and floor loading will be calculated to determine the short- and long-term governing stress combinations on the core.

4.3.1.4 Additional aspects

Dynamical effects

To determine the dynamical effects on the observatory tower the applicable building codes are used. According to these codes the maximal occurring acceleration at the top of the building can be estimated with empirical formulas. The acceleration should keep within a certain maximum allowable acceleration to remain comfortable for human beings. The Eurocode does describe a method to determine the standard deviation of occurring accelerations in a certain point of the building structure. However for the allowed acceleration no criteria are prescribed. Therefore these are adopted from the NEN 6702 building code. (NEN-EN1991-1-1 2002) (NEN-6702 2007)

In the figure below can be observed that the allowable acceleration depends on the natural frequency of the building and on the function of the building. The maximal comfortable acceleration appears to be higher with low frequency movements. Thereby people are more sensible for vibrations of a building when standing or sitting still and when in contact with a building, for example when sleeping. For this reason higher accelerations are allowed for office buildings than for dwellings. The observatory tower can be assigned to the category office buildings for this calculation.

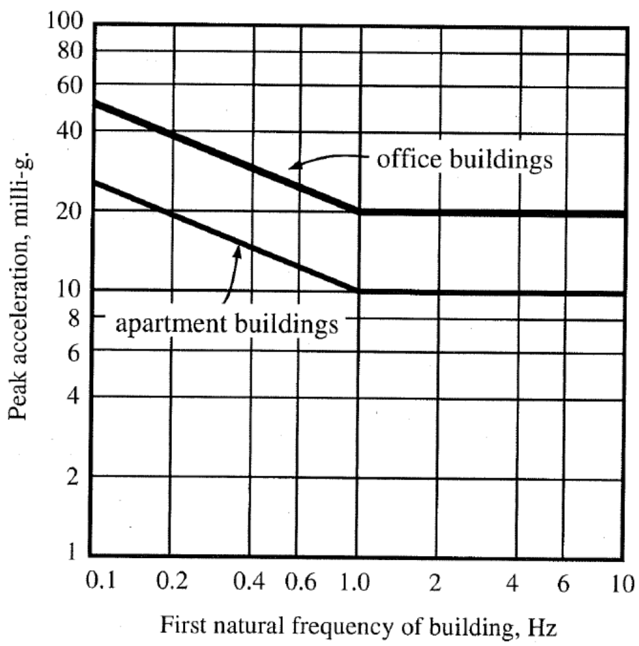


Figure 141: Dynamical effects (Hoenderkamp, 2007)

The natural frequency for buildings below 50 meter is not described in the Eurocode, probably because lower buildings normally do not suffer from significant dynamical problems. However since this observatory tower is a very slender structure it will be wise to check the dynamical effects.

The dynamical behaviour of a building is determined by stiffness, mass and damping and can be analysed by using a mass-spring-damper system.

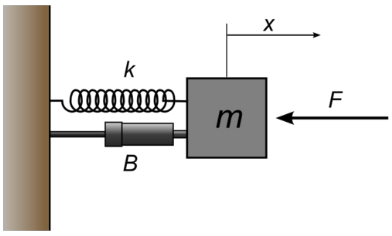


Figure 142: Mass-spring-damper system. (MIT 2012)

The system can be simplified by neglecting the effect of damping. The effect of structural damping is usually very low compared to the mass and stiffness influences and difficult to estimate. The natural frequency of a system with stiffness of the spring *k* and mass m will now be:

$$n_1 = \frac{1}{2\pi} * \sqrt{\frac{k}{m}}$$

The stiffness of the spring will be mainly determined by the stiffness of the building and the mass will be determining the force on the spring. The amount of movement in the top of the building caused by the mass of the building applied in horizontal direction (x) is representative for the spring stiffness. This is expressed with the following formulas:

$$F_v = m * g \qquad and \qquad k = \frac{F_v}{x}$$

Deflection *x* can be computed using the average mass distributed over the whole length of the structure as variable load in horizontal direction. As the weight calculation is already performed, the deflection can be calculated more accurately by using those data. The height of the centre of gravity is attributed to all resulting forces and the deflection is calculated with the 'vergeet-me-nietjes' for a force on a cantilever beam. Both direct deflection as deflection by rotation is taken into account resulting in the following table:

permanent loads	n	r	h (or t)	A (m2)	(t or h)	V (m3)	ρ (kN/m3)	Frep (kN)	w,dir (mm	th (rad)	w, eind
Sphere	1	5		314,16	0,005	1,57	12	18,85	23,52	1,31E-03	33,98
Floor sphere	1	5		78,54	0,1	7,85	12	94,25	117,62	6,53E-03	169,90
Core	1	2	0,15	1,81	28	50,80	12	609,59	207,15	1,78E-02	517,88
Floors core	7	2		87,96	0,1	8,80	12	105,56	35,87	3,07E-03	89,68
Lower dome	1	7	5	255,78	0,005	1,28	12	7,67	0,11	2,63E-05	0,87
Ground floor	1	7		153,94	0,15	23,09	12	138,54	0,24	1,19E-04	4,03
										Sum:	816,3

Figure 143: Deflection of the core due to self-weight applied in horizontal direction.

Filling in the formula with the above expressions for stiffness and mass gives:

$$n_1 = \frac{1}{2\pi} * \sqrt{\frac{k}{m}} = \frac{1}{2\pi} * \sqrt{\frac{F_v/_x}{F_v/_g}} = \frac{1}{2\pi} * \sqrt{\frac{g}{x}} = \frac{1}{2\pi} * \sqrt{\frac{9{,}81}{0{,}816}} = 0{,}55\ Hz$$

The graph from the Eurocode 1 prescribes for this frequency a maximal allowed acceleration of about 28 mili g, so 0,028*9,81= 0,275 m/s^2.
(Woudenberg 2006)

The standard deviation for the acceleration can now be computed according to the Eurocode 1, with the formula: (NEN-EN1991-1-1 2002)

$$\sigma_{a,x}(y,z) = c_f \cdot \rho \cdot I_v(z_s) \cdot v_m^2(z_s) \cdot R \cdot \frac{K_y \cdot K_z \cdot \Phi(y,z)}{\mu_{ref} \cdot \Phi_{max}}$$

With c_f	the force coefficient for wind, on average this is assumed to be **0,4**
ρ	the density of air, prescribed to be **1,25** kg/m^3
$I_v(z_s)$	the turbulence intensity at height z_s above the ground
$v_m(z_s)$	the characteristic average wind speed at height z_s above the ground
R	the square root of the resonance factor
K_y and K_z	factors depending on the vibration mode, in this case 1 and 3/2 respectively
μ_{ref}	the reference mass per surface area of the core, total mass/(h*D_{core}) = (974000/9,81)/(35*4) = **709** kg/m^2
$\Phi(y,z)$	the vibration mode, for slender buildings clamped at the foot: $\Phi(y,z)=(z/h)^{1,5}$
Φ_{max}	the value for the vibration mode at the point with the highest amplitude, for the natural frequency this will be the top: $\Phi(y,z)=(35/35)^{1,5}= 1$

After working out this formula as described in Appendix G, the standard deviation of the acceleration can be calculated, this is done for the platform level, the largest height that visitors can reach: 27 meters.

$$\sigma_{a,x}(y,z) = c_f * \rho * I_v(z_s) * {v_m}^2(z_s) * R * \frac{K_y * K_z * \Phi(y,z)}{\mu_{ref} * \Phi_{\max}}$$

$$= 0{,}4 * 1{,}25 * 0{,}165 * 31^2 * 1{,}19 * \frac{1 * \frac{3}{2} * \left(\frac{27}{35}\right)^{1,5}}{709 * 1} = 0{,}135\ \ {}^{m}/_{s^2}$$

Now the highest occurring acceleration can be computed by multiplying the standard deviation with a certain peak factor, k_p, computed for the natural frequency n_1=0,55. With T as the average time of the reference wind speed is 600 s.

$$k_p(n_1) = \sqrt{2 * \ln(n_1 * T)} + \frac{0{,}6}{\sqrt{2 * \ln(n_1 * T)}} = 3{,}58$$

Now the peak acceleration becomes 3,58*0,135=0,48 m/s^2 ≥ 0,275

The acceleration is obviously higher than the prescribed maximum, however this is a frequency that will seldomly occur. It can be considered to close the observatory deck during high velocity windstorms. Another option is to investigate whether this amount of acceleration is experienced as unpleasant if people are only on the platform for about 15 minutes and continuously walking and moving.

This method was used to perform a quick check on dynamic properties of the structure. Of course these empirical formulas are not completely reliable, certainly not for unfamiliar building materials. To be able to determine the behaviour more precise it will be necessary to do scale-model tests in a wind tunnel to determine the natural frequency and the acceleration behaviour. It could be interesting to investigate the damping capacity of the material itself, as it is not unthinkable that the visco-elastic properties of transparent plastics will contribute to a more favourable dynamic behaviour.
When testing results still show a critical dynamic behaviour other measures that can be taken are: Increasing the mass at the top, increasing the overall stiffness or providing more damping capacity.

Global stability

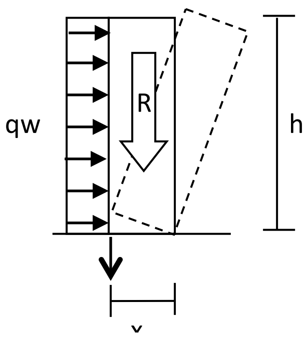


Figure 144: Global stability visualised

The overall stability is regarded conform the above picture. It is a quick check whether the building will tend to 'top over' when wind is pushing the top aside. If the moment due to wind forces is larger than the maximal moment that the self-weight can produce (which is just before the center of gravity moves beyond the support of the structure), the wind will force the structure beyond it's toppling point causing a progressive collapse.

$M_{w,d} < 0,9 * R * x \quad thus \;\; 2276 < 0,9 * \;\; 974 * 4 = 3506$

The global stability is thus sufficient.

Second order effect

The second order effect is caused by the fact that the centre of gravity of a structure will move with the deflection of the tower under wind loads. This eccentricity will result in an additional displacement which can be of a significant size for high rise buildings. Of course the mass of the building is a main component in this effect and because the mass of the transparent plastic design will be relatively low it is expected that the second order effect can be neglected.
However a quick check is performed to see whether that is correct.

To determine the second order effect the magnification factor n is computed

$$n = \frac{Q_k}{Q_{optr}}$$

With Q_k being the moment caused by the wind on the building and Q_{optr} being the moment caused by the displaced mass. As described by the following formula's:

$$Q_k = \frac{1}{2} * q_w * h^2 \quad and \quad Q_{optr} = M * \frac{1}{2} * \delta_{top}$$

The average q_w over the building is found by the sum of the wind forces divided by the height of the building part subjected to wind: 70/(35-3)= 2,2 kN/m

Now the magnification factor *n* can be computed, as all variables are known. Both for calculating the mass and the average load on the structure, the subsurface room is not taken into account. Spreading that over the whole height of the tower would be very unrealistic regarding the situation.

$$n = \frac{Q_k}{Q_{optr}} = \frac{\frac{1}{2} * 2{,}2 * 35^2}{975 * \frac{1}{2} * 0{,}07} = \frac{1345{,}5}{34{,}1} = 39{,}5$$

Which means for the influence on the final deflection of the top:

$$\delta_{top,end} = \frac{n}{n-1} * \delta_{top} = \frac{39{,}5}{38{,}5} * 70 = 1{,}026 * 70 = 71{,}8$$

A factor of 1,026 clearly makes no significant difference and will be neglected from now on. (Woudenberg 2006)

4.3.2 Observatory sphere

The observatory sphere incorporates the observatory deck at a height of 24 meter and will have a radius of 5 meter. The starting point was to create a sphere that is completely transparent and apparently structure-less, a way is sought to approach this desired effect as much as possible. This to make sure that a visit to the sphere will be an extraordinary experience offering visitors a spectacular 360° view of the environment.
Another important objective is to create a sphere that is feasible and reproducible. These objectives will be probably conflicting with one another and therefore a balance has to be found between a sufficient transparency level and acceptable practical aspects as costs, construction process and more.

A completely smooth transparent sphere is practically not realisable. Transparent plastics possess presumably not sufficient rigidity to keep the wall thicknesses low and thus a heavy, costly structure would result. A perfect sphere is however a very stiff and stable shape of itself, which should provide possibilities to design a lightweight sphere structure.
Options to use the formability and flexibility of plastics will be explored to reduce material use and increase stiffness.

As material for this part of the structure polycarbonate is chosen. This because the intention is to make a thin-walled system and thin-walled elements, opposite to thick-walled elements, can be made both from polycarbonate and from acrylic. When this choice is available, polycarbonate is an obvious choice, in this unprotected environment at 19 to 29 meter high the better mechanical properties can be of use. The high impact resistance, lower sensitivity to stress concentrations higher modulus and allowable design stresses make this material very suitable for thin-walled structures.

Aims to keep in mind during the sphere design process:
- The overall shape of the structure should be as close to a perfect sphere as possible, to keep the intentional image upright and the shape stable.
- The structure needs to be as transparent as possible, to provide a clear view at the environment.
- The structure should be as lightweight as possible while keeping the former goals in mind. This way the material-use can be reduced.

Two options to design a realisable structure:
- The use of uniform elements; repetition means cost reduction and as well eases the construction process.
- The use of flexible elements; flexibility can provide the opportunity to use the same design or elements, slightly adjusted, for other building (parts) as well.

4.3.2.1 Shell theory

Thin shells form a very stable structure because of the developing of membrane action when loaded. This means that the (out-of-plane) loading is transferred to stresses within the shell, called in-plane stresses or membrane stresses. This is provided by the geometry of a shell; imaginable closed lines can be drawn around a spherical structure, these spread the loads and make that the structure is quite resistant to deformations. Stresses can be divided in ring stresses and meridional stresses. Materials tend to resist in-plane stresses a lot better than out-of-plane stresses, therefore these shell structures can be very slender.

Mechanically speaking membrane stresses exist when one of the three principal stresses is zero. This occurs in structural elements for which one of the three dimensions is very small compared to the other two. In this case, the stresses with respect to the smaller dimension are negligible as they are not able to develop within the thin material and are small compared to the in-plane stresses. The element can now be analysed as a 2D plate element.

The ideal shape for a dome structure is the catenary shape, this line is found when hanging a chain or cable between two points, the self-weight then results in a curve called the catenary. A dome or arch with this shape will only be subjected to pure normal forces due to self-weight as the structure follows the line of thrust for it's gravity. This principle worked quite well for heavy masonry arches in the past as self-weight was dominant for this type of structures and tensile stress had to be prevented.

For 2D elements bending moments will be developed when the element shape deviates from the line of thrust. The special characteristic of 3D structures is that this deviation will lead to corrective ring forces in the shell instead of bending moments.
By drawing the line of thrust, the funicular line, it can be observed in which sectors of a differently shaped dome the correcting hoop forces are tensile or compressive. The funicular line of gravity forces is the catenary arch.
Thus if the shape of the structure deviates from this funicular line, horizontal forces are needed to compensate, they sort of push the structure 'back' into its line of thrust. For a dome structure this thus results in the development of the ring stresses, also called tangential stresses. These ring stresses are compressive stresses where the structural shape is within the line of thrust, on top of the sphere and tensile stresses where falling outside the line, here in the lowest part of the sphere. (Coenders 2008)

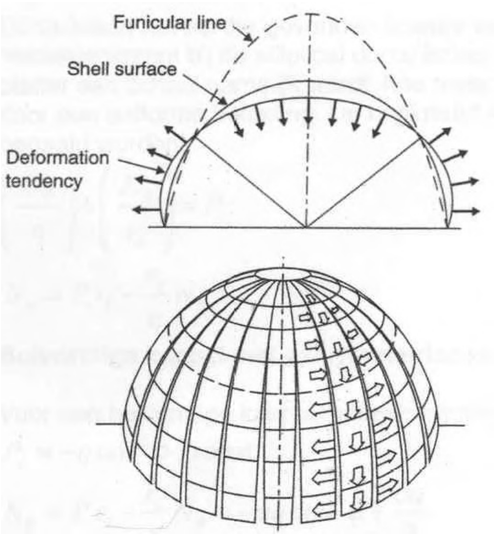


Figure 145: Ring stresses in a dome structure.

In lightweight building the dominant loading of the elements will not be the self-weight of the structure but snow or wind loading. Therefore a catenary arch would no longer be the perfect shape as the line of thrust will be different. With form finding techniques in model building it is possible to find the perfect shape for this kind of loading. However as these loads are variable it will not be a guarantee for success. Therefore the development of ring forces is inevitable.

The membrane theory knows some restrictions as it assumes a perfect shell, developing only membrane stresses, equally distributed over the shell thickness. In some regions this theory will not hold. For example at locations where a concentrated load is applied or at the edges where the support conditions may not be that perfect as assumed, the so-called edge disturbance. These conditions and the resulting membrane disturbance are illustrated in the picture below.

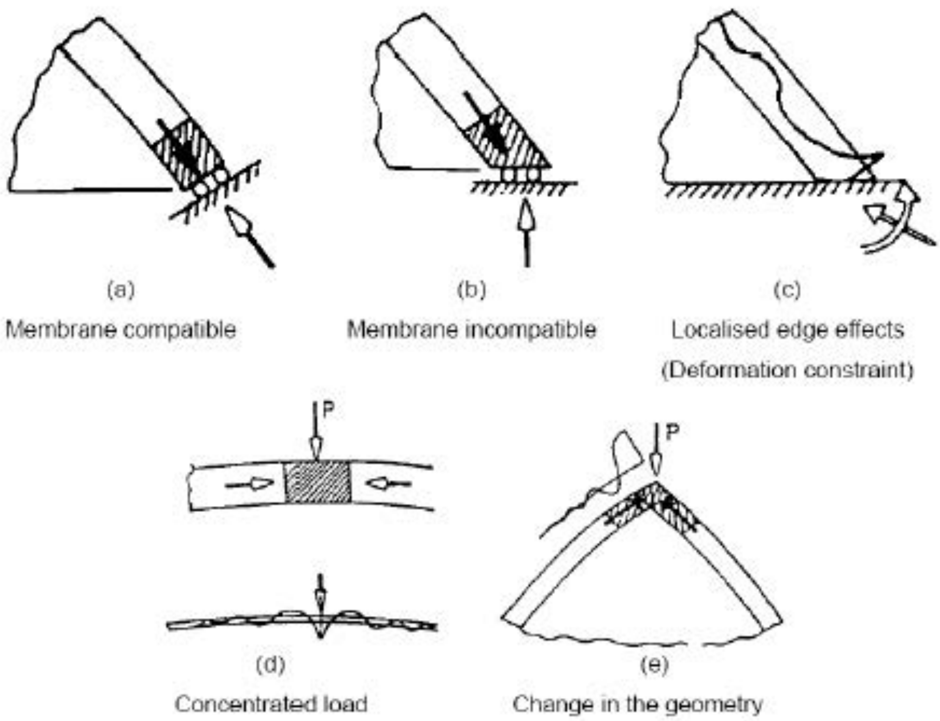


Figure 146: Membrane theory compatibility conditions in a shell. (Maten 2011)

For these regions bending components are needed to compensate for the disturbed membrane, therefore locally the bending theory should be used. The undisturbed and major part of the shell will not be influenced by edge disturbance and still behave as a true membrane. The influence length can be calculated with the following formula:

$$l_i = \frac{\pi\sqrt{Rt}}{\sqrt[4]{3(1-\nu^2}}$$

Which is equal to half of the natural wavelength of 2 π. Conform the theory edge disturbance is negligible beyond this length. During finite element modelling as a rule of thumb this length should be divided into at least 6 elements to make sure that sufficient accuracy is reached. (Maten 2011)

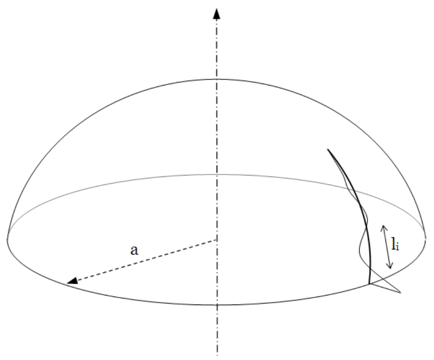


Figure 147: Edge disturbance and influence length for a dome structure

Buckling

The load carrying capacity of shells is very efficient due to the developing membrane stresses. Shells can be very thin-walled because of this behaviour. However this slenderness has a disadvantage, the shell will have a low bending stiffness. As a consequence, if in-extensional deformations occur (thus out-of plane deformations causing only bending and no membrane stresses) a shell can fail by buckling. If such a structure fails it will fail immediately, without warning.

The critical buckling load and critical membrane force can be calculated for all types of regular shell structures with following set of equations.

	Critical loading $p_{cr}[N/m]$	Critical membrane force $n_{cr}[N/m]$	Imperfection sensitive
Open cylinder, radially loaded (in-extensional deformation)	$\frac{1}{4(1-\nu^2)} * \frac{Et^3}{a^3}$	$\frac{-1}{4(1-\nu^2)} * \frac{Et^3}{a^2}$	no
Open cylinder, axially loaded		$\frac{-1}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	yes
Open cylinder, torsion loaded		$\frac{1}{3\sqrt{2}(1-\nu^2)^{\frac{3}{4}}} * E\sqrt{\frac{t^5}{a^3}}$; shear force	no
Hyperboloid, axially loaded (cooling tower)		$\frac{-1}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	yes
Closed cylinder, loaded in all directions	$\frac{2}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	$\frac{-1}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$; hoop direction	yes
Sphere	$\frac{2}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	$\frac{-1}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	yes
Dome; base radius$> 3,8\sqrt{at}$	$\frac{2}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	$\frac{-1}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	yes
Hyppar	$\frac{2}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	$\frac{-1}{\sqrt{3(1-\nu^2)}} * \frac{Et^2}{a}$	no

Figure 148: Critical loading and critical membrane forces for elementary shells (Coenders 2008)

The sensitivity of shells to imperfections makes that shells usually fail under significantly lower compressive loads then predicted by the above formulas. These imperfections can be, among others, residual stresses, thermal stresses, creep or eccentricity of loading. Effects that can certainly exist in a polycarbonate shell structure.

Experiments showed that the necessary safety factor to be used in buckling calculations, the so-called knockdown factor, of shells could be up to a value of C=1/6. Because of the uncertainties existing around the structural use of thermoplastics it is considered safe to use this ultimate knockdown value. Now with the knock down factor and the formulas the minimal monolithic shell thickness concerning buckling can be computed. An indicative load of 1,2*0,15 +1,5*0,7 = 1,23 kN/m^2 (the maximal snow load combination) is used to get an idea of the minimal solid shell thickness required:

Critical buckling load per square meter for short-term loading:

$$p_{cr} = \frac{2}{\sqrt{3*(1-\nu^2)}} * \frac{C*E*t^2}{a^2} = \frac{2}{\sqrt{3*(1-0{,}4^2)}} * \frac{1515*10^3*t^2}{6*5^2} = 1{,}23\frac{kN}{m^2} \quad thus \quad t_{min} = 9{,}8mm$$

Another way of computing critical buckling loads is the use of Finite Element programs. These are able to determine the critical load by analysing the possible buckling patterns and the accompanying critical load factors. The real critical load is determined by the smallest found load factor, as this belongs to the load case that is closest to critical loading.
(Coenders 2008)

For concentrated loads the bearing capacity of a shell can also be computed, the theory is based on the moment capacity of a shell. Thereby the radius of the application dimple (b in the formula) is taken into account as this has a high influence on the local behaviour of the shell. The following equation approximates the ultimate bearing capacity; it was derived in (Ameri 2011).

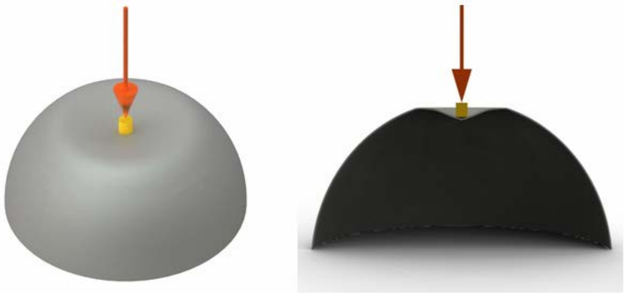


Figure 149: Post buckling behaviour for initial collapse load P_0 (Ameri 2011)

$$P_v \approx 2\pi * \left[\left(b + \frac{t_0}{2}\right) * t_0 * \sigma_0\right]$$

For a load of 1,5 kN, which is required for roof structures, a boss radius of 0,1/2=0,05 m and σ_0 is the allowable design stress, here 8 MPa or 8000 kN/m^2, minimal thickness of:

$$P_v \approx 2\pi * \left[\left(0{,}05 + \frac{t_0}{2}\right) * t_0 * 8000\right] = 1{,}5\ kN \qquad thus\ t_{min} = 0{,}04\ mm$$

This formula is based on the punching shear acting on the material along the radius of the boss, for the short-term allowed stress in outside application. The capacity for a load concentrated in one point can be calculated with the following formula:

$$P_0 = 2\pi * M_0 = 2\pi * \frac{\sigma_0 * t^2}{4} = 2\pi * \frac{8000 * t^2}{4} = 1{,}5\ kN \quad thus \quad t_{min} = 8{,}9\ mm$$

The influence of the boss size is very obvious, the larger the surface the load is spread over, the less stresses will occur at the edges of the loaded area.

Initial determination of in-plane stresses

The polygon of forces is a method to get an indication of the shell behaviour of a certain structure. A uniform dome with a 5-meter radius is regarded and divided in segments, in this case of 20°. For one segment the forces caused by self-weight and the resulting forces necessary to have equilibrium are computed from top to bottom. From top to bottom the segment is divided in steps of 15°, for each resulting facet the surface area, self-weight and angle of tangent line is calculated. This angle determines the necessary horizontal force to compensate for the vertical force.

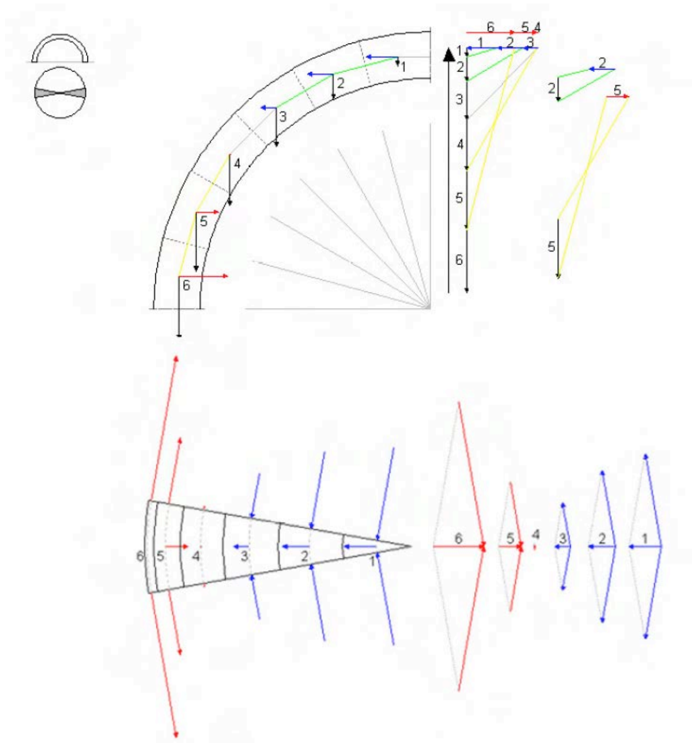


Figure 150: Polygon of forces in a dome section.

Used variables:

r(m)	5	h, part	1,31	pg (kN/m2)	0,06
n	12			pq	0,8
alpha	20	t (mm)	5		
beta	15	g (kg/m3)	1200		

The calculated hoop forces are the imaginary forces perpendicular to the shell to ‘push’ it back in the shape of the thrust line (the numbered horizontal arrows in the picture). The calculated ring forces are the in-plane forces in circumferential direction in the shell, for which the hoop forces are the resultant forces.
The in-shell compression forces are the resulting forces in meridional direction, all components of the self-weight of the shell, in the direction of the tangent line.

		r1	r2	bgem	A (m2)	Mass (kN)	F hoop (kN)	F ring (kN)	sigma (N/mm2)		In-shell compr (kN)	sigma (N/mm2)
upper half	1	0,00	1,29	0,23	0,30	0,02	0,06	0,19	0,03		0,07	0,06
	2	1,29	2,50	0,66	0,87	0,05	0,05	0,15	0,02		0,14	0,04
	3	2,50	3,54	1,05	1,38	0,08	0,03	0,09	0,01		0,21	0,04
	4	3,54	4,33	1,37	1,80	0,11	0,00	-0,01	0,00		0,29	0,04
	5	4,33	4,83	1,60	2,09	0,12	-0,05	-0,13	-0,02		0,39	0,05
	6	4,83	5,00	1,72	2,25	0,13	-0,10	-0,29	-0,04		0,51	0,06
Lower half	7	5,00	4,83	1,72	2,25	0,13	-0,17	-0,50	-0,08		0,67	0,08
	8	4,83	4,33	1,60	2,09	0,12	-0,27	-0,78	-0,12		0,88	0,11
	9	4,33	3,54	1,37	1,80	0,11	-0,43	-1,24	-0,19		1,23	0,18
	10	3,54	2,50	1,05	1,38	0,08	-0,78	-2,24	-0,34		1,91	0,36
	11	2,50	1,29	0,66	0,87	0,05	-2,10	-6,04	-0,92		3,88	1,17

Figure 151: Calculated hoop and ring forces for the 5-meter radius sphere structure

Snow load is added on the upper 4 elements to see what the influence is on the resulting stresses in the shell:

		r1	r2	bgem	A (m2)	M +Q(kN)	F hoop (kN)	F ring (kN)	sigma (N/mm2)		In-shell compr (kN)	sigma (N/mm2)
Upper half	1	0,00	1,29	0,23	0,30	0,25	0,95	2,73	0,42		0,98	0,87
	2	1,29	2,50	0,66	0,87	0,74	0,78	2,25	0,34		2,00	0,60
	3	2,50	3,54	1,05	1,38	1,18	0,45	1,31	0,20		3,09	0,59
	4	3,54	4,33	1,37	1,80	1,54	-0,03	-0,09	-0,01		4,30	0,63
	5	4,33	4,83	1,60	2,09	0,12	-1,12	-3,22	-0,49		3,99	0,50
	6	4,83	5,00	1,72	2,25	0,13	-1,03	-2,97	-0,45		3,98	0,46
Lower half	7	5,00	4,83	1,72	2,25	0,13	-1,10	-3,17	-0,48		4,26	0,50
	8	4,83	4,33	1,60	2,09	0,12	-1,34	-3,87	-0,59		4,89	0,61
	9	4,33	3,54	1,37	1,80	0,11	-1,90	-5,46	-0,83		6,14	0,89
	10	3,54	2,50	1,05	1,38	0,08	-3,32	-9,56	-1,46		8,85	1,68
	11	2,50	1,29	0,66	0,87	0,05	-9,04	-26,02	-3,98		17,29	5,22

Figure 152: Snow loads are added on the top part of the sphere

This preliminary calculation gives some insight in the occurring ring and meridional stresses, the maximal occurring stresses in a 5 mm shell are expected to be lower than the allowed design stresses of 8 N/mm2 for tension and 13 N/mm^2 for compression. This is however not a design calculation, it only takes into account the shape of the structure, the influence of support configuration and asymmetrical loading will be investigated later with the finite element modelling.

Division of the shell

There are a lot of different options for dividing the sphere into elements. As in plastic design repetition is very important in making the design realisable, a way is sought to divide the sphere in as much similar elements as possible.

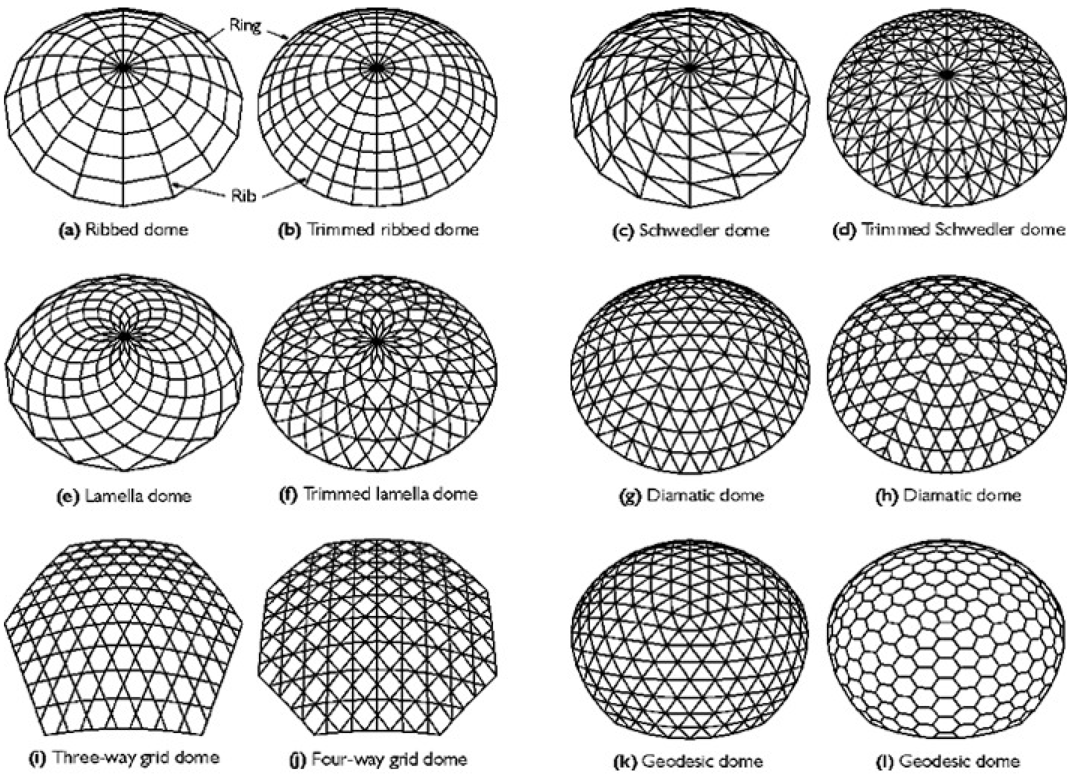


Figure 153: All kinds of possibilities to create a dome structure

The most suitable layout considering repetition seems to be the geodesic dome. This type of dome is based on a regular icosahedron, a polyhedron consisting of twenty equal equilateral triangular faces. These equilateral triangles can be divided in more triangles to create a spherical structure that approximates a real sphere. The more facets are created, the better this approximation. The frequency of a geodesic dome indicates in how many part each edge is divided. A v3 dome for instance divides each of the icosahedron edges in three and thus each triangle in six new triangles.

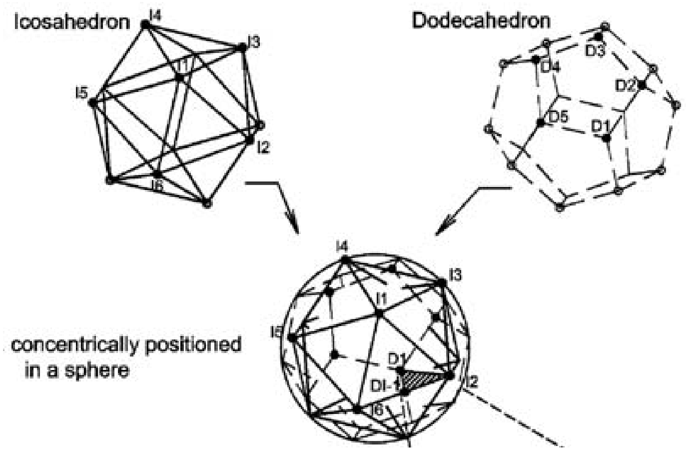


Figure 154: Icosahedron with its dual (dodecahedron) and its truncated form.

The so-called dual of a triangular geodesic structure is a truncated geodesic sphere. In the figure above this is shown for the regular icosahedron. Truncating all vertices of the icosahedrons creates its dual, the dodecahedron; a regular shape consisting of equal pentagons. Every facet of the triangular structure becomes a vertice of its dual and vice versa. So the dodecahedron has twelve regular pentagonal faces and twenty vertices.

Usually the triangular structure is used to create lattice girder dome structures. The triangles provide a stable structure and all forces are transferred by normal forces trough the girders.
For facetted shells, where the facets actually form the structure, the truncated structure is more suitable. The facets will carry loads by in-plane forces that can be transferred from edge to edge.

It is common to use flat instead of curved elements in facetted geodesic dome design. These elements can be made of various materials, for instance steel or wood and as flat sheets are standard products this will create a feasible structure.
Facetted shells with flat facets carry the forces locally by bending of the facets, this way transferring the load towards the simply supported edges. There the stresses will be transferred to in-plane stresses in the surrounding elements. This principle is relying on the fact that no bending moments can be transferred between the plates; they are thus connected with pinned connections.
Governing for large sheet elements will now be the deformation of the individual facets. As plastics have a low Young's modulus and can be easily processed into curved elements this is not a favourable plastic design. Double curved elements will have to be used to make good use of the material properties. Actually the suitability of geodesic dome segmentation for plastics is only because of the division in apparently equal shell elements, not because of the special behaviour of the shell consisting of local bending and global membrane behaviour.

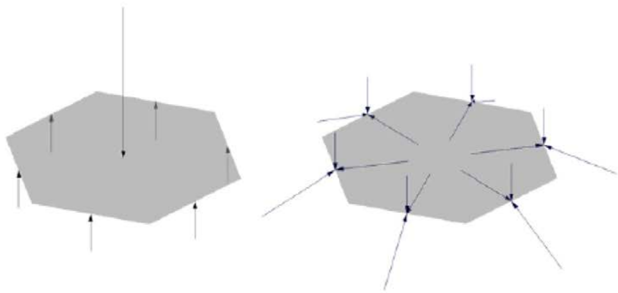


Figure 155: Mechanism of local bending of facets in a shell.

4.3.2.2 Element design

As stated earlier this paragraph it is important in plastic element design to reach a high degree of repetition. Here several variants are presented both from the starting point of uniform elements as from the point of flexible elements.

Flexible elements

A: Standard polycarbonate sheets folded to ribbed triangles

In this design the folded edges act as a kind of struts, which means that now the triangular structure again is the most favourable. These ribs of the triangles approximate the geodetics of a dome, the shortest distance possible to connect two points on a sphere. This is an efficient way to transfer forces.
An extra possibility is to hot form the plates with double curvature, but this will make folding the edges practically impossible. If formed double curved with integrated edges, (expensive) moulds are needed for every element, which will sweep away all flexibility of the method.

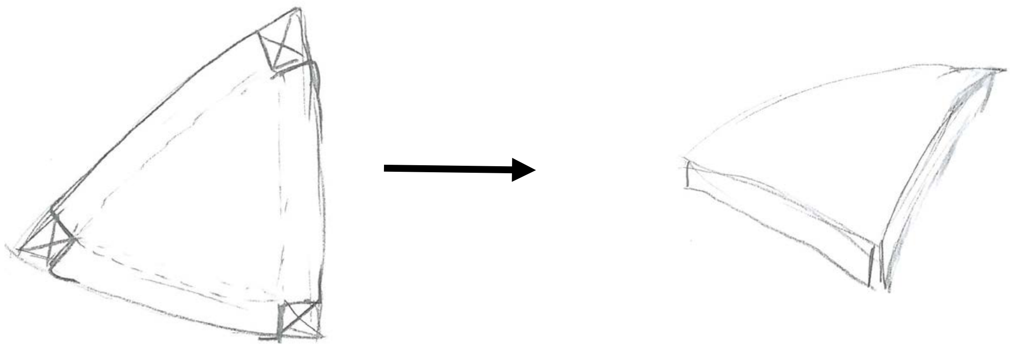


Figure 156: Hot formed elements with ribs

- \+ Pragmatic, practical structure
- \+ All necessary sizes can be custom made without expensive moulds
- \+ Because of this flexibility it is also suitable for the lower dome structure.
- \+ Conventional bolted connections can be used to connect the ribs to each other

- \- Only small elements can be used to prevent extensive local bending, about 55 cm large triangles are achievable with 5 mm thick sheets, based on maximal span tables from the design guideline of Lexan. (GE structured products n.d.)
- \- Folding can cause residual stresses between the ribs and the facet
- \- It will be difficult to achieve a high precision level as no moulds are used
- \- Assembly of a lot of different elements can cause trouble on the building site
- \- The necessary watertight sealing will always be visible

B: Flexible uniform joints (injection moulded) and extruded struts with a cladding of standard polycarbonate sheeting

This method is based on the strut model used for all steel and timber geodesic domes. Nodes are connected with struts to form a stiff sphere structure; separate cladding will have to be used to close the sphere.
The nodes could be all the same (except for the ones that connect five struts instead of six) as the flexibility of the polycarbonate will be able to take small irregularities. The struts can be made of an extruded polycarbonate profile; one mould can then be used to make all lengths of elements desired. The struts or the nodes could be hollow to make them fit together easily. It would be best to make at least the struts hollow, as they need the highest stiffness and buckling resistance.
Still the stiffness of the cladding will be partly determining the maximal element size.

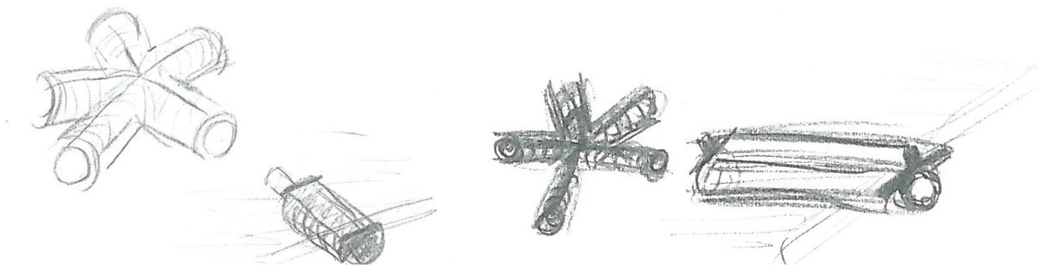


Figure 157: Nodes for connecting struts.

- + Joints can take small dissimilarities in the geometry
- + A mould can be made for extrusion in such a way that the facade panels can be mounted easily to the profiles
- + Extruded profiles can be cut to all sizes and thus all necessary different size elements can be easily made. No additional expensive moulds are needed.
- + Standard sheets can be used for the cladding, these can as well be cut to all necessary sizes.

- - Problematic will be again the size limitation, the same size of 55 cm large triangles are achievable which will result in a lot of different element sizes.
- - Lot of different elements necessary, among which multiple different sizes of struts and cladding.
- - A lot of assembly work will have to be done, as large number of elements is needed to put together the whole sphere structure.
- - The cladding has to be added separately and is not part of the structure

Uniform elements

C: Injection moulded hexagons and pentagons
Injection moulding will be a way to produce high quality products with low tolerances, which is necessary to create a watertight and well fitting sphere. Thicknesses of 4-5 mm will be about the maximum achievable with an element size of about 1 square meter.
This production method is ideal to create 3D elements with a ribbed pattern. By doing this a very stiff plate can be produced with relatively little material, which makes a lightweight stiff sphere structure. As the material itself is very flexible this is the only way to create elements larger than the earlier mentioned 55 cm.

Ribs will definitely influence the clearness and transparency of the sphere structure, a solution can be found in creating a sort of circular ‘window’ in which no ribs are placed. Ribs are now spanning between this ring and the edge and along the edge also ribs are applied, mainly to ensure the stability of the perpendicular ribs.

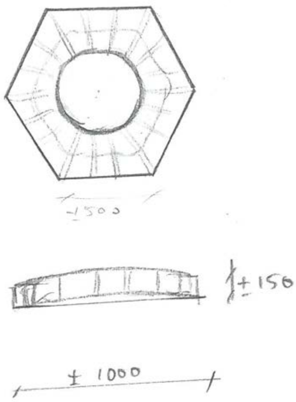


Figure 158: Injection moulded element with ribs and a circular rib-free 'window'

- \+ High quality elements can be produced with injection moulding.
- \+ High precision production with low tolerances.
- \+ Connection devices as snap-fits can be moulded in, creating an easy, precise and cheap connection possibility.
- \+ Large elements can be made, as with injection moulding it is possible to apply ribs over the whole surface.

- \- High fixed costs by the large steel moulds that have to be made, approximately €100.000,- for one mould of 1 square meter.
- \- Only feasible from a production of about 100 of these spheres
- \- As at least a dual of a v4 dome is needed to keep within the maximal element size, this subdivision results in elements of 1,5 meter and needs one pentagonal and three different hexagonals moulds to create the sphere. It is difficult to adjust the mould with inserts in such a way that it can be used for more than one element shape thus multiple moulds are required.
- \- The injection moulding process is sensitive to unequal shrinkage and expansion.
- \- Injection- and demoulding points will always stay visible on the element surface.

(EKF 2012)

D: Vacuum formed hexagons and pentagons

Vacuum forming uses standard extruded polycarbonate sheets which are heated and then pulled into the desired shape by vacuum.
A specific way of vacuum forming is twin-sheet or dual-sheet forming. This process uses two moulds and two sheets of polycarbonate, which are pulled in shape and sealed together in one action. This creates hollow elements. These double walled elements will obviously be stiffer than the single walled ones. An advantage is that the curvature could be made slightly larger than the sphere curvature, which provides more stiffness as shown in the figure below.

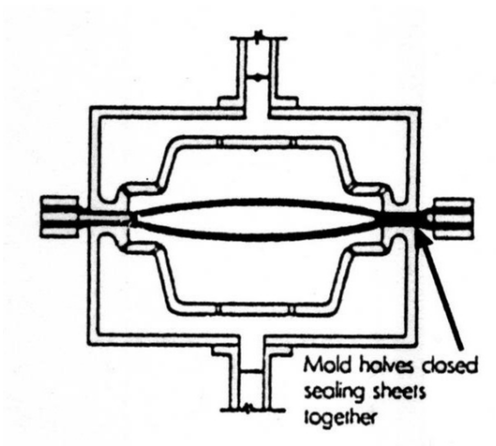


Figure 159: Twin sheet vacuum forming.

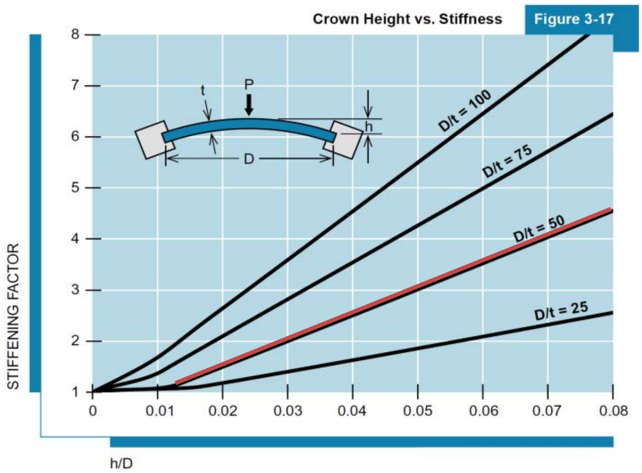


Figure 160: Crown height vs. Stiffness

- \+ Lower pressures are needed than for injection moulding but still a high level of precision can be achieved.
- \+ This method will result in significantly lower mould costs, as aluminium moulds are sufficient for this lower pressure technique; single walled elements even just need one mould-half per element.
- \+ Standard sheets can be used as basis material making it a relatively cheap technique.
- \+ The elements can be formed and sealed together in one go
- \+ Under-pressure is created when the element is cooling down, the shape will become even more stable.

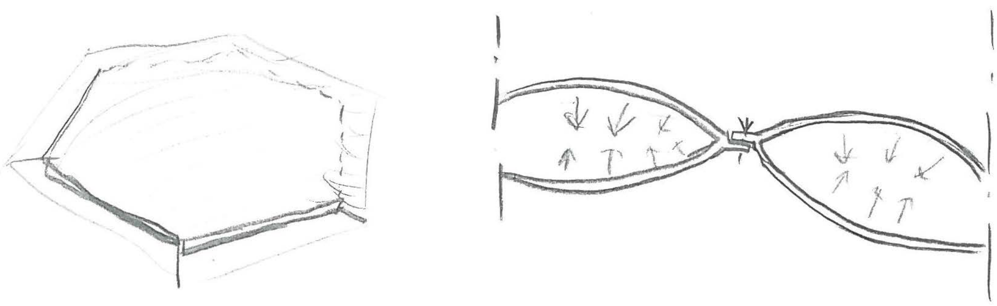


Figure 161: Vacuum formed elements visualised.

- \- Smaller elements necessary (approximately 55 cm in diameter again which means at least a V12 dome) because of the lower stiffness, as no ribs can be applied besides the edges of the element.
- \- A lot of different moulds are needed, as this high frequency dome has to be used.
- \- Detail devices cannot be moulded-in, as was the case for injection moulding.
- \- Hollow elements are sensitive to condense.

Geodisic domes – repetitive elements? Reconsideration

Geodesic domes seemed to be a suitable way of constructing a sphere structure with polycarbonate elements. However the appearing repetition in elements is disappointing for the desired element sizes that can be maximally used in this case study.
The higher the frequency of the dome, the more deviations occur in the separate elements. This can be explained by the original icosahedron. Five equilateral triangles meet in each vertice, all angles of those triangles are thus 60°. When each triangle is divided in smaller triangles, the newly developed vertices are projected to the imaginary dome. Now still five triangles are meeting in the original icosahedrons vertices. But as this ‘pentagon’ has flattened out by the projection of the newly arised vertices to the dome surface, it is impossible that the angles of the meeting corners are still 60°. The meeting angles will have increased by this stretching. Thus it is also impossible that the structure consists still of only equilateral triangles. Every further partition of elements results in a larger deviation of the original equilateral triangles. Of course the same principal holds for the truncated versions of the dome. As an example the deviation of one of the icosahedron facets is shown for a 4V frequency dome. For the triangles all edges with the same length have the same colour. The accompanying truncated deviation is drawn beside it, the colours here indicate which elements are equal.

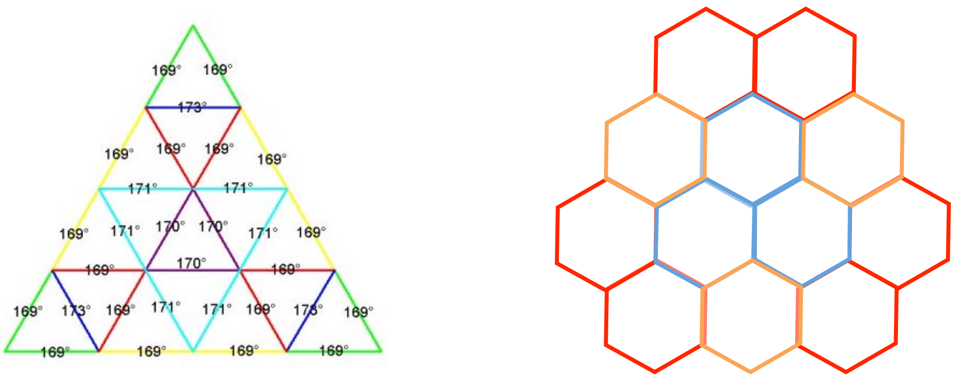


Figure 162: Elements in a 4v dome and its dual

Altogether the repetition in geodesic domes is not convincing and beside that problems will arise at the connections to the core and the observation floor as no straight edges can be created. Thus another way of creating a sphere from segments is investigated:

E Vacuum formed ribbed elements

Another, quite common, layout for shell segments is obtained by dividing the shell along its meridians and rings. The frequency of repetition of elements depends now on the amount of segments that the sphere is divided in. The upper half and lower half of the sphere can be mirrored except for the top elements that will have to connect to a smaller diameter core than the bottom elements. Thereby the shell will now have straight edges that can be connected to the core structure and the observation floor.
The elements can be vacuum formed with half aluminium moulds using standard extruded polycarbonate sheeting.

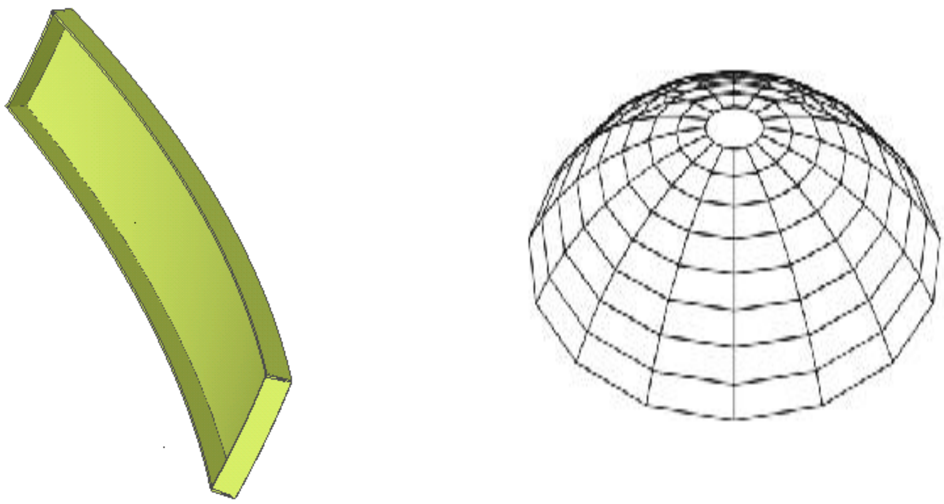


Figure 163: Possible segment (left) and deviation of the sphere (right) for a ribbed dome

- + Vacuum forming requires less pressure than injection moulding
- + Less expensive, one-half, moulds are needed.
- + The observatory floor can be easily integrated with the sphere halves as the elements follow this ring line.
- + The same elements can be used for the upper half and the lower half of the sphere, only the parts connected to the core will be shorter than for the upper half.
- + Assembly can take place in complete rings or segments, which will be less complicated than assembling pentagons and hexagons.
- + Ribs are applied in the direction of the ring and meridional stresses, which is favourable considering the transfer of loads.

- - Sizes are still restricted by vacuum forming; this can be performed up to 4 meter although that is not quite standard.
- - More than one mould is needed. The amount of elements one half 'orange peel' is cut into is equal to the amount of moulds that is needed.
- - The elements cannot directly be used for the lower dome structure as well, however the system will be suitable for that structure as well

4.3.2.3 Design decision

MCA sphere	A folded	B struts	C inj mould	D vac form	E ribbed
Structural behaviour	+	+	++	-	+
Material use	0	-	+	-	0
Transparency	-	-	+	+	+
Architectural value	0	0	++	+	-
Assembly	-	--	0	0	++
Costs	+	+	--	0	+
Sum	0	--	++++	+	++++

The limitation in element size for cheap moulding techniques is restricting the very promising design of geodesic shaped shell structures. Too much different elements will result in high moulding costs, difficult assembly and a limitation of the transparent appearance of the sphere.
Therefore the last option will be further computed.

For vacuum forming size limitations of about 4 meter length were found, the shell segments forming half a sphere will have a length of one quarter of the circumference minus the core radius. About 7,1 meter for the upper half and 5,9 for the lower half. It is thus possible to divide the parts in only two pieces over the length.
As the ring shaped ribs will make the structure more structurally sound it is chosen to divide the parts in three over the length, this will as well result in good sizable shapes to be handled by the builders.
The total mould size is not affected by the segmentation in meridional direction, the difference between two large or three smaller moulds will be negligible.
The width of the elements actually determines the mould costs, the more meridional segments the sphere is divided in, the smaller the mould size. A high repetition rate can thus be achieved.

A heart-to-heart distance at observatory floor level of 560mm is chosen, this is based on the prescribed element size for two-sided clamped Lexan roof elements of 5 mm thick with a loading of 0,8 kN/m^2 (GE structured products n.d.). This is dimensioned on a deflection of 1/20 times the heart-to-heart distance, but it is expected that the double curvature of the shell will provide enough additional stiffness to restrict this deformation.
The size of 560 mm is also one of the smallest sizes possible that provides enough transparency for the visitors. But with a repetition of 56 elements per ring, 112 elements can be made from one mould, and thus a very efficient shell structure is created.

As for the thickness of the elements, earlier this paragraph an estimation was made for the minimal equivalent shell thickness necessary to prevent buckling. The highest result obtained was a thickness of 10 mm. The ribbed structure will improve the buckling behaviour and thus a lower shell thickness can be applied. The ribs should not be too slender to prevent lateral torsional buckling of the ribs.

The minimal ratio between rib width and rib height can be computed with Roark's formula:
(Crawford 1998)

$$\frac{t}{h} = \sqrt{\frac{\sigma_d * (1 - \nu^2)}{1{,}2 * E}} = \sqrt{\frac{8 * (1 - 0{,}4^2)}{1{,}2 * 1653}} = 0{,}06$$

An initial shell thickness of 5mm is chosen, this to make sure the elements of itself will be rigid enough for assembly and will not be damaged that easy by small concentrated loads, imperfections and other influences.

The ribs now can have a maximal length of 5/0,06 = 83 mm. But as the ribs will be 10 mm thick when the elements are assembled, a maximal length of 10/0,06 = 167 mm would be allowed.
Ribs do offer a lot of stiffness and can significantly lower the buckling load of a shell as the ribs stabilize the shape. An initial rib height of 100 mm is chosen.

It will be checked by finite element modelling whether these initial dimensions are sufficient.

4.3.2.4 3D Modelling and analysis

The sphere is modelled with SCIA[2] Engineer; the ribbed dome is made of polycarbonate with short-term properties, as the most important load cases will be wind and snow and thus short-term loading. For deformations the short-term situation will certainly be governing. Stresses still can be calculated for both the short and the long-term load cases in the model.

All load cases that were earlier determined are adopted, leading to the following table:

Naam	Type	Belastingsgevallen	Coëff. [-]
UGT1-Long term	Lineair - UGT	BG1	1,35
		BG2 - Vloerlast BG	0,38
UGT2-Short term	Lineair - UGT	BG1	1,20
		BG2 - Vloerlast BG	1,50
UGT3-Short term- wi	Lineair - UGT	BG1	1,20
		BG2 - Vloerlast BG	0,38
		BG3 - Wind	1,50
UGT4a-Short term- sn -ev	Lineair - UGT	BG1	1,20
		BG2 - Vloerlast BG	0,38
		BG4 - Sneeuw - evenly	1,50
UGT4b-Short term- sn- un	Lineair - UGT	BG1	1,20
		BG2 - Vloerlast BG	0,38
		BG5 - Sneeuw - unevenly	1,50
BGT1-Long term	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	0,60
BGT2-Short term	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	1,00
BGT3-Short term- wi	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	0,25
		BG3 - Wind	1,00
BGT4a-Short term- sn- ev	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	0,25
		BG4 - Sneeuw - evenly	1,00
BGT4b-Short term- sn- un	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	0,25
		BG5 - Sneeuw - unevenly	1,00

Figure 164: Load combinations sphere structure

The local wind load factors are used to compute the load pattern of the wind. This is based on the figures from the Eurocode concerning the wind pattern around a spherical structure. Pressure is applied on one side of the sphere, resulting in a maximal suction on all sides of the sphere and some lower suction at the back. The transition between those loading areas is determined on an angle of 60°, with this angle and the radius of the dome the areas of application could be computed for each wind load.

[2] Nemetschek SCIA is a software developer

With a peak wind pressure of 1,19 kN/m^2 at the highest point of the sphere the following surface loads are obtained:

Pressure:	+0,4 * 1,19 = 0,48 kN/m^2
Maximal suction:	-0,6 * 1,19 = -0,71 kN/m^2
Minimal suction:	-0,2 * 1,19 = -0,24 kN/m^2

The wind load situation in the model looks as follows:

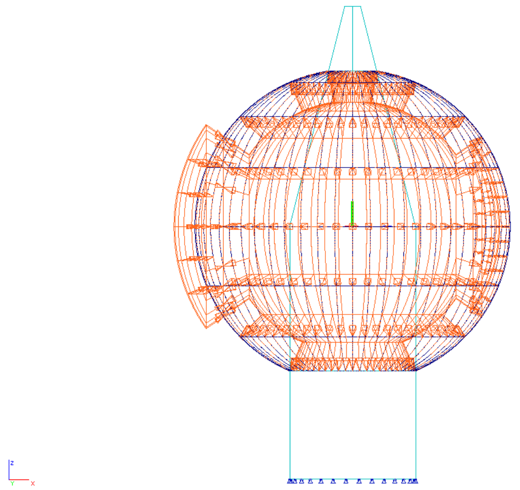


Figure 165: Distribution of wind load in three zones

For the snow load the evenly spread snow can be directly applied to the sphere structure. The radius for which the roof angle is less than 60 degrees was determined to be 4,33 m. Within this circle the load of 0,56 kN/m^2 is applied.

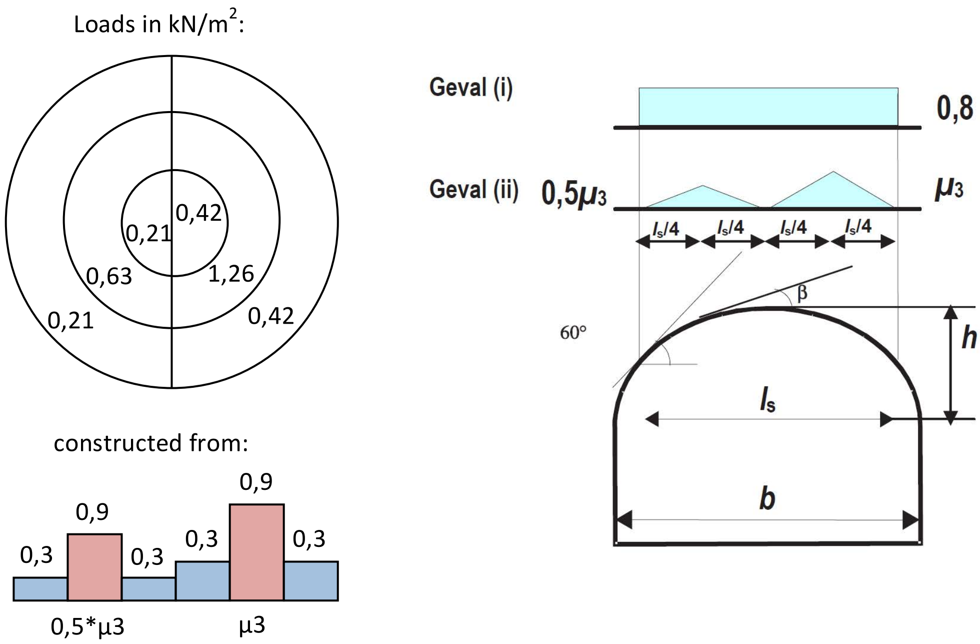


Figure 166: Load zones for asymmetrical snow load. Top view and factors for µ3. (NEN-EN1991-1-3 2003)

The exact load case for unevenly distributed snow described as ‘*Geval (ii)*’ is slightly adjusted. As the roof is spherical and not cylindrical it is not realistic to apply the snow in linear zones. As well it is impossible to apply these loads with the prescribed triangular distribution in available FEM software. These problems are omitted by dividing the load into circular zones conform the figure above.

The snow loads applied to the model gives the following images:

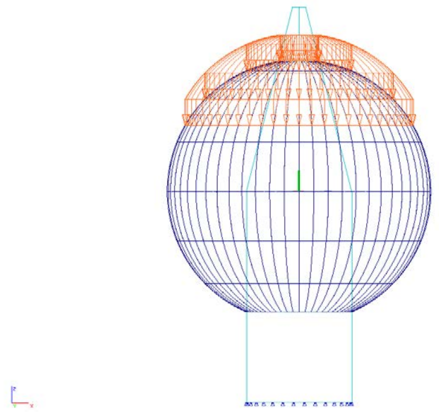


Figure 167: Evenly distributed snow load

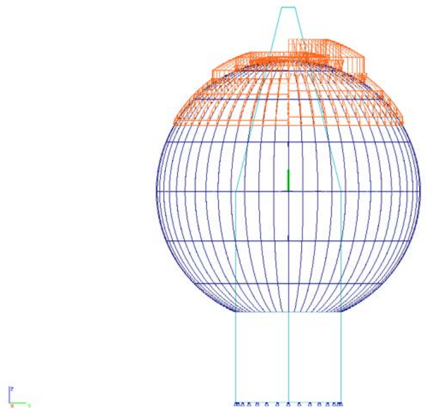
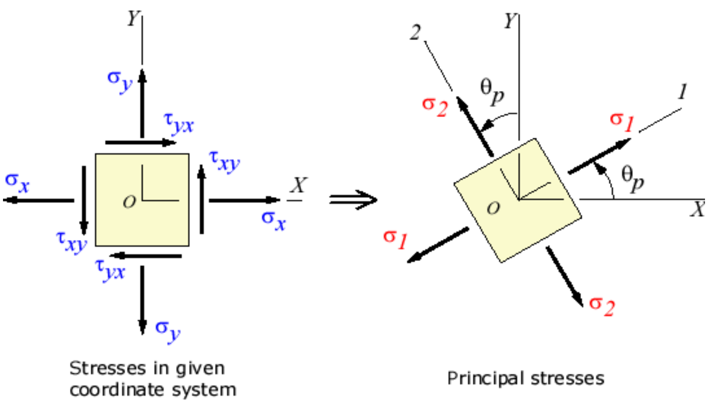


Figure 168: Unevenly distributed snow load in circular zones

Stress analysis

All kind of stresses can be calculated by FEM software, to be able to check whether the design stresses will be exceeded it is important to determine with which stresses these should be compared. In a simple beam it is clear in what direction forces and stresses work, but in a membrane stresses can work in all directions in the 2D plane.

To determine the maximal occurring normal stresses, the stresses in x and y direction are combined with the shear stress. An orientation is determined for which the shear stresses are eliminated. The stresses perpendicular to the sides that are found for this orientation are called the principal stresses. These are the maximal normal stresses that exist in a certain point.



$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\;2}}$$

$$\tau_{\max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\;2}} = \frac{\sigma_1 - \sigma_2}{2}$$

$$\tan 2\theta_p = \frac{2\tau_{xy}}{\sigma_x - \sigma_y}$$

Figure 169: Principal stresses visualised. {efunda.com)

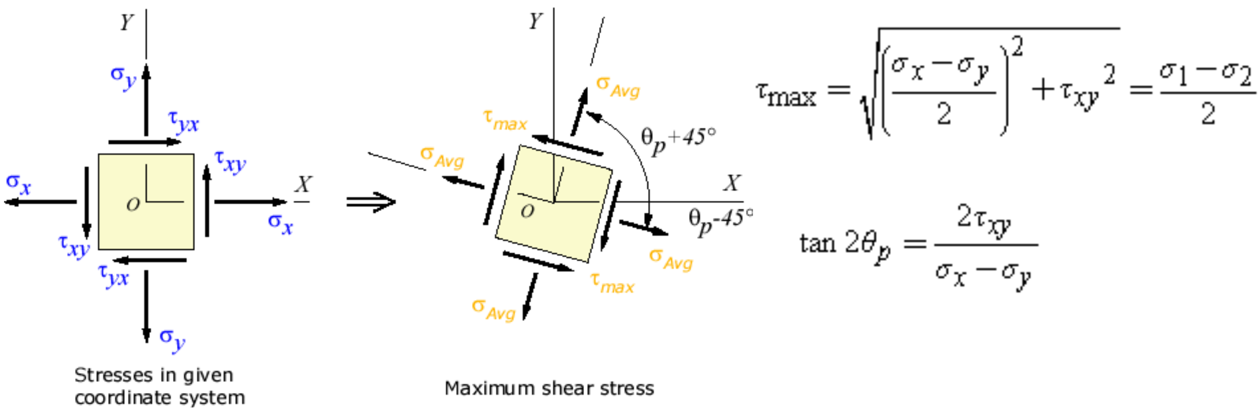
The maximal principle stress theory states that failure will occur when the maximum principle stress in a system reaches the value of maximal stress for simple tension. This theory is especially suitable for the analysis of brittle materials, as brittle materials will fail on normal stresses.

The last normal stress that can be checked is the equivalent stress; both principle stresses are now combined with the following formula:

$$sigE = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}$$

This is called the von MIses criterion; it is based on the theory that yielding is related to the shear energy rather than the maximum shear stress. The calculated equivalent stress should be lower than the design value for tensile stress.

In a same way as for the maximal normal stresses the maximal shear stress can be determined, the orientation for which the shear stress is at its limit is shown here:



The theory for maximal shear stress assumes that failure will occur when the maximal shear stress reaches a certain value. It is applicable to ductile materials that fail on shear stress rather than tensile stress in a tensile test. The maximal shear stress can be checked with the design value for shear strength. (Hibbeler 2006)

The model

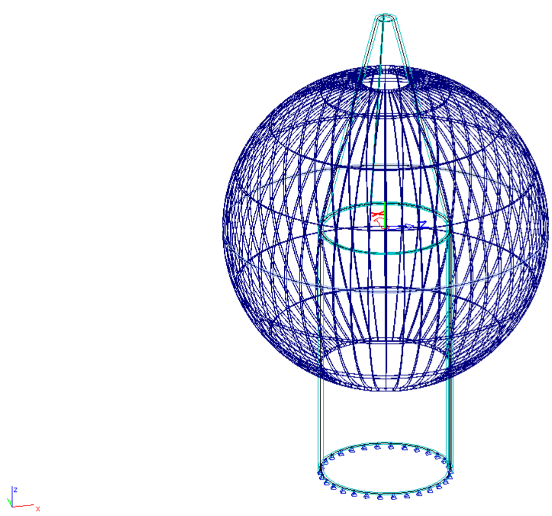


Figure 170: Overview polycarbonate sphere structure

- A sphere with a radius of 5 meter
- 56 ribs with the double thickness of the shell elements as two elements will be connected along those lines.
- Suported by the core with a radius of 0,75 meter at the top of the sphere and a radius of 2 meter at the bottom of the sphere
- The observatory floor that will be supported by the shell as a cantilevering floor would lead to a necessary increase from an equivalent thickness of 100 mm to 300 mm. Thus a factor of 3^3=27 in floor stiffness. Compared to that the influence on the sphere structure is very small, leading to slightly higher stresses and some more deformation, which could be solved within an extra millimetre shell thickness. Thereby it could certainly have a positive effect on the critical buckling load as well, stabilising the sphere circumferentially.

The allowed design stress for polycarbonate in short-term loading conditions in an outside environment is 8,0 MPa in tension and 13,7 MPa in compression. For the long-term loading case these are 6,5 MPa in tension and 11,1 MPa in compression. The nominal shear strength of polycarbonate is 41 MPa, which is 75 % of the tensile strength, thus a design stress of 0,75 * 8 = 6 MPa for short-term and 0,75 * 6,5 = 4,9 MPa for long-term loading will be used.

The principal, equivalent and maximal shear stress can now be checked, if they are all within the design limit stress, the structure can be regarded safe. As the combined stress theorems are based on the behaviour of materials in a tensile test, it is safe to check all stresses for the maximal allowable tensile strength.

Optimization

From the calculation some stresses appeared to be too high, this occurred in the UGT 2 loadcase, with maximal floor load. The exceeding stresses occurred in the following structural elements:

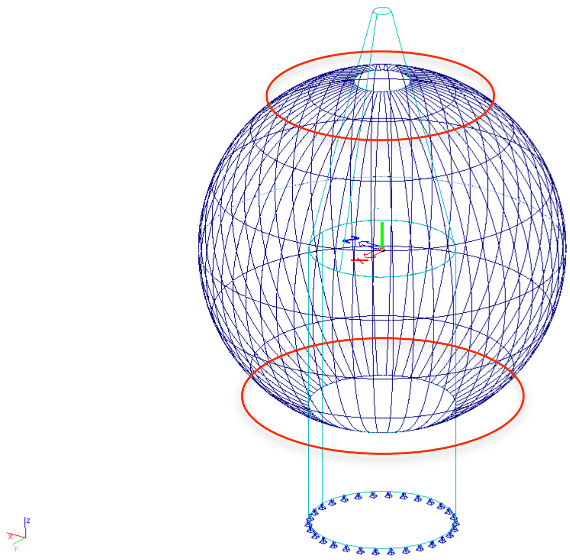


Figure 171: areas with stresses higher than the design stresses

The elements and ribs are obviously the most heavily loaded around the supports as all loads will have to be transferred to the core at these locations.

Another explication is the earlier described influence length. The edge disturbance caused by the supports will cause bending moments to occur in the shell segments, influencing the membrane behaviour over a certain length. This can be noticed by the large differences between the stress on the positive face and the negative face of the shell, that shows as well that bending moments are present.

This statement becomes clear by the calculation procedure for the stresses; as the elements are modelled as 2D elements, the difference in stress between the both faces is determined by using the thickness of the plate. Normal stress and bending stress are summed for the positive face and the subtracted for the negative face.

$$\sigma_{x+} = \frac{nx}{h} + \frac{6 * mx}{h^2} \quad \text{and} \quad \sigma_{x-} = \frac{nx}{h} - \frac{6 * mx}{h^2}$$

The influence length for this shell will be:

$$l_i = \frac{\pi\sqrt{Rt}}{\sqrt[4]{3(1-\nu^2}} = \frac{\pi\sqrt{5000 * 5}}{\sqrt[4]{3(1-0{,}4^2}} = 394\,mm$$

In the FEM results this area also looks a little disturbed, showing high and irregular stresses. This is improved by refining the mesh of the top and bottom row of elements. As an indication the earlier mentioned design rule was used, stating that at least 6 elements should be within the influence length. The original mesh has elements with an average size of 0,2 meter, this is now refined for the elements at the support edges to an average size of 0,05 meter. This made the results already a lot smoother but still stresses were too high in these areas. Therefore the element thickness for these same elements was raised to 6 mm, the rib thickness was as well adjusted to that increased plate thickness locally.

The following improvement is now obtained:

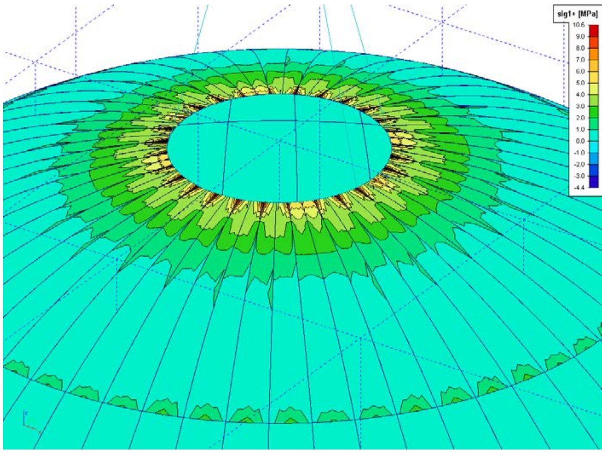


Figure 172: Stresses around edge before mesh refinement and raising thickness

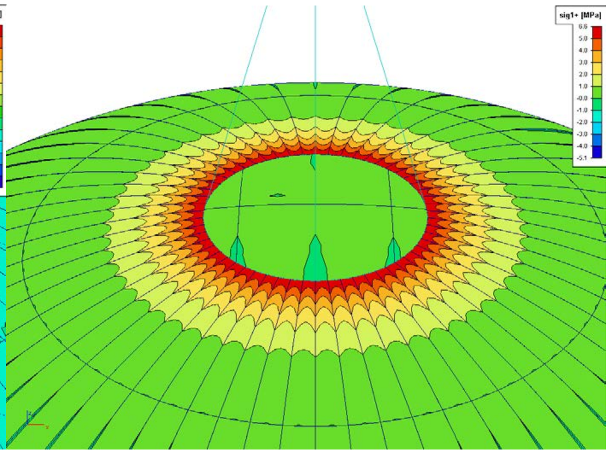


Figure 173: Stresses around edge after improvements

Now all stresses are within the design stress of 8 N/mm^2 for short-term and 6,5 N/mm^2 for long-term situations, as well for the elements as for the ribs.

The deformation behaviour of the structure is as well very intersting, the sphere clearly is dimensionally stable. Around the supports the sphere is sort of sagging around the core, this behaviour has certainly a roll in the high stresses occuring at those locations.

The floor is hanging on the upper half of the sphere, loading the ribs and elements in tension, while pushing the lower half down causing compression in the ribs of this part of the sphere. The lower part is therefore bulging slightly outwards while the upper part is pulled slightly inwards. However these deformations are quite small, the sagging of the floor is with 17 mm still the largest occurring deformation.

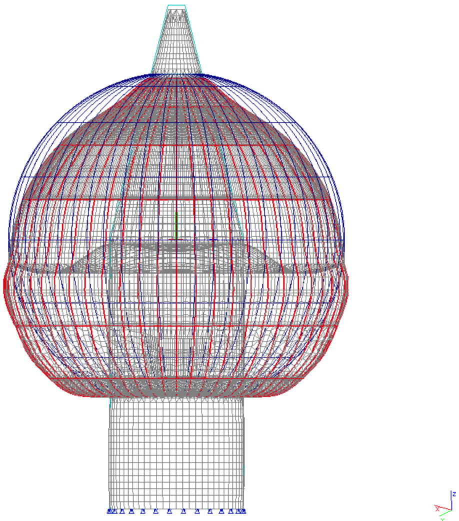


Figure 174: Deformed structure, loadcase UGT2

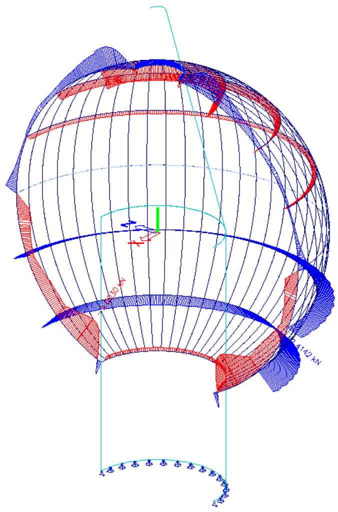


Figure 175: Normal forces in ribs, UGT2. Red for compression, blue for tension

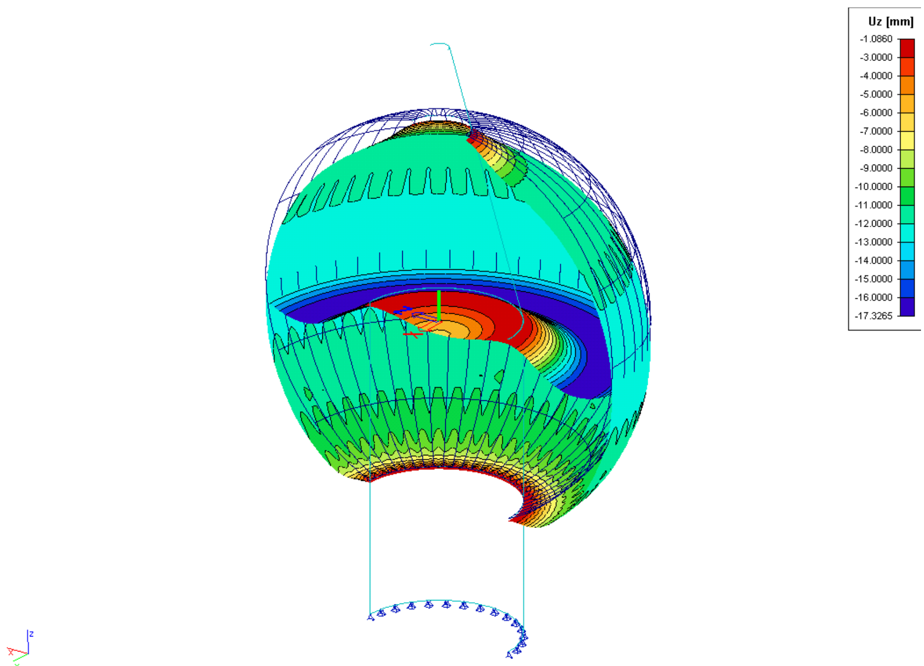


Figure 176: Vertical deformations, BGT2

The floor is modelled as a solid acrylic plate of 100 mm thickness. The allowable deformation of the floor would be 0,004*3000 = 12 mm for a simply supported floor and 0,008*3000= 24 mm for a cantilevering floor. This situation is somewhere in between as the supporting sphere sags already about 12 mm at the floor edge. When pulling a line between that edge and the core, in the middle an initial deformation exists of 6 mm. Adding the allowable 12 mm for a simply supported floor makes an allowable deformation of 18 mm. This requirement is met as can be seen in the picture.

To reduce the material use and floor weight it can be considered to use a ribbed floor instead of a solid floor. The edge however should be solid to provide a nice transition between the floor edge and the sphere segments. This alternative is not incorporated in the model.

The complete calculation report and more pictures can be found in appendix H.

4.3.2.5 Ground floor dome

Same structure as for the observatory sphere

As repetition is of the utmost importance for plastics design, the same structural system that was used for the observatory sphere will be applied to the ground floor dome. It is regarded that the upper sphere is governing as the wind loads are higher at 30 meters high and the support of the full sphere structure is way less favourable.

The ground floor dome is supported around the core and on ground floor level. As it is wrapped around the core, the outer radius is different than that of the sphere and it will be not possible to use the exact same element but the sheet thickness and approximate element size can be the same. As the support will be less heavily loaded no extra element thickness will be needed around the supports, all element can have a thickness of 5mm.

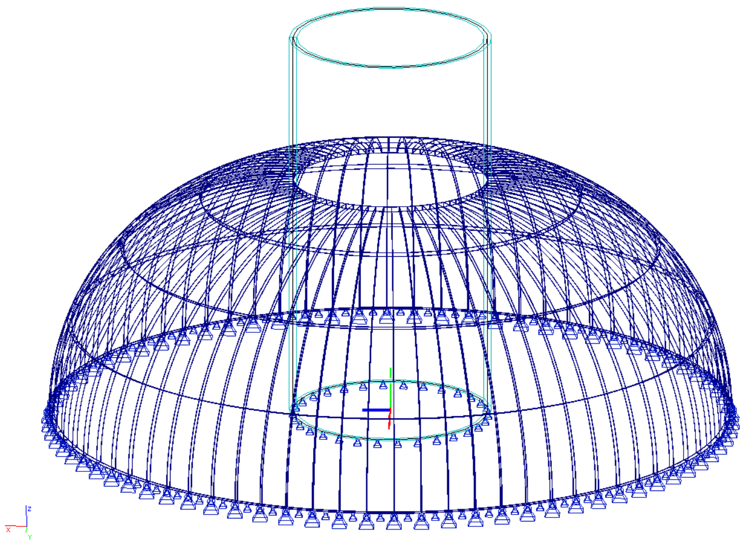


Figure 177: Overview lower dome structure

The same loads and load combinations are used to get an idea of the occurring stresses and deformations. As no floor load is influencing the structural behaviour, the asymmetrical snow load is now the governing load combination, UGT4b.

Indeed the stresses appear to be a lot lower for this structure, with a maximal principal stress of 2,2 N/mm^2. The maximal deformation is 7 mm in vertical direction, for BGT4b (asymmetrical snow).

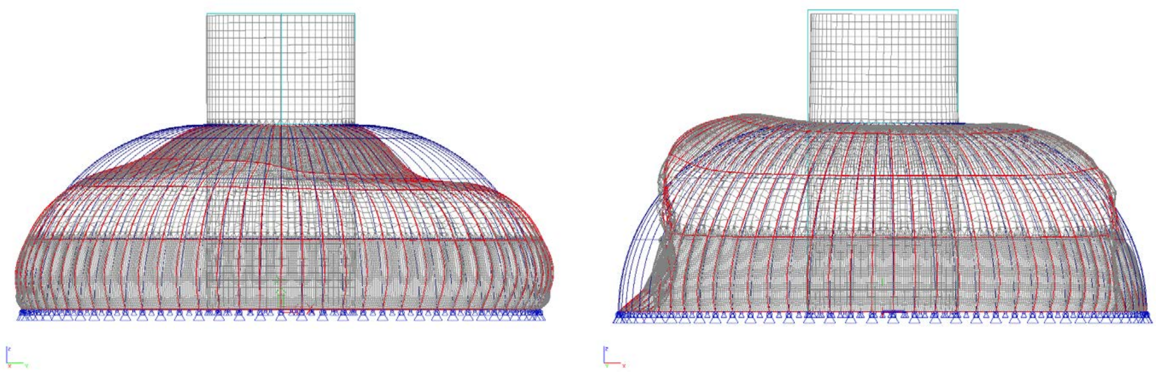


Figure 178: Deformation behaviour of the dome for BGT4b (left) and BGT3 (right)

The complete calculation report can be found in appendix H.

4.3.2.6 Stability of stiffened shells

The stability of a ribbed shell is different from that of a monolithic shell. Several buckling mechanisms may occur. Mostly governing for this type of shell are local panel buckling and stiffener buckling.

- local panel buckling

The Distance between the ribs and the thickness and stiffness of the shell determine whether this will be according to the mechanism of solid shell buckling or at another mode. If the distance between the ribs is smaller than the buckling length over which a solid shell buckles, the allowable membrane stress will be larger. The buckling of a solid shell is calculated with a standard formula, shown below, the local buckling between ribs is calculated with the standard formula for plate buckling. (Katsikadelis, et al. 1990)

$$\sigma_{cr} = \frac{-1}{\sqrt{3 * (1-\nu^2)}} * \frac{Et}{r} \qquad for \ \frac{b}{\sqrt{rt}} > 2{,}44$$

$$\sigma_{cr} = \frac{\pi^2}{3(1-\nu^2)} * E\left(\frac{t}{b}\right)^2 \qquad for \ \frac{b}{\sqrt{rt}} \leq 2{,}44$$

In this case the shell is 6 mm thick at the location where the highest membrane stresses occur. The radius is 5000 mm and the width is varying from top to bottom, from 85mm to 560 mm.
At the location of the highest compressive membrane stress in the sphere, the shell has a radius of 2 meter. As there are 56 ribs, they lay at that point 2*π*2/56 = 224 mm apart.

Thus now a critical membrane stress can be calculated

$$\frac{b}{\sqrt{rt}} = \frac{224}{\sqrt{5000 * 6}} = 1{,}29$$

$$\sigma_{cr} = \frac{\pi^2}{3(1-\nu^2)} * E\left(\frac{t}{b}\right)^2 = \frac{\pi^2}{3(1-0{,}4^2)} * 1653\left(\frac{6}{224}\right)^2 = 3{,}3\ N/mm^2$$

This means a maximal allowable membrane force of 6*3,3 = 19,8 N/mm = 19,8 kN/m

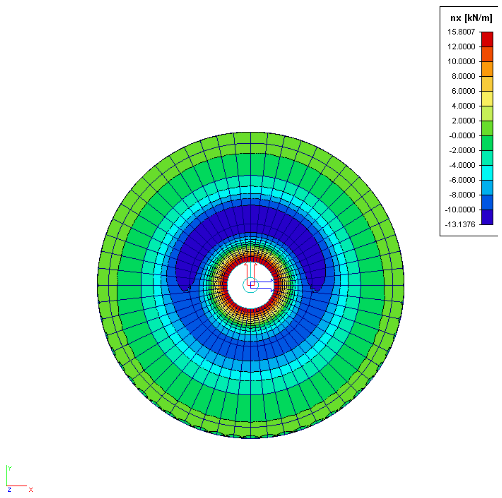


Figure 179: Membrane force nx sphere structure for UGT4b

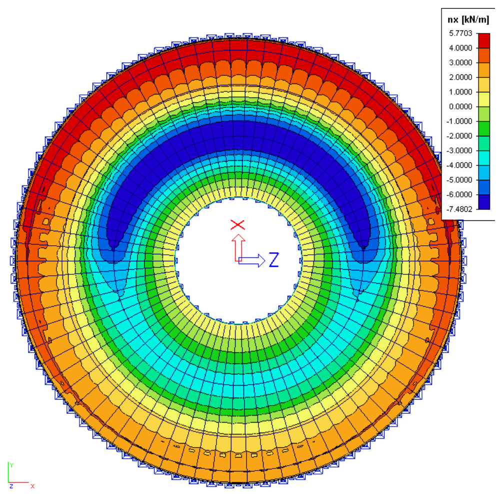


Figure 180: Membrane force nx dome structure for UGT4b

For the sphere the occurring membrane force is 13,1 kN/m now, thus a knock-down factor of γ=13,1/19,8=0,65 would be obtained.

For stiffened shells the sensitivity to imperfections is less than for a monolithic shell, when the ribs and stiffeners are properly used. The required knock down factor can be determined with the following formula: (Katsikadelis, et al. 1990)

$a_{sp} = 0,65$ when $\frac{A_s}{bt} > 0,2$

$a_{sp} = a_o$ when $\frac{A_s}{bt} < 0,06$

In between those values interpolation can be used to determine the knock-down factor. NASA even uses this γ=0,65 as a starting value, up to γ=0,83 and this report mentions that it is advised to develop less conservative shell buckling knockdown factors as it will save significant amounts of material. (Lovejoy, et al. 2010)

In this situation for the sphere:

$$\frac{A_s}{bt} = \frac{2*6*100}{224*6} = 0,89$$

The obtained safety level is thus regarded sufficient at this moment.

For the dome structure the above values can as well be determined. The highest membrane force is occurring approximately at the same location, but as the dome is wrapped around the core, the radius is 4 meter at this location. With an amount of 78 ribs, the in-between distance will be: 2*π*4/78=322 mm. The thickness observed for this area is 5 mm and the radius significant for the buckling is 6 meter (distance to center of dome). The calculation is now as follows:

$$\frac{b}{\sqrt{rt}} = \frac{322}{\sqrt{6000*5}} = 1,86$$

$$\sigma_{cr} = \frac{\pi^2}{3(1-\nu^2)} * E\left(\frac{t}{b}\right)^2 = \frac{\pi^2}{3(1-0,4^2)} * 1653\left(\frac{5}{322}\right)^2 = 1,56\ N/mm^2$$

The allowable membrane force will now be 5 * 1,56 = 7,8 N/mm = 7,8 kN/m. with a maximal occurring membrane force of 7,48 kN/m, this has not the observed safety level, with only a knockdown factor of γ=7,48/7,8 = 0,96.

The necessary knockdown factor is determined by:

$$\frac{A_s}{bt} = \frac{2*6*100}{322*6} = 0,62 > 0,2$$

And thus as well maximal γ=0,65.

When the shell thickness is raised to 6 mm, the following result is computed:

$$\sigma_{cr} = \frac{\pi^2}{3(1-\nu^2)} * E\left(\frac{t}{b}\right)^2 = \frac{\pi^2}{3(1-0,4^2)} * 1653\left(\frac{6}{322}\right)^2 = 2,25 N/mm^2$$

Thus resulting in an allowable membrane force of 6*2,25 = 13,5 and a knock down factor of γ=7,48/13,5 = 0,55 which is sufficient.

- Buckling of stiffeners:

Another buckling mechanism that can occur is the buckling of stiffeners, whether this will happen can be checked with the following formula:

$$\frac{h}{t_w} \leq 0{,}35 * \sqrt{\frac{E}{f_y}}$$

This is approximately the same as the earlier mentioned Roark's formula, but with a safety factor. Thus:

$$\frac{h}{t_w} = \frac{100}{2 * 6} = 8{,}3 \leq 0{,}35 * \sqrt{\frac{E}{f_y}} = 0{,}35 * \sqrt{\frac{1653}{8}} = 5{,}03$$

This criterion thus suffices for the long-term outside application design stress (being 8MPa), which is not exceeded in both current designs.

3D modelling

The results for the stability check can be supported by SCIA stability calculations, the safety factor for each load combination is then calculated, being equal to the reciprocal of the knock down factor, so 1/ γ. Apparently the above calculated situation was not the governing one, the safety factor obtained is now only 1 for the governing load situation UGT4b. (Asymmetric snow)

To make the behaviour of the shell more stable an extra rib is applied at the elements that are now buckling first. This measure appeared to have not enough result and thus thickness of the upper rings of elements is raised from 6 to 7 mm, now giving a safety factor of 1,72. The results next to each other:

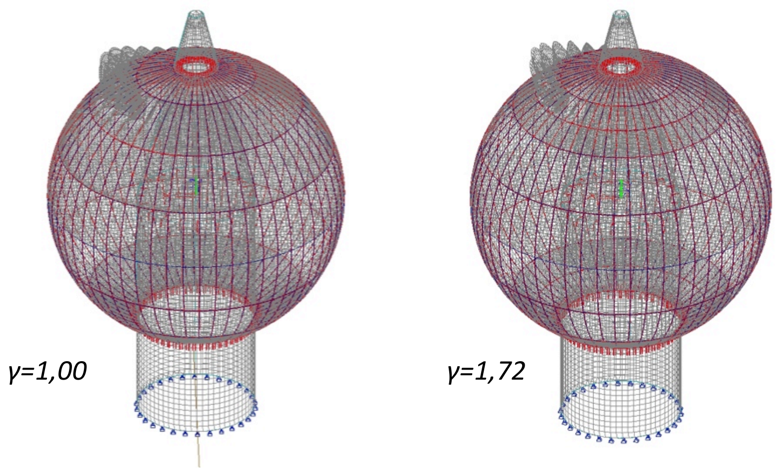
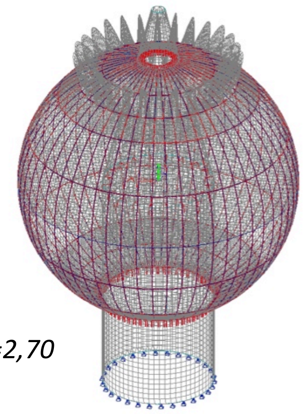


Figure 181: Safety factor and buckling before (left) and after (right) optimization

The obtained knock-down factor is now slightly lower than the factor that NASA uses for their stiffened aluminium cylinder calculations, 1/1,72= 0,58 ≤ 0,65 and therewith way lower than the generally advised factor of 1/5 to 1/6 for solid shells to take into account imperfections. (Coenders 2008)

The behaviour for the situations with extreme imposed loads (UGT2) and wind loads are shown here in the figures below.



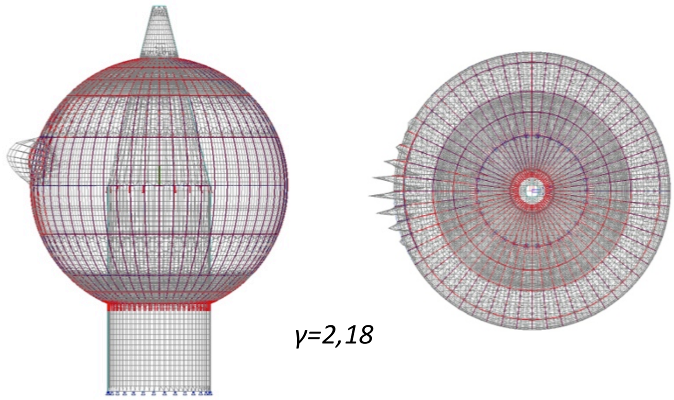


Figure 182: Result of stability calculation for UGT2 **Figure 183: Result of stability calculation for UGT3**

In the figures it is clear that for all situations compressive ring forces result in local panel buckling. For the wind load situation it is as well observed that the meridional ribs are slightly buckling outwards. However the first mechanism that will occur is local panel buckling in the second top row of elements for the load combination UGT4b, asymmetrical snow load.

For the dome structure the same calculation is performed in SCIA, this resulted in a safety factor of 1,44 for the above calculated necessary plate thickness of 6 mm and a buckling behaviour as shown in the picture below.

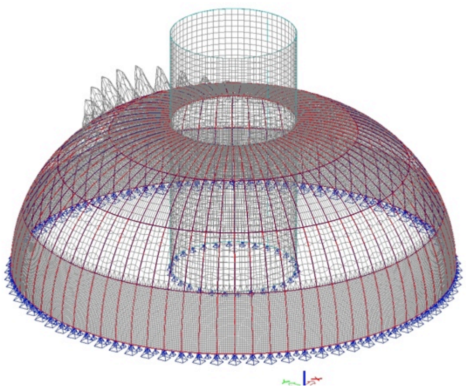


Figure 184: Buckling behaviour of the dome structure for UGT4b

This gives a knock down factor of 1/1,44 = 0,69 which is thus higher than the computed factor of 0,55 and as well slightly higher than the allowable knock down factor of 0,65. Being very close to the observed result the structure is no further adapted. Because of the still present uncertainties considering the stability of stiffened transparent plastic shells this is not regarded to add value.

Probably the deviation of the calculated values is caused by the fact that not the highest membrane force determines the critical location for buckling but the most unfavourable combination of membrane force and rib-to-rib distance. As the rib-to-rib distance increases along the meridians and thus the allowable membrane force decreases simultaneously, the critical location can lay further from the central axis than the highest membrane force.

More research into the stability of transparent plastic stiffened shells is necessary to draw a reliable conclusion on the stability of this structure. The production process of plastic elements offers a high accuracy and low tolerances. So a knockdown factor of 1/6 will of course result in a too conservative design, the value of 0,65 on the other hand might too optimistic. Tests on stiffened transparent plastic shells will have to show which factor is required.

4.3.3 Subsurface observatory room

The subsurface observatory room is build up of a ground and water retaining circular wall of PMMA. The presence of these pressures, up to a depth of 3 meters below ground level, make that PMMA is the only suitable material of the two transparent plastics that are used in the design. The use of PMMA as aquarium wall is already proved successful but as the wall is connected to a PMMA floor and indirectly to the core as well instead of being clamped between concrete walls this design is slightly different from conventional aquaria. Therefore the structure will be analysed by 3D modelling with Scia Engineer.

The water level of open water and groundwater is assumed to be equal, at 1 meter from the top of the wall. The ground surface is situated at the top of the 3-meter subsurface wall. As the water depth in the Veluwemeer is less than 2 meter there will probably be some extra ground pressure on the side of the open water, which is neglected. This situation provides the highest pressure on the walls and the largest difference between water and ground pressure and so the governing situation.

As ground and water pressure are regarded to be long-term loads the long-term load situation will be governing for the wall. Therefore the long-term design stresses are checked and the long-term modulus of elasticity is used for the PMMA modelling.
For the floor the governing stress situation will be the short-term loading. The stresses can still be checked for both the long term and the short-term combination, as the stresses do not depend on the modulus. For deformation the long-term situation is governing, as the floor will develop permanent deformation due to creep and then still has to be able to carry the full variable floor load.

	PMMA-ST	PMMA-LT
Modulus	1894	909
Tensile stress	10,6	6,2
Compr stress	23	13,5

Figure 185: Design values PMMA for application in water.

Load situation

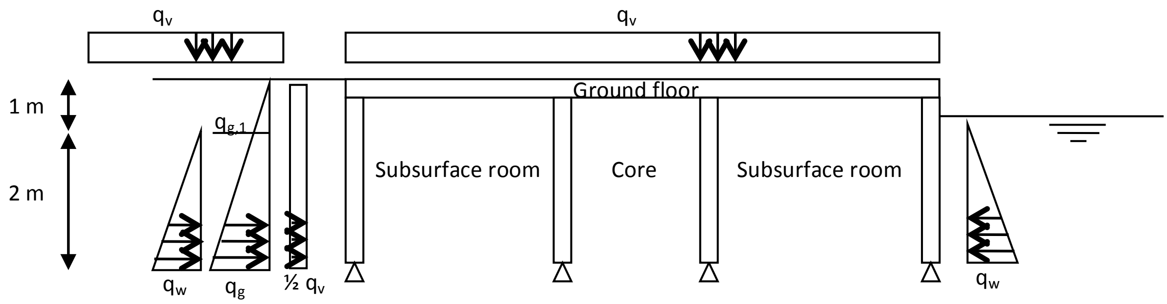


Figure 186: Loads on subsurface room wall

The following loads act on the subsurface structure:

$q_v = 3$ kN/m^2, thus ½ $q_v = 1{,}5$ kN/m^2
$q_{w,max} = 2*10 = 20$ kN/m^2
$q_{g,1} = 1*16*K_n = 16*0{,}5 = 8$ kN/m^2 , the horizontal ground pressure at groundwater level, with the factor 0,5 for neutral horizontal ground pressure.
$q_{g,max} = 8 + (2*20- 2*10) * K_n = 8 + 20*0{,}5 = 18$ kN/m^2

Calculation of ring stresses conform pressure tank formula

First the required thickness of the wall will be estimated by hand calculation. The occurring stresses can be approached by the formulas for ring stresses in a pressure tank. The difference is that the stresses are not equal on both sides and that the stress decreases linearly from bottom to top. At least the part of the load that is equal on both sides will result in this type of ring stresses. The resulting load will be transferred to the foundation by a moment and shear force on the total section. As shown in the above load situation the highest present water pressure is 2 meter and thus 2 kN/m^2, the highest ground pressure at 3 meters depth is determined (with a neutral horizontal ground pressure factor of 0,5) at 18 kN/m^2.

Total long-term design pressure: 1,2*20 + 1,2*18= 45,6 kN/m^2 = 0,046 N/mm^2.

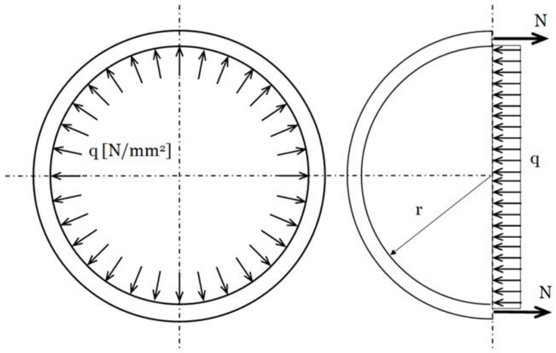


Figure 187: Picturing the ring stresses in a cylinder caused by a uniform compression

$$N = q * 2r * dh$$

$$\sigma = \frac{N}{A} = \frac{q * 2r * dh}{2 * t * dh} = \frac{q * r}{t} = \frac{0{,}046 * 7000}{t} = 13{,}5 \qquad thus\ t_{min} = 24\ mm$$

The allowable horizontal wall deformation is 0,004*3000= 12 mm. To make an estimation of the deformation behaviour the situation for uniform pressure is considered.
A deflection of 12 mm would be reached under uniform pressure when the radius of 7000 mm would become 6988 mm. The maximal allowable strain can now be calculated, giving a maximal stress of:

$$\varepsilon = \frac{\Delta l}{l} = \frac{\Delta r}{r} = \frac{12}{7000} = 1{,}71 * 10^{-3}$$

$$\sigma = E\varepsilon = 909 * 1{,}71 * 10^{-3} = 1{,}56\ N/mm^2$$

It is clear that the deformation is governing; an allowed stress of 1,56 N/mm^2 would result in a wall thickness of:

$$t = \frac{q * r}{\sigma} = \frac{0{,}046 * 7000}{1{,}56} = 206\ mm$$

As the upper and lower boundaries of the wall are connected to stiff floor elements, the radius will not decrease at these locations. Assuming the maximal deflection about in the middle of the wall, the load will be only half of the maximal load as it is not uniform over the height and thus a wall thickness of 206/2= **103 mm** would be sufficient.

3D Modelling

These formulas thus assume a stable cylindrical wall and a uniform pressure on the cylinder. For this situation the pressure is not uniform in two ways. First the pressure builds up linearly downwards along the wall and secondly the pressure is higher on the side for which both ground and water pressure are present. Now a resulting moment will be working on the cylinder section. Thereby as the ground floor slab connects the cylinder wall to the core structure the behaviour of the complete system is not obvious. Therefore a model was made in SCIA Engineer to examine the way the loads are transferred to the foundation and to which extent the approximation of the ring stresses is correct. Another advantage of such a model is that the deformation of the wall can easily be checked, it is expected that this could influence the required dimensions because of the low stiffness of the material.

From calculation of the ring stresses a wall thickness of approximately 100 mm resulted, this is used as a starting point in the model to check whether this thickness is sufficient or can be optimized.

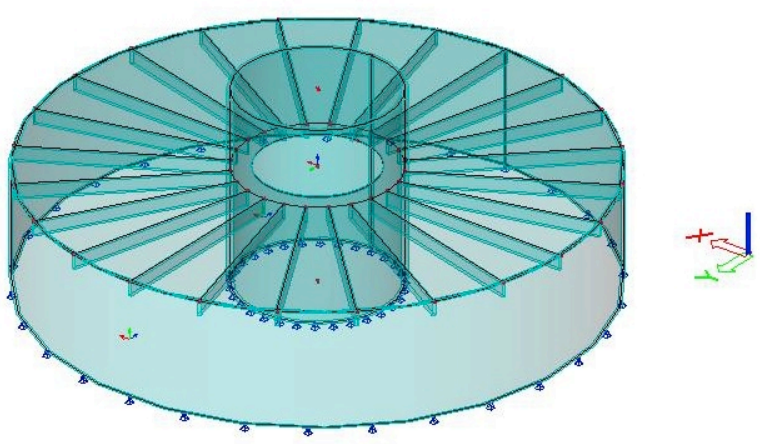


Figure 188: Overview subsurface structure

The following load combinations are used, conform the Eurocode:

Naam	Type	Belastingsgevallen	Coëff. [-]
UGT-Short term	Lineair - UGT	BG1	1,20
		BG2 - Vloerlast BG	1,50
		BG3 - Gronddruk	1,20
		BG4 - Waterdruk	1,20
UGT2-Long term	Lineair - UGT	BG1	1,35
		BG2 - Vloerlast BG	0,38
		BG3 - Gronddruk	1,20
		BG4 - Waterdruk	1,20
BGT1-Short term	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	1,00
		BG3 - Gronddruk	1,00
		BG4 - Waterdruk	1,00
BGT1-Long term	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	0,60
		BG3 - Gronddruk	1,00
		BG4 - Waterdruk	1,00
BGT1-Long term_icm wind	Lineair - BGT	BG1	1,00
		BG2 - Vloerlast BG	0,25
		BG3 - Gronddruk	1,00
		BG4 - Waterdruk	1,00

Figure 189: Load combinations subsurface room

The critical deformation appears to occur around the transition point between ground and water; the maximum deflection at that point is 13 mm and thus slightly too high.
It is also observed that the maximal deflection occurs at a lower stage than the middle of the wall. This is caused by the linearly increasing pressure on the walls, the lowest part of the wall carries the most load. The wall is therefore optimized by tapering from 130 mm at the bottom to 80 mm at the top, now with only a little amount of extra material the deformation requirement is met. Thereby the stresses are nowhere higher than the allowed stresses, as was expected from the hand calculations.

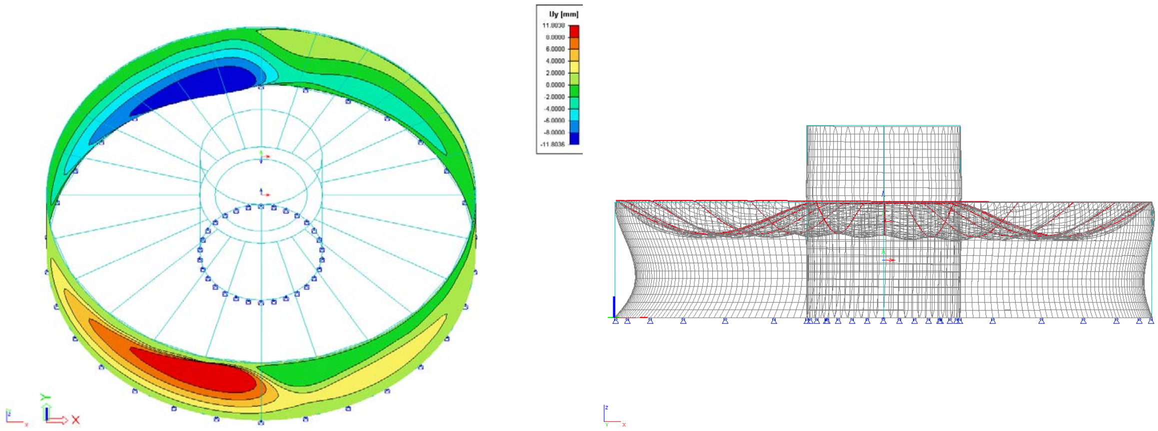


Figure 190: Maximal horizontal deformations in y direction (left) and deformed structure (right)

The complete calculation document is added in appendix [H]

Floor at ground level

Allowable vertical floor deformation is 0,004*5000= 20 mm

The ground floor is modelled together with the subsurface structure. It appeared that a lot of material would have to be used when applying a solid slab. More than 150 mm thickness is needed to carry the opposed floor load of 3 kN/m^2. Ribs are applied to reduce the material use in this floor. The floor is equipped with 24 ribs leaving a floor span in between varying from 0,5 meter to 1,8 meter. Now a balance had to be found between the stiffness of the ribs and the stiffness of the floor. The final design has ribs with a cross-section of 75*350 mm and a floor height of 45 mm.
The deflection conform the long-term serviceability limit state load combination is now 18,4 mm:

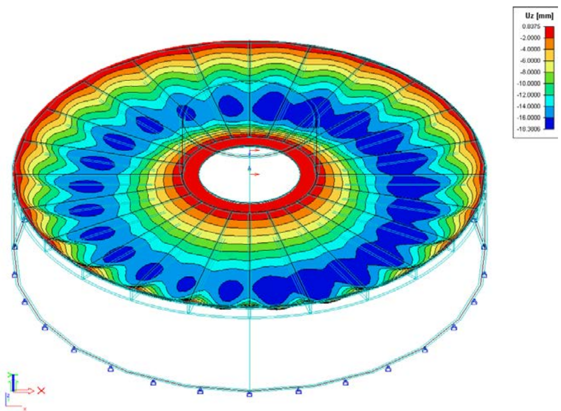


Figure 191: Maximal vertical deflection of the floor

The attachment of the ribs did cause high stress concentrations on the subsurface wall and core. As this part of the structure will be above water and maybe even above ground over time the material can be exposed to outside conditions and even less stress is allowed.
Ring-ribs are added along the subsurface wall and along the core to spread the loads over a larger surface and hereby reduce the stresses.

The allowed design stresses for application in an outdoor environment are 3 and 6,5 MPa for long-term and 5 and 11 MPa for short-term situations. Therefore the stresses on the outside face or the wall element at the location of the attached ribs should be checked with these more severe conditions. This is the equivalent stress SigE- at element E1 in the document of appendix [X].
For the long term this stress is computed at maximal 2,9 MPa, for the short term it is 4,6 MPa. The other maximal stresses keep within the underwater criterion that was earlier mentioned. As the criteria for application inside, in direct sunlight are less strict, the parts on the inside of the subsurface room, the ground floor and the core do automatically meet these.

The applied ribs do have a rectangular cross-section, this is a shape that can easily be processed from acrylic blocks. It might be attractive, concerning material-use, to apply another, more efficient shaped profile. The optimized I-beam developed by Uwe Gleiter could for example be of use here. This is not further investigated in this design research.

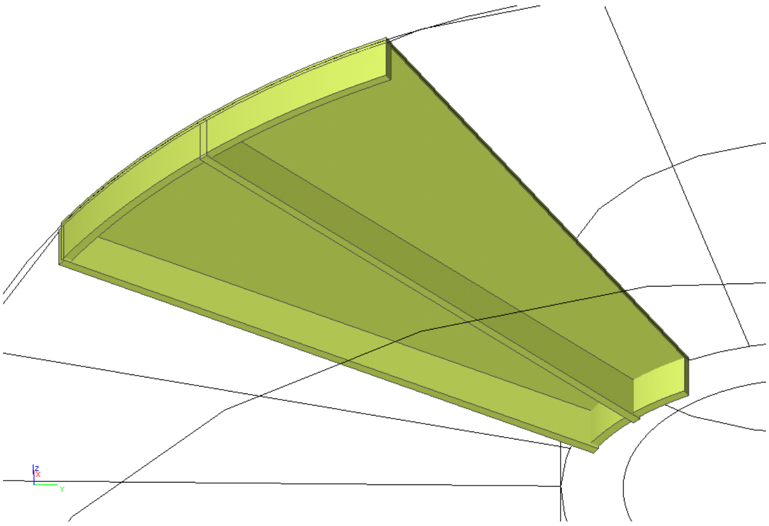


Figure 192: Floor segment

Critical stress ribs

Roark's formula is used for a quick check on the risk of buckling of the ribs:

$$\sigma_{cr} = \frac{1{,}2 * E}{(1 - \nu^2)} * \left(\frac{t}{h}\right)^2 = \frac{1{,}2 * 909}{(1 - 0{,}4^2)} * \left(\frac{75}{350}\right)^2 = 99\ MPa$$

As maximal design stress in tension is 7,7 MPa for long-term inside application in direct sunlight and the maximal occurring stress in short term even is 4,2 MPa, buckling will not be the critical failure mode for this situation.

Influence on core deflection

When calculating the necessary moment of inertia of the core an assumption was made about the influence of the subsurface room on the core behaviour. A force was applied at the connection level of the ground floor to account for the resulting load caused by the asymmetrical loading.

From the 3D model the deflection and rotation of the core at ground-floor level can be read to check whether the previously assumed deformation was sufficient.
A deflection of 0,34 mm and a rotation of $3{,}7 * 10^{-5}$ are occurring in the core by the influence of the subsurface room. When filled in in the calculation table for the core deflection, the following satisfying result is obtained, a total deformation below the maximal 70 mm:

Wind loads	h zwpunt (m)	Frep (kN)	w,dir (mm)	th (rad)	w, eind
Top	33	1,37	3,26	1,48E-04	3,56
Sphere	27	13,93	17,39	9,66E-04	25,12
Core high	25	9,04	8,96	5,37E-04	14,33
Core strip 1	21	8,56	5,03	3,59E-04	10,05
Core strip 2	17	8,00	2,49	2,20E-04	6,45
Core strip 3	13	7,20	1,00	1,16E-04	3,55
Core strip 4	9	6,32	0,29	4,87E-05	1,56
Core low	5	4,80	0,04	1,14E-05	0,38
Lower dome	5	10,37	0,08	2,47E-05	0,82
Subsurface	3	136,50	0,34	3,70E-05	1,52
				Sum:	67,3

4.3.4 Secondary parts

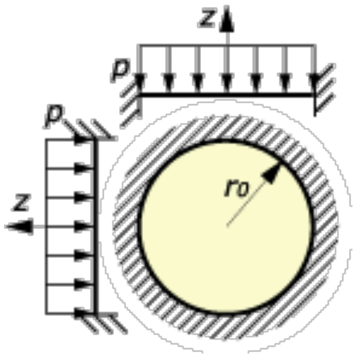
4.3.4.1 Floors

The floors of the core will be made from acrylic as well; because of the high loads these will be exposed to thin-walled elements will not be sufficient.
As a first approximation the floors are concerned as on all sides supported complete discs. As the floors are stacked in between the core elements this will indeed provide rotation resistance, but no complete clamped support. The real situation will therefore probably be somewhere in between pinned and clamped.

The bending stiffness of a plate can be described by the classical plate theory:

$$D = \frac{Et^3}{12(1-\nu^2)}$$

For the calculation of moments and deflection of circular plates under uniform loading with clamped supports the following formulas are applicable:



$$w(r) = \frac{pr_0^4}{64D}\left[1-\left(\frac{r}{r_0}\right)^2\right]^2$$

$$M(r) = -\frac{p}{16}[r^2(3+\nu) - r_0^2(1+\nu)]$$

Figure 193: Moments and deformations for clamped circular floors (efunda.com)

In the middle of the circle (r = 0) as well the deflection as the positive moment is at its maximum. Filling in r=0 in the formulas gives for w_{max} and M_0:

$$w_{max} = \frac{pr_0^4}{64D}$$

$$M_0 = \frac{q}{16} * r_0^2(1+\nu) = \frac{(1+\nu)}{16} qr_0^2$$

The maximum moment (per meter) occurring is the negative bending moment around the edge ($r=r_0$)

$$M_{max} = -\frac{q}{16} * 2r_0^2 = -\frac{1}{8} qr_0^2$$

The maximal bending stress will therefore occur in the same place, with $W=1/6*b*t^2$ (with b=1000mm as the moment is calculated per meter), and can thus be computed with the formula:

$$\sigma_{r,max} = \frac{M}{W} = \pm \frac{{}^1/_8\, qr_0^2}{{}^1/_6\, t^2} = \pm \frac{3qr_0^2}{4t^2} \qquad \left(or\ \frac{6M}{bt^2}\right)$$

These equations are applicable to thin plates and are thus only reasonably accurate if the thickness is less than 10% of the diameter, so in this case less than 0,10*2000 = 200 mm.

A variable uniform load of 3 kN/m^2 is applied and to incorporate the self-weight of the structure as well, the necessary monolithic thickness is calculated with Excel. The thickness is now calculated in steps by taking the newly determined self-weight into the next calculation step. Within four steps the result is the same for two sequential steps and the necessary thickness is found.

Long-term deformation is used to determine the necessary thickness, then both the stresses for short term behaviour and long term behaviour are calculated. All conform the earlier determined load cases.

Used variables:

p (kN/m2)	3
v (-)	0,39
Es (N/mm2)	1515
El (N/mm2)	727
ρ (kN/m3)	11,9
σs max	5
σl max	2,9

The following results are found:

		Long term						Short term			
		Load factors 1 and 0,6			Load factors 1,35 and 0,38			Load factors 1,2 and 1,5			
R	w,toel	D ben (Nmm)	t ben (mm)	e.g. (kN/m2)	M(0) (kNm/m)	M(r0) (kNm/m)	σ,mx (N/mm2)	M(0) (kNm/m)	M(r0) (kNm/m)	σ,mx (N/mm2)	Rd (kN/m)
2000	16,0	28125000	73,3	0,87							
2000	16,0	41751834,7	83,6	0,99							
2000	16,0	43669950,1	84,9	1,01							
2000	16,0	43904444,5	85,0	1,01	0,87	-1,25	-1,04	1,99	-2,86	-2,37	6,24

Figure 194: Iterative determination of necessary floor height

A floor height of 85 mm will be sufficient according to this calculation.

Now the floors are modelled with Scia Engineer to see whether the core wall really does provide a clamped connection and to investigate the influence of a stairwell in the floor.
For an uninterrupted floor of 85 mm thickness the floor has a deflection of 17 mm when subjected to the long-term load case. When the core and floors are completely bonded the way as intended it will be nearly a fully clamped connection.

Now the staircase and corresponding stairwell is designed. There are several options.

- A spiral staircase. In this case a central column will be necessary to bear the stairs. The steps will be connected to this column on the narrowest part, which is unfavourable. An extra support will be needed at the other side of the steps; this could be integrated in the handrail.
- Winding stairs along the core wall. It could be possible to cantilever the steps from the core wall. Or an extra support could be added as proposed in the previous option as well. An advantage is that the steps are now supported at their widest edge.

Several designs were considered, for example:

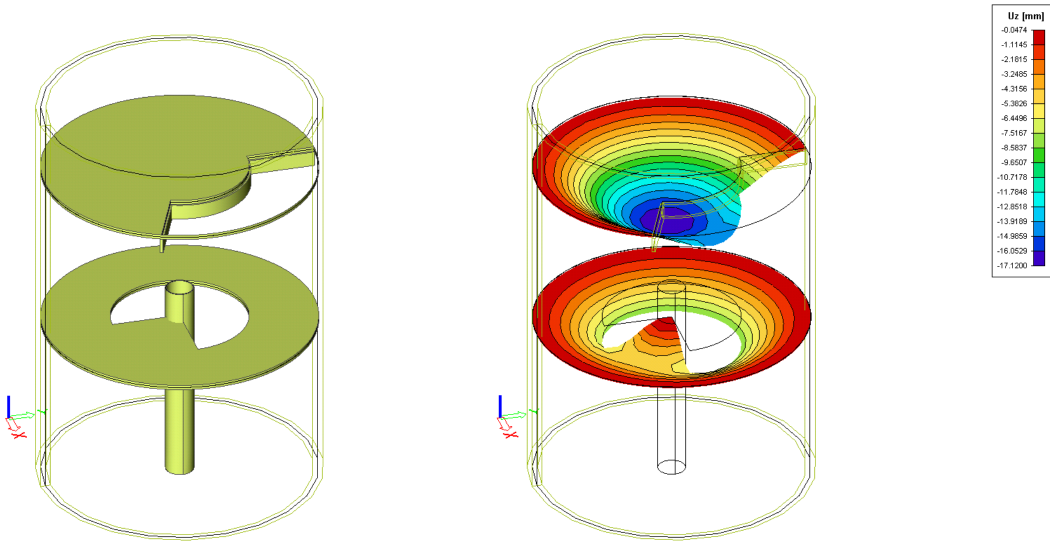


Figure 195: Example of a stairwell for a winding staircase and a spiral staircase, floors of 75 mm

A disadvantage of the spiral staircase is that an extra structure is needed to provide sufficient bearing capacity, thereby the opening is really disturbing the space on the landings. The stairwell needs to be three quarters of a circle to provide enough space (the minimal 2 meter) above the head of a person climbing. When the stairs are situated alongside the core a lot of free space remains where people can have some rest, wait for someone, let each other pass, enjoy the view and so on. Thereby the steps of the stair are more efficient as the radius of the winding is way smaller. The steps approach more of a rectangle than a triangle and a meter wide step will now provide more usable surface.

The decision is made to place the stairs along the core wall; the design of the staircase itself and the influence of the cantilevering steps on the core are described in the next paragraph.

The above picture shows an example for a stairwell suitable for winding stairs that leaves the ultimate amount of space on the landing. However the floor will tend to leap over along the edge of the opening. The application of a rib does help but the resulting torsion in the rib causes high stress concentrations on the core.

The final design eliminates that problem for the largest part by making a smooth curved rib instead of these abrupt changes in direction. The slight amount of surface area that gets lost is acceptable; thereby the thickness of the floor can be limited in the new configuration.
The floor has now a thickness of75 mm with a rib of 50 by 225 mm applied on the floor edge. That results in the maximal allowable long-term deformation of 0,004*4000 = 16 mm. This is shown in the next picture.
The strictest applicable design stress is the 5 MPa allowable tensile stress for outside application, this requirement is met by all 2D elements and ribs although part of them are placed inside. Again it is shown that deformations are leading in the design with thermoplastics.

The complete calculation report is added in appendix [H]

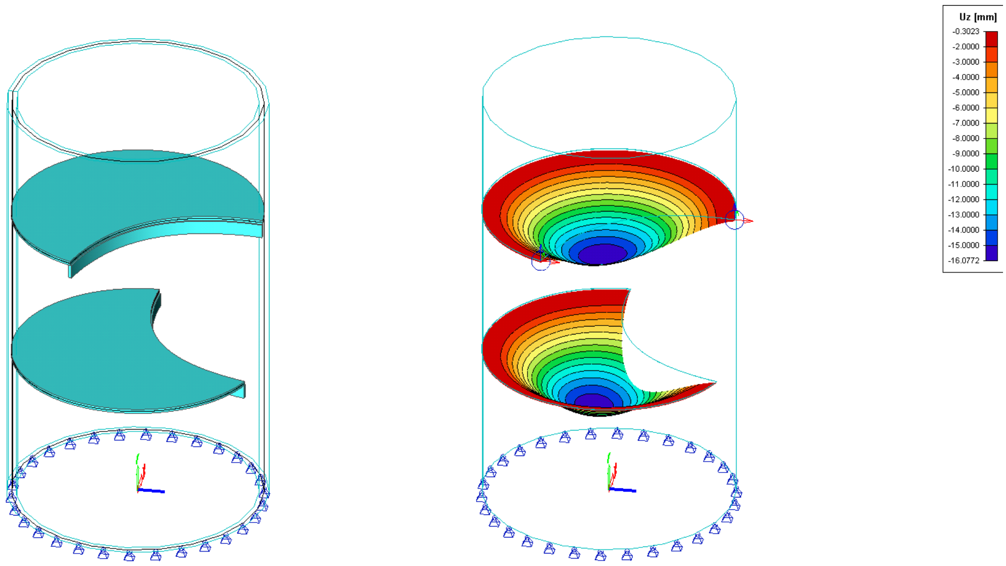


Figure 196: Final design landing lay-out and resulting deformations

The floors will have a relief layer to prevent inconvenient transparency while keeping them translucent and to provide a buffer for damage and wear of the surface. Thereby the floor can be made less slippery with this kind of texture. The layer can be replaced by a new one when damage and wear are threatening the structural acrylic part.

Ribbed floors

An option to save material is to apply ribs under the floors; The more height is brought in the ribs, and the smaller the distance between them, the thinner the floor can be.
In this design no ribs are used as it is not a suitable floor surface for a ribbed pattern.

One option is the application of ribs in only one direction, then the floor acts as an ordinary beam structure with a span decreasing from a core diameter length to zero at the side walls. Disadvantage is the one-way span, as that eliminates the favour of an all sides clamped floor, and the fact that this pattern would coincide with the opening in the floor for the stairs.

A two way system is practically impossible, the elements will be cast. The casting of acrylic normally produces sheets and blocks that are processed to customized elements afterwards. A two or more way ribbed pattern can only be produced by bonding all pieces together which makes it very labour intensive. A customized mould of this size, if possible in this configuration, would be way to expensive.

Radially orientated ribs are a last option; but they will coincide to a very complicated node in the middle and would, as all other options, not improve the aesthetics. It is therefore accepted that the floors have a thickness of 75 mm, opposed to that material use the assembly will be a lot easier this way.

4.3.4.2 Stairs

For stair design several rules or guidelines are of importance, these are prescribed in the building regulations called 'bouwbesluit'.

- The riser cut (O) and the tread cut (A) should comply to the following: 2O+A =60 ±3 cm. Thus the height and depth of the steps.
- The headroom should be at least 2 meter. Thus the space above the head of a stair climber.
- The walking line is situated on 2/3 of a tapering step; from the edge closed tot the rotation centre.
- On the walking line the tread cut should be at least 22 cm, generally it is between 25 and 30 cm.
- Public staircases often have a riser cut of 16-17 cm and a tread cut of 25-28 cm.
- The vertical distance between two landings may not exceed 4 meters.

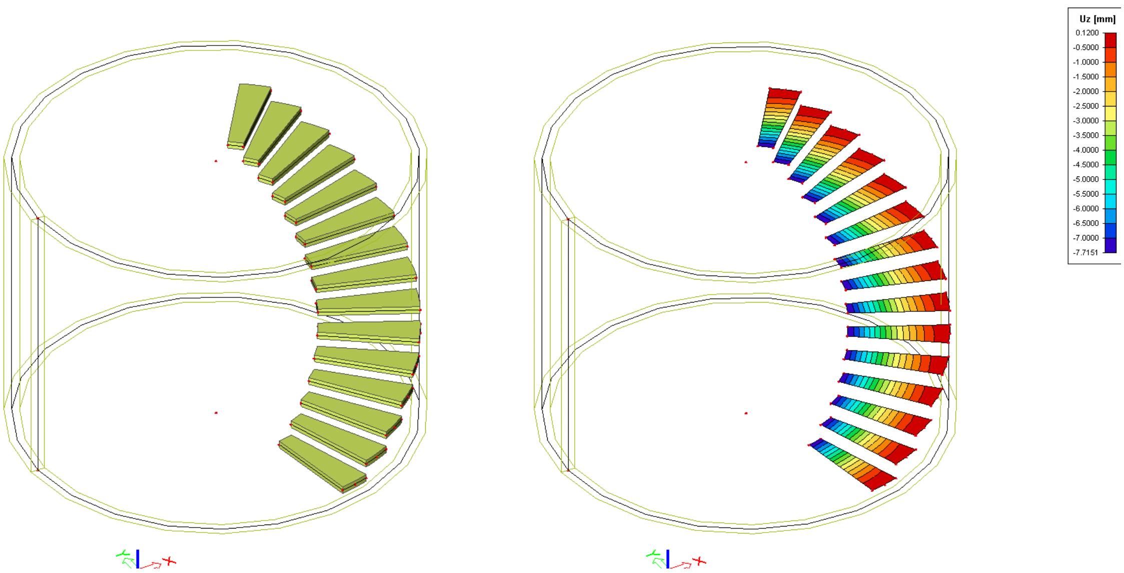
In this design the landing levels lay 2,5; 3 and 3,5 meter apart. When looking for a riser cut between 16 and 17 cm a distance of approx. 167mm is found that suites well within those three ranges. That leads to respectively 15, 18 and 21 steps to bridge the distance between the landings.
This results for a winding staircase along the core wall in 1 meter wide steps with a walking line at r=1,67 m with a tread cut of 60-2*16,7=26,6 cm which can be rounded to step parts of 9°. Now measuring 314 mm along the core wall and 157 mm at the cantilever edge.

By hand the estimated thickness is calculated with the restrictive maximal deflection of 2* 0,004 *l = 2 * 0,004 *1000 = 8mm and for the long-term load situation. The self-weight is assumed to be 1 kN/m^2, the variable load is still 3 kN/m^2.

$$w = \frac{q * l^4}{8EI} = \frac{(1 + 0{,}6 * 3) * 1000^4}{8 * 727 * I} 8 \qquad thus\ \ I_{req} = 60 * 10^6\, {mm^4}/{m}$$

$$I = \frac{1}{12} * 1000 * t^3 = 60 * 10^6 \quad thus\ t = \ 90\ mm$$

As the structure is tapering the load is distributed slightly more favourably distributed. A model in Scia is used to make a nice picture of the stair system and to investigate the stress concentrations in the core.



The deformation appears to be indeed less than calculated, a thickness of 80 mm is sufficient, the steps now deflect 7,7 mm. The stresses in the core due to the cantilevering stairs is insignificant, the stress concentrations do not exceed 0,5 MPa.
The complete calculation report can be found in appendix [H]

To make sure that stairs and floors are not transparent but just translucent a relief layer will be added on top of the stair steps. This layer simultaneously protects the structural part of the stairs to damage and wear as well as forming an anti-slip protection.

All steps will be connected by an acrylic sideboard, this will form the railing of the stairs. By attaching the stair steps to each other in such a way the peak loads of walking people will be spread over multiple steps and thus provide a better distribution of forces and decrease of deformations.

The dynamic behaviour of the steps is considered outside the scope of this research but should be investigated before realisation.

4.4 Final design

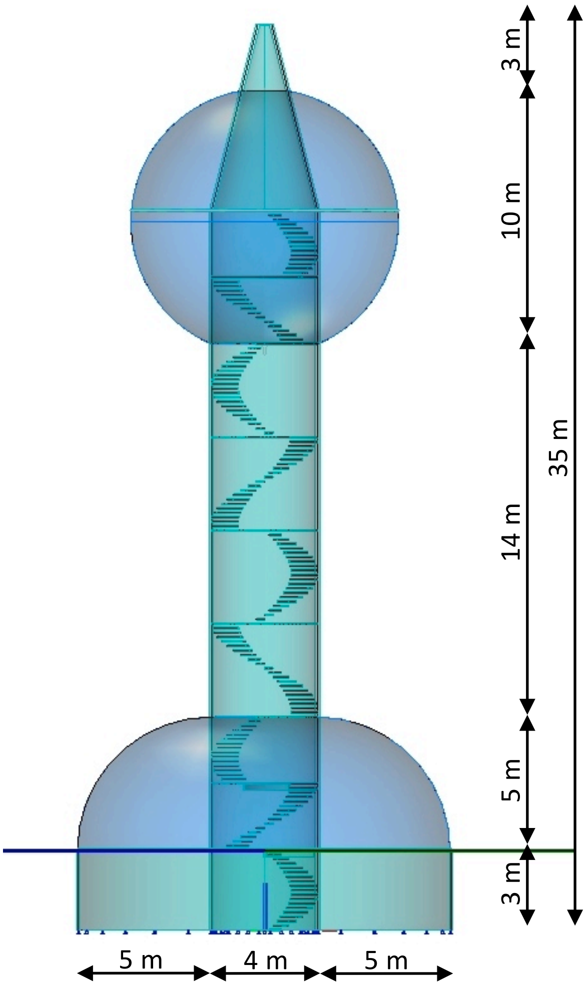


Figure 197: Overall dimensions

- Tube core structure of cast acrylic blocks: t_{net}=155 mm, t_{gr}=165 mm.
- Observatory sphere and dome of vacuum-formed polycarbonate elements with ribs at the edges, t=5-6 mm, ribs of 5-6x100 mm, l≈2 meter and w=84-564 mm.
- Observation platform of acrylic, t=100 mm.
- Acrylic floors within the core, t=75 mm, edge rib of 50x225 mm
- Cantilevering stairs of acrylic, t=80 mm, l= 1meter, w=157-314 mm
- Ribbed ground floor of acrylic, t=45 mm, ribs of 75x350 mm.
- Subsurface ground and water retaining wall of acrylic, tapering thickness t=80-130 mm.

+ Slender core structure
+ The core is simultaneously forming the facade around the winding staircase
+ The landings prevent the core from buckling and provide a support to the shell and sphere by developing ring stresses.

+ Parts sensitive to falling objects or vandalism are of polycarbonate, which is impact resistant and vandal-proof
+ Cast acrylic is said to be non-smoking when on fire, positive as the escape route will be the acrylic tube staircase
+ Lowest part of the facade is polycarbonate, which is fire class B2, the minimal required class for facades parts that are within reach of people, in a public area.
  ➔ The core is protected from fire and vandalism by the polycarbonate shell.

+ The connection between core and foundation is located 3 meter below ground surface, this is favourable as below surface temperature differences are smaller and no direct sunlight is caught. Therefore thermal movement in the connection will be limited.
+ Horizontal surfaces, that will get the highest temperature from sunlight, are all of polycarbonate, which is the most heat resistant material of the two.

4.4.1 Mass calculation

To calculate the resulting stresses of the complete structure on the foundation and the core, all permanent and variable loads are summed according to the previously determined load combinations.

First the final representative values are calculated.

Self-weight:

permanent loads	n	r (m)	h (or t)	A (m2)	(t or h) (m)	V (m3)	p (kN/m3)	P found (kN)	core factor	P core (kN)
Peak	1	1	2							
Sphere	1	5		314,16	0,005	1,57	12	18,85	1	18,85
Floor sphere	1	5		78,54	0,075	5,89	12	70,69	1	70,69
Core	1	2	0,165	1,99	28	55,66	12	667,94	1	667,94
Floors core	7	2		87,96	0,1	8,80	12	105,56	1	105,56
Lower dome	1	7	5	255,78	0,005	1,28	12	15,35	0,50	7,67
Ground floor	1	7		153,94	0,06	9,24	12	110,84	0,50	55,42
Wall subs. room	1	7	0,1	4,37	4	17,47	12	209,61	0	0,00
Total rep. load								**1198,82**		**926,13**

The surface of the lower dome was calculated with the following formula:

$$A_{dome} = 1/2 * (4\pi r^2 + 4\pi^2 r) \qquad with\ r = 5\ m$$

This formula is derived from the integral that is solved to get the surface of a normal sphere, hereby adding the core radius in the expression for the ring length before integration.

For the imposed live loads the following table is generated:

Imposed loads	n	r (m)	A (m2)	q (kN/m2)	Q (kN)	ψ	P found (kN)	core factor	P core (kN)
Floor sphere	1	5	78,54	3	235,62	extr	235,62	1	235,62
Floors core	7	2,25	111,33	3	333,99	0,25	83,50	1	83,50
Ground floor	1	7	153,94	3	461,81	extr	461,81	0,50	230,91
Foundation slab	1	7	153,94	3	461,81	0,25	115,45	0	0,00
					1493,24		**896,38**		**550,02**

Wind load:
The wind load was already discussed in detail during the core design, the resulting design stresses are calculated based on those earlier data.

	ru	**ri**	**t**	**A (m2)**	**Izz (mm4)**	**Wy (mm3)**	**Md (kNm)**	**σb,d (N/mm2)**	**Vd (kN)**	**σs,d (N/mm2)**
C tube	2000	1845	155	1,87	3,47E+12	1,73E+09	2275,7	1,31	268,2	0,143

Snow load:

The snow load resultant is calculated for as well the evenly distributed snow as the redistributed snow which is schematized as a half ring with top μ_3 and the other half ring with top 1/2 μ_3. In the end the evenly distributed snow appears to result in the largest total vertical force.

	Snow loads	mu	r (m)	ru <60°	A, netto (m2)	s (kN/m2)	Sk (kN/m2)	F (kN)	Ftot(kN)
Evenly	Sphere	0,8	5	4,33	58,90	0,7	0,56	**32,99**	
	Lower dome	0,8	5	6,33	113,32	0,7	0,56	**63,46**	
Redistr	Sphere- mu3	2	5	4,33	29,45	0,7	1,4	13,74	**20,62**
	Sphere- 1/2mu3	1	5	4,33	29,45	0,7	0,7	6,87	
	Lower dome- mu3	2	5	6,33	56,66	0,7	1,4	26,44	**39,66**
	Lower dome- 1/2 mu3	1	5	6,33	56,66	0,7	0,7	13,22	

Resulting core stresses

Representative stresses for the core with a thickness of 155 mm and thus A= 1,87 m^2 are computed from the loads on the core that were determined above, the wind load already is a design stress:

	G	**Qv**	**Qw**	**Qs**
σ,rep (N/mm2)	0,50	0,29	+/- 1,31	0,03

When combined with the load combinations the following results are obtained:

U.L.S.	**G**		Favourable		**Qv**		**Qw**		**Qs**		**Sum**
Long term		σ (N/mm2)		σ (N/mm2)		σ (N/mm2)		σ (N/mm2)		σ (N/mm2)	σ (N/mm2)
1	1,35	0,495	0,9		0,38	0,294					0,78
Short term											
2	1,2	0,495	0,9		1,5	0,294					1,04
3+	1,2	0,495	0,9		0,38	0,294	1	1,31			2,02
3-	1,2		0,9	0,495	0,38	0,294	1	-1,31			-0,75
4	1,2	0,495	0,9		0,38	0,294			1,5	0,034	0,76

The wind appears to be the governing stress on the core. None of the stresses do exceed even the determined long-term design stresses of 2,9 MPa in tension and 6,5 MPa in compression.
The compressive stresses will cause no problems in the support of the core, the tensile stress however is something to take into account for the design of the details.

Fire combination

Still 132,5 mm of tube wall will be remaining uninfluenced by a fire within 15 minutes, assuming the fire only affects one side of the core wall.
As the surface is constantly shifting due to the burning rate of max 1,5 mm/min, both the thicknesses resulting from the burning rate and the heat penetration are subtracted from the wall thickness of the core to obtain the minimal unaffected core thickness.

$$t_{red} = 155 - 22{,}5 - 25{,}2 = 107\ mm$$

The weight calculation was checked for the extraordinary load combination to see whether the reduced core section has sufficient stiffness and strength during an emergency evacuation.

t,red (mm)	107
I (mm4)	1,32E+12
E (N/mm2)	1515
h,tot (m)	35
wmax (mm)	70
A (m2)	0,71
factor	0,2

Wind loads	Cf	r	h	A (m2)	qp(z) kN/m2	h z (m)	Vrep (kN)	Mrep (kNm)	w,dir (mm)	th (rad)	w, eind
Top	0,5	0,75	3	2,25	1,22	33	0,3	9,1	1,65	7,49E-05	1,80
Sphere	0,2	5	10	58,54	1,19	27	2,8	75,2	9,16	5,09E-04	13,23
Core high	0,5	2	4	16	1,13	25	1,8	45,2	4,72	2,83E-04	7,55
Core strip 1	0,5	2	4	16	1,07	21	1,7	36,0	2,65	1,89E-04	5,30
Core strip 2	0,5	2	4	16	1	17	1,6	27,2	1,31	1,16E-04	3,40
Core strip 3	0,5	2	4	16	0,9	13	1,4	18,7	0,53	6,10E-05	1,87
Core strip 4	0,5	2	4	16	0,79	9	1,3	11,4	0,15	2,56E-05	0,82
Core low	0,5	2	4	16	0,6	5	1,0	4,8	0,02	6,01E-06	0,20
Lower dome	0,4	7	5	39,27	0,66	5	2,1	10,4	0,04	1,30E-05	0,43
Subsurface	1	7	3	42,00		3	27,3	81,9	0,12	6,16E-05	2,09
						Sum:	41,2	319,8		Sum:	36,7

Figure 198: Calculation deflection of top during fire, reduced core section

The resulting deflection of 36,7 mm is only slightly more than half of the deflection for the governing wind load case, so the core capacity is sufficient. Even with a highly reduced modulus by temperature influences the core will suffice for the extraordinary load case.

The surface of the reduced core section is now a factor 1,8/0,7=2,6 less, the stresses due to self-weight and variable loading can thus be assumed to be 2,6 times larger. The maximal occurring compressive stress will now be 2,02*2,6 = 5,25 N/mm^2, which is still within the allowable long-term compressive stress for PMMA. In reality the compressive stress will even be decreasing with the burning core material.

4.4.2 Detailing

An important aspect of building design is the detailing. The details that are designed for the observatory tower are split up in categories determined by the materials that are connected. For all details a point of attention is that stress concentrations should be avoided. Thereby when connecting plastics to other materials it should be assessed whether excessive stresses due to unequal thermal deformations may occur. More basic information about detailing can be found in paragraph 3.4.2.

PMMA-PMMA

An advantage of PMMA-PMMA connections is that the material can be bonded with polymerizing glue. This creates very strong bonds that are able to reach the strength properties of the virgin material. That is explained by the fact that the polymerizing glue actually creates the same bonds between polymer chains that exist in the virgin material. Precondition is that the bonds are executed very precisely and that they are cured after bonding to eliminate residual stresses.
On a building site this is more problematic than in the factory but it can be performed, by creating a protective environment around the to be bonded parts to achieve a high quality bond.
Another favourable characteristic is the almost invisible seam after bonding, the bond itself exists of the same material as the element, only a difference in reflection is noticeable.

However bonding is very expensive as it is labour-intensive and a precision job, especially on-site. Dams have to be set very securely around the bond, then the polymerizing cement is applied and polymerization will start, the whole process will take at least several hours during which temperature and bond gap should be tightly controlled. Then still post-curing at elevated temperature is necessary to achieve a bond strength of over 50%.

Core parts

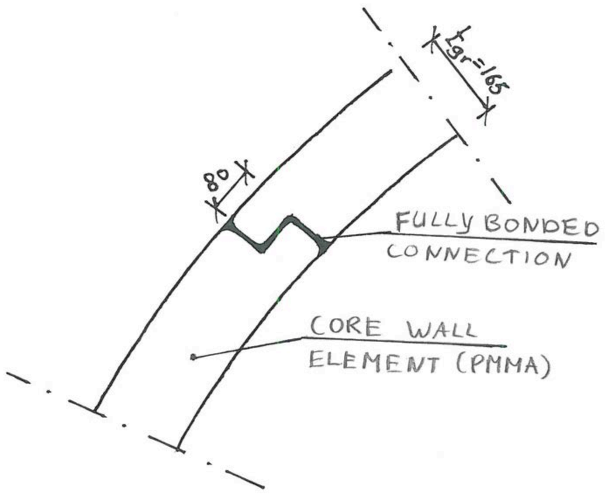


Figure 199: Core elements bonded by polymerizing glue

Two half circle elements will form one floor height of the tube core wall, these are bonded together at the two vertical edges. As these elements can be bonded on the ground before being hoisted onto the structure, the bond strength can be assumed to be above of 80% of the virgin material strength. For the core dimensions the occurring deflection at the top was governing. As a result the stresses

are quite some lower than the allowable design stresses. So 80% of the material strength will be sufficient for the bonds and the polymerizing glue can be safely applied.
A step joint configuration is chosen to make sure the core parts are assembled correctly. Thereby the bond surface is enlarged, increasing the strength of the bond.
Rounded edges are applied to all elements to prevent stress concentrations in the angular points.

Core-floor
The core-floor connection will be bonded with solvent adhesive. When a tube segment is finished and placed, the floor element can be hoisted on top. It will be difficult to control the quality of a bonded connection in this position. During the curing the connection must not be compressed. The acrylic components should be able to move freely to compensate for the shrinking of the polymerizing cement. This is necessary to achieve a stress-free joint. That means that to bond the floors to the core the bond gap and movement should be controlled by a crane or with jacks.

Since there is no bond shrinkage in solvent bonded joints these are very suitable for the assembly of acrylic parts where movement during curing is not possible. The adhesive must be drawn into a zero width bond gap by capillary action. If part edges are not perfectly matching, the adhesive can be thickened with acrylic to be able to close minor gaps. As large surfaces need to be bonded it is advised to use a two-component adhesive, to avoid drying problems.
Solvent adhesive softens and swells the surface of the acrylic parts and hardens by evaporation and dissipation through the material. The strength of the bond is slightly less than for polymerizing glue, reaching up to 50% of the virgin material strength. But as the self-weight rests on these bonds, only the wind can produce a local short-term tensile stress of 0,75 N/mm^2, which can easily be resisted. The appearance of the joint might be a little less; a slightly coloured thin joint can be visible. But as this joint coincides with the attached floor it will not be catching much attention.

By the configuration of the joint, as well a step joint, the floor will be immediately supported by the core elements. The next set of core elements can be stacked on top of the floor again, creating a clamped connection in the core wall. Stresses from the floor loading can be transferred to the whole surface of the core section, as the bond will make the core and floor act practically as one part.

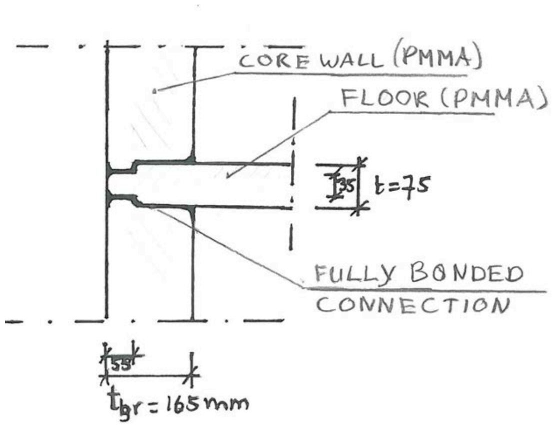


Figure 200: Floor integrated in the core wall

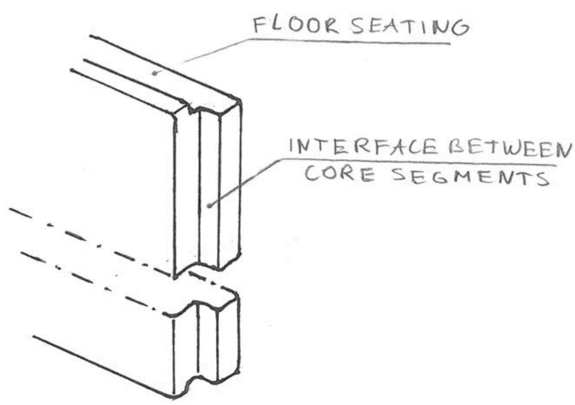


Figure 201: Core element with step joint on two sides

Stairs to core

The stairs are cantilevering from the core wall. The appearance of these joints is very important as it determines the appearance of the core wall. Polymerizing glue will be used to bond the stairs into the core wall. This is achieved by cutting holes in the core wall, the stair steps can then be slid in the

hole after applying polymerizing glue, creating a fully bonded connection with the core wall. The core wall will not be weakened by this construction as the holes are completely filled with acrylic.
With a rise of 167 mm and a step angle of 9°, for the 2,5m and 3,5 high core parts the stairs make respectively a turn of126° and 180°. Thus for every floor height only one core element has to be made with holes in it. Every floor the core structure, including the floor and the stairs will, make a turn of 90°. This way the elements can be the same on each floor, but the seams and stairwells are spread in all directions of the core to make sure the influence can be neglected.

Two additional options that can be considered are; casting the holes in the core element by attaching elements of the right size in the mould. And secondly tapering the holes in the core so the steps should be slid in from outside and will be locked automatically in the right position.

A relief will be cut in the stairs and floors for several reasons:

- The profile will make the surface less slippery
- Wear will only affect the relief and not the structural part of the elements
- The relief will make the elements less transparent; transparency can be inconvenient for floors where one can walk on ánd beneath. Translucency is desired to keep the experience of walking in a transparent building.

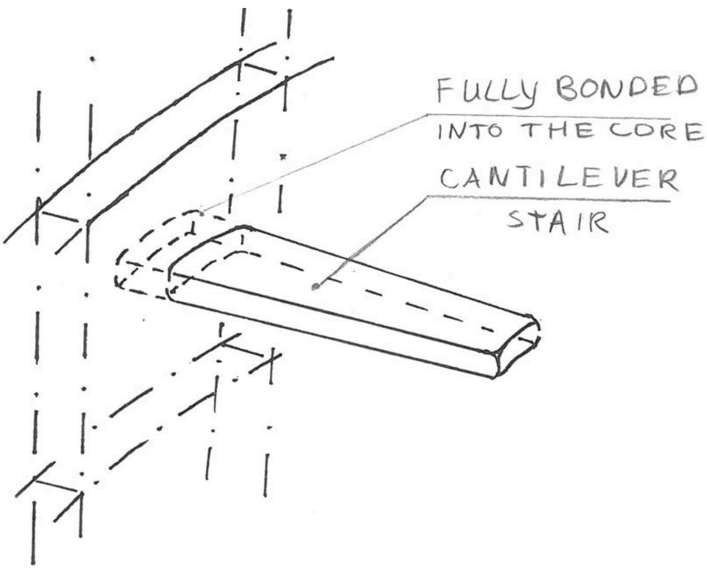


Figure 203: Connection between stairs and core

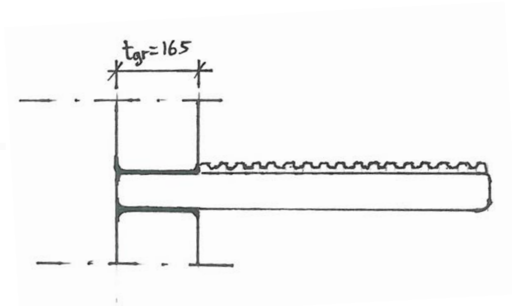


Figure 202: Optional relief of the stairs

Subsurface room segments

The elements can be bonded together as was applied for the core structure, but an alternative is presented here. A more common detail, used in aquarium design, being a compression joint that uses non-shrink grout to transfer the compressive stresses and silicone sealant to make the connection water tight.
As for the subsurface room the main loads will be the ground and water pressure, compression forces in the wall are dominant. For this type of structures this compression joint is very suitable and easy to install.

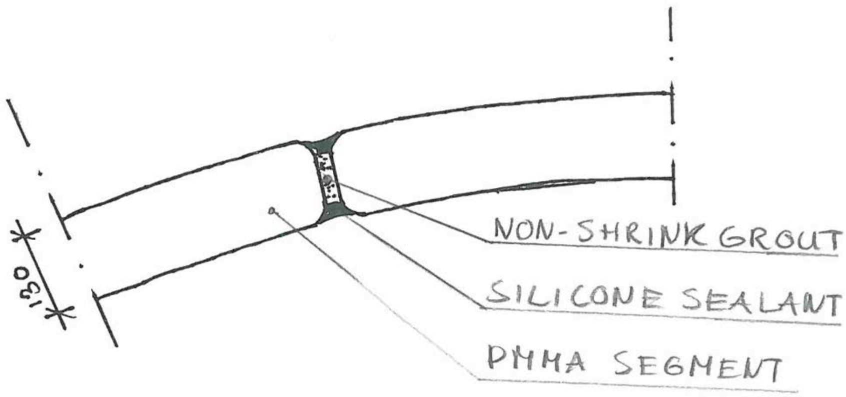


Figure 204: Subsurface room wall segments

PC-PC

Polycarbonate cannot be bonded the way acrylic can as the polymerization cannot take place that easy. Solvent adhesive bonding however is a very useful way of joining polycarbonate elements. These connections should be able to reach a strength of about 90 % of the virgin material strength. As the bonding procedure will not be that easily controlled for the complicated sphere assembly a bond strength of 70 % is assumed.

Shell segments

The shell segments will be bonded with solvent based adhesive, also here a two-component system will be used to make sure that the drying process can be completed. Otherwise the bond strength cannot be guaranteed. To make sure that the adhesive hardens to a reliable connection, compression should be applied to the joints. This is achieved by the application of standard bolts and nuts to connect the elements, using holes with a certain margin and large rings or plates for better stress distribution. Simultaneously these holes make sure that during assembly the elements are fitted correctly. Small disturbances and imperfections in the sphere surface could drastically decrease the safety of the structure as the risk of buckling may increase.

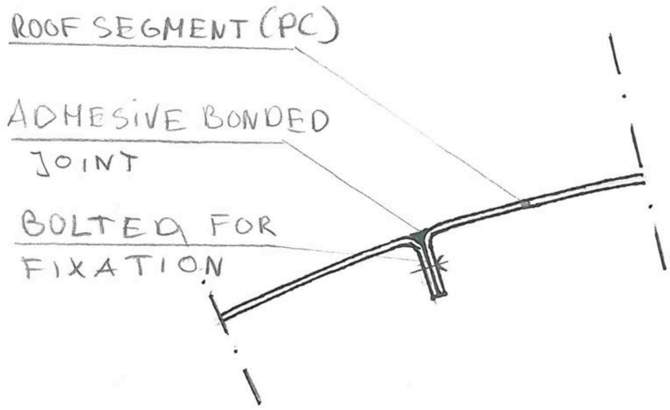


Figure 205: Roof segments connection

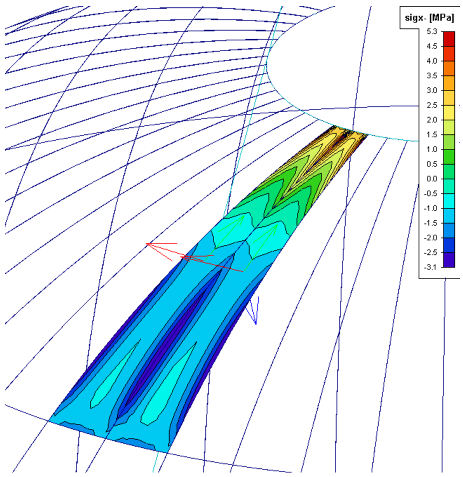


Figure 206: Maximal ring stressess taken by connection

Tensile forces will be governing for the bond capacity. The maximal force that has to be transferred by the bond is the tensile ring force occurring in the upper ring of panels, for load case ULS 2. Locally this is a stress of 5,3 N/mm^2. The bonded surface cannot be taken completely into account as the membrane force is transferred through the element surface and thus a stress concentration will exist in that plane. The allowed design stress is 8 N/mm^2 so 70% is 5,6 N/mm^2. Thus the requirement is easily met, as the occurring stress is already lower than the allowable stress just on the plate thickness without help of the rest of the bonded surface.
The adhesive bonding will provide waterproofing of the sphere; no extra devices are needed.

PMMA-PC

Shell segments to core, top and bottom connection

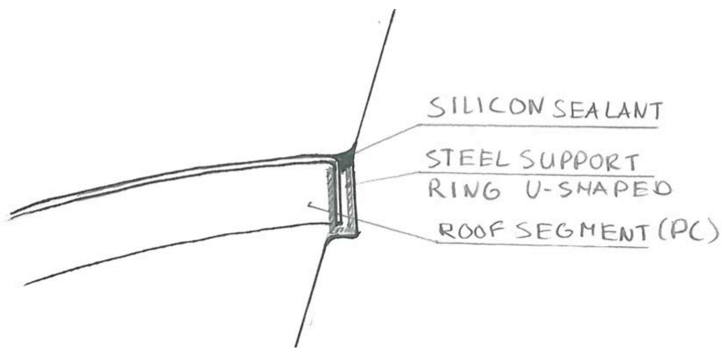


Figure 208: Section PC roof segment to core joint, top of the sphere

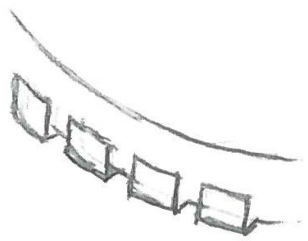


Figure 207: 3D view part of the steel ring with support-hands

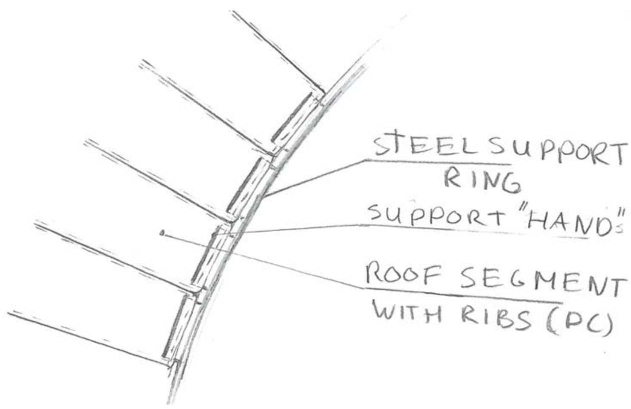


Figure 209: Top view PC roof segments and steel ring, top of the sphere

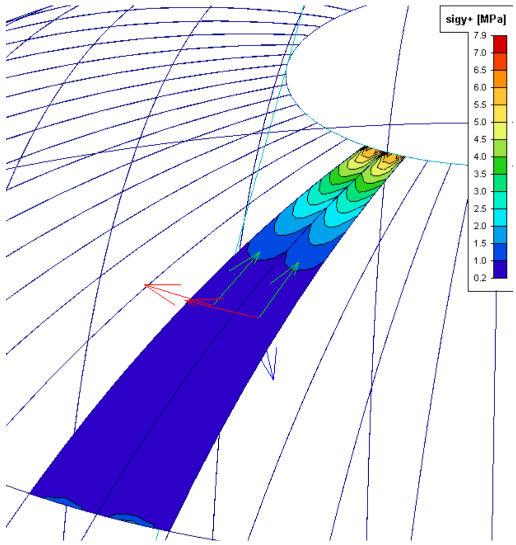


Figure 210: Meridional stress in top segment for load case ULS 2

The upper connection is loaded in tension by the connected roof segments. Tensile stress is the least favourable stress that plastics can develop so it is important to spread the stresses over a large surface to avoid stress concentrations. This is achieved by the installation of a steel ring with so-called support-hands; the polycarbonate elements can catch in these hooks, coated with some EPDM (rubber) for a better load spread. As this ring is situated at the intersection point of the core and the sphere it will not affect the appearance of the transparent structure.

The maximal occurring tensile stress in meridional direction, approximately perpendicular to the support, is locally 8 N/mm^2, for load case ULS 2, the material is 5 mm thick and 84 mm wide as 56 elements are connected to this ring with a diameter of 0,75m. Now this local load is used for a conservative approximation of the total design load of 5*84*8=3,36 kN on each steel hook. These will be 100 mm high as the rib height and thus a moment of 0,336 kNm will occur. This can be taken by a steel surface of:

$$t = \sqrt[3]{\frac{6 * M}{b * \sigma}} = \sqrt[3]{\frac{6 * 0{,}336 * 10^6}{75 * 235}} = 4{,}85\ mm$$

So a steel thickness of 5 mm will be sufficient. When all elements are installed the topside of the ring will be completely sealed with silicone sealant to assure the waterproofing.

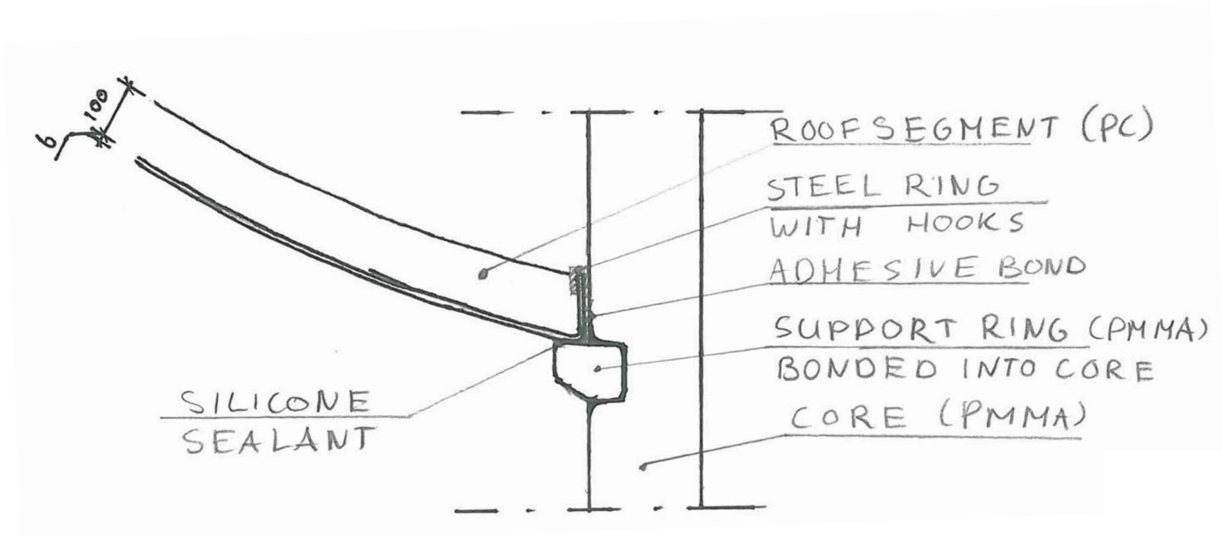


Figure 211: Section of joint Polycarbonate segment to the core, bottom of the sphere

The lower support is formed by an acrylic ring that is installed in the core wall with solvent adhesive, this ring will carry the vertical component of the resulting force from the sphere. It was considered an option to create a support by milling a ridge into the core; this was supposed to weaken the core too much, as a 360-degree support is needed. To simplify the assembly of the sphere segments a ring with steel hooks is applied also here. These can be used as a starting point for assembly; the polycarbonate sphere segments can be hooked behind the steel profile, getting immediate support from the acrylic ring. When the first complete ring of sphere segments is installed and bonded the stress will be released from the steel hooks and they could even be removed again.

For this bottom support only compressive stresses occur. Again the ULS2 load case is governing. The component will be in horizontal direction, for compressive forces this is no problem at all as the core wall is thick and even a landing floor is situated at the same level restricting large movements of the core wall.

The largest meridional stress, acting almost perpendicular to the core, occurring is 9,4 N/mm^2, which for a 5 mm thick element is a force of 47 N/mm. As the sphere is cut at the point where the radius is 2 meter, the incoming angle of the elements at this point is about 66° with the core.

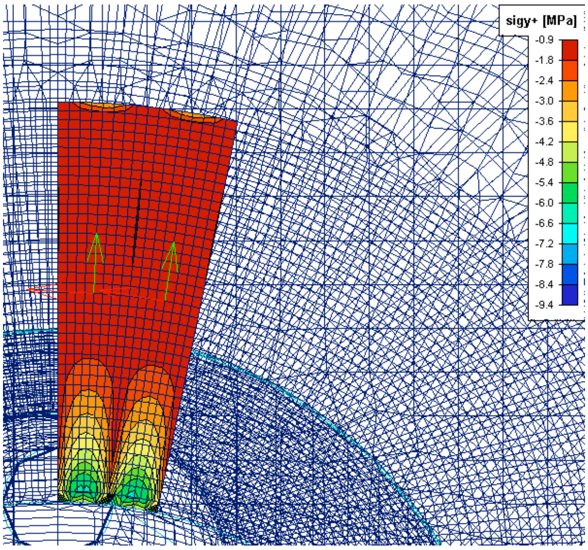


Figure 212: Meridional stresses in lowest sphere segment for load case ULS 2

The resulting vertical load on the acrylic console is now computed with the cosine of this angle, being 19 N/mm. For a design stress of 3 N/mm^2 thus a surface of 19/3=6,3 mm is needed to transfer the force to the core. The acrylic ring is dimensioned on a height of 75 mm and a ridge depth of 50 mm so that will be easily sufficient, even when a small moment would occur due to eccentric loading.

Both rings are made of steel, which could cause problems concerning thermal deformations. However as the ring itself is not attached to the thermoplastic materials the occurring stresses will be limited and well spread. Say a temperature difference of about 30K could exist between installation temperature and summer heat, the a thermal stress could occur of:

$\sigma = \varepsilon * E = 30\ [K] * (0{,}00007-0{,}000012)\ [-/K] * 1653\ [N/mm^2] = 2{,}88\ N/mm^2$
Which should not be problematic when not combined with other extreme stresses..

Shell segments to observatory floor

The connection between the sphere segments and the observatory floor is mainly loaded on compression; the shell segments are pushed into the floor. Only for ULS3, wind loading, tension is dominant; the suction could cause tensile stresses in the connection. The dominant compression for other load cases can be explained by the deformation behaviour of the sphere. As it is supported at the top and the bottom all vertical loads will make it sort of hang from these rings. The sphere structure will thereby be forced to elongate a little, which causes a slight decrease of radius in the middle. The principle is shown in the following picture:

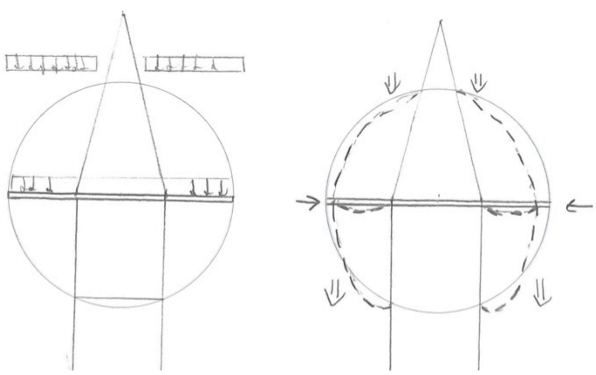


Figure 213: Development of compressive stresses between sphere elements and observatory floor

The occurring stress however will be low, probably because it is at the maximum ring length and stresses can be spread along the complete circumference of the sphere. A maximum of 1,0 kN/m of tensile ring force for ULS 3 and a maximum of 2 kN/m ring force for ULS 4b, results in a horizontal force of Nx/r and thus 0,2 and 0,4 kN/m respectively. In meridional direction as well only for the wind load combination tension can exist, a force of about 3,5 kN/m caused by wind suction.

The designed connection will be again bonded with two-component solvent-based adhesive, a ridge will be milled in the acrylic floor to make the parts fit together, which will ease the assembly. Floor parts will be put onto the lower half of the sphere; thereafter the upper sphere elements will be placed. As the adhesive should be clamped together but the space under the floor can difficultly be reached, a steel plate with screw thread will be attached to the upper rib of the segment below floor level. Now after placing the floor a bolt can be screwed through a hole in both floor and sphere segment to fixate the elements. It can be tightened during the curing of the bond, then it can be used again when the upper sphere elements are mounted. After the assembly the stress should be released from the bolts to prevent stress concentrations in case of large thermal deformations.
The bolt can stay in place for in case very sudden extreme storm might rip the adhesive loose. This is not expected to happen, but it would probably cause a collapse of the whole sphere structure and therefore the bolts are kept as a safety device.
The occurring stresses are so low that even a 5 mm wide adhesive bond would theoretically be sufficient. If the whole rib is adhesive bonded to the acrylic floor, no problem will occur with these low stresss.

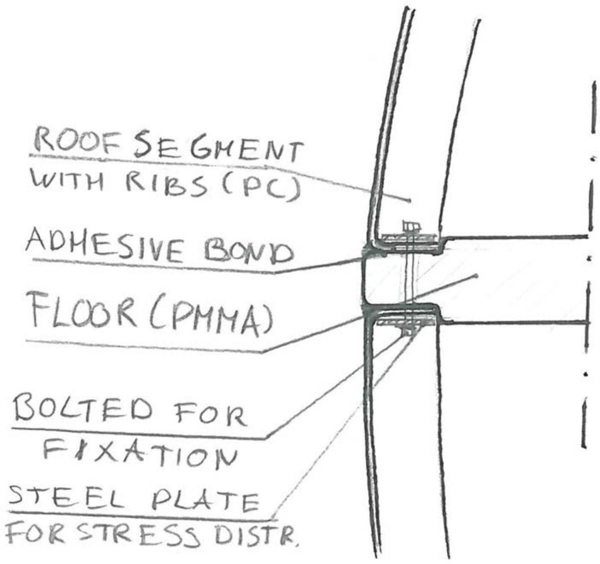


Figure 214: Joint between sphere and observatory floor

The other type of stress that could occur here is thermal stress. As the acrylic floor is situated inside the sphere structure, no direct sunlight is falling on the acrylic surface. The polycarbonate is thereby thinner and will heat up a lot quicker after sunrise. Say a maximal temperature difference of 30 degrees of temperature difference can exist, that would lead to a stress of:

$\sigma = \varepsilon * E = 30$ [K] *0,00007 [-/K] * 1653 [N/mm^2]= 3,47 N/mm^2

This is within the allowable design stresses for acrylic used inside and polycarbonate used outside but still a significant amount of stress even when equally distributed. This needs to be investigated further in later research.

PMMA-concrete slab

Core to foundation

The way the core is connected to the foundation is an important one. The core should be connected quite rigidly to the foundation as freedom of movement could cause a rotation of the core and thereby an extra deflection of the top of the building.
A sort of steel shoe consisting of two steel angles that is adhesive bonded to the core makes the connection with the foundation. This two-sided support will provide a good stress distribution along the inner and outer contact surface of the tube.
The maximal occurring tensile stress In the core followed from the weight calculation, a stress of 0,75 N/mm^2 was found, occurring only in the outer fibres of the core under bending.
As the core is 155mm wide, the total stress will be 155 * 0,75= 116 N/mm. Now this stress has to be divided over the two surfaces, and with a maximal allowable short-term stress of 0,7*5 N/mm^2 this would result in ½*116/3,5= 17 mm of contact width per side. A 100 by 100 mm angle is used, with a setting block of 25 mm the contact surface will be about 75 mm wide on each side.
Compression loading can increase up to 2 N/mm^2, thus a factor 2,7 more. To be able to take this load the connection surface should thus be 17 *2,7 = 46 mm wide. So even the compression stress can be transferred by the joint. The acrylic setting block is used to fit the core segments precisely in place, as small deviation at foundation level can lead to large deviations in the total building. Thereby the setting block is able to transfer compressive forces to the foundation.

Point of attention is that the adhesive should have quite a low modulus to be able to use the whole contact surface. Adhesives with a high modulus will cause high peak stresses on the edges of the connection.

Thermal deformations are supposed to cause no excessive stresses; the support of the core is situated below ground level and will be subjected to quite constant temperatures. Thereby an adhesive with a sufficiently low Young's modulus will be probably be able to distribute occurring stresses evenly along the core wall. The occurrence of stress concentrations will however need to be investigated, as it is difficult to predict the behaviour that precisely at this moment.

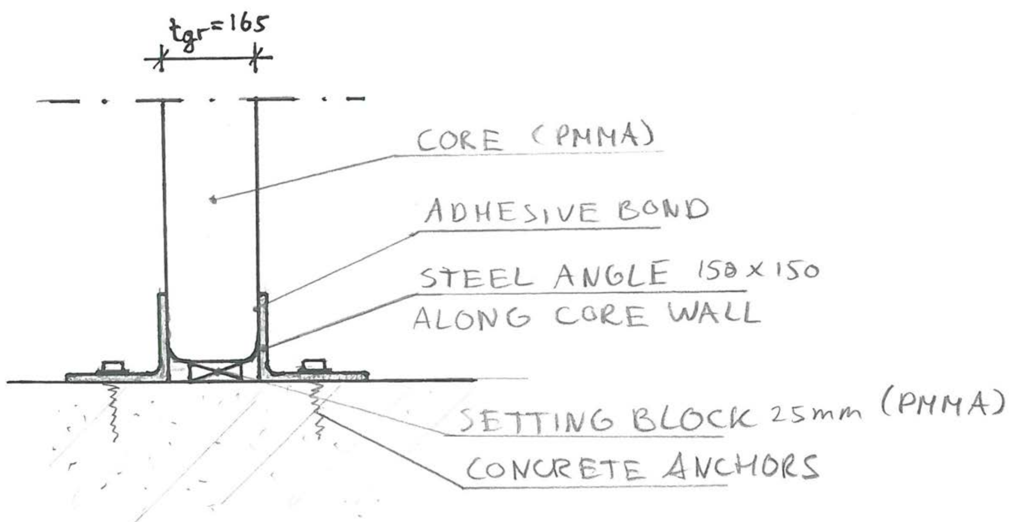


Figure 215: Connection of core parts to the concrete foundation

Subsurface room to foundation

For the connection of the subsurface room walls to the foundation a quite standard aquarium detail is used. As the ground and water pressure are the dominant loads to which the wall is subjected, only compressive ring stresses will occur. Therefore the core wall is slightly embedded in the concrete allowing the core wall to transfer the horizontal forces directly to the concrete. A smooth connection is provided by the non-shrink grout. The maximal stress that will occur at the support is a horizontal force of 39 kN/m or 39 N/mm. Locally this should be transferred to the concrete by shear in the PMMA element. If a maximal long-term under water shear stress of 6,5 N/mm^2 is allowed, the core thickness should at least be 39/6,5= 6 mm, the core of 130 mm thickness is therefore well over sufficient

Waterproofing is ensured by the use of silicone sealant and the application of a water-proofing layer along the part of the concrete that is subjected to water pressure. Again a setting block is used to put the core elements exactly in place
In case large differences in water temperature occur, the core wall could expand slightly. But as the compressive loading on the outside of the wall is permanently pushing it back into position this will not be problematic. A point of attention is the prevention of shrinkage, as this could damage the joints. To make sure no shrinkage will take place in the connections, the wall should be installed below or at service temperature.

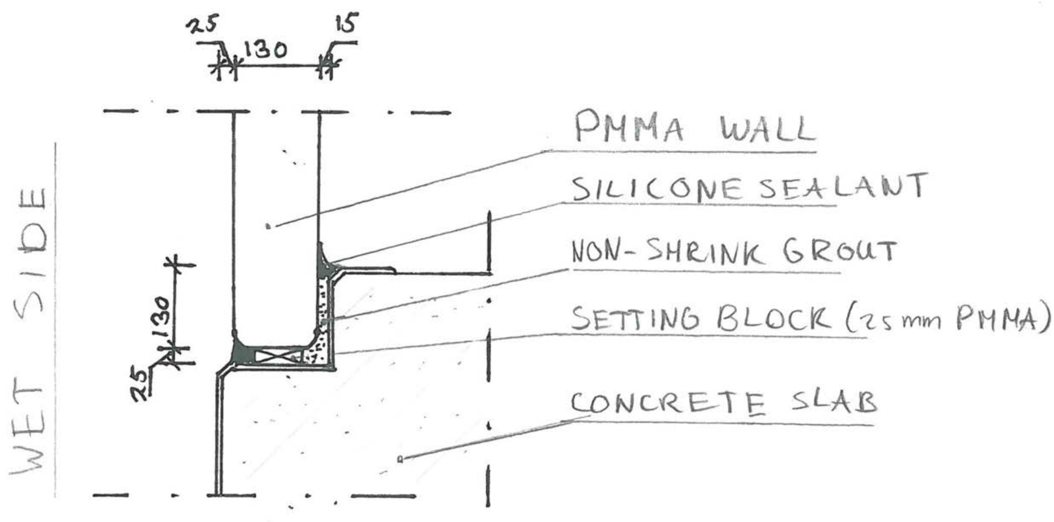


Figure 216: Joint subsurface PMMA wall and concrete foundation

4.4.3 Temperature development

As the sphere is transparent the radiation of the sun will be able to get inside the structure. The sun will warm the air inside and in summer it will become undoubtedly very hot inside if no measures are taken.
Therefore it is advised to analyse the development of temperature in the spheres and core, this will be a sinusoidal movement slightly lagging behind the curve of day and night temperature. In the summer the sphere will have the highest heat load, as the sun will be very high at the hottest moment of the day. The core will have the highest heat load during the spring and autumn season, as the sun will then be lower and directly shining on the core surface.
The results can be the starting point for the design of the ventilation and/or sun-shading plan that will be necessary.
It is at least recommended to apply natural ventilation. As the core works as a chimney where hot air will rise through the stair wells it will be easy to provide this type of ventilation by adding some openings in the sphere roof or the conical top of the core.
If that does not provide enough air to cool the building sufficiently, it can be considered to apply sun shading. For plastics this can be performed by applying a relief or print on the surface that blocks part of the light. The relief can be applied locally to keep the structure as transparent as possible.
Another option would be mechanical ventilation, however that is not desirable, as it would bring on a lot of new problems. The ducts and pipes will have to be transparent as well, threatening the clear image of the building. A manner will have to be found to integrate the necessary installations in an acceptable way in the building. Additionally electricity will have to be present in the building if mechanical devices have to be installed, increasing the risk on fire by the chance on short circuit.

The further computation of this part of the building design is left out of this design study, as it is not relevant for the research on structural design with thermoplastics.

4.4.4 Foundation

It can be considered to apply a foundation on footings as the subsoil around the Randmeren consists mainly of sand layers. Thereby the total mass of the building is quite small.

As a reference project the Bostoren in Putten is examined, for that project the foundation was indeed installed directly on the sand layer subsoil. The mass of this 40 m high structure is way larger than for the transparent design. This mainly because of the 17 m diameter platform incorporating a piece of forest with real trees and soil, weighting about 4800 kN. A lot compared to the total weight of 1300 kN of the whole transparent observatory tower.

This Bostoren structure is founded on a concrete slab of 2,5 meter thickness in the middle and 1,5 around the edges. The columns are connected to this slab very rigidly with M36 anchors to prevent deformations that could cause large deflection of the top.
The conclusion can be drawn that for this transparent observatory tower a foundation on footings will as well be realistic. When installing the observation tower somewhere else in the Netherlands, there is a high chance on other, weak, subsoil, in that case a foundation on piles is advised.

Precondition is that the foundation should be as rigid as possible. Small deformations in the foundation can cause large deflections of the top of the tower. And as the acrylic core material has very low stiffness, deformation of the core is already governing for the structure. So to reduce material use the rotation of the foundation should be minimized, then the allowed deflection of the core itself can be as high as possible.

During the design the rotation of the foundation was assumed to be negligible. If there is deflection in the top due to rotation of the foundation this can easily lead to a core of significant more material. The deflection in the top by bending will have to be restricted then to for example h/750=35000/750=46,7 mm. As this is linearly related to the moment of Inertia, the necessary moment of Inertia will rise with a factor 750/500= 1,5, Thus I_{req}= 1,5 *3,48 $*10^{12}$ = 5,22 $*10^{12}$.
That means an increase in wall thickness from 155 mm to 250 mm which results in an increased material use of 359/155=1,6 times the former core structure.
It is clear that the foundation should be made as rigid as possible; of course this is not feasible at all costs. The foundation will also need more material to make it more rigid. Therefore a well-considered decision should be taken on this subject, when the results of the wind tunnel tests are at hand and the exact location is known.

As the subsurface room has to be installed below ground level and also below ground and surface a building pit should be realised to facilitate the construction. The acrylic panel bonding should take place in a protected and dry environment so a dry building pit is required. The drainage of this pit will be quite costly and vertical ground water pressure will be high. The weight of the tower and concrete slab should be higher than the maximum upward water pressure to prevent driving up of the structure. Thereby the foundation slab and subsurface wall should be completely watertight otherwise water will start seeping in by this pressure.

Overview of a possible foundation slab with the resulting representative loads for the current situation:

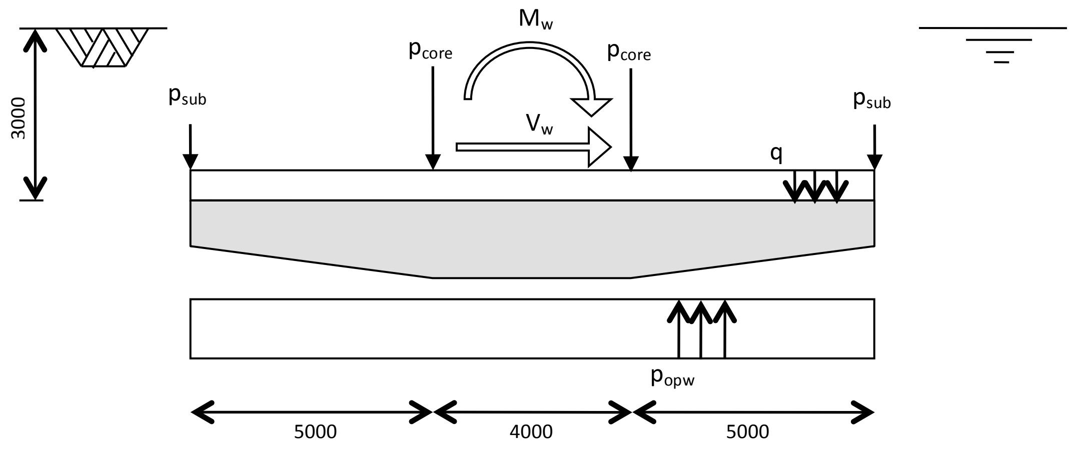


Figure 217: Possible foundation slab with resulting loads of the structure above

The maximum water level is assumed to be at the top of the subsurface wall, so 3meter above the surface of the foundation slab. And the slab has a diameter of 14 meter, just as the subsurface room. This results in an upward pressure of:

$$P_{up} = \pi * r^2 * (3 + d) * 10 = 154 * 10 * (3 + d) = 4620 + 1540d \; kN$$

Only the self-weight of the structure and slab, with the favourable load factor of 0,9 should be taken into account, resulting in a downward pressure of:

$$P_{dn} = 0{,}9 * (1330 + \pi * r^2 * d * 24) = 1197 + 3326d \; kN$$

When solving the equation $P_{up}=P_{dn}$ the minimal thickness of the slab is obtained:

$$4620 + 1540d = 1197 + 3326d \quad makes \quad 3423 = 1786d \quad thus \quad d = 1{,}9 \, m$$

With an equivalent thickness of 2 meter the driving up of the structure can be prevented. The application of tension piles could reduce this thickness.

Further computation of the foundation is considered outside the scope of this research

4.4.5 Assembly

A suggestion for the assembly procedure is illustrated by pictures of the separate building steps. The subsurface part can only be properly installed in a dry building pit and for the rest of the building process this will be very practical as well.
When the building pit is drained dry and the foundation is installed, the first step will be to stack all core parts and landings on top of each other. The hoisting crane can now easily reach the core structure without damaging the lower dome and subsurface room structure. The core parts are hoisted in tube segments of which the two halves can already be put together previously. These segments will weigh about 8400 kg each. During the core assembly the stair steps can be mounted into the already placed core segments.

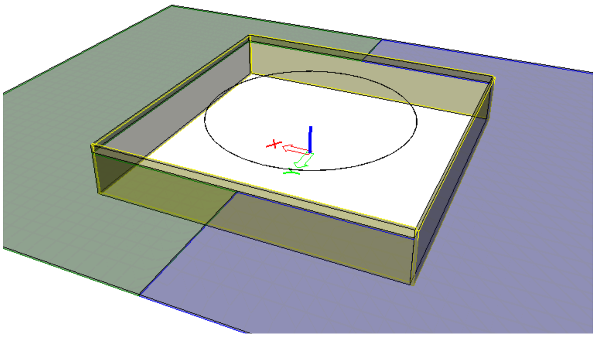


Figure 218: Step 1: The dry building pit

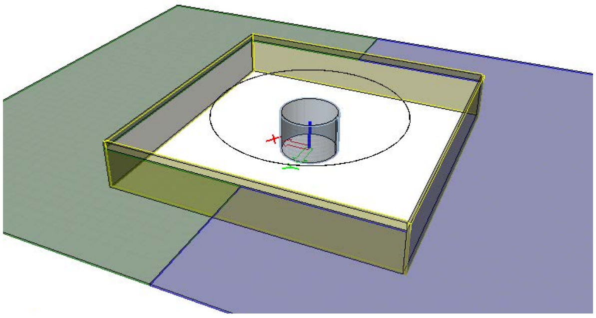


Figure 219: Step 2: The first core section

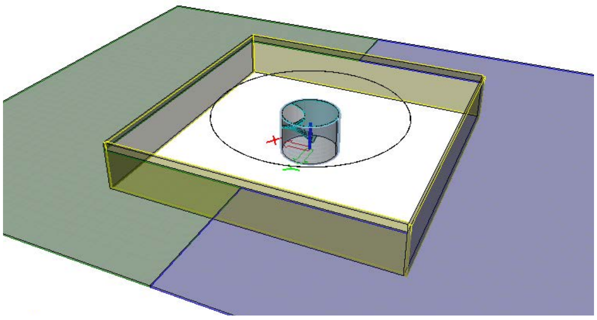


Figure 220: Step 3: The stairs and landing

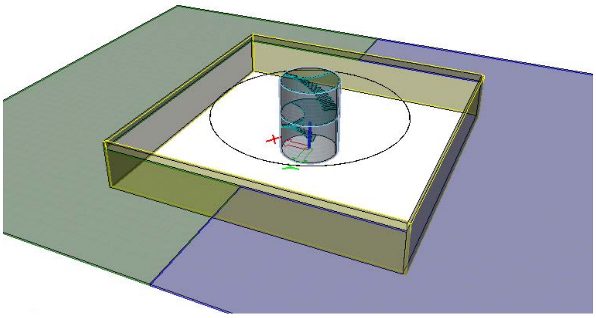


Figure 221: Step 4: Stacking the next core section, stairs and landing

When the core is completed, the lowest half of the sphere structure can be installed. As the individual parts are very light-weighted, the largest problem will be the wind during hoisting and construction. It would be best to assemble large sphere segments on the ground and then hoist them in place, then the least amount of difficult adhesive bonds will have to be made when the sphere parts are in their final position at about 30 meters above the ground. It might be interesting to investigate whether the sphere halves can be hoisted and connected in only two separate parts. Such a part would weigh about 800 kg.

When the lower half of the sphere is completed, the observatory floor will have to be hoisted on top of the structure. If possible this should be done in one piece, with a weight of approximately 9500 kg. That would at once make a stable structure of the lower sphere halve, if segmented floor parts are applied, the sphere will become unstable and large deformations may occur.
When this floor is installed, the conical core part can be placed on top, then allowing the upper sphere halve to be assembled. This can be again done by mounting two separate parts on the floor, and connecting those when hoisted in place. But the stability problem for this half is less worrying as

the segments will be supported automatically by the core and the observation floor thus it is also possible to mount this sphere half in more segments.
The next step will be the placement of the soil and water retaining wall below ground level, the ground floor segments can then be installed on top of that. When all connections are sealed it is possible to fill the building pit again with soil and water. At last the ground floor dome can be assembled and put in place.

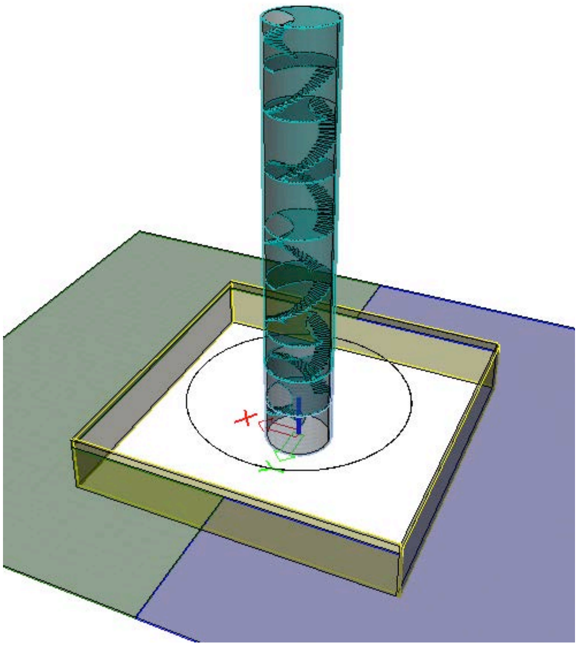


Figure 222: Step 5: Rest of the core is installed likewise

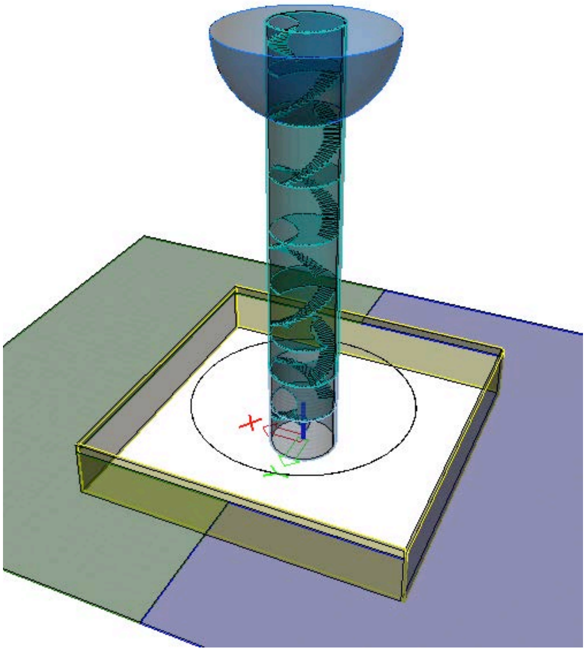


Figure 223: Step 6: Lowest half of the sphere

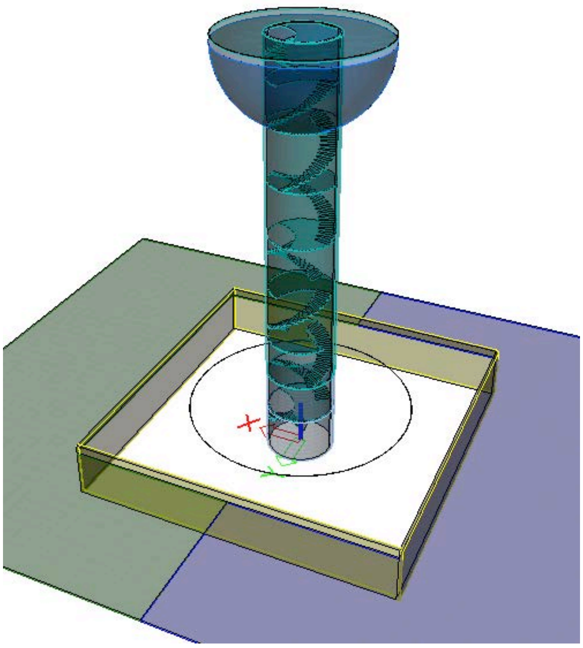


Figure 224: Step 7: The observation floor.

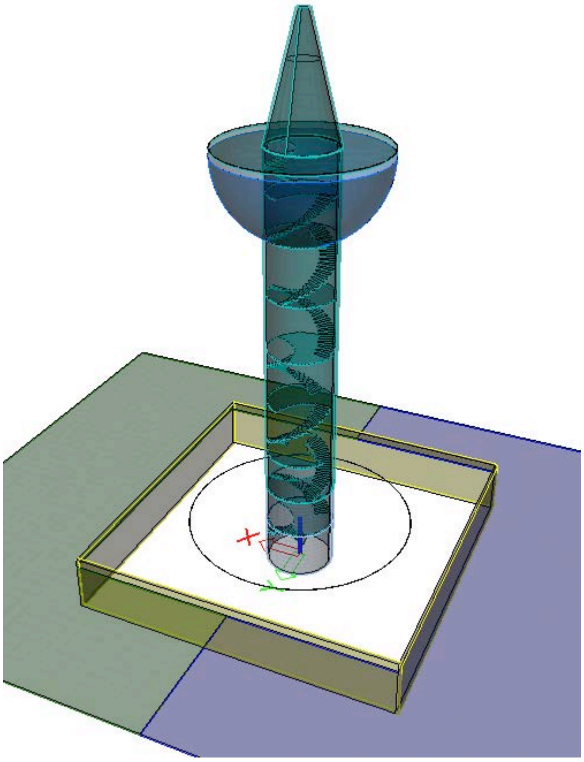


Figure 225: Step 8: The conical core element.

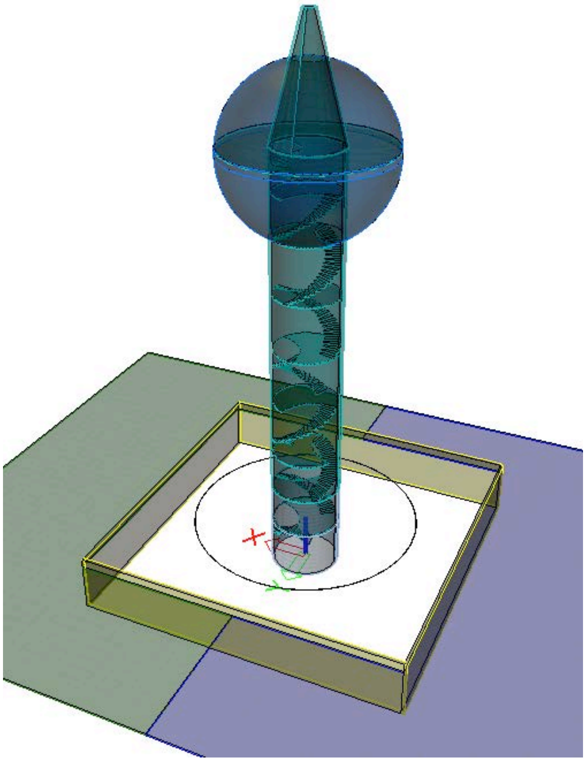


Figure 226: Step 9: Upper half of the sphere

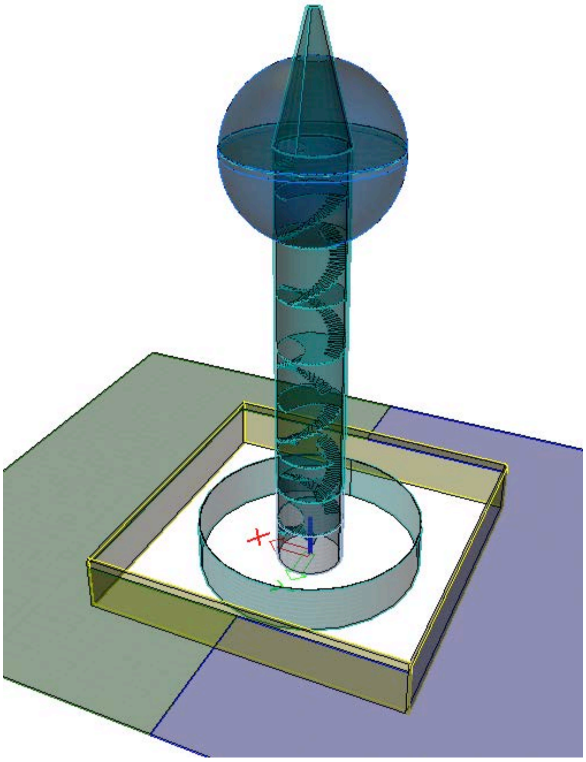


Figure 227: Step 10: The subsurface soil and water retaining wall

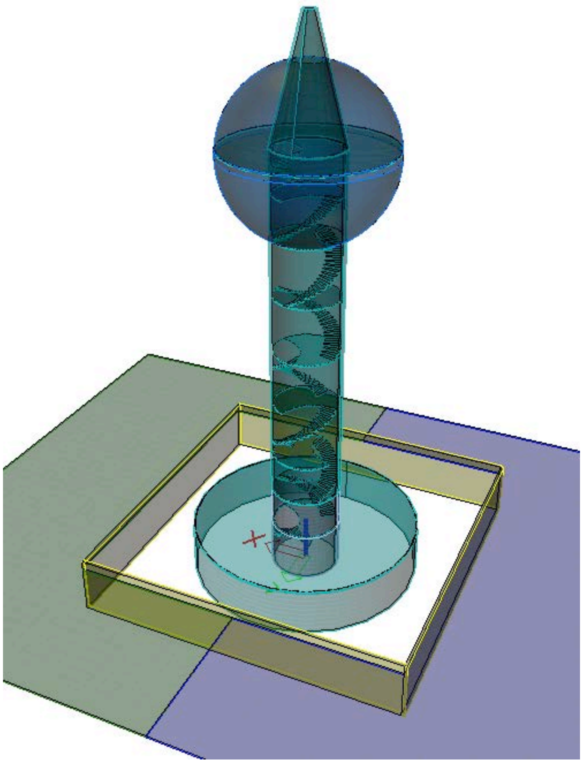


Figure 228: Step 11: The ground floor

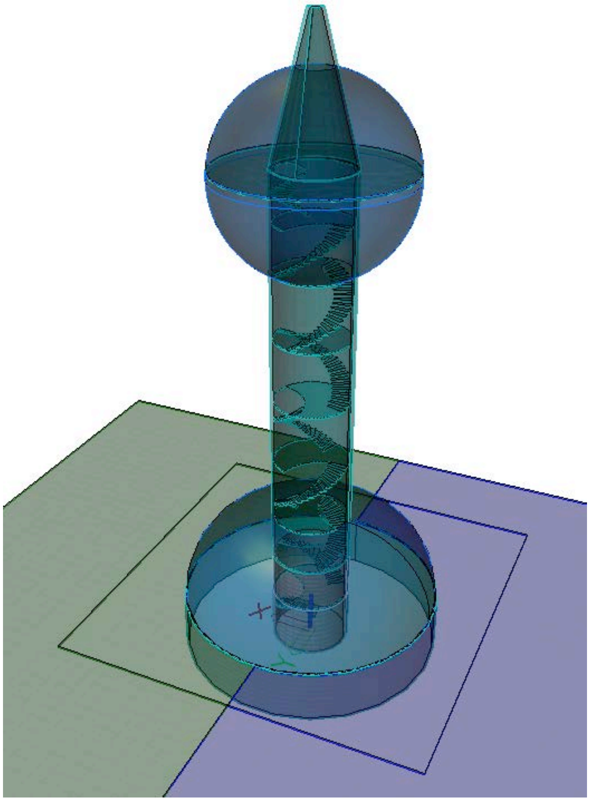


Figure 229: Step 12: The lower dome and removing the building pit.

4.4.6 Realisation

Speaking of an assembly procedure is actually a little premature. Before such a structure can be realised a lot of research and testing will have to precede.
As there are no building regulations available specified to building with transparent plastics, it will be necessary to prove the reliability of the used materials conform the principle of equivalence, as stated in the national Building Decree. In that case the functional requirements should be met, but not the performance requirements. Instead it needs to be proven that the designed alternative solution really does comply with these functional requirements. (Bouwbesluit 2012)
In this paragraph for several components of the structure and specific subjects it is listed which aspects need further testing before the design can be approved for execution.

Structure in general

The bearing structure
As no reference projects can be used to verify the behaviour of acrylic as bearing material, it will be required to perform tests that prove the abilities of acrylic in this function.
The testing procedure could be as follows:

- Long term tests on the core elements, for about 2 weeks, to investigate the behaviour.
  - After these two weeks pressure can be increased until collapse
  - Best would be to perform the tests at elevated temperatures, as that accelerates the creeping process.
- During the element casting small samples can be cast along for quality-checks and testing.
  - Tensile tests on dog-bone samples subjected to UV radiation in a climate chamber will be useful to prove sufficient UV resistance.
  - Tensile tests at very low temperatures, for instance -30°C will be very interesting to investigate the embrittlement of the material.

The sphere structure
For the sphere structure especially the development of properties under long-term exposure to an outdoor climate are of importance. The material is by its location subjected to a maximal amount of environmental influences; UV radiation, temperature changes and rainwater. The ageing of the material under these circumstances will have to be investigated.
The same test procedure as for the acrylic could be followed with tensile tests on dog bone samples under various circumstances.

Detailing
A point of attention for the details is the occurrence of stress concentrations. These should absolutely be prevented. For plastics specific thermal deformations are one of the main reasons for stress concentrations.
Full-scale testing of details and thorough analysis with a finite element program will have to prove the bearing capacity, especially for the adhesive bonded connections as this kind of bonding is not an accepted structural connection yet.

Fire safety
Probably the most complex part will be to prove a sufficient fire resistance of the transparent plastic structure. Fire testing is complicated, expensive and it is hard to draw conclusions from the results. Every fire is unique and the risk on a devastating fire is small, but the consequences can be immense. This makes it is hard to put unambiguous requirements regarding fire safety of buildings and building materials. Thereby the applicable requirements are region dependant as the fire brigades have a large influence on which structures are approved and which not.

Fire testing could include the following:

- Fire testing on a full-scale core element
    - Putting a burner on one side of the wall element and measuring the temperatures on both sides of the wall. The temperature on the opposite wall should keep below a certain critical value within 15 minutes or half an hour to make sure the structure is sufficiently fire resistant.
    - Putting a core element into a bath of petrol and ignite the petrol. It can now be observed how the material behaves when a thick-walled element burns down completely. (Partly) burnt material could be used for material property tests.
- The escape route should be proved to be safe and smoke free for a sufficient period of time. Cast acrylic is known for its nearly smoke-free burning behaviour. For polycarbonate however it should be shown that it produces no excessive amounts of (poisonous) smoke that could be threatening the safe evacuation.
- A fire simulation could be carried out on a façade element. The most plausible cause for a fire in this design will be a deliberately cause fire. The case of throwing a firebomb on or through the lower dome structure could be used as a test case.
- A detailed 3D finite element model, which can be the same as the one necessary to analyse the detailing, can be used to apply a very high heat load on the structure. It can be analysed in such a model how the heat spreads through the structure and when the critical temperature is reached.

Fire tests can be performed in Arnhem at the Fire Brigade Academy.

Fatigue

Another complex problem is the fatigue behaviour. For plastics this behaviour is very complicated and as all plastics act different on sustained cyclic loading it is not possible to formulate a general design rule. The external use with a combination of wind loading, temperature differences, UV radiation and rain even increases the complexity. Still an indication should be given on the risk of fatigue failure before the design can be approved.
Possible tests could involve:

- A 2-year test program for both materials
    - Fatigue tests on samples when subjected to UV radiation in a climate chamber
    - Testing of UV radiation aged samples
- 6 Month testing program: To get some relevant results within a short period of time, the development of the elongation at break could be investigated over a 6 month period. That would give an indication of the fatigue sensitivity already and could be used to determine design values.

Technically speaking fatigue is an important aspect for the design as it could determine the critical values for the stresses. However practically it will not have a large influence on the design itself as it would in the worst-case lead to increased thicknesses of the elements.

Costs

It is hard to say anything about the costs related to building this tower. As it will be a real pioneer project, a lot of costs will have to be made with the testing and research previous to the build.
A lot of the budget will as well be necessary for practicing the quite uncommon bonding and construction methods on scale. The craftsman will need to be well trained to be able to produce high-quality reliable bonds. As the bonds will be part of the bearing structure the reliability of the whole structure will depend on the bonding quality.

The costs are obviously not with the material it self but with the process involved. Production and transport of the large custom elements will be very expensive at this moment. But as soon as the

plastic industry recognises the opportunities and demands will rise from the building industry developments can move very fast.
The investment of one or more large companies in research is not unthinkable and that would be a huge opportunity to get these prices down. It is a great chance on advertising for specialized companies, simultaneously giving them a head start in this new market of plastic structures.

For now it would be only a wild guess to put a price on the structure. It is decided that such a guess would not be an added value to this research and costs are not further specified.

Conclusion

In this research it is shown that a structural design completely in transparent plastics is technically possible. However practically the idea is not yet realisable. It will be a costly and time-consuming procedure of testing and research to come to a reliable design that is fulfilling all functional requirements that are asked for in the building regulations.

Once this whole process is gone through completely, the results can be used as a reference in future projects and every next design the process will be quicker and easier than the previous one. For other building materials already decades or even centuries of experience are used in the current design procedures, these are therefore hard opponents for new materials as plastics.
A leading company in the plastics industry should be willing to invest in the development of structural applications of transparent plastics, using it as an excellent way of advertising. That would provide a huge leap towards the realisation of the first completely transparent plastic structure.

5 Conclusions and Recommendations

5.1 Conclusions

Material properties
The molecular structure of polymers is the basis of a lot of properties. The viscoelasticity of thermoplastics will lead to significant creep deformations above certain stress levels of sustained loading and relaxation of stresses for constant deformations. Thereby the structure of polymers makes them sensitive to temperature differences and environmental influences.

The selected plastics, polycarbonate and acrylic show very good mechanical properties compared to other plastics. The instant mechanical properties of acrylic are slightly better but PC is less sensitive to creep, temperature and environmental issues. PC is a very tough material with a high impact strength, acrylic shows brittle behaviour; it will not shatter but the low ductility does not allow large strains before failure.
The Young's modulus of both materials is much lower than that of conventional building materials, the ratio between stiffness and strength is very low. Deformations are mostly governing in the design.

Production
The available production techniques are very diverse and will determine for a large part the possible applications.

Polycarbonate can be excellently 3D formed with various processing techniques as for instance injection moulding and vacuum forming. Disadvantageous is that element thickness is still restricted to about maximal 15 mm. Applications with in-plane stresses will be very suitable for thin-walled polycarbonate elements to avoid excessive deformations. Double curvature and ribs can be used to increase the out-of-plane capacity of the elements.

Acrylic can be cast to large elements with already standard thicknesses available to about 100 mm and custom sizes up to a meter thickness. The elements can be bonded with special techniques to practically unlimited sizes. The most favourable load condition for acrylic is compression, which makes the material immune to crazing.

As all forming techniques are requiring the use of (expensive) moulds, repetition will be a key word in transparent plastic design.
Polycarbonate and acrylic are potentially interesting building materials. They offer high freedom in the design of 3D shapes and are able to provide enough structural capacity as well.

Guidelines
Proper design guidelines for the use of transparent plastics in building applications are lacking. The existing guidelines do offer a way of calculating design stresses for various thermoplastics but the tables are mostly incomplete and values are very empirical. As long term testing results are scarce most factors are found by extrapolation and thus not very reliable. However it is possible to make a preliminary design based on these guidelines.

Striking in the current design guidelines is that the design values are tremendously lower than the basic material properties found with material factors up to 12 for exterior applications. All available tests show an enormous decrease in properties.

Case study
In the case study all findings were transformed into a design with transparent plastics. The aim was create an entirely transparent structure; an observation tower of about 30 meters high.

As a result of the fact that deformations are leading for most design cases the building elements subjected to bending will require a high moment of inertia. The occurring stresses will therefore generally be low and thus cause only low creep deformations.

Stress concentrations are a bigger issue; at locations where elements are connected stress concentrations can easily occur. The detailing will determine whether the stresses can be transferred between the separate parts the way as modelled. The equal distribution of stresses over the complete connected surface is the solution with the least risk on stress concentrations. Therefore the use of adhesives in connections is recommended for most situations.

It can be concluded from the design study that an all-transparent structure with plastics is technically possible. Parts of the design will be certainly feasible. For buildings with a special function, as for instance pavilions, the use of transparent plastics could offer very interesting architectural opportunities to create a unique appearance.

The lifetime of transparent plastic structures is still uncertain as test results for over 10 years are scarce. A service life of 20 years is realistic at this moment and it is expected that further research could extend the lifetime significantly.

Transparent plastics as building material
For bearing structures of buildings element sizes and loads will be large compared to ordinary plastics applications. As acrylic can already be cast to large elements, suitable for aquarium windows, the cross-section of the material can be adapted easily to load-bearing applications in building structures.

The bonding of acrylic elements is a very specialised job, which if not done securely will not lead to the reckoned strength. Thereby it is time consuming and should be performed in a controlled environment. This is the complicated part of applying acrylic in building structures. Developments in the plastic and building industry may improve this in the future.

With polycarbonate load-bearing structures are more difficult to realise because of the limiting available production techniques. Until now only thin-walled elements can be produced leading to large deformations and high risks of buckling when severely loaded.

Shell structures however are a very suitable application for polycarbonate, as mainly in-plane stresses occur and the stable shape prevents large deformations. The production of standardized elements for the building of dome structures could be certainly made feasible if the demand is high enough. Double curved elements are radius dependant and thus one series of elements can only be used to make domes with the same radius. A recognisable series of buildings is a possibility, as kiosks, post offices or bus stations.

Because of the good mechanical properties other standardized elements might also be an option. As injection moulded ribbed floor and façade segments, or extruded profiles. Developments in the plastics and building industry could do lot in extending the possibilities.

Combining transparent plastics with other materials in a building structure will lead to several problems. The plastic parts then need to be designed at very low stresses to avoid large deformation differences. And the large difference in thermal expansion between plastics and other materials as

steel, concrete and glass ask for precise detailing. The connections should allow deformations while not inducing stress concentrations.
A chance for combining acrylic and steel or concrete in bearing structures might be the limitation of acrylic creep behaviour. As the volume of the material will be constant, a biaxial compressive stress could significantly reduce deformations. This might be achieved with certain reinforcement perpendicular to the load direction, keeping the structure together or by applying the acrylic clamped in between concrete or steel elements.

More knowledge of the behaviour will be needed to be able to perform a reliable analysis of a combined structure. A redistribution of forces could easily lead to unpredictable stress concentrations and (local or global) failure.

The growing use of constantly improving 3D finite element modelling software will make structural applications of transparent plastics and the combination with other materials accessible to designers and engineers. Occurring stresses can be accurately analysed when using these modelling programs correctly.

Final conclusion
Technically speaking it appears that a structure as shown in this design case is possible but still a lot will have to happen in the building industry before a structure, as the transparent observatory building can actually be build.
However these problems might solve themselves in the future. When manufacturers in the plastics industry recognize the opportunities of their products in building design, they will invest in the development of better production and bonding techniques for these large-scale applications. Simultaneously the building industry will perform testing programs and make sure that a proper design guideline becomes available. Other materials that we regard as normal today have also come this long way until current applications became possible.

To get back to the research questions that were posed at the start of this research; the main questions were:

- *What are the structural possibilities of polycarbonate and acrylic and how can these be used in building design?*
- *Is it possible to make a structural design for a building or building part in which the favourable properties of polycarbonate and/or acrylic are used in such a way that the limits of the current transparent building can be stretched?*

Polycarbonate and acrylic offer a lot of unique possibilities, mainly because of their good formability. To compensate for the low Young's modulus they can be used in building design by applying the materials in cross-sections with a high Moment of Inertia or in shells where mainly in-plane stresses occur. In those cases the materials are used in a favourable way and a structural design is certainly possible as showed in the case study.
The transparent plastics offer shapes and connection methods that are unique in building design; this can certainly stretch the limits of current transparent building. It will be possible to build large-scale transparent structures without the need for an additional, visible, substructure; something that only exists in dreams now.

Probably glass will be the conventional transparent building material forever. It is very suitable for all kind of standard glazing applications. Transparent plastics will not be an enemy to glass in the future, more of a colleague. The behaviour and applications of both types of material are incomparable; one will never be able to replace the other. Each material has its own strengths and weaknesses.
It can be concluded that plastics do not form a threat for glass but they will further extend the possibilities of transparent building.

5.2 Recommendations

This research forms a good basis for further (thesis) research into the application of transparent plastics in the building industry. The following subjects are all of importance for the further development of all-transparent building structures.

Material properties
The design factors are now composed of separate factors for time, temperature and environmental influences, it will be interesting to perform tests with combined circumstances. Adding the separate factors might be too conservative; a combination of influences could give a lower design factor. Especially a higher design Young's modulus could save a lot of material in the design of structural elements.

Standard tensile tests are now used to determine the deterioration of properties under various influences. It is not unthinkable that the thickness of the used material has a significant role in the results of such tests. Testing on thick elements could prove whether only the surface of the material is affected by environmental influences, that might lead to a significant reduction of design factors for thick acrylic elements.

Long-term testing programs will be required to investigate an extended design life of transparent plastic. At this moment the design life is limited to 20 years by a lack of information on the behaviour of transparent plastics thereafter.

Detailing
The development of standard details will be an important step forward in structural design with plastics. Workable connections that provide an equal distribution of stresses and room for thermal movements will make building with transparent plastics easier, faster and cheaper.
For instance fibre-reinforced polymers could be used to strengthen connections and help distributing the stresses.
Physical testing combined with detailed 3D modelling in a finite element program will be necessary to determine the strength, rigidity and reliability of certain connections. The risk on stress concentrations should be thoroughly analysed forming a high risk on preliminary failure.

Production
Especially for polycarbonate a great step forward could be made when production possibilities are extended. Research to the processing of polycarbonate may bring up new ways of moulding or casting, a lamination technique or a change in material composition that would allow for the production of larger and thicker building elements. That would highly increase the suitability of polycarbonate as a building material.
Manufacturers can be of good help on this subject as these developments are to their own advantage, creating a new market of plastic products.

Fire safety
Concerning the subject of fire resistance there is also lack of knowledge, before it is allowed to use the plastics as a bearing structure, more research will be needed on the burning behaviour of polycarbonate and acrylic. For instance the following subjects:

- Behaviour of thick thermoplastic elements in fire. Thickness might have favourable effect on the burning speed and propagation.
- Determination of reduced cross section. it should be investigated whether a reduced cross-section may be taken into account for fire calculations. As used for design of timber structures.

- Remaining strength in the core material. If a reduced cross-section may be used, what properties will be fair to use. Temperatures will raise and influence the properties.

With these results it might be possible to set up design regulations for thermoplastic structures exposed to fire.

Stability

As structures subjected to in-plane stresses are very suitable for thin-walled polycarbonate elements it will be interesting to get to know more about the buckling behaviour of polycarbonate. How will the material fail and for what loading. Due to the viscoelastic behaviour it is also possible that sustained loading causes buckling over time while the modulus will slowly decrease.

Dynamic behaviour

The dynamic behaviour of transparent plastics would also be an interesting research subject. As often visco-elastic damping devices are used in buildings, maybe positive damping effects are obtained as well if the whole building possesses viscoelastic properties.

Prestressing

Prestressing would be a way of controlling the creep and deformation behaviour. Biaxially stressed elements will show the least deformations. It could be investigated whether it is possible to control the prestress regarding the relaxation behaviour of the plastics. Thereby the prestressing material should be applied in such a way that transparency is still secured.

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