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GLASS AS A STRUCTURAL MATERIAL

Text by Rob Nijsse.

Building at the limits of the possible: In the last 20 years, load-bearing glass constructions have triumphed in architecture. One of their pioneers, Rob Nijsse from the Netherlands engineering office ABT, explains the achievements on the way towards the new age of glass architecture.

Below On top of the ruins of an 18th century tea pavilion, Rotterdam architect Dirk Jan Postel erected a pavilion with glazed walls, which at the same time supported the strongly cantilevered roof. The walls consisted of 2 x 10 mm laminated glass and were fixed to the block work and the underside of the roof by bolts and steel angles.

PHOTO BY CHRISTIAN RICHTERS

Glass is a fascinating material. It combines remarkable and even contradictory properties. You can look through it, and yet water, which penetrates almost everything, cannot pass through it. On the one hand it is strong and almost unbreakable, on the other hand one scratch lets it break easily.

The quest to introduce this material into the world of structural engineering has only been going on for a few decades, but it is my sincere conviction that in another few decades people will regard structural glass to be as trustworthy as for instance steel and reinforced concrete. One should not forget that steel/iron as building material is only about 200 years old and concrete even only about 100 years.

GLASS BEAMS

Glass for windows and even floors has been used for a long time, although in small measurements. Glass beams, however, are one essential step ahead from the early days of the Roman Empire. The idea of a glass beam is in itself very tempting but also dangerous: if glass breaks, it breaks completely, because the cohesion of the material is lost. An overload or a stone thrown at it results in a total and sudden failure of the beam. This is also unacceptable because we like to have some kind of warning mechanism in our structures that will be activated when there is a problem. A steel beam, for instance, warns by excessive deformation or plastic yield.

Glass in itself gives no such "warning" sign. It is only the invisible gluing together of individual panes, a process called laminating, which enables us to make a safe beam. Laminating of glass was invented in the early 1900s when – so the story goes – a scientist accidentally dropped a glass bottle filled with glue and as a result found two glass fragments glued together invisibly on the floor, a few days later. In the evening papers on the same day, he read about a girl who died in a car because she had been injured by a broken windscreen which smashed when hit by a piece of gravel. He realised that if the windscreen had been built of two layers of glass, glued together invisibly, this tragic accident might never have happened. This idea was an initial impulse for the industrial production of laminated glass. Another major impulse came when the chemical firm DuPont de Nemours invented a transparent foil called pvb (polyvinylbutyrate), which glues glass sheets together. Production takes place under pressure in an autoclave at a temperature of around 250°c. The glass sheets and the foils or plies are rolled together under considerable pressure. The result is a perfect, transparent piece of glass, composed of two, or even up to ten individual layers of glass. In this way, safe glass beams are produced not by making one beam but by gluing two or more beams together. If a malevolent person throws a stone at your precious glass beam, he can only break the outside glass layers. These broken layers keep on sticking to the central ones and therefore protect them.

For these reasons, the concept of a glass beam was "up in the air" in the 1980s. Various members of the international community of structural engineers carried out studies. But who would dare to put the first glass beam in a real building? The psychological barrier was enormous, because we know from everyday practice that glass breaks easily. Clients and contractors have a tendency to avoid risky experiments. The building industry is one of the most conservative industries. New developments need an enthusiastic client willing to take a certain risk. The engineer naturally has to assume the obligation to analyse all possibilities of unwelcome effects of the proposed innovation. The introduction of glass beams is a good example of a cautiously accepted innovation.

GLASS FLOORS

Glass panels in the floor of a room have been known for quite some time but only in small sizes. However, it was the introduction of a disco dancing floor with coloured lights from underneath in the 1970s movie "Saturday Night Fever" which gave the glass floor a real impulse. Architects began thinking about integrating glass floors into buildings. This implied, of course, that they had to be transparent. Walking on a big transparent floor is exciting but also a frightening thought to many. Besides, in the case of an abnormal fear of heights (acrophobia), people are afraid because our logical thought processes cannot accept the fact that something transparent will carry our weight safely. There was a film made in the 1950s by a big glass company in which a mother places her baby on a table where half the table top is made of glass. She walks around the table and calls to her baby to crawl to her over the glass section of the table top. Despite the fact that his mother, a person he loves, calls him, the baby refuses to crawl across this surface. This behaviour is typical of people who have to walk over a glass floor. Even if the engineer proves that it is ten times safer than a wooden floor, people simply don't trust it. And, admittedly, even I have to take a deep breath before stepping on a transparent floor. Therefore, it is wise to make at least part of a glass floor translucent rather than transparent. People feel safer although the difference between a translucent and a transparent glass panel consists in no more than a translucent foil that is only 0.46 mm thick!

Architects and many users are excited at the possibility of 'walking on air' and experiencing a building in three dimensions. Since safety is a major design criterion, it will be clear that all glass floors have to be made from laminated glass. Also, we have to be aware of the fact that walking on the glass will create scratches on the surface due to sand or gravel stuck to the soles of shoes. So we have to ensure that this scratched zone is not in a tensile loaded area, for then the scratches would act as a stress concentration point resulting in further stresses in the glass. Often people think of glass as being slippery to walk on. In fact, in dry conditions it is not slippery at all. Tests have shown that the surface conditions of glass are more or less comparable to natural stone or tiles. However, when wet, glass becomes a potentially slippery surface. One of the ways to avoid this danger is to use a special type of glass that has been given the following treatment: a glass panel is heated to the point where the surface melts and becomes slightly syrupy. Then grains of sand or small parts of broken glass are scattered onto it. Because of the slightly molten glass surface, they sink halfway into the surface. After cooling down and rehardening, the result is a super-rough surface even when wet. The advantage with this treatment is that the surface does not wear easily; the scattered sand or grains adhere well to the glass and protect the original glass surface.

This process of melting and rehardening reminds me of an old but unfortunately invented story told in Arab chronicles about the structure of one of the Seven Wonders of the ancient world, the Pharos of Alexandria. This very tall and big lighthouse was said to have its foundations connected to the rocks by "claws of glass". On second thoughts, this is not entirely out of the question. Glass could be melted easily and poured into cracks in the rocks. Once solidified, it could take enormous pressure so it is worthwhile considering a new application of this old construction method.

GLASS COLUMNS

While we have been able to make glass floors, glass roofs, glass walls and glass beams, the last structural element still resisting its transformation into glass is the column.

In general, a column is a difficult element in a structure. Architects and clients do not like columns; they stand in the way and they block the view. If it is impossible to reduce them in number, architects ask for them to be made as small as possible.

Structural engineers, by contrast, love columns: they reduce the span of beams and floors, and make structures less complicated. So how do we overcome this aversion by architects? I like to quote from a text by Le Corbusier on his Villa Savoye: "Proudly they stand a-straight the columns; the soldiers of architecture, carrying their load." This goes a little way to help as no one would dare contradict so great an architect as Le Corbusier.

But engineers should make columns more attractive, too. One way to do this is to make their shape more expressive, which I tried for instance in a study on the shape of columns for the restaurant of the Educatorium project. As a starting-point for the structural design of these columns, we asked the architect to look into how columns collapse.

There are three ways in which this can happen. The first one is under pressure by crumbling, slowly yielding under too big a compression load. The second is by buckling under pressure, and suddenly breaking in the middle. In most cases, this is critical. The third is by breaking due to shear force . I made a number of column designs relating to each type of problem. The intention was to choose a typical column for each location and thereby give the space around the column identification. Unfortunately, the cold wind of financial constraints only led to a variation in size and in a round or square cross-section with an identical cross-shaped column (the so-called Mies van der Rohe quotation).

Another way to make columns more attractive and less repulsive to architects would be to make them out of glass. Although glass performs well under compression, there is the danger of buckling, which makes it hard to conceive a safe glass column. Buckling will result in tensile stresses and miniature cracks in the surface will spoil the construction. Therefore, safe structural glass elements have to be double or triple layer or more. If one part fails for whatever reason, the remaining parts must still be able to carry the load so that the damaged element can be replaced. But will a glass column not be the utmost achievement in a structural application? Imagine high-rise buildings resting on mysteriously shining beams of light (bear in mind the immense potential bearing force of glass); a dream would have come true. The journey on the road to realise this has, however, only just begun.

GLASS WALLS

Walls separate areas in a very physical way. Glass material offers the possibility of creating a real physical separation between two spaces, while at the same time allowing full insight into what happens beyond. In principle, walls have two different functions: inside buildings they chiefly serve acoustical and optical requirements. As part of the façade, they protect the inside of the building from the outside climate.

Regarding the structural aspects, a wall is just a special type of column. It is only far wider than thick. Therefore, the remarks we made concerning columns could be repeated here. Instead we will concentrate on the question of how glass walls may be designed. Basically, we are following in the footsteps of the builders of gothic cathedrals. For the glory of God, they sought to make the walls of their churches as transparent as possible. They were only familiar with blockwork walls with windows in, but with stone and glass they achieved almost immaterial walls with colourful stained-glass windows. The invention of the kinked high-rise arch, the flying buttress and the pier buttress led to enormous heights. Starting with a maximum height of 15 m, in Beauvais (1245) they reached the enormous height of 48 m.

But Beauvais marked the end of this development: in 1284, during a heavy storm, the straight parts of the vaults collapsed. It is amazing that those light-weight structures were built in a time when there was no theoretical understanding of how arches of beams or plates work and no computer programs existed which were able to deal with such spatially complicated structures. People then simply used their common sense. They learned from failures (which we do not see any more because only the successful solutions have survived) and tried each time to make things a little higher and a little more slender.

Today, that method of working is no longer acceptable. Most of all, we have to erect safe structures with no chance of collapse. Fortunately, we now have a sound theoretical knowledge about structures and we do have computers that can calculate the stresses and deformations of very complicated spatial structures.

For safety reasons, nowadays we always use laminated glass for structural elements. The critical collapse criteria for a wall will be buckling or plying. Therefore, a glass wall must have a considerable thickness and hence quite a few layers. We could improve on this aspect by making a corrugated glass wall, but this type of glass has only recently become available. The Casa da Musica in Porto is the first building to have these walls. Another critical point is how to get the loads from the structure resting on top of the glass wall into the glass wall without causing too many concentrated stresses. The support should be as centralised as possible and an elastic material (neoprene) should be incorporated. Also, the detail at the bottom of the wall, where the forces have to go into the foundation, has to be designed with these starting-points in mind.

GLASS FAÇADES

A façade is a special type of wall. It separates the inside from the outside. The difference in position implies that this special type of wall has to satisfy substantial requirements in terms of building physics. Also, the wind force on façades pulling and pushing against them, as well as temperature-induced movement and water-tightness, play an important role. These requirements make the design and building of façades a difficult but challenging task – which, however, offers engineers the opportunity to devise appealing structures: "Every disadvantage has an advantage," to quote the famous Dutch soccer player Johan Cruijff.

Glass plays an essential role in the façade. With its transparent property, it opens up our buildings to the outside world. This psychological effect is very valuable. People may enjoy the view of the outside world and are not divided from it by a solid closed wall. Especially in the colder regions in the world, this is an essential aspect. Houses and offices can be kept comfortable much more easily without having to give up the possibility of looking outside. But the introduction of glass into the façade has opened up the building not only from inside to outside but also from outside to inside. Certainly in modern architecture there is a tendency to open up buildings by using very large façades that are as transparent as possible. The visual borderline of what is inside or outside of a building cleverly merges into one. However, creating complete glass walls leads to new problems concerning the comfort inside the buildings. In winter, warmth passes easily through the glass façade, and in summer the heat of the sun is absorbed inside leading to excessive temperatures.

A single glass panel is not a good insulator, warmth travels easily through it. The introduction of double glass was a major improvement. The closed-up small gap filled with air in between the two glass layers provides good heat insulation. Double glass improves the comfort in the building, avoids condensation in winter and reduces the amount of energy required to heat the building. Nowadays, double glazing is improved even more by filling the gap in the insulated panel not with air but with inert gases such as argon and by vaporising thin layers of precious metals on the glass surface.

The heat insulation rate has been improved to a degree that a new danger is now present: in summer, the heat cannot escape! Air-conditioning is not a good solution to this problem. Architects and engineers need to be more critical of automatically constructing façades with insulated glass panels, as they have been doing for decades now.

Rob Nijsse is a director of ABT Consultancy for Construction Engineering in Arnhem. He has specialised in experimental structures in glass, concrete and steel, collaborating with architects such as MVRDV or Rem Koolhaas for the Dutch EXPO pavillion in 2000, the Educatorium in Utrecht and the Casa da Música in Porto. Since 2003, Rob Nijsse has been a part-time professor at the University of Gent. In the same year, his book *Glass in Structures* was published by Birkhäuser.