Structural design in glass

Engineered Transparency

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Glass, a material with the unique property to let light inside an area, is normally used in building practice as just an enclosure. Its use in facades is also due to its chemically inert properties; it can be cleaned easily and lasts for many years. However, when applied correctly, there is so much more possible with glass! Mechanically, glass has the capacity to withstand high compression forces and also high tension forces if heat- or chemically-threatened. As knowledge and production methods progress, larger glass units can be produced as well as designed. In the last decades, glass has been used more and more in major structural elements, by applying it as glass fins. It can be bonded to steel to create special composite structures. So-called hot or cold bent glass is also possible in order to create single or double curved elements. Combining these possibilities of glass one can reach one of the ideal concepts of architects and engineers, almost invisible transparent load-bearing elements in every shape: engineered transparency!

Structural properties

The particular material properties of glass greatly influence how a system is designed and built. Glass is a brittle material, which means that glass will not plastically deform prior to failure. Glass will fail once it surpasses its elastic deformation and reaches its maximum yield stress. One small peak stress can lead to the breakage of the total glass pane. Tension stresses are always normative in glass design as glass is much stronger in compression. Heat treating or chemical strengthening increases the overall tensile strength of glass by introducing pre-stress; compression stresses at the glass surface where fracture starts and tension stresses in the center of the section. When glass breaks, the breakage pattern reveals the pre-stress (stored energy) that was present before. The larger the pre-stress, the smaller the glass particles. Due to the nature of the pre-stress, allowed tension stresses are different in the center of a glass pane than at the edge of a glass pane. Also, allowable stresses are time dependent. For example, allowable stresses in case of snow load are significant lower than in case of wind load.

Glass fin structures

Glass fins (or beams) are the most commonly used structural elements in structural glazing. In horizontal position one can compare it with a steel girder, which supports a roof or a floor. In vertical position one can compare it with a wooden column or aluminium mullion. Glass fins represent one of the most transparent forms of structures. One of the earliest use of glass fins as a structural element dates back to the 1950´s: the application of the Hahn suspended glass system at Maison de la Radio in Paris, which used single ply glass fins as stiffeners to reduce deflection. In the following years this system evolved to allow even larger glass facades, with Norman Foster's Willis Faber & Dumas building as one of the first modern glass fins on a commercial scale. However, due to production limitations, maximum dimensions of the glass parts were just a couple of meters. Even until recently, most float glass was produced with standard maximum lengths of 3,6 – 6 meter depending on the manufacturer. Hence, in the past fins longer than 6 meter have typically been composed of multiple pieces spliced end-to-end, with

Figure 1: V&A Museum in London

moment stiff coupling elements between the pieces. Just after the millennium the possibility to produce larger fins by new tempering ovens initiated the possibility to make glass structures with full glass fins as the major structural beams in the following years. A development partly driven by the high standards set by the worldwide 'flagship' Apple stores, engineered by Eckersley O'Callaghan. Current maximum measurements in reach of manufacturers in China and Germany are around 18 by 3.6 meters, including lamination, hot bending, coating and tempering. However, these measurements require extreme investments of the manufactures in material, knowledge and time to master production.

In recent years Octatube has designed, developed and built numerous projects with glass fins, e.g. translucent glass fins for the V&A Museum in London (*Figure 1*), quadruple laminated main glass fins for the roof of the Municipal Museum in the Hague, where glass fins span 10 meters (*Figure 2*) and glass fins for the roof and the facade of the Van Gogh Museum in Amsterdam that span up to 12 meters (*Figures 4 and 6*). All these projects display glass fins as main component for the load bearing structures in roof and facade. Their safety behavior after breakage was reason for research as well. Execution of the safety philosophy of glass differs per country, but always leads to a safe situation in which progressive collapse and a second load bearing system is taken into account.

Figure 2: Municipal Museum in The Hague

If a monolithic element is broken, the glass and all that it supports will most likely collapse. Laminated glass solves this issue of brittleness. Glass plates are bonded to each other to make sure they always stay in place when they break. When one glass plate breaks, the adjacent one will keep it in position. When all plates break, the supports are designed to prevent the glass from falling and can often remain in place until the area is cleared of occupants. These failure scenarios have been part of experimental testing at Octatube, as proof for third parties. For example, the breakage of all fully tempered glass plates of a glass fin is shown in *Figure 3*.

Figure 3: Failure of tempered glass after a bending test

Stabilizing glass

Next to using glass as primary structural elements, glass is often used by Octatube to stabilize other structural members. For example, in the design of a glass facade for Centro de Arte de la Fundación Botín, designed by Renzo Piano, slender stainless steel mullions (22 x 220 millimeter) up to 16 meters in length were supported sideways by the glass units in between them. In plane, the glass units are very stiff due to their large width to height ratio. To act as bracing the connection between the glass and steel is very important. For this connection, often small blocks of the material polyoxymethylene (POM) are used due to their high stiffness and strength properties compared to rubbers, but relatively low stiffness compared to glass (Glass E=70 000 N/mm^2; POM E=3 000 N/mm^2) to minimize peak stresses in the glass. Only compression forces are transferred through the connection, which, as mentioned before, is favorable since glass has a great capacity to withstand compression forces.

Figure 4: Roof and facade of the Van Gogh Museum in Amsterdam

Likewise, for Octatube's most recent project, expansion of the Van Gogh Museum in Amsterdam, glass is used to stabilize other elements. In this case, the insulated glass units in the facade and roof are used to stabilize glass fins mentioned earlier. Therefore, in this case glass supports glass. The connection between glass fins and glass units

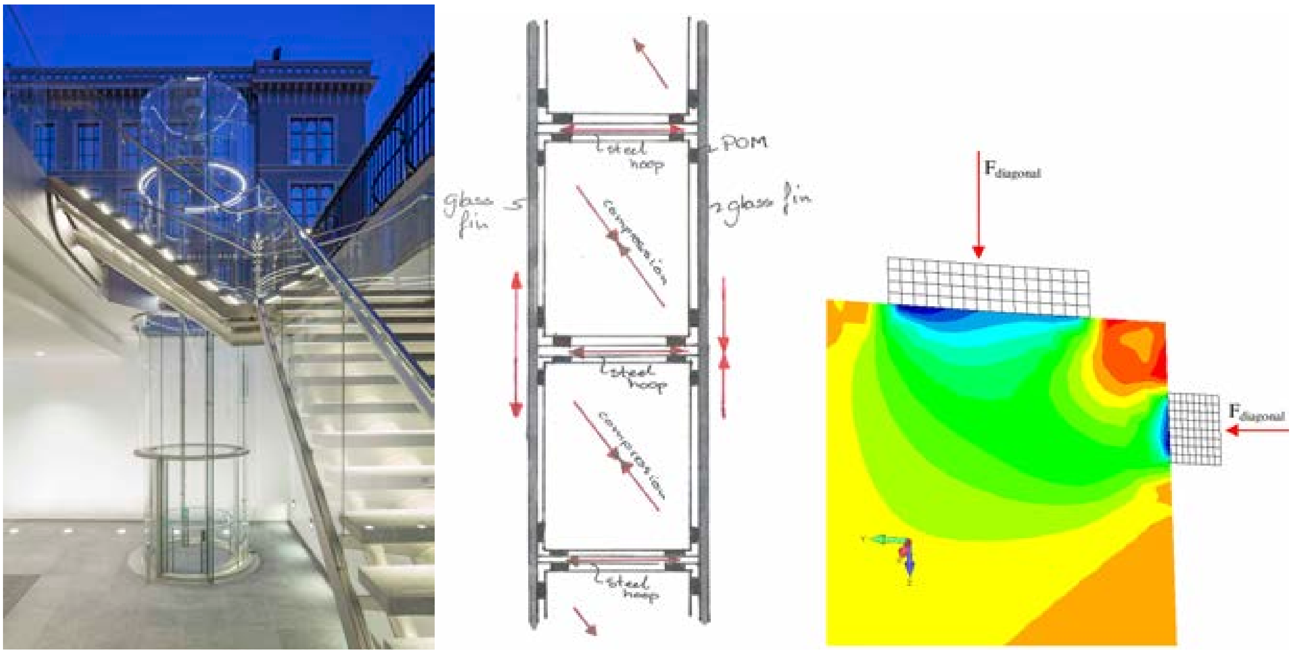

Figure 5: a) Royal Picture Gallery Mauritshuis in The Hague, b) Sketch of structural system and FEM-model of the corner of a glass pane

is made by bonding stainless steel rectangular hollow sections to the glass fins on which blocks of POM are screwed.

For the glass elevator of the Royal Picture Gallery Mauritshuis in The Hague (*Figure 5a*), glass is even used as the main stability system. Vertical glass fins act as columns and hot bent laminated glass plates act as bracing. The connections between the glass fins and bend glass units are designed to generate a compression diagonal in the curved glass. This is done by applying two blocks near the corner of the pane as shown in *Figure 5b*. The exact position and dimensions of these blocks are very important as this determines the tension stresses that also exist when a compression diagonal is present.

Instead of 'simply' locking in the glass units by POM elements, also mechanical connections between the glass units can stabilize a glass structure as done at the Dreefgebouw in Haarlem (*Figure 7*). Moment connections transfer forces between the glass units in the facade and roof to create one connected glass enclosure. To ensure the load introduction in all glass panes of the laminated unit, special injection mortar is used that fills the space between glass and steel connector.

Figure 6: Van Gogh Museum by night

Future: Robust, transparent and efficient buildings
Laminated glass is tough, resilient and not prone to sudden breakage and would greatly deform before yielding. A great material to build with and to optimize our structures with. With the latest glass engineering milestones like the Zorlu Center Apple Store in Istanbul, absolute transparency is reached by a total absence of steel fixings. As well as the extension of the Van Gogh Museum where glass is omnipresent, i.e. to stiffen the steel structure and used as main structure of the glass staircase, shows the diversity of glass usage. These concepts of architects included full transparent structures. Concepts that can only be reached by an intensive engineering process. What will the possibilities in the future be? What will our boundaries be? Let architects challenge the engineers and let the engineers inspire the architects!

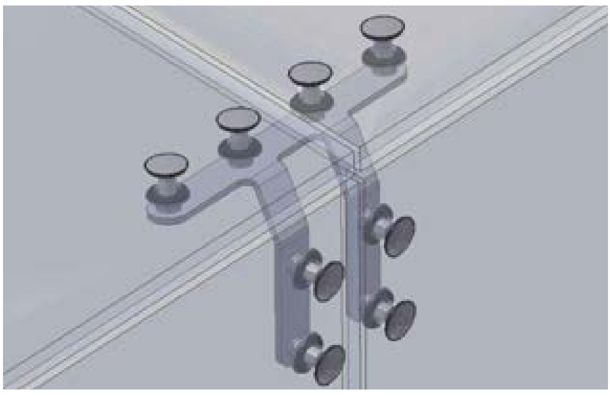

Figure 7: Glass mechanical connection elements in Dreefgebouw in Haarlem

Footnote:
The title of this article is taken from a biennially glass conference held in Dusseldorf. Together with Challenging Glass and Glass Performance Days (GPD) the leading conferences on glass engineering. Check those conferences if you want to know more about state of the art glass engineering.

Figures:

Header	*Jacqueline Knudsen, ArchitectuurNL*
1,2,3,4,5b,7	*Octatube Delft*
5a	*Luuk Kramer*
6	*Jan Kees Steenman, Van Gogh Museum*