

Development of a Super Slim Façade System for InHolland Polytechnic, Delft

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The initial conceptual 'wild idea' for the INHolland project by architect Rijk Rietveld, New York, was elaborated through different design brainstorming sessions towards a radical innovative system for ultra-slim glass façades. In this façade system insulated glass panels of a depth of maximum 50 mm are integrated with internal pre-stressed structural composite cables, stabilising the façade against wind forces. Dead weight is taken over by vertical deadweight rods in between the vertical silicone seams between the panels. The insulated glass panels are sealed by composite spacer frames. Many different solitary tests were done with the sealing and the carbon fibre components, with adhesion of silicone sealant on the carbon fibre frames and on the perforation of the carbon fibre used through the frames. In the actual engineering phase structural analysis was performed and tests on several levels were executed. The composite frames were substituted by conventional metal frames. Due to the refusal by the glass panel manufacturer to supply a guarantee on inadequate number of tests with inadequate quality, the integrated system had to be changed into a duo-system with internal pre-stressed cables and integrated dead weight suspension rods. The façade had to keep in pace with the progress on site.

Keywords: ultraslim façade, composite tubes, cable stabilisation

1. Introduction

All-glass facades for larger spans need stabilising systems for wind and deadweight loadings. Frameless facades show ultimate visual lightness as daylight is not hindered by obstructing steel purlins and aluminium framing profiles.

In an experimental process of design and development of a composite façade for the INHolland Polytechnic in Delft a system was selected and developed in which pre-stressed cables were developed for taking up horizontal wind forces while deadweight suspension rods transfer the vertical deadweight of the system. Both types of pre-stressed cables and suspension rods were initially designed to be located within the thickness of the insulated glass panels. The pre-stressed Aramide cables are located inside the tubes in the inner spaces of the double glass units, while the suspension rods are located in the end zones, seams, between the panels. The development of the process highlights the many hindrances and risks involved in this dense integration of the two independently developed 'alien' components: the double glass units and the pre-stressed

cables. The experimental design scheme and the realistic engineering answer on that are described in this contribution.

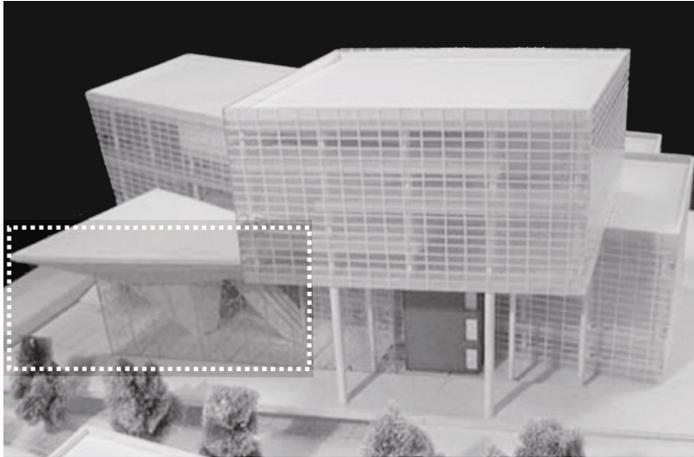


Figure 1: Model of the new building of the INHolland Polytechnic in Delft designed by Rijk Rietveld

2. First Phase: The Experimental SIA-Raak Design Process

The INHolland Polytechnic has a Composites Laboratory that wishes to pronounce itself to the world. In 2007 an experimental design process was started to design a composite glass façade system with the aid of members from the Polytechnic School, the Composites Laboratory (dr.Michiël Hagenbeek), two professors of the Delft University of Technology (prof.dr.Ulrich Knaack and prof.dr.Mick Eekhout) and a number of industries (Octatube and Asahi Glass Company) and advisory engineers. A major role was played by the project architect of the new Polytechnic School in Delft Rijk Rietveld of New York (www.rietveldarchitects.com) who challenged the development team, by his very design of the School building, to design an innovative composite glass façade system, as the facades in his design could function as the zero-series of application. However, the architect had ‘wild ideas’ that in combination had a too high number of experimental challenges that in the first phase hardly could be met. This experimental process started after the award of a Dutch research grant ‘SiaRaak’, to stimulate research at Polytechnical Schools.

The immaterial goal of the approved Sia Raak research program of INHolland was to promote the use of composites in architecture and to transfer and adapt the knowledge of these materials by designing a glass-composite façade system. A challenging starting point was the: “which knowledge and experience is necessary to come to applications of composites in glass façades for architecture?”

Composites offer a combination of durability, freedom of creating shapes and a high strength and stiffness per unit weight. In the last 2 decades in architecture particular interest arose for façades without metal window frames. This makes it possible to create highly transparent glass façades, leading to transparent architecture. Material goal of the research program was to develop a façade system with a new combination of glass and composites. The initial idea of the architect was to introduce solid composite rods of

50 x 300 mm in between glass panels in ad hoc geometry to improve the structural stability of the façade panels and of the façade as a whole. But this suggestion did not prove to be useful for a realistic invention, even after further development.

The ambition of the INHolland Sia Raak-program was to research the feasibility of glass-composite façade systems with a mutual exchange of knowhow between the Composites Laboratory and the professionals and professors from academia and the SME companies of the building sector. In this process the transfer and adaptation of knowledge on composites between design and engineering companies, small and medium-sized enterprises (SME) and knowledge institutions was foreseen. After the initial phase the target became to improve the position of competition by developing building concepts, as well as spreading the knowledge, best and bad- practices, within the SME and KIS (Knowledge Infra Structure). And specially to improve the education, in interaction with the organized composite industry, with the new knowledge of composites. Parties involved were INHolland Composites lab; INHolland Aerospace Technology; TU Delft, department of Building Technology; TNO Building and Subsoil; Gluing Institute of TU Delft and Syntens, The Hague and a number of companies like Octatube International, Delft NL and Asahi Glass Company, Maasland NL.

The grant enabled the development team members to brainstorm for a year with changing success to develop a more or less realistic scheme for an integrated composite façade as a compromise between the wishes and capacities of the architect, the Composites Laboratory and the generalized building industry, any or the best Dutch glass façades production industry. During the process many meetings did not produce a leap forward, due to the contradictory demands and wishes of the team members involved and the general shyness in these brainstorms, caused by uncertainties of the global experiment. The finale came into sight when the suggestion was seriously drafted on the whiteboard to integrate the supporting and stabilising cables inside the air volume of the double glass units. They were seen as sealed off by a composite framework of four spacers in stead of the usual metal spacers. The composite spacers themselves were integrated with composite tubes for the penetration of the composite cables. These composite elements formed the point of invention. This composite glass construction had to be developed intelligently and with care so that from this originally 'wild suggestion' a solid and trustworthy technical solution could be developed on this idea. On behalf of the development team a patent application was filed by INHolland. The usual and quite linear product development methodology as described in the book 'Methodology for Product Development in Architecture' [Ref. 1] hardly came into use as too many loops were used to restart the thinking and brainstorming process.

The experimental design also contained a large number of small scale prototype tests of the glass panels, the adherence of the sealant to the composite spacers, the air-tightness of the tubes and the tubular end connections and finally a full scale prototype of a segment of the designed façade application in the new premises: 6.0 m high and 4.5 m wide façade segment with pre-stressed cables and penetrations of Aramide cables through composite spacers in double glass units.

Challenging Glass 2

The experimental aspects resulting from the first experimental design phase to the prototyping development phase were threefold:

- The insertion of the composite tubes, penetrating through spacers in the top and bottom;
- The perforated weakness of the spacers and the overall stability of the glass panel;
- The bonding of the silicone and other sealants to the composite and glass surfaces.

Because the cables penetrating the spacer of the insulated glass special holding carbon tubes are foreseen, sealed off air-tight, to create an air-tight box of the insulated glass. The architect was attracted to the high tech look of the resulting system and was inclined to compromise many of his further wishes. The second function of the tubes, in a part of the façade, is to transport the dead weight of the façade to the foundation as the tubes would stick out through the insulated glass panels and the deadweight would be transferred by stacking the glass panels on top of each other. In this way two functions are integrated in these tubes: holding the cable and leading off deadweight. It was foreseen that the dimensions of the tube, cable and spacer are synchronized with extremely small tolerances. The composite spacers had to be developed to obtain a real overvalue of the composite spacers over the metal ones.

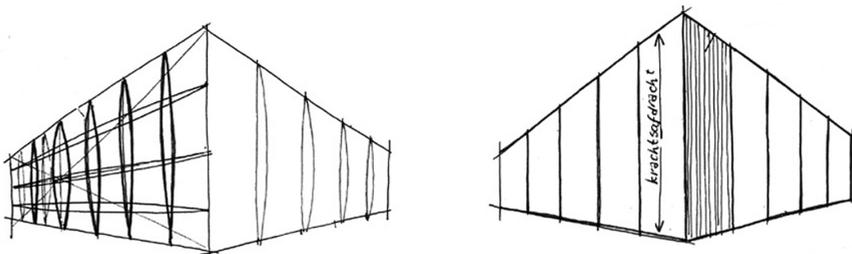


Figure 2: Sketches from brainstorm sessions.

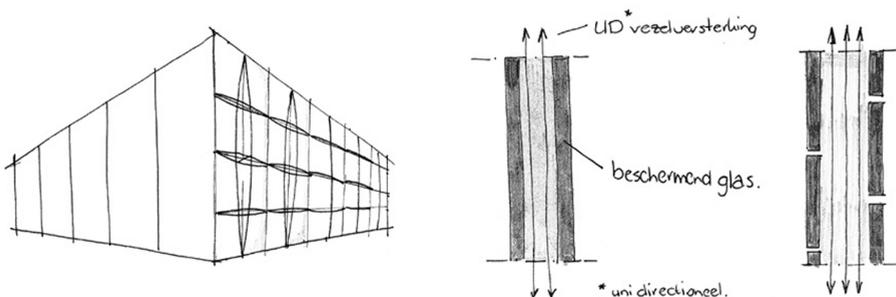


Figure 3 and 4: Sketches from the brainstorm sessions.

The end of the first experimental design phase was in fact the full size mock up in the factory of Octatube, on the other side of the street as the actual INHolland building

under construction. The mock-up was used for obtaining experience with pre-stressing of the Aramide cables and stacking and tolerances of the glass panels.



Figure 5: Overall view of the mock-up.



Figure 6: Detail of the mock-up.

3. Experimental Engineering and Prototyping Phase

After the initial design phase in summer 2008 Octatube, up to then one of the design team partners, was asked to make a quotation for the designed system. At that moment free brainstorming first phase changed into a potential dangerous engineering and prototyping second phase. Now it became really serious. Octatube took up the challenge, well aware of the seriousness of the challenge and the potential dangers. Ultimately the client expected a fully guaranteed façade system, developed up to a trustworthy level of maturity. The process was now connected with the execution of the building of INHolland as the prime application. Deadline of the building was foreseen as opening in September 2009, the starting date of the new school year.

Wind loading on the façade as a whole was to be taken up by vertical pre-stressed cables. As these cables are flat and quite in contradiction with the usual engineering practice of stiff structures, the system would work as a flat cable system and have as a consequence large deflections. The structural action of the individual glass panels would be to bend in a polygonal line under wind loading, the glass panels would act as stiff members in a vertical chain. In the detailing the degree of movement between the glass panels was to be regarded carefully, not to lead to breakage of any kind in the glass panels. The individual glass panels were regarded as multiple supported against wind force by the continuing cables in horizontal direction. The development of the carbon fibre tubes through the panel frames was for a long time quite insecure. Hence at that moment in time it was decided that the deadweight would be transferred through vertical tensile action to the top of the façade, rather than via a downward action to the foundation. This was reached by the introduction of vertical stainless steel suspension rods in between the vertical seams, within the central space to be sealed off from both sides with silicone sealant and hence invisible. The consequence of stacking these cables was the vertical seams had to be in line vertically, in contrast with the brick-mode proposed by the architect, which still was kept in the full-size prototype.

The principal of the 13,2 meter high façade is based on a sail. The insulated glass panels have the freedom to rotate slightly under wind loading. The glass panels are tied like a chain around the aramide cable. The horizontal wind loads are transferred by these cables to both end: the top of the building and the bottom, near the foundation. With extreme wind conditions, appearing statistically only every 50 years, the façade is supposed to deform 330 mm maximal inward and 330 mm outward without any problems. After investigation on the market the composite cable was selected. Phyllystran HPTG cables consisting of a high modulus elasticity yellow aramid fiber core in parallel construction, protected by a black extruded polyethylene jacket. The cables have an excellent resistance for fire and changing loads. The common contemporary applications are bridges, towers and rigging for sailing yachts. The idea was conceived that during installation of the façades the glass panels are temporarily attached to a complete scaffolding on the inside of the building. The feeding of the cables would occur from the top downwards. The pre-stressing and certification of sufficient pre-stress would follow later.

By placing the cables in the spacer of the glass the system is, structurally seen, very efficient for the glass panels. Structurally each glass panel has multiple supports by the cables. Therefore deflections and stresses in the glass planes are quite low. Out of reasons of safety all glass panels are not chosen to be fully tempered only, but laminated from two fully tempered glass panels. This system would result in a façade with a super minimal thickness of only 50 mm! Outside nor inside the two glass planes there would be no structure, both sides of the facade were thought to be totally smooth.

4. Additional testing

The velocity of a real construction process is ruthless for experimenting engineers. Every uncertainty has to be tested and tests take time, especially when also long term behaviour has to be imitated. The obvious choice is often to go back to tested and certificated elements and refrain from new and unknown elements in the construction. Or in case of selection of new elements to test these and come to a certification level in a short time, testing only individual aspects one after the other. Some hesitation on the part of Asahi Glass Company (AGC) as the nominated glass panel producer concerned the connection between composite tubes and the metal spacer frame. In practice AGC was familiar with other examples of composite spacers, however they always had a steel backing for the vapour tightness and proper sealing off. The glass producers refrained from using composite frames and went back to metal frames, as the sealing around would give a trustworthy air-tightness and the tests of composite gluing did not appear to be satisfactorily enough for the supply of all usual guarantees on the glass panels. The client hesitated as the INHolland Compositated Laboratory was not amused at all by this manoeuvre, although it was obvious that further tests were necessary for the certification process, which would make it hard to have the façade ready parallel to the actual building process. Prof. Ulrich Knaack TU Delft was asked for a second opinion on the degree of innovation of the proposed façade scheme with metal frames. After having received his advice the client, INHolland Real Estate department, decided to use this patented metal frame technology as a launching customer in the new building of the INHolland Polytechnic School in Delft. The atrium consists of three facades. It was agreed in this stage that the two large facades would be executed as proposed by Octatube/Asahi and the third, more narrow façade of only one glass panel wide and

13,2 m high, would be executed as per original design completely in composite framing. The narrow composite façade would demonstrate the innovation possibilities with composites in architecture. The further developments and realization of the two main façade were all executed by Octatube, the composite façade was executed under responsibility of the INHolland Composite lab.

5. Structural Analysis of the Realized Façade System

The façade is a planar one-way cable system which stabilize the glass façade through the resistance to deformation of the pre-tensioned cables. The façade system has large service deflections for the maximal wind load event. The lateral deformations are necessary for the system to transfer the (wind)loads and are resisted by the tendency of each cable to return to its straight line configurations between supports. The maximum deflection of the façade is $L/40$ of the facade its height. In this project the façade is 13200 mm height, the deflection is maximal 330 mm, inward and outward. This lead to rotation angles in the façade of approximately 1 degree. This protect the integrity of the glass and sealants and minimized a perception by the buildings occupants.

A first impression of the forces in the cables of the façade can be determined with a very simple rule mentioned in figure 7. With the wind load the height of the façade and the maximal allowed deflection the vertical and horizontal forces can be calculated.

- Wind load effect on deflection of the wall
- First movement small force needed, deformation is necessary to obtain routing of forces, the cables have no bending stiffness
- Number of elements determine the deflection: constraint stiffness, stiffness cables, pre-stressing cable, wind loads. The critical design goal is limiting deflections through adjusting axial stiffness of the cables, and the pretension;
- This also have influence on the own frequency of the façade
- No vortex at the edges so that the wall does not resonate / swingrelative high preload so that the deformation of the recessed construction not become too high during wind ==> Every days deflections of $L/150 = 13200/150$. The wall components are (off course) designed to accommodate this movement without compromising wall performance. The cable of aramide has excellent durability qualities
- The tensioning of the cables must be accomplished with all cables. This requires rigorous methodology frequently involving sophisticated hydraulic jacking gear. Compensating adjustments in the tensioning can be computed and implemented. The trick of the cable structures is in the tension: first determining appropriate theoretical cable pre-tensions with respect to the boundary conditions, then realizing those tensions exactly in the field on site. Any adjustments must be systematically and not locally.

Leading the deadweight to the surrounding structures has been deliberately separated from the wind loadings on the facades. The deadweight of the separate panels is guided by means of tensile rods, in the space between two adjacent double glass panels. The rods are provided by steps, which function as supporting steps. Both suspension rods and steps are located within the volume of the glass units, but in the open space to be sealed off later. The suspension rods in stainless steel. The steps in POM. Gravitational

loads are carried by the suspension rods, because it is hard to make mechanical node attachments on aramide cables. The upper structure had to be provided with the proper suspension provisions, which were not present in the main steel structure due to the late decision for the experimental façade. In the concrete the usual drillings had to be made, this time in large holes of 300 mm diameter which was complicated because of the heavy reinforcements and the uncertainty with the actual location of reinforcement bars. On the inside of the façade a complete scaffolding was to be build up with clamps on the outrigging elements, so as to enable temporary purlins to be attached. On these purlins the individual glass panels are temporarily attached, stabilised against wind loadings, while the deadweight is already carried by the suspension rods and saddles. The glass panels are positioned in alignment of the vertical and horizontal seams on the one hand, but even more precise will be the alignment of the tubes, through which the cables will be fed. This was the situation of development in spring 2009. In the mean time the reaction forces, not only from the suspension rods, but also from the prestressed cables had an important strengthening and stiffening on the substructure of the roof, from which the cables were stressed. The 2 corners of the glass facades presented a further engineering challenge. The two glass pales of the 2 facades can move outward both as well as inward, 330 mm from the neutral position. This leads to the conclusion that the largest deflection would be in the middle, decreasing towards the top and bottom of the corner. In order to allow the g both glass facades complete freedom of movement without the danger of collision and hence breakage, the corners have a rubber detailing in lens form. The material is a double rubber membrane with a rubber insulation material as a sandwich in between.

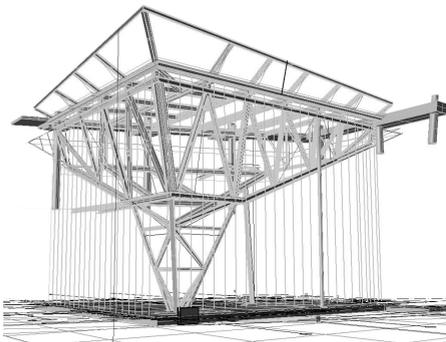


Figure 7: 3D view of steel – concrete structure with aramide cables

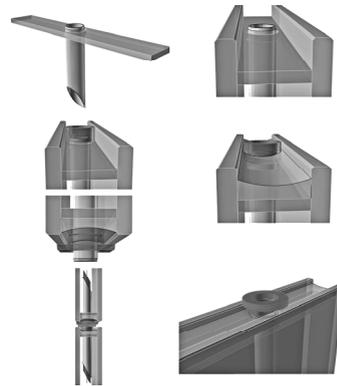


Figure 8: Detail of the tubes between the insulated glass panels

6. Third Phase of Productions and Realization

In this experimental process also the production appeared to offer more unsuspected problems: the glass panels manufacturer had discovered that the tests did not provide satisfactory results as to the air tightness of the tube-to-frame connections and the air-tightness of the carbon fibre tubes themselves. The direction of Asahi would not issue the normal guarantees of the glass panels in this case. In a dramatic week in may 2009, the author took the decision to reposition the cables with the carbon fibre mantle tubes to the inside of the spec, adjacent to the insulated glass panels. So with this manoeuvre

guarantees were given again, but the project had lost one of its innovative potentialities. A potentiality, however, that could easily lead to the necessity of the complete replacement of the entire façade when the insulated glass panels. On costs of the supplier within 10 years and on costs of the client after that date. So the client also agreed. The architect indicated that Octatube would have to develop the system further as he would want to apply the original integrated glass/cable system in a future building. Other set-backs were caused by the supplied stainless steel end pieces of the aramid cables that were produced by a yachting supply industry in New Zealand. They appeared to have only 60% of the breaking strength compared with the ultimate expected breaking strength. In an ultra short time these end pieces had to be redimensioned, produced and flown not to cause delays in the crucial construction time, where steel structural engineers, concrete engineers, Octatube erection crew and glass producers collided in the planning.

7. Conclusion

An experimental design and development process best is to be organised separate or preceding to an actual zero-series construction process. Independent team players who have their own agenda's are often hard to integrate in the process. In principle it is wise never to combine a highly experimental project with a fast running building construction process. It is worth while to keep incremental steps forward in the development of systems. Small steps each time.

In the first experimental design phase progress was slow and many times contradictory, until the stage was reached of the integration of pre-stressed cables with insulated glass panels. Many long meetings were organized and (even more) good and bad solutions and designs have been made. After a selection it finally led to a design with an air-tight system not easy to be executed as all construction details had to be solved within the thickness of the 50 mm insulated glass panel. In the feasibility study it appeared that the chosen composite-glass façade was technically possible in conformity with the process on the market for design facades. To explore in this phase already the production of the insulation glass panels in detail a demonstrator of 3,6 by 5,0 meter was realized. The mock-up did not only give a good overview of the production and assembly aspects for the material suppliers and producers, but also gave other technical information. It was shown that it is possible to make the façade with very small tolerances of less than 1mm. In the second experimental engineering and prototyping phase several parts of the concept façade have been developed in more detail and tested in a small parts testing program. Major drivers for the tests were the structural behavior and the durability. Most important were the temperature and moisture influences on the composites in the façade, the always changing loads and above all the production and assembly processes. An unexpected draw-back was formed by the composition of the insulated glass panels where the composite frames had to be substituted by conventional metal frames which have proven performance and guarantees. The third phase of experimental productions and realizations had two problems. One in the engineering and production of the end pieces of the aramide cables. The other, as a result of the testing, inadequate trust in the performance of the air-tightness of the feeding tubes thought the framings of the double glass panels, so that for the two larger facades the cables and tubes were repositioned on the inside of the glass panels. The developed facade concept is characterized by its innovative character on multiple levels, the concept as a total, with pre-stressed cables.

Challenging Glass 2

The application of composite materials in this type of façades is exclusive. The total picture is an ultra slender, frame-less, façade, with a high of 13200 mm. This led to a very slenderness ratio of almost 1:300. The built façade proves that a ‘wild idea’, when properly and seriously developed, can be realised within a few years. This is the convincing force of design.



Figure 11: Today's state of construction.



Figure 12: Impression of the living composite glass facade (image Rietveld Architects).

8. References

- [1] Eekhout, M., *Methodology for Product Development in Architecture*, IOS Press, ISBN 978-1-58603-965-3.