From Tensegrity Frameless Glazing to Zappi

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1. INTRODUCTION

During the past decade since the first LSA '86, a new type of lightweight structure has been developed in Europe which makes use of a combination of developments that have originated from a new pioneering generation of building product developers. Interesting progress has been achieved through the design and building of frameless glazing constructions using tensegrity structural schemes, sophisticated insulated glass panels with glued connections for glass façades and roofs. The search for a more structural use for glass resulted in the formation of a research cluster at TU Delft on an unbreakable, structural transparent material called ZAPPI.

Fig.1: Kenneth Snelson's tensegrity tower at the Kröller-Müller Museum in Otterloo, the Netherlands: 'Needle Tower', 1968

In 1949, the American artist, Kenneth Snelson, invented the 'tensegrity principle' while exploring his sculptures. He showed his models to Richard Buckminster Fuller who had been experimenting along similar lines of thought since the 1920's. In the mid-fifties, Fuller published the name 'tensegrity', a blend word formed from the words 'tension' and 'entegrity'. Initially, this new concept attracted interest mainly from academics, mathematicians and sculptors. Structural engineers predicted that the proposed principle would result in structures that would be subject to relatively large deformation under loading. Only after the development of the theory of stretched membranes and cable net *structures by Frei Otto in the 1950’s and 1960’s, was the tensegrity principle introduced as an expedient for the purposes of stabilizing membrane and cable net structures in the form of an individual, ‘free-hanging mast’. Large deformations in this type of structure were acceptable because the membranes and cable nets were flexible enough to tolerate them. The tensegrity principle in structural design is a structural scheme in which compression elements are not directly connected to one other, but instead are stabilized to an integral structural system by means of tensile elements.*

Fig. 2: One of the prototypes designed and realized by students of architecture at the TH Delft, the Netherlands, in 1972: 'Tensegrity Wheel'.

That was three decades ago. During the development of new, flat-roof structures with suspended vertical compression studs, with cables at the top and bottom, and covered with flat glass panels, it became clear where the roots of contemporary, tensegrity glass structures were to be found. The tensegrity principle, which once was of purely academic interest, has finally reached the stage of practical construction in the field of frameless tensile glass structures, by way of the field of membrane and tensile structures. Ten years of continuous development have elapsed in my office since the first prototype model was constructed and exhibited in an exhibition in Rotterdam. The first tensegrity glazing prototypes were truly experimental. Gradually, they evolved from experiments into duplications, and from systemizing into standardization. This paper represents an overview together with insights about the current transition in building products from system to standard. The Design & Development Group of Octatube Space Structures, led by the author, has developed a number of diagonal tensegrity frameless glazing systems which can be architecturally applied in roofs and facades.

Fig. 3: The first structural glass prototype designed and realized as a 1:4 scale model for the Booosting Exhibition in 1988 by civil engineering student Rik Grashoff, at Octatube in Delft, the Netherlands.

The author, a professor of product development, has taken these experiences and transformed them into manageable information for structural designers. This paper describes the knowledge that has been gained over the past decade about the different systems and subsystems of frameless glass structures, all of which are based upon the tensegrity principle. The original tensegrity principle, with its inherently large propensity to deform under external loading, has now been combined with glass panels that are extremely prone to post-installation deformation. It would seem to be a reconciliation of opposite weaknesses. The results dealt with here are a blend of design, development, research and application-engineering.

2. SYSTEMS AND SUBSYSTEMS

A system is an ordered set of elements and components with connection facilities which can be joined and/or applied in different ways according to certain rules or conventions within the application environment. Depending on the system composition, the system can be split into subsystems each of which can function or be produced or purchased separately and/or independently. Systems can be used both in 'immaterial' and 'material' environments. In this article, the immaterial environment is exploited in the design phase, whereas its actual application always takes place in material form in the production and building phases.

The most characteristic differences in tensegrity glazing are to be found in its structural system. The glass panels have been developed for general purposes, that of framed glazing and frameless glazing not based on the tensegrity principle. The nodal systems have also been developed for a wider range of connection possibilities; tensegrity glazing only has a limited selection of suitable nodal connections.

Architecturally, the total building is composed of different characteristic building sections, each having different functions, technical schemes, materials and connections. Each building section is a set of components with a similar function. Components are collections of elements which form the smallest units with monomaterial content and which are non-composed. As in chemistry, the elements are the smallest indivisible material building blocks. To avoid misunderstandings about complex compositions, the prefixes 'sub' and 'super' are used to fine-tune concepts. This results in a 6-level hierarchy: subelement, element, superelement, subcomponent, component and supercomponent.

These 6 levels really are a subdivision of a main system into subsystems in six hierarchical levels. Elements and components have a place in the Hierarchy of Building Products:

Raw Material
Material
Composite Material
Commercial Material
Subelement
Element
Superelement
Subcomponent
Component
Supercomponent
Building part
Building

From the point of view of the science of product development, system-building products are halfway between special building products and standard building products. They can either be developed from one-off or special products which attract public interest, and could be followed by a duplicated design, and so on. Alternatively, a duplicate can undergo some alterations until a common average design answering the majority of demands has been defined, but which can still undergo minor modification, thereby giving birth to a new system product. If standard building products with **production before sale** have to be modified because of unusual specifications, the other approach is used: **production after sale**. In this sense, the answer is a partly designed product with all its essential characteristics predetermined, apart from changes to aspects of a technically minor nature, such as for example, exterior form or colour. In reality, design takes place in two phases: the **system design** and later, the **application design**. A technician, however, would prefer to call these phases initial **technical design** and subsequent **dimensional engineering.**

In today's construction industry, a shift in interest can be detected away from standard products to special products, certainly as far as the prominent parts of buildings are concerned. Quality dominates quantity, within the limits of technical feasibility and economics. This influence can partly be attributed to the efforts of the high-tech architects of the 1980's. While the product development of special components was taking place in those architects' offices, the design & development departments of manufacturers were engaged in the design and development of standard products and system products. This paper draws on the experiences of many prototype designs, one-offs and duplicates, into main systems and subsystems.

3. THE TENSEGRITY PRINCIPLE

Definition: the tensegrity principle in structural design is a structural scheme where compression elements are not directly connected to one other, but are instead stabilized to an integral system by means of tensile elements.

The non-relationship between compression elements is *essential* to this definition of the tensegrity principle. Individual compression elements are only connected to other compression elements by means of tensile elements. The nature of forces is usually axial, that is to say, either compression or tension. Loading under bending is avoided because it is considered an uneconomical and mass-consuming principle. This principle is based on a visual interpretation. Other interpretations such as those with their roots in mathematics or statical analysis, refer to statical indeterminacy. If tensegrity structures are considered in a pure way, it could be held that pure tensegrity structures are closed structural systems.

On the other hand, by definition, open schemes rely on the surrounding structures which are not part of the structural system. They have to produce sufficient horizontal reaction forces for horizontal spans, or vertical reaction forces for vertical spans in order to maintain equilibrium. When the external reaction forces can be exerted by the surrounding load-bearing structure, then it is easy to design a tensile structure. It is a question of definition as to whether these 'open' structures really belong to the family of tensegrity structures, since the entity of tensile and compression forces play an important role in the definition. In order to minimize the amount of material in structures, tensegrity structures without surrounding compressive rings are also considered members of the family, possibly 'brothers-in-law': **open tensegrity structures**. These are smart structures in the sense that they make extensive use of the over-rigidity of the existing surrounding structures. Considerations regarding the size of the building and the tensegrity structure often originate from deformations under external mechanical and thermal loading, leading to disconnection of the tensegrity structure and the substructure. In such cases, the open character of the structure evolves into a closed one. However, the internal statical principles in the tensegrity scheme remain unchanged. It can be stated that the overriding characteristic of a tensegrity structure in the internal system is that its compression elements are never directly connected with one another. Depending on the material used for the covering, the main structural tensegrity system has to create sufficient rigidity under external loading.

Many cable-stayed tensegrity domes were built in the USA during the 1970's and 1980's. Larger deformations did not represent a

Fig. 4: Tensegrity suspended mast in the cable-net roof of the Olympic stadium in Munich, designed by Günther Behnish and Frei Otto, and realized in 1972

major obstacle because the membrane material could adapt locally. However, if glass panels or insulated glass panels made from tough, fully tempered glass are chosen as the covering material, a greater accuracy and much smaller tolerances in production, positioning and deformations under loading, are acceptable.

4. STRUCTURAL SYSTEMS

The structural systems derived from the tensegrity principle can be defined according to a number of different principles.

4.1 Open and Closed Systems

Firstly, they can be divided into open and closed systems, though the differences between them are small compared with the core definition. (For the core definition of the 'tensegrity principle', see section 3).

Fig. 5: Open and closed tensegrity systems.

4.2. Singular and Multiple Studs

Secondly, there is the difference between singular and multiple-compression stud configuration. There are numerous examples of open structures having a single span and a central, vertical compression stud, and a cable-stayed tensile rod. This could be called an ‘individual, free-hanging mast’ configuration. The multiple span is called a ‘multiple, free-hanging mast’ configuration.

4.3. Single and Opposite Loading

Thirdly, the resulting configuration for upward and downward loading will be a counterdirectional, individual, free-hanging mast configuration, or a double, multiple free-hanging mast configuration, respectively, as compared with the single configuration which can only accommodate loading from a single direction. This is important in the case of roof loadings where dead weight, snow and a positive wind are crucial, and where negative wind loading is neutralized by a sufficiently large dead weight. With lightweight roofs, opposite loading cases have to be achieved, whereas with heavy roofs, a single loading direction is crucial for the choice of system and for dimensioning. In the case of façades, however, when dead weight is acting in the neutral direction, wind from opposite directions usually results in configurations with opposing stabilizations.

4.4. 2-D and 3-D Configurations

Fourthly, a clear distinction is made between a two-dimensional configuration and a three-dimensional one. 2-D configurations are flat trusses. In combination with the geometrical tensegrity principle in closed systems, the two compression elements acting in two perpendicular directions should only cross, not intersect one another. This can only be achieved if a single stud in one direction is combined with a double, symmetrical stud in the other. Although it sounds somewhat improbable, it nevertheless serves to point out the more elaborate and more complex geometrical systems. The single and double studs are crossing one another without intersecting. With 3-D configurations, only the statically indeterminate possibilities are introduced. The open 2-D configuration, for example, is extremely economical if the same configurations can be used side by side, because only the ends of those configurations require external reaction forces from the surrounding structure.

4.5. Different Geometrical Configurations

Fifthly, the three-dimensional configuration can be a radial, orthogonal, three-way or random configuration of arbitrary directions. Structurally, the difference between the one way and two-way configuration indicates statical determinacy or indeterminacy. The third direction not only adds another direction of tensile elements which themselves contribute to safety in the event that one of the other directions becomes overstressed, but it also increases the complexity in the *analytical* phase, and even more so in the *installation* phase.

4.6. Regular or Irregular Geometries

In line with the current development form, that of modern to post-modern architecture, or even de-modern / de-constructive architecture, it may be worth speculating about the transition from order back to chaos. However, this can only be done once we have mastered, or at least know, how to manage order in chaos. So let’s first try to consider regularities which are always simplifications.

Once we have mastered them, glimpses of chaos or decompositions may be introduced on a controlled and gradual basis.

4.7. Morphological Box

The first five parameters mentioned can be endlessly combined according to the illustrated morphological chart:

Parameter 1: 1.a. Open system
1.b. Closed system
Parameter 2: 2.a. Singular stud
2.b. Multiple studs
Parameter 3: 3.a. Single loading direction
3.b. Multiple loading direction
Parameter 4: 4.a. Two-D configuration
4.b. Three-D configuration
Parameter 5: 5.a. Radial configuration
5.b. Orthogonal configuration
5.c. Three-way configuration
5.d. Random configuration.

A combination of the above 12 possibilities in a flat chart theoretically offers 64 combinations if placed in a 5-dimensional box. A number of these combinations are impossible, or at least beyond the scope of our imagination at present. Their exploration creates surprises that we would never have imagined before.

5. MATERIAL AND DETAILS

As tensegrity structures are normal force structures without any bending, the material most suited for such visually minimal structures is either stainless steel or coated steel in the form of cables and rods for tension, and hollow circular tubes, or solid bars, for the compression elements. There is more freedom of choice for the compression elements: solid aluminium, cast stainless steel, nodular iron or aluminium with conical forms, and even timber poles could be used with steel topping (or copper, for interior or very decorative applications). All these materials indicate that a very careful design of cross section and shaft silhouette (calf-shaped) can be appreciated in environments which are susceptible to design. The details at the connections of these elements primarily depend on which materials have to be connected and in what form. We are now entering the domain of structural design. The personal preferences of the designer play an important role here. Details are mainly governed by technical function, perfected by design details and by other considerations such as abstract or mechanical connections, concealed or exposed bolting, and pure or decorative styling. For example, the design details of Kenneth Snelson are very abstract. The connection ring is shaped like a cork in a champagne bottle with the butt-ends of the cables on the inside. During installation, fitting is only made possible by a little over-stressing of the tensile elements, with the result that the cables are not fully stressed in the structure standing up. Snelson did not like using turnbuckles - which are ideal for post-tensioning.

The use of galvanised steel or stainless steel cables, is best combined with the use of post-tensioning elements like turnbuckles, or post-tightening treaded cable ends. Glass structures are very susceptible to deformation, so large deformations such as those which occurred in early tensegrity structures, are unacceptable. Cable structures have to be post-tensioned because the mechanical deformation created by a cable under tension causes the structure to lengthen and hence deform the entire structure. Tensile rods do not have this disadvantage, and can be tightened without much pre-tension - just enough to avoid buckling under compression loading. The advantage of tensile cables over solid tensile rods is that the high allowable tensile forces result in very slender cross sections.

Often, however, the number of end fittings such as fork terminals and turnbuckles, which are essentially thicker than the cable itself, overshadow the slenderness of the pure cable. The use of tensile rods with treaded ends results in shaft diameters being thicker than the cable, but consistent and simple in their detailing, if the receiving ends of the compression components have adequate treaded holes with room for post-tensioning.

The methods used to connect tensile elements include:

- **Screwing:** turnbuckles on treaded rod terminals on cables, or treaded tensile rods
- **Welding:** simple for mild steel, but are a hazardous operation for high-yield steels
- **Bolting:** usually with shear-loaded cross bolts, through connection plates welded on solid bars
- **Pinning:** more luxurious, with purpose-built cross sections, pin heads and locking devices

The connections at the end of the compression tubes can be accommodated within the tube, or can be detailed as a top on the tube. They can also be designed as a set of flanges welded in the correct directions on the tube, in line with engineering practice, with small refined plates in the correct directions, or alternatively expressive plates for show. They can also be designed as a separate head on top of the tube, like a ring for cables, perpendicularly positioned on the shaft of the compression tube. Or they can be designed as a solid or hollow sphere for cables and tensile rods in different directions, in order to express the omnidirectional capacity of this nodal point.

6. CONNECTION NODES BETWEEN GLASS

The connection nodes between glass panels and steel structures are the same as those that have already been developed for connecting frameless glass panels to other types of load-bearing structures. They were not specially designed for tensegrity glass structures. Their common feature is that they usually connect the corners of four adjacent glass panels by means of a bolt through a metal node which usually has a four-way spider form. The connection node directs forces from the corners of the four panels towards a central node in the back structure. The literature is littered with references to project-designed and proprietary-designed connection nodes.

6.1. Tolerances

One major consideration at this point is the balancing of tolerances. Tolerances are deviations from the theoretical sizing and positioning of the designed elements and components. Since the frameless glazing systems are fragile examples of prefabricated building components, production is based on theoretical drawings. On-site measurement and then adapting components accordingly, as in traditional building practice, is no longer possible because production and construction time are planned in parallel rather than serially. Tolerances have a number of different causes:

Production tolerances:

- Cutting and grinding of elements to size in the factory
- Treatments which occur later on in the production process which affect the form, such as temperature treatments (hot dip galvanizing of steel, glass tempering)
- Positioning of elements in the subassembly process towards components

Positioning tolerances:

- Positioning of components on site with larger-than-expected or acceptable mispositioning
- Positioning of the anchors in the main structure of the building

Deformation tolerances:

- Deformation under the dead weight of the assembled and installed components
- Deformation under external loading acting on the installed components

6.2. Neutralizing tolerances

These tolerances all result in misalignments in relation to the theoretical sizes and positions originally recorded on the drawings. Typical deviations in the positioning of a reinforced concrete structure could amount to several centimetres, and are normally considered acceptable in the building industry. However, the maximum tolerances of frameless glazing can usually be anything between 2 and 4 millimetres. Because architects want to sleeve glass panels sideways into concrete walls, the two magnitudes of tolerances are incompatible. The tolerance zone really must be designed to include all the connections between the different elements, components and building parts, such as:

- Concrete — foot-plate steel structure
- Steel structure internally
- Steel structure — connection node
- Connection node — glass panel
- Bolt through the glass panel

In general the following rule applies: the smaller the number of sites for neutralization, the larger the tolerances are that have to be overcome at any one position. The countersunk bolt which passes through the glass is a visually pleasing solution, but since the bolt is always centred in the countersunk hole, its position cannot play a role in neutralizing tolerances. Connections in drilled and threaded holes do not usually offer much scope for accommodating any lateral tolerances either.

In general, four-armed nodes are made of steel, stainless steel or aluminium. Nodal elements with complicated forms lend themselves to casting. Even fine, wax casting in stainless steel appears to be an economical production technique if the absence of subsequent conservation and coatings is taken into account. Originally, many nodes were made of steel or from welded strips and solid plugs, or pressed, thick, flat sheet metal, laser-cut into a four-legged shape using circular fingertips (frog’s fingers). Both ends of the node have bolted connections, usually with one central bolt passing into the next component.

From a structural point of view, this bolt connects a threaded plug or sleeve hole welded into the structure. On the outer side, directed towards the glass panels, the bolt passes into a plug arrangement worked into the glass panel which has a countersunk hole on the outside, and is equipped with the necessary plastic watertight washers and silicone rings to make the air cavity gastight and airtight. Alternatively, connection is also possible using a bolt straight through the glass panel (through the 2 panes using the same tightening elements), and held in place with a rounded-off, circular stainless steel saucer with a 50 mm diameter. Alternatives to these fully mechanical connections through both panes of insulated glass panel, include the half-chemical/half-mechanical connection, which involves fixing the inner pane by screwing it while the outer pane is silicone glued at the spacers around the glass panes, and the fully chemical connection. This last option involves the use of a stainless steel ‘saucer’ shaped like a trumpet that has been glued under laboratory conditions in the factory to the inner face of the inner glass pane. This saucer has a threaded hole on the inside so that a bolted connection is possible. This glued connection was developed back in 1995, and its proven qualities have been found specially useful with double glazing panels that have sophisticated internal soft coatings which could otherwise be ruined during drilling or machining work.

Airborne silicone dust particles in the factories where double glazing is manufactured, usually result in a silicone film settling on the outer surface of the glass. This film of silicone dust will cause delamination problems if the glued surfaces of the steel saucers and the glass are not properly cleaned, degreased or polished to remove the dust. This method of glued, glass connection has proved to be very satisfactory and less susceptible to permanent watertightness compared with the fully-bolted of half-bolted connections for horizontal roofs, and has been used in vertical façades since 1996.

7. GLASS PANELS

These observations on the connections in or through the glass panels consequently lead to considerations about the glass panels themselves. Structurally, according to Timoshenko’s plate theories, framed glass panels connected at their four corners behave like a flat, solid plate supported at four points with a cantilevering corner. According to his theory, it is prudent to position the supporting point at a place where the support moment and the field-bending moment are equal. However, this is seldom the case when designing façade subdivisions (modules) of glass panels, as there is a tendency to reduce the number and size of the metal components to a minimum. In some cases, the four-point support at the corner does not lead to economical glass thickness. Particularly with regard to rectangular glass panels, the alternative to four corner supports is four supports with a cantilever in one direction. This model is an alternative to a six-pointed support with four corner supports and two supports in the centre of the longer sides. Despite the current tendency among architects to use maximum sizes of glass panels, Timoshenko's plate theory still holds good. In façades, glass panels are made of fully tempered glass. In overhead or roof glazing, the top panes are fully tempered / heat-strengthened, and laminated and full-tempered / heat-strengthened glass panels are used for the bottom panes. Both types of pre-stressed glass pane, the fully tempered and the heat strengthened ones, have both been subjected to a similar heat treatment up to 650°C in an horizontal oven while continuously moving on rollers. At the crucial moment, the glass pane is cooled quickly over a period of one minute in order to produce fully tempered glass, and longer and less forced over a period of 5 minutes in order to produce heat-strengthened glass. The allowable strength of ordinary float glass, that of 50 N/mm^2, is increased to 120 N/mm^2 in the case of heat-strengthened glass, and 200 N/mm^2 in the case of fully tempered glass.

7.1. Nickel Sulphite Fractures

The probability of spontaneous fractures with fully tempered glass resulting from thermal loads, is largely due to 'nickel sulphite' inclusions. These metal particles present in the float glass are apparently undetectable by any existing means. At least, this is what float-glass manufacturers claim. The only way of reducing the frequency of fracturing is to heat-treat the glass using the so-called 'heat soak' test. During this process, glass panels are heated to a temperature of 450°C for 2 to 8 hours. Glass panels which do not break under such conditions are not likely to break under normal temperature variation cycles either. Obviously this approach is not particularly scientific, so any suggestions to improve this rather 'medieval' process would be most welcome. Nickel sulphite fractures can usually be recognized by the double pentagonal ('butterfly-shaped') centres of rupture.

7.2. Production Limitations

The so-called, commercially available *Jumbo* panels of float glass are 6 x 3.210 metres in size, and range in thickness up to 19 mm. Individual glass panels are cut from these jumbo panels. The commercial tempering ovens in Western Europe generally have a maximum width of 2.140 metres, leading to a practical maximum production width of 2.100 metres. Lengths of 3.6 metres are possible, and in some cases 4.5 metres. These dimensions only concern the maximum production sizes.

7.3. Structural Limitations

The structural behaviour of these giant-sized panels requires engineering effort in order to keep the deflection and plate stresses within acceptable margins. With point-supported glass panels, not only are the field-bending moments decisive, but so too are the support bending moments. For this reason, point-supported glass panels need to withstand higher allowable stresses like fully tempered glass panels can, although any sudden air-cooling of the heated glass panel results in a pre-stress mechanism in the pane field, though less so at the edges and at the edges of the glass holes. The cooling air will flow around the glass mass at those panel ends, leaving no compressed glass material in between the two faces. Broken, fully tempered glass panels display the largest irregularities at their edges, although careful detailing can solve such production flaws. Glass panels are usually strong enough, but because they are so thin compared to the span, the design analysis would be dominated by the minimizing of deflections. The acceptance criterion for façade panels is around 2 x T (twice the thickness of the glass panel) resulting in restricted rotations at the corner support points. Technically, even 4 x T could be accommodated, depending on the wind load, thickness, span and positioning of the support points. As far as large deformations are concerned, the point-support mechanism is fully hinged, whereas smaller deformations can be accommodated by rubber or silicone washers which act by deforming the washer. Large deflections, however, are visually unacceptable because the reflections in the panels and the large visual movements across the façade that could prove spooky. With roof panels where, apart from live load and snow load, the permanent dead load is also active, a more stringent requirement is considered prudent: 1 x T to 1.5 x T for flat roofs, provided the water-drainage slope is sufficient. These considerations hold for both single glass panels and laminated glass panels in roofs. Leaving aside all considerations of strength and stiffness, glass panels are extremely susceptible to mechanical damage. As an engineering material, glass is not able to redistribute high loadings because it cannot deform locally.

7.4. Fracture of Pre-Stressed Glass Panels

For reasons of safety, overhead glazing should always be laminated. Fully tempered glass shatters in small cubical fragments; the lamination layer is intended to hold the fragments to the intact pane. If, however, this second pane also fragments, the result will be a plastic film, suspended in the form of a catenary or a suspended wet towel, loaded with fragments on both sides. As the lamination film is only used for bonding and was never designed to hold double fragmented dead weight, the holes will tear and the panel will inevitably fall down with disastrous consequences. The consequences could even be fatal where greater heights are involved. The design criterion is to prevent glass panels from falling at all times. For this reason, laminated glass (VSG) in Germany has to be composed of heat-strengthened glass (TVG) which has a rupture pattern of large random fragments. Since two fragmented panes do not have identical fragmentation patterns, this configuration is usually believed to have a higher safety behaviour. Unfortunately, the resulting structural strength is not as high as that of a laminated, fully tempered glass panel. As a compromise between economy and safety, a fully tempered pane of glass should be used for the upper structural pane, whereas the lower safety pane could be a laminated, heat-strengthened one. In some countries, such as Germany, full structural cooperation between the upper and lower panes in horizontal applications is considered theoretically unsafe. In this case, however, the upper panel has to be analyzed by computer to determine whether it can carry the entire external loads. However, in cases of vandalism involving bullets shot in an upward direction, it is always the lower (safety) pane that gets fragmented first.

7.5. Double Glazing

Frameless glazing is often chosen by architects by virtue of its maximum contrast with closed building parts i.e. concrete, brickwork or metal panels. In Western Europe, double glazing has a more practical character because winter conditions demand higher thermal insulation values. During the early days when double-glazing units were being developed for the purposes of energy conservation during the winter, glazing units were given a low emission coating. Today, modern coatings are of the ‘soft’ type and have higher performances than the earlier, hard types. Furthermore, decades have been spent developing glass with lower solar transmission ratios in order to eradicate or minimize a ‘greenhouse’ effect (resulting in unmanageably high room temperatures in buildings), while still allowing sufficient daylight to penetrate. Nowadays, however, exterior reflection factors have been reduced to those of a normal clear glass level. Developments in the glass coatings industry have led to the introduction of sophisticated soft coatings capable of reflecting the majority of sunlight and a minority of daylight. These developments are aimed at maximizing the difference between the two transmission ratios. At present, the maximum differences are 72% daylight transmission, 32% solar transmission, and an exterior reflection of under 10% - a difference of 40%! Further developments during the next decade must result in sliding transmission ratios. On dark, winter days or at dawn, or at sunset on summer days, buildings need maximum daylight penetration and maximum solar transmission, ideally a difference of 0%. In high summer, however, daylight penetration should also be maximized, or maintained at a lower allowable level, whereas sunlight transmission should be kept as low as possible. The difference between the two ratios should be zero in winter and highly positive in summer, compared with the positive 40% difference at present. The glass coating industry should continue its research in this direction.

7.6. The Quest for Zappi

Besides its positive visual properties, glass has only one set of negative characteristics - its poor mechanical properties. It would be logical to try and improve its mechanical properties, or, as a longer term objective, to develop a new transparent material with more favourable mechanical properties. This alternative material had already been given a name, even before any development on it had began, or before any of the desirable characteristics of the new material had been determined. That name was **'ZAPPI'**. The objective, to initiate a research programme to develop a new structural material, has introduced a research cluster which has been formulated in the ZAPPI Research Master Plan. The ultimate objective is "…the development of transparent structures, built from reliable, tough and stiff plate material for applications such as façades and roofs of buildings, at an affordable price". This undertaking began from the Chair of Product Development, Faculty of Architecture at TU Delft, and has involved the cooperation of the departments of Civil Engineering, Material Science and Aeronautical Engineering at TU Delft, and the Institute for Glass Structures, TH Darmstadt, and the Space Structures Research Centre of the University of Surrey. The programme comprises eight secondary objectives which students are gradually starting to work on, including:

- The design and development of suitable structural schemes
- The development of a new, tough transparent flat building material, by improving the characteristics of glass, or through the combination of existing or improved materials
- The development of numerical methods to describe the loading behaviour of the new plate material in structures
- The development of numerical techniques which describe the behaviour of transparent plate material with regard to physical characteristics like transmission, absorption and reflection of solar energy, daylight and sound
- Material improvement by adding upper layers, intermediate layers and coatings which improve or reduce the transmission of solar energy, daylight and sound, as required
- The development of applications in buildings, especially for façades, roofs and floors, where the magic of visual transparency and reflection can be fully exploited without stabilizing substructures in other materials
- The fabrication of panel components of commercially-produced flat plate material without special equipment
- A cost price/product performance ratio comparable or better than that of current glass products

8. CONCLUSIONS

A decade of design, development, research and application has resulted in a new type of space structure, the 'tensegrity glass structure', which combines material efficiency with maximum visual transparency and elegance. However, because current technology is extremely sensitive to the choice of system, material and assembly mode, only specialists with a great passion for their trade are able to realize such objectives successfully. However, interest is growing among leading high-tech and mild-tech architects. Their designs are encouraging the industry to regard structural and frameless glazing not as some passing whim of fashion, but to accept them as serious statements of the way forward in architecture.

The quest for Zappi has only just begun. The ultimate goal is, like the entire process, very exciting and stimulating, despite the many disappointments and careful manoeuvrings which each step requires. Researchers feel stimulated by a parallel process of various projects when experiments are put directly into practice. Fortunately, there are always project architects who are interested in thinking along with each step forward in technology, and being inspirational. Practice stimulates theory, and theory stimulates practice. Whether it concerns Quattro or any other newly developed building product, ever important considerations include, for example, how it reflects the building's technical value, its practical application, and the increase in the architectural quality of buildings. Zappi would love to see its product development result in better buildings, and buildings with greater characters. The value of developing something new is not enough in itself. Real satisfaction is, like in many other spheres, enjoyed by the victories won at the cutting edge.

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