Glass as Structure

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ABSTRACT

Traditionally glass is looked upon as an "unpredictable" material mainly due to its brittle characteristic. The tendency for more transparency in the last decades was the driving force to use glass more and more as load carrying structural element. Actually glass has a remarkable potential; it may be exploited if certain basic design principles are followed. Today glass is used on a large scale as a basic structural material.

The present contribution starts with a general outline of this evolution. Then selected practical examples like façades and roofs are described, demonstrating what is meant by "glass as structure". Finally a few concepts of glass–oriented design and analyses are explained in more detail. Here the necessity to make a careful and detailed analysis is stressed. Furthermore a few remarks to open questions in this context are given.

**International Association
for
Shell & Spatial Structures**

**INTERNATIONAL
SYMPOSIUM '97**

on

SHELL & SPATIAL STRUCTURES:
DESIGN, CONSTRUCTION,
PERFORMANCE & ECONOMICS

10 - 14 November 1997
Singapore

1.0 EVOLUTION OF GLASS AS STRUCTURE

Glass is one of the oldest man–made material. Its discovery can be traced back several thousand years. It is known that the Romans glazed their windows by panes of about one square meter size; however the creation of large, perfectly flat glass on a large scale started not earlier than in the 1680's when the casting process of plate glass was invented in France. At the beginning of the 20 th century the production of thin good quality glass sheets was industrialized when the drawing process and some years later the rolling technique were developed. These technologies were revolutionized in 1952 by Pilkington when they invented the float process avoiding expensive grinding or polishing steps to get high quality surfaces. Today the vast majority of glass sheets is float glass having a maximum width of about 3.5 m and more: The molten glass is poured over tin and afterwards annealed and post processed.

Transparency, durability and other physical/chemical properties of glass have fascinated the people since its very beginning. A material with a specific weight, stiffness and even (under certain conditions) tension strength of aluminium and a hardness of steel seems to be the ideal construction material [1]. However there was always this ambivalent relationship to this "unpredictable" material: Its brittle nature is being considered as an intrinsically weak and unreliable material, leading to a subconscious rejection to accept glass as a load carrying material. (The reaction of the visitors to the glass plates on the floor of the observation deck of the CN–Tower in Toronto allowing a view to the bottom of the tower is a typical example for a lack of confidence). Transparency has just its too sides. This uneasiness is even increased by the "cutting" feature of glass (Figure 1).

This human reaction is to a certain extent supported by simple facts. Glass carries loads in a linear way up to a limit at which fracture occurs; the structure fails almost explosively. Opposite to ductile material allowing plastic flow and redistribution of the stress state after yielding, glass causes brittle failure and has no resistance towards crack propagation. This in turn means that small flaws may cause immediate failure and there is no tolerance to discontinuities and local stress concentrations. In addition one has be extremely sure about loads, stresses, displacements. Since the absence of defects and the quality of data can never be exactly guaranteed glass is until recently looked upon as an unpredictable material. Consequently it is mainly used as an individual shielding element, as window pane, and the architecture is dominated by bracing systems, glazing bars and mullions which hold the glass in place. This concept nevertheless was brought to perfection, see for example the "skinning" of the highrisers, the so called curtain wall buildings [5].

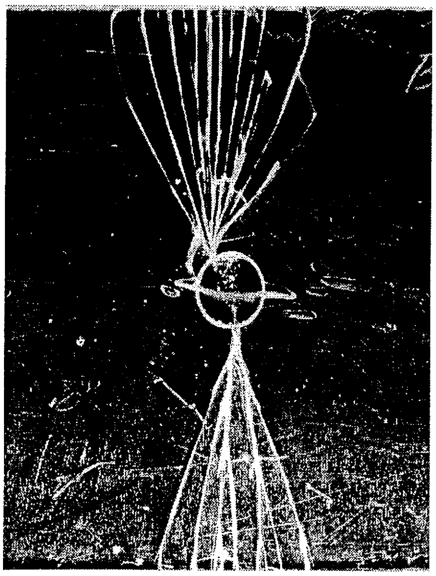

Fig. 1: Typical crack pattern of glass panel with hole under horizontal tension

Despite its problems glass can perform exceedingly well as a structural element. Since the 1960's the designers started to exploit its structural potential. Not that the basic material has drastically changed; however the specific weaknesses are more and more taken into consideration and avoided and special glass–oriented design principles emerged. Glass takes over basic structural functions or even acts as the structure itself, leaving a minimum of bracing to other materials thus giving the transparency of the entire system a greater emphasis. In other words the more non–glass structural elements are removed from the system the more the glass itself has to take over. Therefore the support of the invidual panel is often reduced to a few concentrated assembly points; the four point supported sheet has become a standard component. Typical examples are the curtain wall (les Serres) at la Vilette in Paris [4] where an assembly of sixteen 2m × 2m panels are hung together from the basic frame, or the Benthem House in Almere, The Netherlands [2], where the glass walls stiffened only by glass plates act as load bearer for the roof. Curved or facetted glass panels composed to a shell may act as membrane structure. The question for purity with respect to other materials supporting the system, e.g. by cable suspension, is a question of definition what a glass structure is: the transition from a simple shielding element like a window pane to an all glass structure or "glass container" is continuous.

2.0 GENERAL REQUIREMENTS

The key issue for the use of glass as a structure is its predictability. A lot of progress has been made in this direction over the last years although still a lot has to be done. The national agencies which have to take the overall responsibility in our society are in particular sensitized for these questions : The objectives are "fail safe" conditions. Different techniques exist to improve the strength of the glass, for example:

- Tempered or toughened glass introducing a prestress (with compression on both surfaces and tension in the interior) to improve its bending behavior and to reduce the susceptibility with respect to creep. The residual stress state is disturbed when the glass breaks; consequently it shatters into small blunt pieces which are more or less harmless. Toughening can be done by a heat or chemical treatment; the latter concentrates the compression zone to a narrow layer at the surface. The processes of cutting or drilling holes have of course to be performed before treatment. It is distinguished between full and semi toughening (heat strengthened glass).

- Laminated glass: a multilayer system of two or more glass panels combined with thin clear adhesive layers of plastic, mostly polyvinyl butyral film (PVB). The glass pieces in a broken pane stick to the film so that the overall geometrical integrity of the sheet is maintained and the risk of injuries is reduced. This might still be a problem for point supported panes where the stress concentration of the membrane may cause sooner or later a failure (Figure 2).

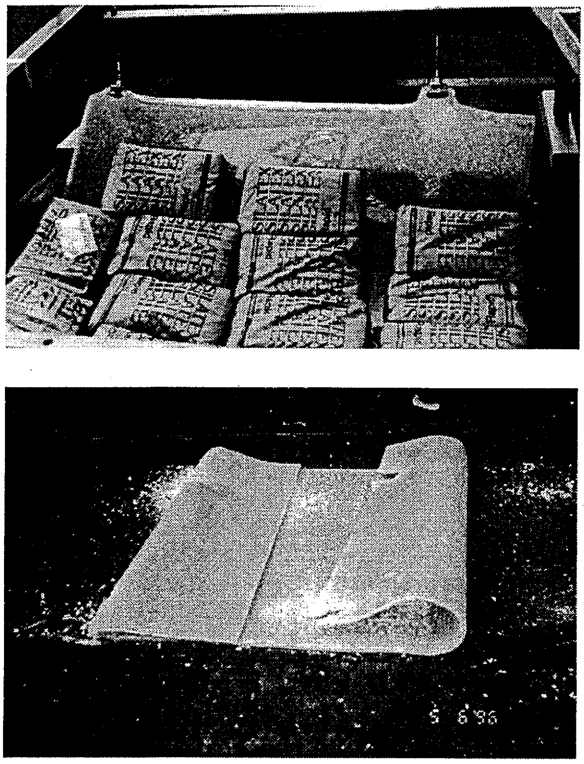

Fig. 2: Failure test of laminated glass panel

- Wire reinforced glass: a wire mesh is embedded into the glass to increase the overall strength.

The term security glass is not uniquely defined. Of course glass is also combined to multiple glazing systems with one or more inside cavities in order to improve its characteristic to environmental influences; for their mechanical behavior towards so called climate loads see [3].

In order to underline the potential and the features of glass as structure some typical examples the authors have been involved in practice have been selected and will be described in the next Chapter. It is followed by some remarks on glass–oriented design and analysis principles.

3.0 SELECTED GLASS STRUCTURES

3.1 CANOPY OF STUTTGART CASINO [7]

A cross section of the structure, Figures 3 and 4, is shown in Figure 5. The canopy has a length of about 11 m and a width of 4.5 m. Laminated glass with a thickness of (2 × 8+1.52 PVB) mm.

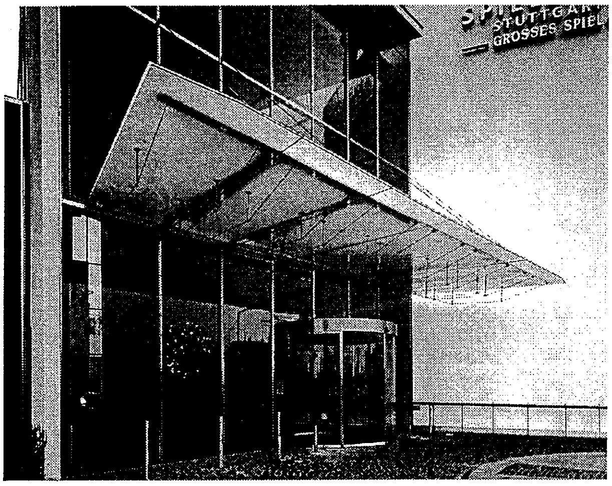

Fig. 3: Canopy of Stuttgart Casino

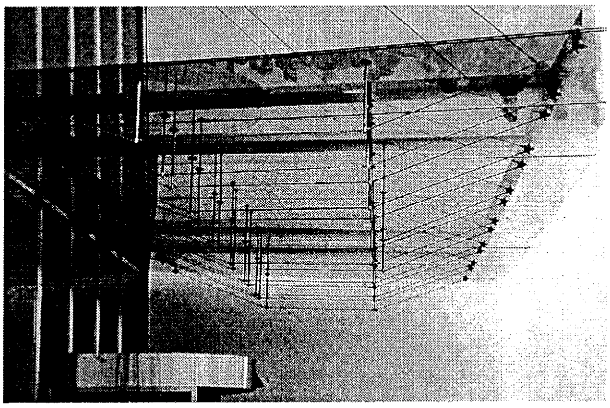

Fig. 4: Canopy of Stuttgart Casino

The principle of glass as structure is partially verified: The panels are hung to a base structure out of stainless steel suspended from the frame of a conventional façade; each individual sheet is in turn supported by two cable suspensions with concentrated supports. The glass itself acts as compression member of the combined system. It could also be activated as a stiffener for the entire façade construction.

Due to the pointwise support a very careful finite element analysis of the local stress state at the holes using shell and volume elements has to be performed. This includes the modelling of the excentricity of the support system (Rodan) and its elastic liner and sealing. Since glass and suspension form a statically indeterminate system the entire structure has also to be investigated to represent the individual stiffnesses.

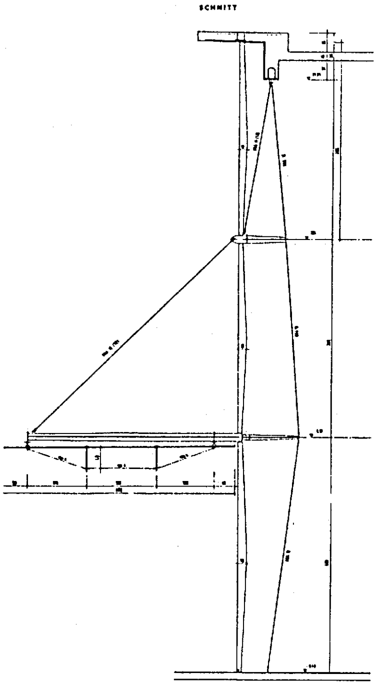

Fig. 5: Casino façade cross section

3.2 FAÇADE MARYLEBONE GATE, LONDON

The façade, shown in Figure 6, has a length of 18 m and a height of 17 m. It consists of four rows of glass panels 2 × 4 m and two rows with 2 × 1.6 m sheets. They are suspended by an orthogonal system with double S–shaped vertical stiffeners which in turn are horizontally fixed by cables. Glass panels are interacting with eachother by concentrated connectors (Litewall); i.e. no mechanical contact is provided. In this case the entire glass wall acts to a certain extent as compression member for the compound system, transmitting the forces through the concentrated support system. However its main purpose is to stabilize the steel stiffener against buckling. At this point it should be mentioned that glass façades have also

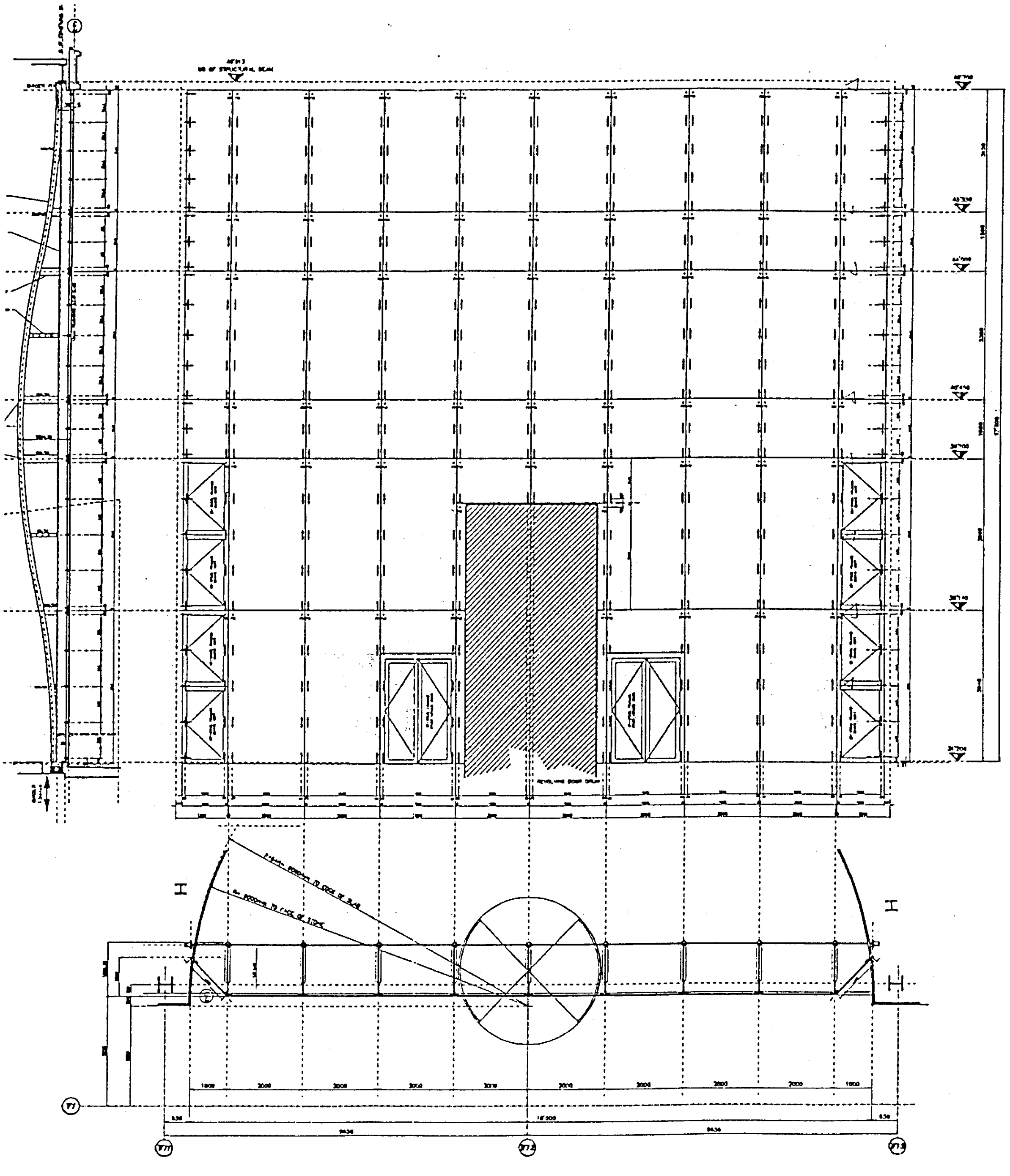

Fig.6: Façade Marylebone Gate

been stiffened by considerable glass fins which of course have to be braced against lateral buckling in case of suction. However the stringers have to be composed out of several glass elements. This requires again connecting elements (e.g. patched plates) which might spoil its transparent appearance.

3.3 GLASS FAÇADE AT KIRCHBERG, LUXEMBOURG

The glass façade, shown in Figures 7 and 8, with overall dimensions of 17 × 23 m is also suspended by a steel cable system. The horizontal cable truss consists of two single strand cables, parabolic in shape

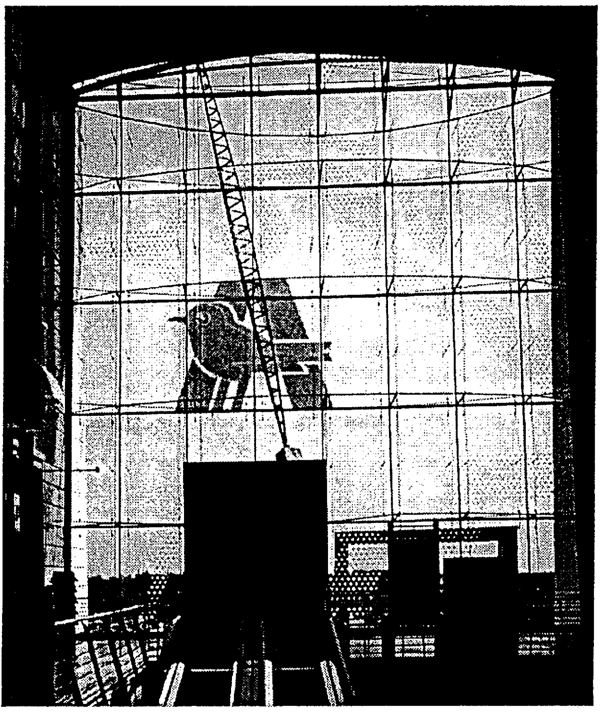

Fig.7: Façade Kirchberg

and connected to a steel tube by struts; they are fixed to the side walls. These systems are vertically stiffened by orthogonal cables which are spanned between the big arch frame at the top, also cable suspended, and the floor. The entire dead load is thus carried by the arch. Each individual glass panel 2.1 × 3.6 m (thickness 10÷12 mm) is hold at the four corners by a concentrated support system (Rodan) to the steel tube. In addition these plates are individually suspended from both sides, see the detail in Figure 9.

Wind pressure and suction can be equally taken by this structure. The concept again means that glass is used as basic structural element to carry the compression in the suspended system.

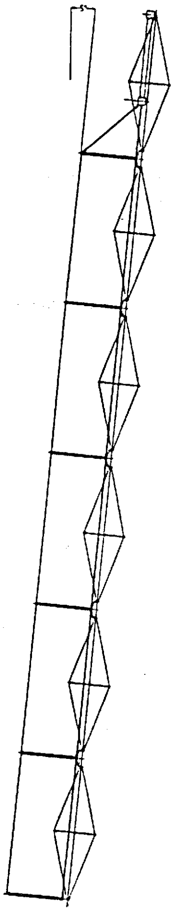

Fig.8b: Façade Kirchberg – Vertical section (Height 23m)

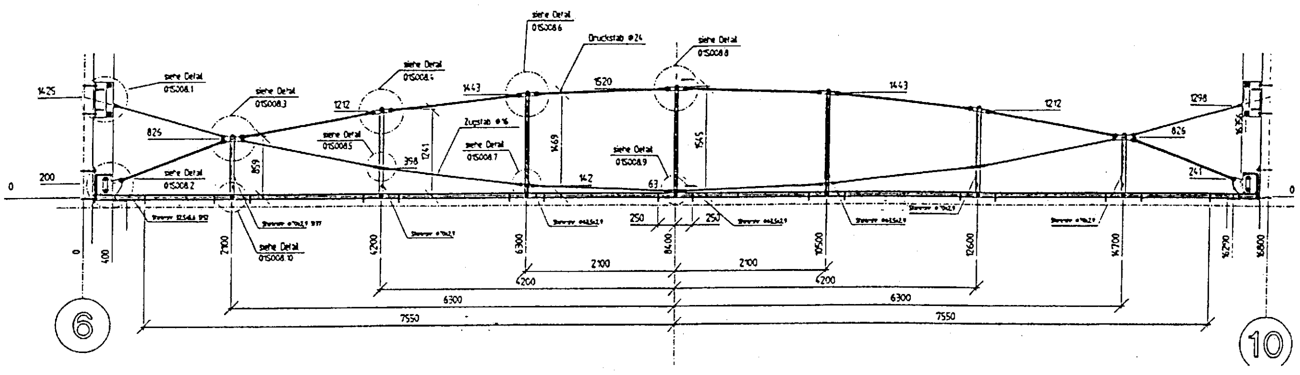

Fig.8a: Façade Kirchberg – Horizontal section

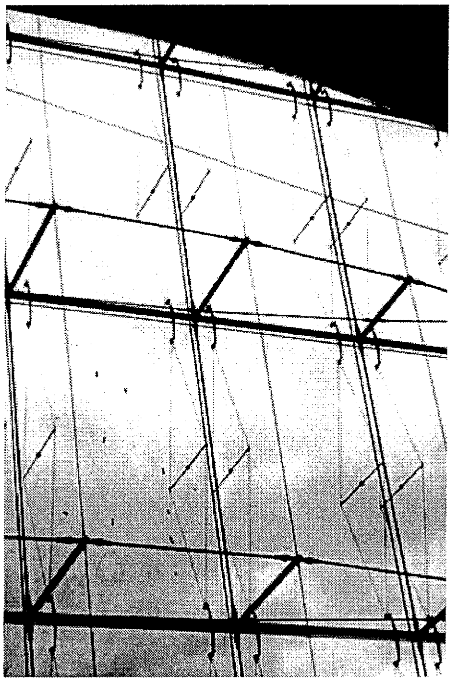

Fig. 9: Façade Kirchberg – Detail

As alternative construction principle an orthogonal prestressed cable system anchored in the surrounding structure could be used ("tennis racket"). Of course this main outside construction has to be layed out for the considerable prestress forces. The present case (Kirchberg) could be done without real prestress. This also eases the erection of the wall since prefabricated elements manufactured in the shop could be used thus reducing the construction time. The supporting system is rather slender so both components glass and steel interact for wind load, but also for temperature changes. This coupling has to be taken into account in the analysis.

3.4 GLASS ROOF OF CASTLE JUVAL, SOUTH TYROL, ITALY

Part of the ruin of the South Tyrolean Castle Juval, owned by the mountaineer Reinhold Messner, had to be covered by a roof to protect the building from further disintegration. As a very unique, but also delicate design a glass roof was chosen (designer Robert Danz), see Figures 10 and 11 [6]. As main structure a filigree cable suspended steel frame is used. Laminated glass panels (2 × 8 mm with 1.56 mm PVB film) are connected to these main girders by a concentrated support system (Rodan), see Figure 12.

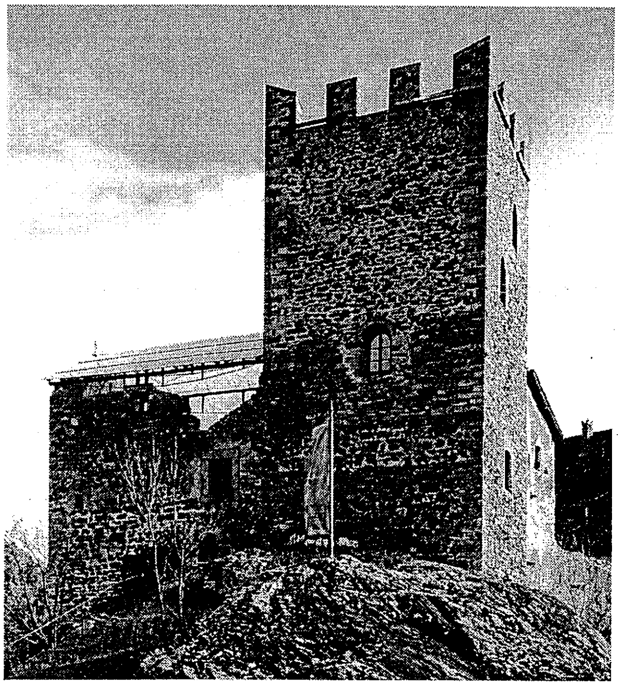

Fig. 10: Castle Juval

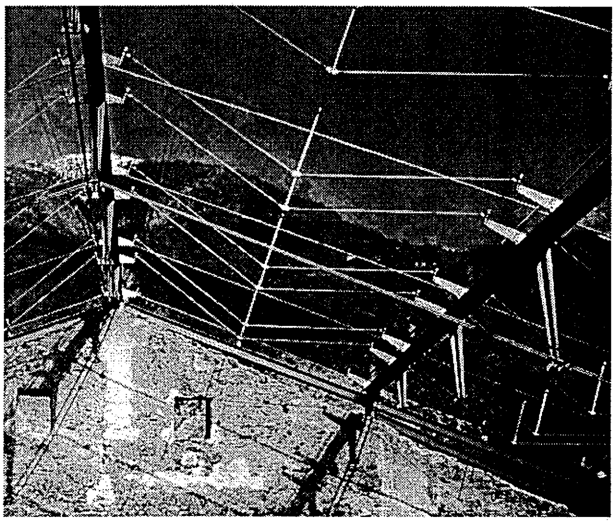

Fig. 11: Castle Juval – Glass roof

Each panel is supported by two cable suspensions using the glass as compression member. Dead and snow load have been defined as 1.85 kN/m^2. Again concentrated forces have to be transmitted from the support system into the glass. The suspension has another advantage compared to the plain glass sheet used in an overhead situation: The remaining load carrying behavior after a glass panel fails is at least to a certain extent taken care off by the cable suspension.

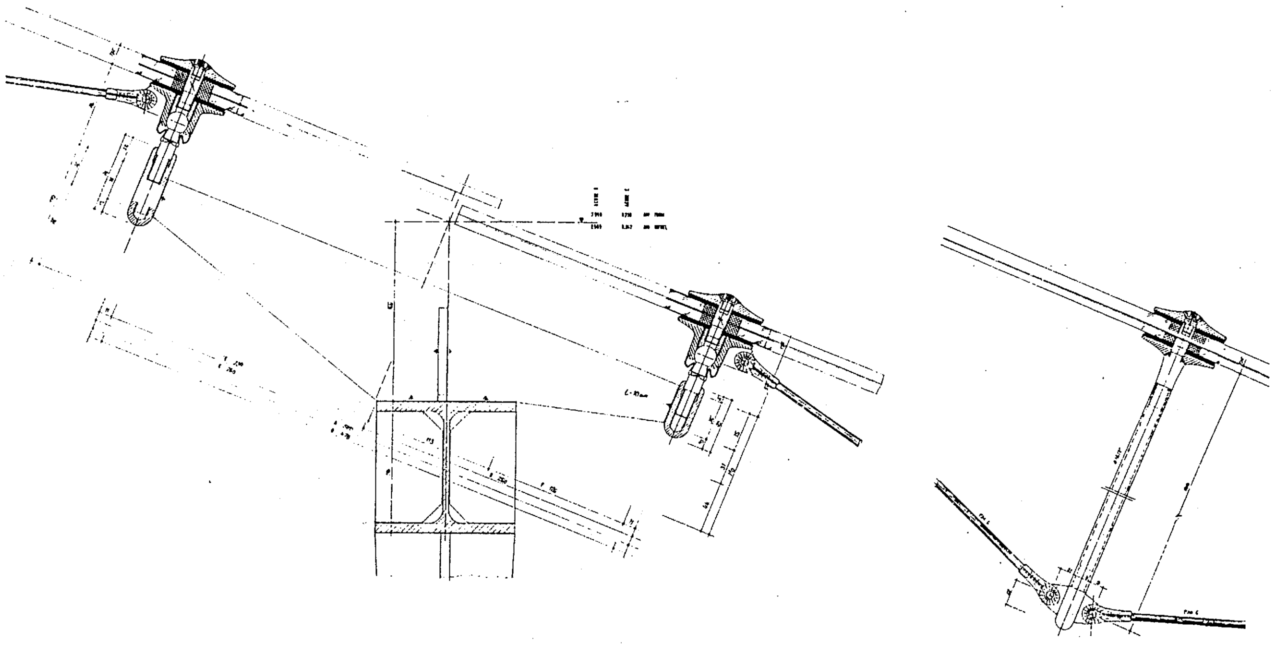

Fig.12: Castle Juval – Suspended roof system

4.0 GLASS ORIENTED DESIGN AND ANALYSIS

It belongs to the principle of predictability that refined analyses have to be performed, i.e. it is not sufficient to base a design on selected experimental work. Fortunately detailed finite element analyses are nowadays available.

For the glass panel support systems would be ideal which do not touch the integrity of the system (e.g. bonding, glueing) ; unfortunately they are not yet available (or still under research, resp.) Current glass support systems are applied to holes in the panel, which naturally become the most sensitive part. The objective of the support system is glass–friendliness, i.e. stresses have to be minimized usually on the account of additional deformations. The ideal of a bending free, statically determinate support can in general not been achieved. Figure 13 shows three common support systems. In the planar system (Pilkington) it is tried to avoid bending and twisting forces in the glass through the use of a spatial hinge located in the plane of the panel.

These distinct mechanical advantages compared to excentric support systems may on the other hand cause more constraints and less flexibility during erection. Excentric connectors with sliding facilities in the plane may therefore be preferable. In other words the integral performance of the connecting element has to be judged.

In many cases forces and moments have to be transmitted into the glass at the hole. Since it is essential to capture the concentrated stress state (characterized by the maximum principal stress) a detailed model of the connecting system is necessary. This could be linear, except of the influence of contact, but definitely has to be three–dimensional. Figure 14 shows such a three–dimensional finite element model of the Rodan support (roof described in Chapter 3.4); in Figure 15 the stress trajectories on the surface are displayed for two supports, in the middle (Figure 15.a) and at the boundary (Figure 15.b) of the panel. It can be seen that in both cases the tension stresses are extremely concentrated and rapidly decay into the glass body. This has also been judged in view of the residual stresses emerging from the tempering process.