Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

Dubai International Airport Expansion. A self adjusting pre-stressed tension rod façade system.

Matthias OPPE*, Markus GABLER[a], Thorsten HELBIG[b]

*Project engineer at Knippers Helbig KHing gmbh
Tübinger Straße 12-16, 70178 Stuttgart, Germany
m.oppe@khing.de

[a]Research Assistant at University of Stuttgart, Germany
[b]Director - Knippers Helbig KHing gmbh, Stuttgart, Germany

Abstract

The growth of Dubai can probably be best seen through the increase in passenger traffic. Over the last years passenger throughput increased from 4.3 million in 1988 to approximately 60 million in 2010. To meet the travel needs of the influx of travellers and airlines, the government of Dubai has committed to a major expansion plan of US $ 4.1 billion for Dubai International Airport and its affiliated divisions.

For the recently opened Terminal 3 consisting of Concourse 2 and Concourse 3 (all dedicated to Emirates Airlines) a self-adjusting pre-stressed tension rod façade system has been developed by Knippers Helbig KHing gmbh. It is used for the 84 ‘teardrop-windows’, which differ slightly in geometry, within the 950-metre-long building of Concourse 2 as well as for the 58 ´teardrop-windows´ within Concourse 3. Furthermore the four gable end walls have been designed by KHing gmbh.

The structure of the ´teardrop-windows´ consists of two orthogonally arranged tension rod strings, which are curved in opposite directions. They are connected to an edge beam and horizontal compression members, therefore an in itself closed static system is formed. Thus no reaction forces caused by pre-tensioning have to be carried by the primary construction.

A combination of pinned and restraint free supports causes low constraint forces within the façade system. Consequently the structure is widely decoupled from influences and especially deflections caused by the primary structure. The pre-tensioning level of the facade system is controlled by detailed geometrical specifications either for fabrication stage as well as within the erection phase. Hence the measurement of pre-tension forces can be reduced to random spot checks.

This paper presents the particular features of the structural system developed for the ´tear-drop windows´. Furthermore it deals with special constructional details for fabrication stage and erection phase.

Keywords: façade, steel-glass structure, parametric design, airport, tension rods, Dubai

1. Introduction

In compliance with ACI traffic statistics Dubai International Airport is ranked as being one of the fastest growing airports in the world. In 2003, it catered to 18 million passengers, while in 2004 Dubai International Airport attracted 21.7 million. According to projections 60 million passengers are expected by 2010.

The new expansion programme includes construction of Terminal 3, concourse 2 and concourse 3 all dedicated for Emirates airline and a Mega Cargo Terminal.

Located beneath the taxiway area and directly linked with concourse 2, terminal 3 incorporates an innovative design that promotes simplified, easy passenger flow (inbound and outbound) and decreases walking distances across the terminal.

The design of the concourses by Aéroports de Paris (ADP.i) is in the shape of an airplane wing, Figure 1.

Figure 1: Expansion of Dubai International Airport (Concourse 3 and Concourse 2)

The quality of the 950-metre respectively 600-metre long buildings reflects Dubai's self-confidence. Its functionality and aesthetics give it a particular position among the world's airports.

With its metallically shimmering surfaces and oval cross-section, increasing in height and width towards the centre, the long building is reminiscent of an aerofoil – an appropriate metaphor, which creates an unusual spatial atmosphere in the interior. This is enhanced by a long, light-flooded hall with a silvery ceiling and tall pillars running parallel to the access area. Functionality and practicality are the dominant elements. Glass facades, formed liked teardrops, allow a view of the runway.

The recently opened Terminal 3 consisting of Concourse 2 and Concourse 3 (all dedicated to Emirates Airlines) is scheduled to be completed by 2011.

2. Pre-stressed façade systems

2.1. General

The design of the steel-glass façade systems occupies a central roll within the overall architectural composition of the concourses. A self-adjusting pre-stressed tension rod façade system has been developed by Knippers Helbig KHing gmbh, Figure 2.

Figure 2: Teardrop windows within Concourse 2 (without glass -left- / finalized -right-)

The conceptual and detailed design was conducted in close collaboration to Josef Gartner GmbH, Germany (Concourse 2) respectively S.G.B. Consulting GmbH, Austria (Concourse 3). It is used for the 84 ‘teardrop-windows’, within the building of Concourse 2 as well as for the 58 ´teardrop-windows´ belonging to Concourse 3.

Since the oval cross-section of Concourse 2 is increasing in height and width towards the centre of the building, the teardrop windows differ slightly in geometry. The teardrop windows at the centre of the concourse consist of an overall height of about 29.0 m and a corresponding width of 17.0 m, while the teardrop windows at the end of the building are 17.5 m high and 13.0 m wide. Since there are only two mirror images of each other within the overall sum of the 84 teardrop windows of Concourse 2, 42 different geometries have to be built.

The structure of Concourse 3 has a constant width, but an increasing height. Thus the teardrop windows consist of 19 different geometric dimensions. Their height varies between 31.5 m and 26.0 m, the teardrop window with the largest height consists of a corresponding width of 16.0 m, while the teardrop windows at the end of the building are 17.0 m wide.

Pre-stressed facades usually need a significant effort to adjust the pre-stress level in order to assure a proper structural behaviour. Since there is a limited installation capacity a self -calibrating system which is controlled by easy-to-check geometrical surveys has been developed. The pre-tensioning level of the facade system is controlled by detailed geometrical specifications either for fabrication stage as well as within the erection phase.

2.2. Structural system of ´teardrop windows´

The structure of the ´teardrop-windows´ is composed of two orthogonally arranged tension rod strings, which are curved in opposite directions, Figure 3.

Since they are connected to a perimeter edge beam (RHS 300 × 100 × 8) and horizontal pre-stressed interlocking tension rod bow trusses with compression members (∅ 114.3 × 6.3), an in itself closed ´self-contained´ static system, which works like a tennis racket, is formed. In view of the fact that all pre-stress forces stay within the system, no reaction forces caused by pre-tensioning have to be carried by the primary steel construction.

A combination of pinned and restraint free supports causes low constraint forces within the façade system. Consequently the structure is furthermore widely decoupled from influences and especially deflections caused by the primary steel structure.

The pre-cambered Vierendeel-girder, situated at the bottom of the teardrop structure, is acting as a tensional spring for the overall system. The Vierendeel-girder can be realized as a very slender structural element, by means of the following cross-sectional dimensions (upper chord: ∅ 114.3 × 10, vertical posts: ∅ 101.6 × 20, lower chord: RHS 100 × 300 × 10).

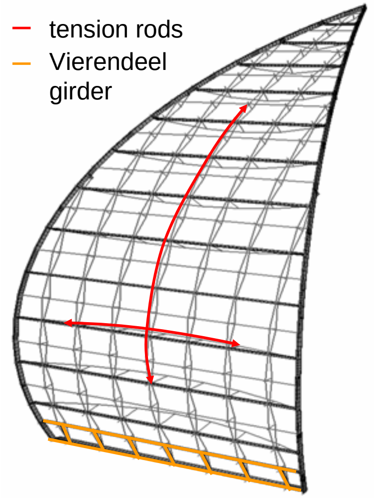


Figure 3: Structural system

2.3. Parametric design

Since it was possible to characterise the 61 different geometries of the teardrop windows by means of the following parameters:

- 27 coordinate points (X;Y;Z) per teardrop window, extracted from the relevant 3D-modells of the concourses
- width of glass-panels
- rise of interlocking tension-rod bow trusses
- excentricity of glass panels in relation to facade structure
- inclination of vertical tension rods

the numerical models, to be used for structural verifications, have been developed using simple parametric tools.

)

Furthermore fabrication drawings for all teardrop windows have been automatically generated within the 3D-CAD-programme Pro/ENGINEER based on this parameters. Going very deep into detail, even the exact positions within three-dimensional coordinates for each single bolt respectively weldseams have been identified. Nevertheless single adjustments have been required e.g. to consider the passenger-bridges within single teardrop windows.

2.4. Consideration of pre-tensioning within numerical simulations

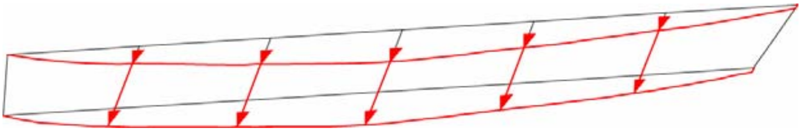
2.1.1. General

The procedure to consider pre-stressing of tension rods and pre-cambering of Vierendeel-girder within numerical calculations is exemplarily shown for a teardrop window situated at the end of Concourse 3.

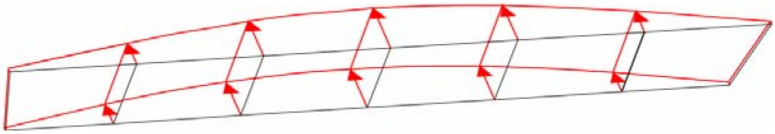
Using a geometrical non-linear analysis (theory 3rd order) all calculations are carried out by means of the programme module *ase* by Sofistik, Germany [1]. Whereas pre-cambering of the Vierendeel-girder has been considered as a primary loadcase. A certain loadcase was required in order to take initial pretension level of all tension elements into account. Furthermore some slight adjustments had to be included in order to reach the desired geometric conditions of the structure.

2.1.2. Pre-cambering ´Vierendeel-girder´

Pre-cambering of Vierendeel-girder, situated on the bottom of the teardrop, has been taken into account by means of a certain loadcase (LC98), whereas initial deflections are oriented in direction of strong respectively weak axis, Figure 4.



strong direction - downward deformation *[mm]*



weak direction - inward deformation *[mm]*

Figure 4: Pre-cambering of Vierendeel-girder

The Vierendeel-girder is not connected to the vertical tension rods within loadcase 98.

Afterwards LC98 as been considered as a primary loadcase (plc) within all load combinations carried out. The deflections induced by pre-cambering have been set equal to 0 (facv 0), while the initiated stresses are applied in opposite direction (facl -1).

2.1.3. Pre-tensioning of tension rods

Loadcase 99 provides the initial pre-tensioning level for all tension elements, Figure 5.

Pre-stress loads are applied by means of axial forces, which will be achieved within the final state through ´shortening of tension rods´, using Hooke´s law

$$\varepsilon = N_p / EA \qquad (1)$$

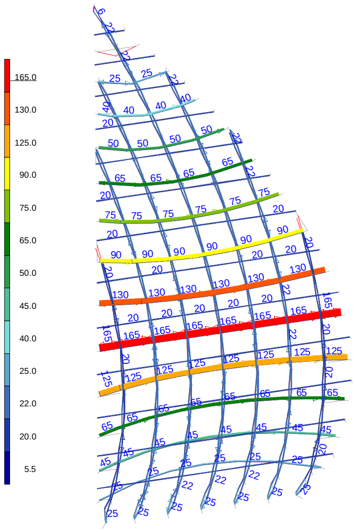
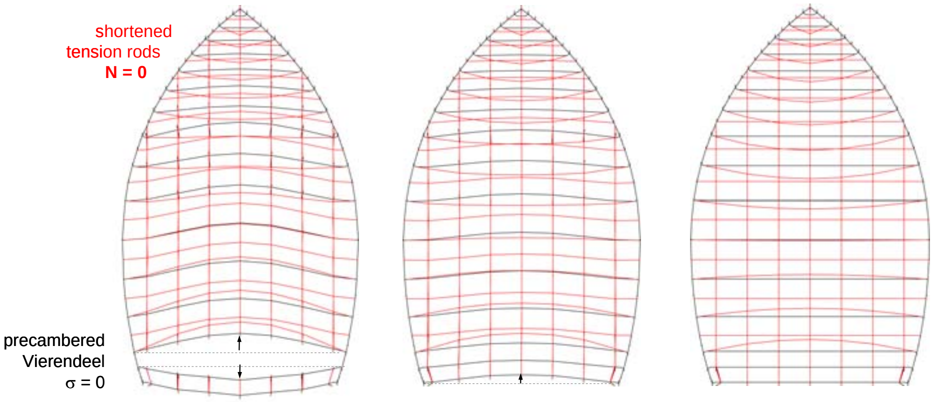


Figure 5: Axial forces (LC99)

2.1.4. Calibration of pre-tensioning level and pre-cambering of Vierendeel-girder

Besides this a certain situation had to be defined in order to guarantee a basis of calibration the pre-tensioning level of the tension rods and accompanying pre-cambering of Vierendeel-girder.

When the vertical tension elements are connected to the Vierendeel-girder the tension elements will be pre-stressed automatically while the Virendeel-girder is pulled into the desired geometry. Pre-tensioning forces within horizontal bow trusses as well as vertical tension rods can be adjusted in order to achieve the desired geometry, which is defined to be *´perfect´* under deadload (including glass panels – LC 110), where deflections of ℓ / 1000 are within the allowable range, Figure 6 and Figure 7.



LC 99 (shortening tension-rods)
LC 98 (pre-cambering Virendeel)

LC101 (without glass)

LC110 (with glass)

Figure 6: Geometry of teardrop windows within different loadcases

Furthermore the pre-tensioning forces keep the overall static system stable, but should remain within the allowable maximum resistance limit provided by the supplier of tension rod system, e.g. Macalloy.

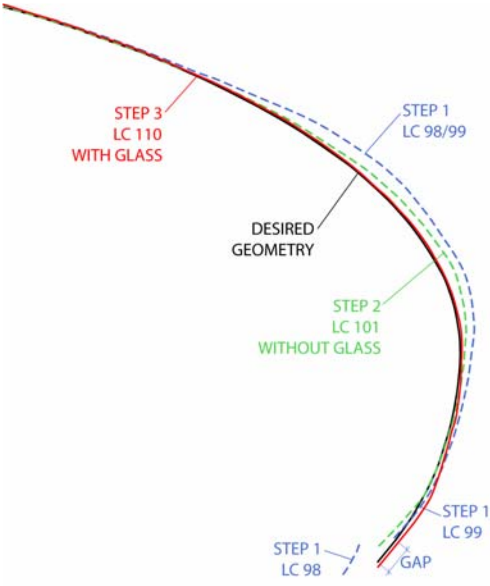


Figure 7: Desired geometry resp. geometry under pre-cambering, pre-tensioning and DL

2.5. Bow Truss – Influence of variations

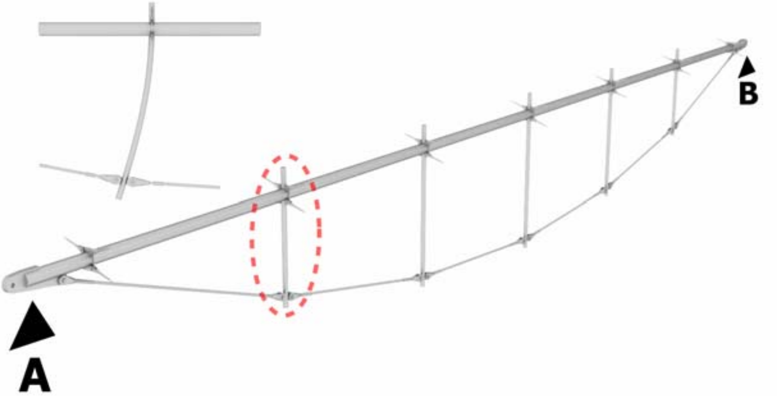
2.5.1. General

The interlocking bow trusses are assembled and pre-stressed in shop before mounting at construction site.

The pre-tensioning process for the bow-trusses, which consists of four different steps, is presented within Figure 8.

1.) Positioning of bow-truss, using special device with exact span length (A-B)
2.) Checking geometric conditions (CHS uniformly cambered in vertical direction, pins orientated in vertical direction without any bending effects)
3.) Impose vertical loads similar to own weight of glass panes
4.) Application of pre-stress within tension rods until CHS reaches its final horizontal position
5.) Release of imposed loads causes deformation within bow-truss

1.) & 2.)



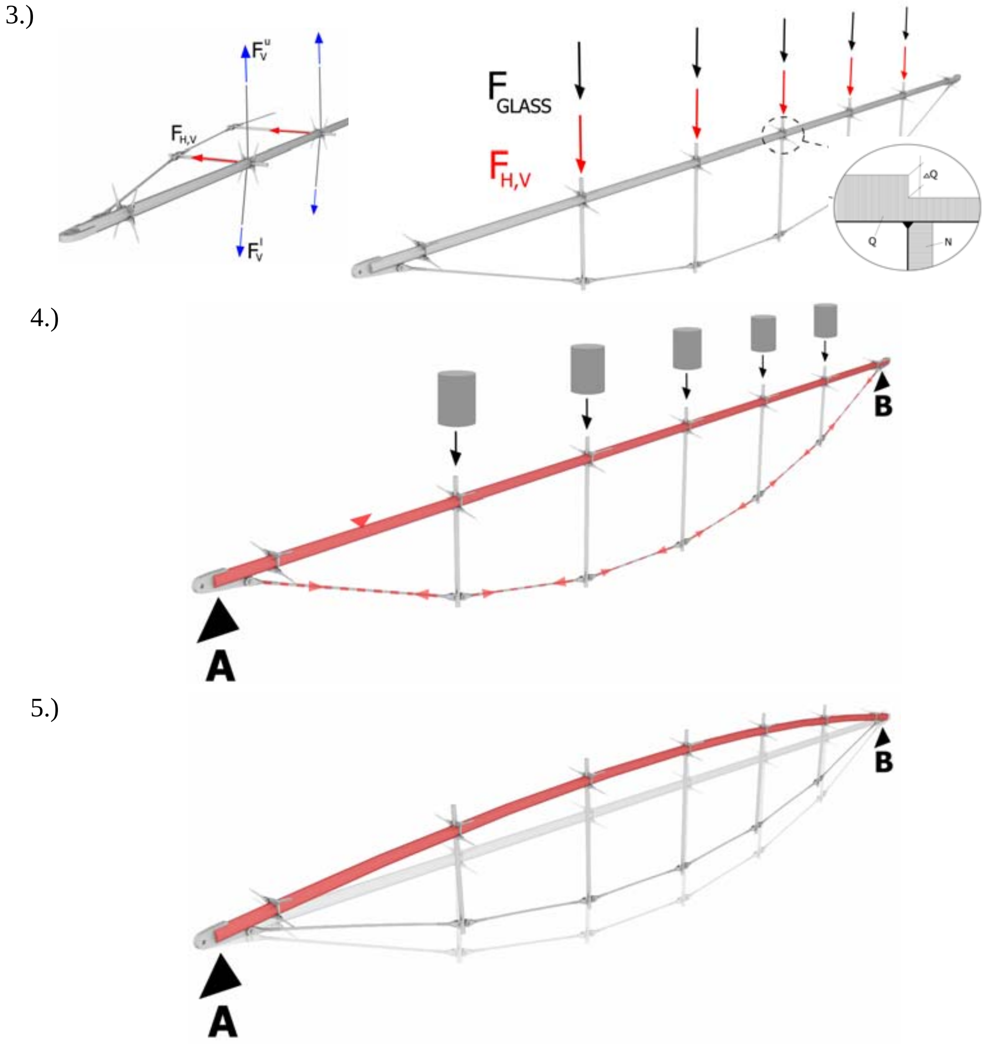


Figure 8: Pre-tensioning of bow-trusses

2.5.2. Influence of variations

In order to determine the influence of variations within the pre-tensioning a parametric study has been carried out. The figure below presents vertical displacement in the workshop over pretension (100% = given value) exemplarily for one bow truss.

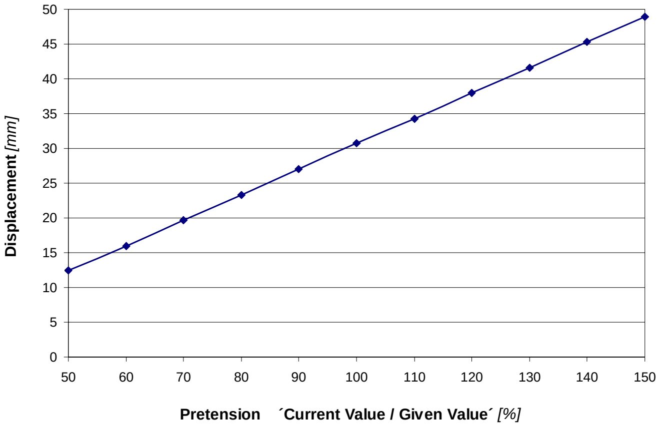


Figure 9: Interrelationship between pre-tensioning and displacement

A linear interrelationship between pre-tensioning and displacement has been achieved.

For shop assembling the requested tolerance is minor to $\Delta z \leq 2$ mm, therefore a maximum variation of pretension of $\Delta P \leq 5.5$ % can be guaranteed. Determining the influence on the overall structural behaviour, certain variations of pre-tensioning level have been applied within the complete system. E.g. an increase of 15% within the bow trusses causes an enlargement of utilization level for the tension rods of about 6%.

2.6. Installation sequence of vertical tension rods

Based on a precisely defined pre-cambering fabrication in the workshop all installation steps on site are presented below.

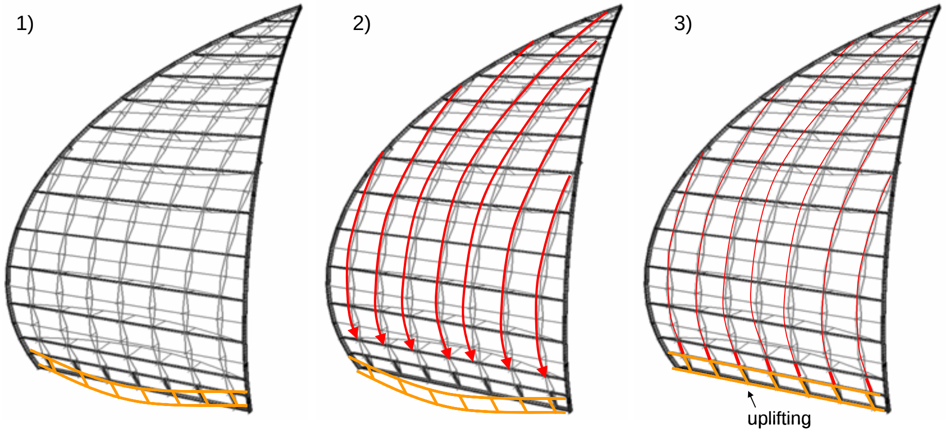


Figure 10: Installation sequence of vertical tension rods

The Vierendeel-girder will be assembled in a way to have a downward respectively inward deflection (1). After mounting the vertical tension rods, from top to bottom (2), the Vierendeel-girder has to be lifted upward in order to connect the bottom row of tension rods with the Vierendeel-girder (3). Releasing the Vierendeel-girder will now cause the pre-tension of the vertical rods.

After installing the glass panels successively the geometric conditions respectively pre-tensioning level within the final position can be controlled by means of

- measuring deflection of the horizontal bow-trusses in horizontal and lateral direction
- determining axial forces within the lowest row of tension rods (above Vierendeel-girder

3. Structural design

3.1. Material

Since axial forces are the leading actions within the construction and bending effects are relatively small, the structural steel elements have been designed using S355J2G3 in order to reduce cross-section dimensions.

Instead of using one of the standard tension rod systems [2] a custom-made product has been developed in direct cooperation with Macalloy. Therefore the systems could have been realized using high-strength steel S690 for the tension bars. All fittings are designed and tested to provide a tensile capacity equal or superior to that of the theoretical strength of the bar.

In comparison with the use of standard materials the application of tension rods made of high-strength steel, the cross-sectional areas have been reduced to 50% of the initial value. Furthermore the mechanical handling of pre-tensioning process on site has been improved.

Figure 11: Teardrop window

Insulating glazing, with an exterior pane etched on the outside, has been used in order to cover all teardrop windows, cp. Figure 11. The interior pane is conducted as laminated safety glass consisting of two heat strengthened sheets, glued together by means of an PVB-interlayer. According to current codes and design guidelines the laminated glass sheets are designed in decoupled state [3]. Which means, that the material properties of the PVB-interlayer have not be taken into consideration, i.e. for calculation purposes, the glass panes slide without any bond over each other. A restrain-free connection has been achieved, using four point fixings.

3.2. Structural detailing

Figure 12: Tension rods to bow-truss

The basic concept of a straightforward and reduced structure has been followed up within conceptual design of structural detailing. Most of the connections between, tubular sections, gusset plates and beams have been conducted by ´inserting and welding´, therefore elegant joints have been achieved. Single structural elements are melting together instead of being connected (cp. Figure 12).

At all connections, subjected to high bending stresses, as junctions within Vierendeel-girder or connection between bow-truss and perimeter beam, very compact steel plates and thick weldseams have been required. Using welded connections instead of casted parts inconspicuous and compact connections (cp. Figure 13) could have been achieved.

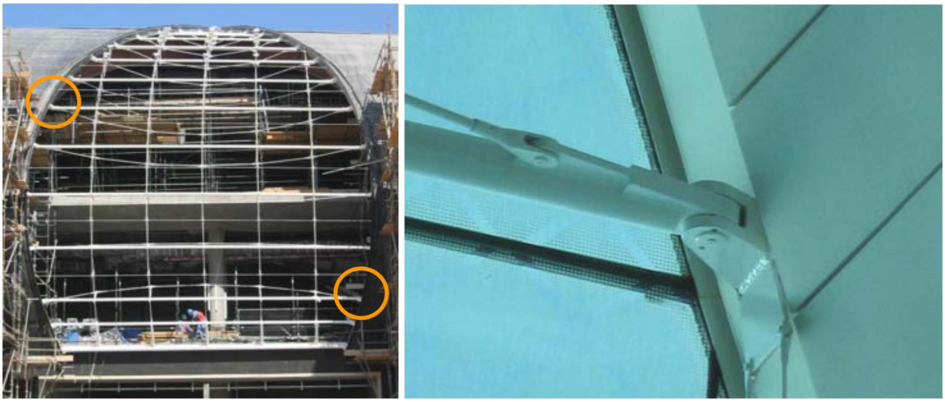


Figure 13: Connection ´tension rods to bow-truss´ -left- / bow-truss to edge beam -right-

A horizontal pre-stressed interlocking tension rod bow truss, where glass panels are connected by means of spiders and point fixings, is located at every second horizontal abutting edge. The intermediate levels simply consist of horizontal tension rods, where the spiders and point fixings are linked, Figure 11.

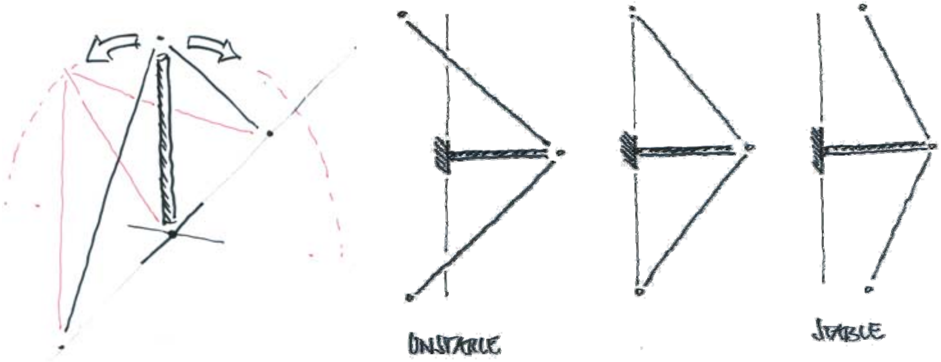


Figure 14: ´Automatically´ stabilization of vertical tension rods

Those horizontal tension rods are fixed by the vertical tension rods, which satisfy the ´automatically stabilization according to Figure 14.

4. Summary

Pre-stressed facades usually need a significant effort to adjust the pre-stress level in order to assure a proper structural behaviour. The self-adjusting pre-stressed tension rod façade system, developed by Knippers Helbig KHing gmbh, gives is an impressive example for a self - calibrating system which is controlled by easy-to-check geometrical surveys.

The pre-tensioning level of the facade system is controlled by detailed geometrical specifications either for fabrication stage as well as within the erection phase.

References

[1] Sofistik - ase *´General Static Analysis of Finite Element Structures´*, SOFISTIK AG, Oberschleißheim 2007

[2] ETA -07/0215- *´Tension Rod Systems –MACALLOY 460, S460 and 520´*, European Technical Approval, Deutsches Institut für Bautechnik, October 2007

[3] DIN 18808-1 *´ Glass in Building - Design and construction rules - Part 1: Terms and general bases´*, Beuth Verlag, March 2006