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POST-TENSIONED SEGMENTAL GLASS BEAMS – EFFECT OF INITIAL CABLE TENSION ON LOAD-BEARING BEHAVIOUR

Jens Oman [1)], **Bernhard Weller** [1)]
[1)] Institute of Building Construction, Technische Universität Dresden, Germany, *jens.oman@tu-dresden.de*

ABSTRACT: Architecture of the 21st century is characterised by the extensive use of glass. Structures made of glass have to meet high safety requirements. In order to comply with those requirements, technical as well as aesthetical compromises have to be made. A promising option are post-tensioned segmental glass beams. These beams consist of glass segments that are supported by a continuous pre-tensioned suspension cable. The special characteristic is the innovative structural concept: In direction of gravity the beams are linked with hinges, but semi-rigid in the direction against gravity. Thus, the structure can be adjusted to individual demands. To investigate the load-bearing behaviour, three-point bending tests were performed at the Institute of Building Construction, Technische Universität Dresden. The results presented in the paper show that the initial tension of the suspension cable is an effective tool to improve the load-bearing behaviour of post-tensioned segmental glass beams.

Keywords: segmental, glass, beam, post-tension, suspension, cable

1. INTRODUCTION

Representative architecture has always benefitted from aesthetic demands and technical impulses. In addition to the aesthetic ideals of the respective zeitgeist, technical innovations find their way into architectural designs.

The integration of segmental glass beams in building structures is mainly useful for two reasons. On the one hand, the segments are used as an instrument for creating a unique structure design. On the other hand, it is a neat solution to create structures which exceed the current production limits.

A much-noticed construction in which segmental glass beams are used is the glass roof of the head office building of Chamber of Industry and Commerce Munich (see Fig. 1). The roof has a unique segmental structure design and was completed in 2002. The segmental glass beams span about 14 m and are made of 5 segments each. The segments overlap each other and are linked via bolts. This connection design creates a segmental glass beam with rigid links. Independently from the architectural individuality, the structure requires an enhanced amount of glass layers to bear the loads. In some exposed sections, the glass beam is composed of 5 girders with a total glass thickness of 165 mm (Ref. 1).

Nowadays glass beams are available up to a length of 18 m. Considering that, one might think that segmental beams are obsolete. However, segmental glass beams are still viable options due to the high price of oversized glass beams and the fragility of the material.

One of the main challenges of engineering load-bearing glass structures is to create aesthetic as well as economic structures that are in accordance with the safety requirements. In addition to the load-bearing behaviour when intact, the post-breakage behaviour has to be analysed properly as well.

On order to fulfill the safety requirements, the number of glass layers is usually increased. As a result, the statically required cross section is thickened by adding sacrificial layers.

This course of action is effective for safety, but uneconomic with regards to the resources used. In view of that, a glass structure that provides an alternative load-bearing path – both when the structure is intact and after breakage – is an attractive option. One approach to create this characteristic is the post-tensioning of the segmental glass beams, like the system which was developed and investigated at the Institute of Building Construction, Technische Universität Dresden.

Fig. 1 Segmental Glass Beams in Load-Bearing Roof Structure, Chamber of Industry and Commerce (IHK) Munich, Germany. © Betsch Architekten, Munich.

2. STRUCTURE DESIGN

The investigated system is a glass beam made of two glass segments which are post-tensioned by a steel cable. Each glass segment consists of two parallel glass girders (see Fig. 2). The glass girders are made of laminated safety glass made of two layers of heat-strengthened glass. (Ref. 2)

The segments are connected to each other via hinge and compressive force link. The hinge functions as a pin-joint in the direction of gravity. In contrast, in the direction against gravity the hinge acts as a semi-rigid joint in interaction with the compressive force link.

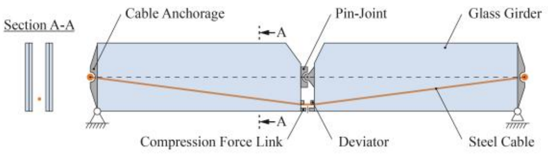

Fig. 2 Simplified Illustration of the Construction of the Post-Tensioned Segmental Glass Beam Tested.

The heart of post-tensioned segmental glass beams is the continuous suspension cable that runs between the parallel glass girders. Depending on the number of segments, the beam has one girder joint. At the girder joint the cable is deviated and relocated in longitudinal direction. To improve the load-bearing capacity, the glass beam is post-tensioned. For this purpose, the steel cable is pre-tensioned and anchored to both ends of the glass beam.

Due to the pin-joint in the direction of gravity, the load-bearing behaviour of post-tensioned segmental glass beams depends directly on the load-bearing path of the steel cable. To use the capacity of a double segmented glass beam the only deviator is positioned at the bottom of the girder joint. That means the eccentricity of the deviator gives the pre-tensioned suspension cable its shape. This deviation provides the segmental glass structure with reliable support and transfers vertical forces between the suspension cable and the glass beam.

The pin-joint is positioned at the very centre of the system. To avoid additional rotation moments due to the horizontal components of cable tension, the cable's anchorage is positioned at the same height as the pin-joint. The compressive force link is positioned at the very bottom of the girder joint to maximise the semi-rigidity in the direction against gravity.

3. EXPERIMENTAL INVESTIGATION

3.1 Test Setup and Procedure

This paper focusses primarily on the effects of initial cable tension on the load-bearing behaviour. To analyse the effects, four systems with different cable tension values in initial state were examined. Therefor, three-point bending tests were performed with a central test load (Q) as it is shown in Fig. 3. As the parameter under scrutiny, the initial tension (S_0) of the steel cable was varied (30 kN, 60 kN, 90 kN and 120 kN).

The test procedure consisted of three steps. At first, each system was loaded force controlled up to a maximum test load of 60 kN in the direction of gravity. The maximum load was reached with a load ratio of 0.25 kN/s. After that, the load was held for 10 seconds. Finally, the system was unloaded with a load ratio of 5.0 kN/s. During the tests the vertical displacement values and the cable tension values were measured via laser displacement transducer and ring force transducer.

The tests were performed with double segmented glass beams with compact segment dimensions of 1500 mm in length and 500 mm in height as it is shown in Fig. 4. The glass girders are made of laminated safety glass consisting of two layers 12 mm heat-strengthened glass and 1.52 mm SentryGlas interlayer. The steel cables were spiral strands made of 37 unalloyed quality steel wires, and had a diameter of 20.1 mm (Ref. 3). In non-deformed state the cable angle is 7.125°.

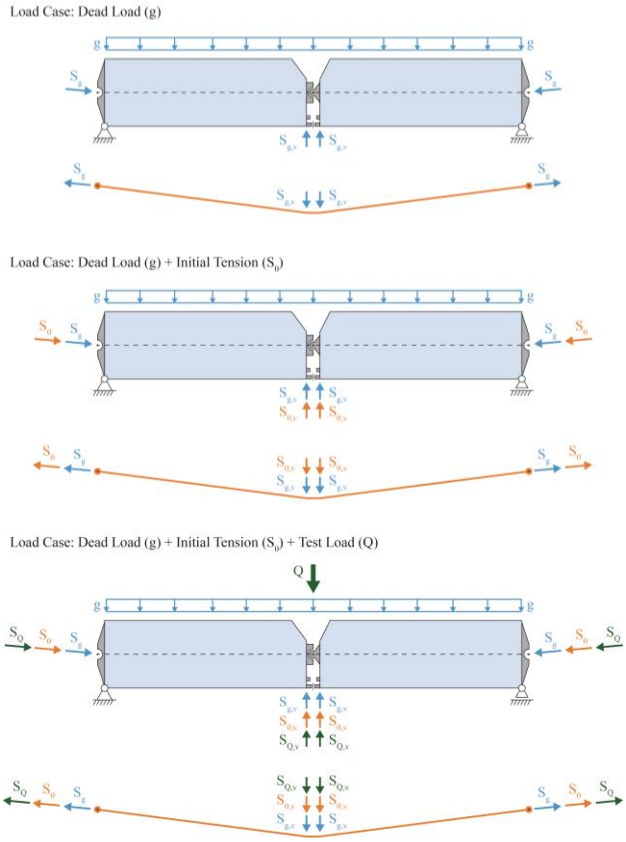

Fig. 3 Load-Bearing Mechanism of the Post-Tensioned Segmental Glass Beam Tested.

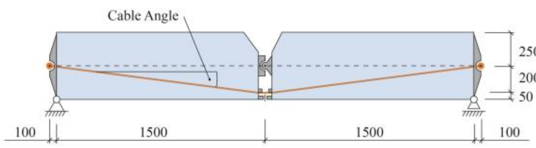

Fig. 4 Dimensions of the Post-Tensioned Segmental Glass Beams Tested.

Test temperature during the testing period was 21°C ± 1.5°C with an air humidity of 30 % ± 10 %. Following experimental results, arithmetic mean values of three specimen per system will be discussed below.

3.2 Results and Discussion

To evaluate the load-bearing behaviour of segmented glass beams, the general effects of parameters are to be compared step-by-step. The present paper serves as an overview of the cable tension measured and the vertical displacement values of the segmental glass beams resulting from different values of initial cable tension.

Fig. 5 shows the vertical displacement measured in the middle of the four systems tested. In the diagram, the vertical displacement is shown on the x-axis and the test load on the y-axis.

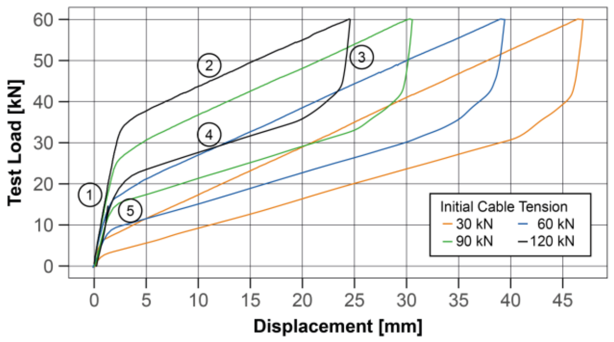

Fig. 5 Effects of Initial Cable Tension on Maximum Displacement.

In general, the graphs follow the specific load scenario with its loading and unloading periods. More precisely, the upper part of all graphs represents the loading period and the lower part is the unloading period. For a better understanding the graphs can be categorised into five sections plus crossovers:

1. Steep straight line at lower displacement values
2. Long, semi-flat straight line up to the maximum peak of 60 kN test load
3. Almost vertical line down from the maximum peak
4. Long, semi-flat, nearly straight line
5. Steep straight line to coordinate origin

Both the starting point and the end point of each displacement graph were almost identical. That means that the systems almost returned into their original position after the load test. Comparing the four graphs, it is noticeable that the respective sections were nearly parallel to each other. This similarity underlines that the load-bearing behaviour of the systems tested was not converted fundamentally, but the key points could be well modified by initial cable tension.

The effects of initial cable tension on the measured cable tension values are shown in Fig 6. The diagram shows how the initial cable tension affected the cable tension under test load. The graphs can be categorised into five sections analogous to the displacement graphs in Fig. 5.

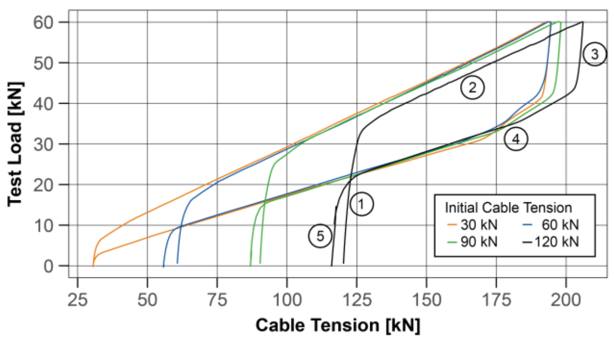

Fig. 6 Effects of Initial Cable Tension on Cable Tension.

The deviation of the pre-tensioned suspension cable transmits a vertical support force from the longitudinal cable tension into the glass beam. The value of support force varies with the particular cable tension and suspension cable angle during each single load situation.

As long as the test load did not exceed the value of the vertical support force resulting from the initial cable tension, the system responded relatively stiff. Thus, the initial cable tension determines the initial stiffness of a post-tensioned segmented glass beam. This load-bearing behaviour is documented in section 1 of Fig. 5 and Fig. 6. In this section of graphs, the test loads were smaller than the support force values. The vertical support force values in the non-deformed state are listed in Tab. 1. A comparison of the initial support force values with the graphs shows that section 1 covers the ratio of smaller test loads than initial support force values. The change of the cable angle can be neglected at this point.

Table 1. Selection of Test Values

Initial Cable Tension	Initial Support Force*	Maximum Cable Tension	Maximum Displacement
30 kN	7.4 kN	194.4 kN	47.0 mm
60 kN	14.9 kN	194.6 kN	39.4 mm
90 kN	22.3 kN	198.1 kN	30.6 mm
120 kN	29.8 kN	206.1 kN	24.6 mm
* in non-deformed state, resulting from a cable angle of 7.125°			

As soon as the test load exceeded the initial support force significantly, the stiffness of the post-tensioned segmental glass beam decreased. The load-bearing behaviour at this stage is nearly linear and categorised by section 2.

Displaying the four systems together shows that the glass beam with the highest initial cable tension (120 kN) had the lowest displacement value (24.6 mm). Simultaneously, this system had the highest maximum cable tension (206.1 kN). In comparison to that, the system with the lowest initial cable tension (30 kN) had a maximum cable tension of 94 % (194.4 kN), but a maximum displacement of 191 % (47.0 mm). The maximum displacement value of the system with 60 kN initial cable tension was 39.4 mm, while the maximum cable tension was 194.6 kN. The system with 90 kN initial cable tension had 30.6 mm maximum deflection and 198.1 kN maximum cable tension. In summary, the highest amount of initial cable tension brought the greatest benefit.

Although the maximum displacement values differed significantly, the maximum cable tension values were similar to each other. This opposing trend shows that the cable angle which increased with the displacement had a relatively small effect on the maximum cable tension. The similarity of the maximum cable tension values stems from the direct equilibrium condition of the maximum test load and the vertical support force of the suspension cable. The gaps of the maximum displacement values result from the different initial stiffnesses of the systems tested.

Beside the ratio of the values measured, the load-bearing behaviour at the beginning of the decrease of the test load was conspicuous. After holding the full test load for 10 seconds, the test load was decreased. During that period (test load decreased from 60 kN to approximately 42 kN), the system went back conspicuously slow. This means that the values of displacement and cable tension measured while the test load was decreasing differed significantly from the values measured during the increase of the test load (see Fig. 5, 6; Section 3). Studies on this topic are in progress. The current state of the studies indicates that the non-linear modulus of elasticity of the spiral strand is the reason for this. Internal wire movements inside the spiral strand especially located at the deviation are under suspicion to cause the load-bearing behaviour in section 3 of the systems tested (Refs. 4, 5).

The displacement decreased nearly linear with the test load when the test load felt significantly below a value of approximately 40 kN (see Fig. 6, 7; Section 4). As soon as the test load value went significantly below the present support force value, the systems became stiffer again (see Fig. 6, 7; Section 5). The present support force values for systems with small displacements are similar to the initial cable tension values which are listed in Tab. 1.

In contrast to the displacements, the starting points and end points of the cable tension graphs were not identical at all. While the cable tension of the system with an initial cable tension of 30 kN returned to its origin position after loading, the systems with initial cable tension of 60 kN or higher had a lower cable tension after the test than before.

4. CONCLUSIONS

The authors investigated four varying test systems of post-tensioned segmental glass beams. The aim of the research was to figure out the effects of initial cable tension on the load-bearing behaviour of the segmental glass beams. Therefore, three-point bending tests were performed.

The results show that the load-bearing behaviour of post-tensioned segmental glass beams can be highly modified by the initial cable tension. The maximum cable tension values measured under full test load were correlating, while the maximum displacement values differed by a factor of up to 1.9. In other words, the maximum displacement values can be efficiently adjusted by the initial cable tension. However, the effect on the maximum cable tension was significantly smaller.

Beside the ratio of measured values, the load-bearing behaviour had a peculiarity. During the first period of the decrease of the test load, the relaxation of the glass beam was slower than the contraction during the last period of load increase.

5. OUTLOOK

The results described in this paper render the post-tensioned segmental glass beam a promising object for further research activities. In this context, numerical analyses as well as studies on the effect of local bending of spiral strands on the load-bearing behaviour of post-tensioned segmental glass beams are part of ongoing research.

In addition to the initial cable tension, the segmental glass beam system analysed provides further very promising parameters that might improve the load-bearing behaviour of post-tensioned segmental glass beams. A selection of those parameters includes the position of cable anchorages and the deviator position as well as the eccentricity of the pin-joint.

These and other parameters are part of the ongoing research project at the Institute of Building Construction, Technische Universität Dresden. More results will be documented in forthcoming publications.

6. ACKNOWLEDGEMENTS

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