Design of a Lighting Tensegrity Sculpture for the Bella Sky Hotel in Copenhagen

Olga Popovic Larsen[1], Daniel Sang-Hoon Lee[2], Tom Hay[3], Anne Bagger[4]

[1] Professor and the Leader of BÆK Group, The Royal Danish Academy of Fine Arts, the School of Architecture, Denmark, *Olga.Popoviclarsen@karch.dk*
[2] Assistant Professor, BÆK Group, The Royal Danish Academy of Fine Arts, the School of Architecture, Denmark, *Daniel.Lee@karch.dk*
[3] Ph.D. Candidate, BÆK Group, The Royal Danish Academy of Fine Arts, the School of Architecture, Denmark, *Tom.Hay@karch.dk*
[4] Anne Bagger Aps, *glass@annebagger.dk*

Summary

This paper presents a tensegrity design/research project by the Loadbearing Structures research group (BÆK) of the Royal Danish Academy of Fine Arts School of Architecture, in collaboration with the architecture practice 3xNielsen (3XN), both based in Copenhagen Denmark. The project involved the design and the construction of a tensegrity for a lighting sculpture with the integration of a LED system. The key agenda for the project was to enhance the aesthetic quality of the tensegrity structure by achieving an overal elegant design solution with special emphasis on the detailing and component design. The geometry form-finding, connection and components design as well as the the project development are presented in this paper.

The paper presents the tensegrity project from conception, through project development and concludes by presenting the final - finished design. A separate paper also submitted to this conference describes the construction methodology and the instalation of the chandelier.

Keywords: *Tensegrity structure, Design, Connection, Detail, Analysis, LEDs*

1. Introduction

The paper presents a collaborative design project between a Copenhagen based academic research team (the BÆK group) and the Copenhagen based architecture design practice 3XN. The main tasks within the project were to design, and to construct a chandelier for the main entrance hall of a recently completed hotel which works as a tensegrity structure. The scope of the paper is within the design aspects of the project, and the discussion points include the form-finding of the tensegrity structure, the analysis and dimensioning of the structure, as well as the connection detail design.

The project was started by drawing design sketches of concept models on 3D CAD software. As commonly seen in design projects, the consecutive studies gradually developed the concept model which was more balanced in both the aesthetics and the constructability. The constructability and the realisation of the concept model were demonstrated through building the scaled physical models (section 4). This particular task was incorporated into the student workshop (section 3), where Masters level students were given the task to build models as precise as possible to the computer generated model. The students were asked to come up with more viable geometrical solution, and also to look at the connection details between the compression and the tension members.

The sizes of the structural members are designed based on the required structural capacities and the deflection limit. The deflection of the compression members was one of the issues that required careful attention; the deflection had to be within the certain limit to avoid any physical contacts between the members. Thus the deflection of each member was carefully monitored, and the stresses in the cables and the geometrical orientation of the whole structure were adjusted during both the analysis and the construction process.

The connection details, together with the overall geometry, were one of the key aspects that govern the overall aesthetics of the chandelier, and it was the aim to find the most slim and neat solution. The type of grip-glider (which holds the tension cables and connects to the compression member), and the design of the end-cap (the aluminium caps at both ends of the compression bars; the grip-gliders are screwed into the end-caps) are illustrated in section 5 in more detail.

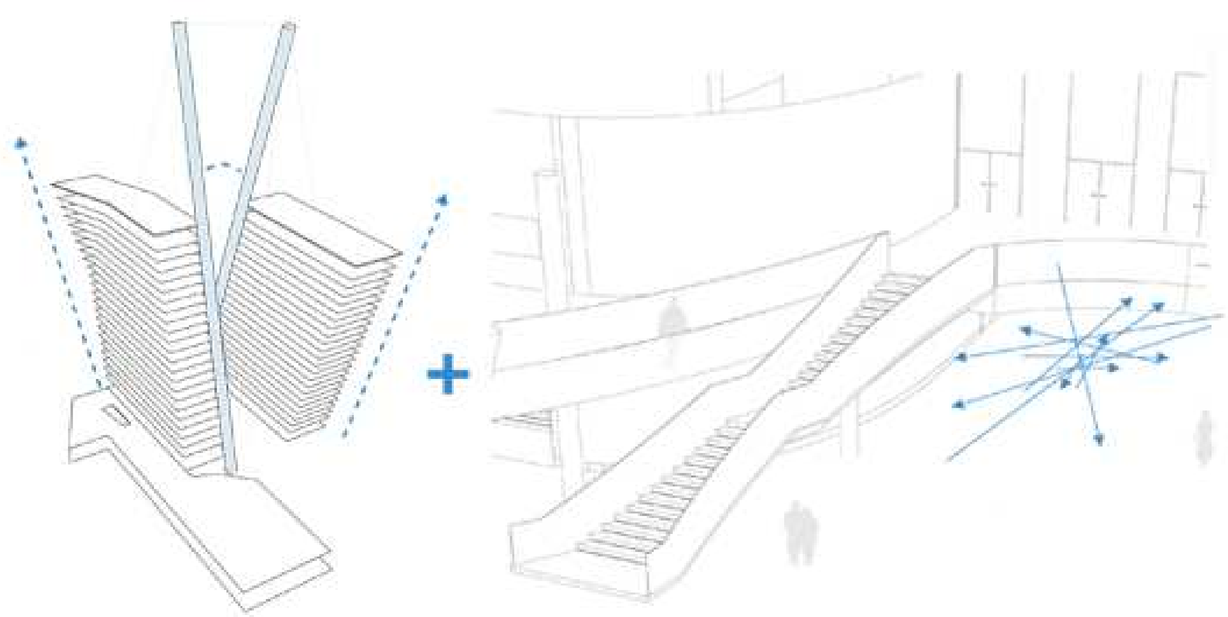

Figure 1. Image showing the inclination of the hotel towers, and the concept idea for the chandelier (courtesy of 3XN)

2. Background

The 'Bella Chandelier' project (completed in May of 2011) started from the architect's idea to build a lighting tensegrity sculpture, which would be located in the ground floor lobby of the Bella Sky Comwell Hotel; situated in Ørestad at about 8.0 km from the Copenhagen city centre. The hotel consists of two leaning towers with the inclination of 15 degrees, and the initial idea was to adopt and express the inclination of the towers in the design of the chandelier. Hence the initial concept was developed to have six lighting bars in three pairs, and each pair had the inclination angle between them. The three pairs of the lighting bars were then arranged in an irregular pattern to express the disorderly float of the bars.

Historically the appealing aesthetics of tensegrity structures has been drawing designers from various professional fields to work on the diverse applications of the system. The sculptures by

Buckminster Fuller, Keneth Snellson are excellent examples of artistic applications of tensegrities. Not many tensegrities however have been used in built projects due to the danger of inherent progressive collapse in a case of loosing the continuity of load-path in the tension cables. This made the project and the challenge of achieving both a beautiful as well as a structurally viable tensegrity more interesting. From the start of the Bella Chandelier project there was the common hope in the design team to bring out an interesting, and hopefully an inspiring result.

The timing of the project coincided with a research-led course in Conceptual Structural Design which made it possible to include Masters level students at the School of Architecture in the initial, conceptual stages of the design process by running a student workshop. The students had an opportunity to learn about design through their involvement in a real project which they both enjoyed and valued. Their feedback was very positive.

3. Student Workshop

The student workshop involved about 30 students who were in their forth year. The course was planned in advance well before the BÆK group was involved in the tensegrity project for the Bella Sky hotel. The aim of the workshop was to learn about space structures such as tensegrities, gridshells, reciprocal frames etc. and to conduct explorations using physical and computer modelling. As BÆK became part of the design team it was very timely to involve students. It was an opportunity for them to learn about tensegrities but also, the project was at its initial stages in terms of the geometry definition, detail and component design so the student's explorations were valuable input into the conceptual stages of the design.

The students had one day of lectures which also included a presentation about the project. They were then divided into three groups where the first group had a task to build a 1:3 scaled physical model of the tensegrity structure using the geometry as given by the architects (3xN). The second group had a task to carry out an investigation into possible details and materials that could be used for the construction and the third group were given a task to come up with a new concept design of a tensegrity which does not follow the geometry requirements as given by the architects, yet proposes a completely new form.

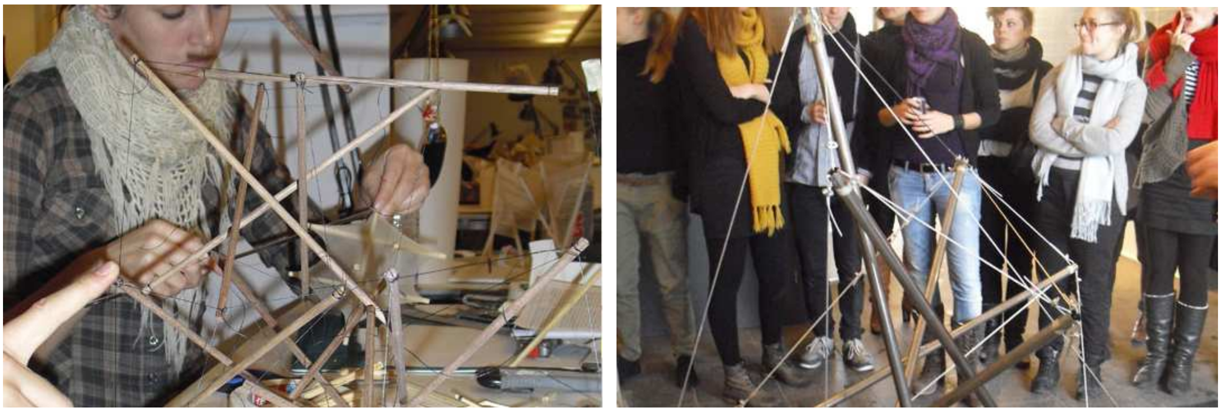

Figure 2: Student Workshop

After a week of hard work – the students presented their work to us and to the whole design team. It was interesting that they pointed to some possible directions the project could develop in. This valuable input was taken into account in the further design stages.

4. Schematic Designs

After the student workshop, the geometry of the structure was further revised and modified. The form continued to have the disorderly characteristic by having the compression members in an irregular pattern, and the cables were placed wherever it was necessary to hold the compression members in place.

A scaled physical model was constructed for the design, which was then digitised to a 3D model, and it was later used to verify the induced forces in the structure and the deflected shape. The analytical result of the form showed that the stress values varied significantly from member to member, and the simulation indicated some difficulties in constructing the design in the 1:1 scale. The main problem was in stressing the cables to give the correct geometry for the structure.

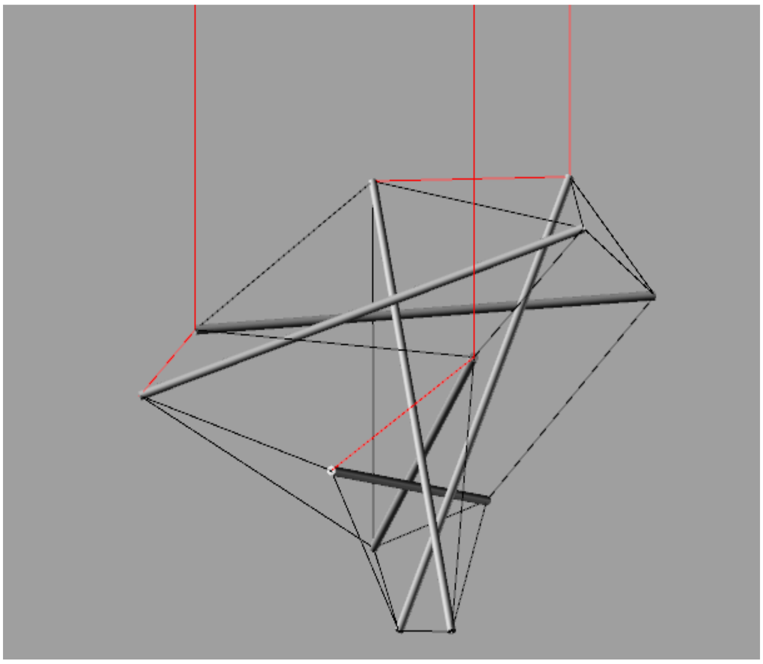

Figure 3: The first concept model of the chandelier

As the form becomes more complex and deviates more from the symmetrical arrangement, the behaviour of the structure becomes more difficult to predict whenever there are changes of applied forces. For example, during the construction phase the cables had to be tensioned one at a time, and it seemed very difficult to predict how much the tensioning of cable will affect the rest of the members. Also, if any adjustments to the cables would have been required on site after the assembly, it would be more difficult to work out which cables to adjust and to what extent. Thus it was thought that a geometry optimisation was required, without the compromising of the aesthetical merits of the initial design.

The later geometry of the structure was based on the form of the tetrahedron. The shape and size of the four triangular faces were modified, and this time it was agreed to keep the form in more symmetry than before. Later, the analysis showed that the new geometry required a smaller number of cables and the induced stresses in the members were also reduced.

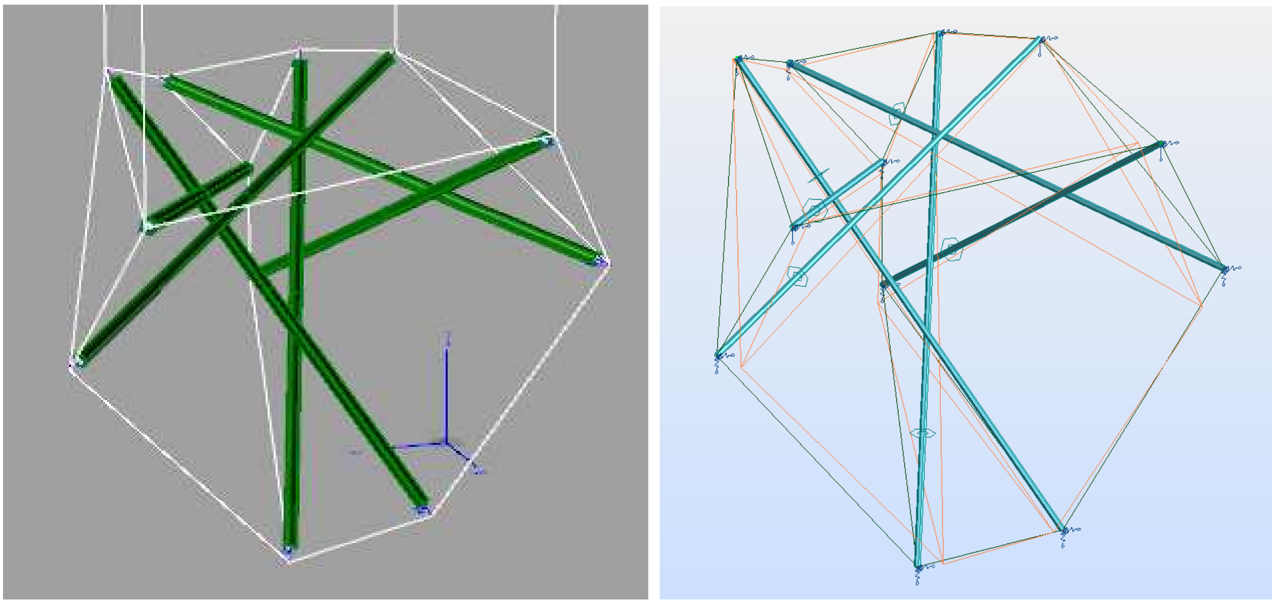

Figure 4: The revised model (above) and its deflected shape (below).

5. Connection Design

5.1 Assembly of the compression bar

The compression member consists of an aluminium core, which sustains the compressive stresses, the strips of LEDs that are attached on the aluminium core, the lamella strips that diffuse the light, the acrylic spacers are used to support the outer acrylic tube casing, and the acrylic casing is there to

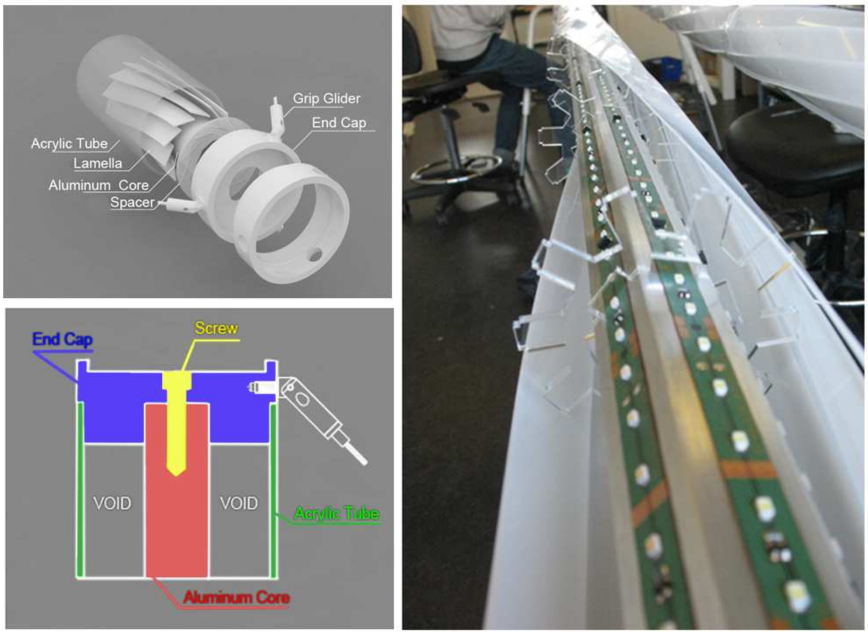

Figure 5: Assembly of a compression member (left top and right), a drawing of an end-cap (left bottom)

enclose all the elements. The acrylic casing was closed at both ends with aluminium caps, to which the tension cables are connected. The stresses of the cables are transferred directly to the aluminium core by the end caps, and the acrylic casing was designed not to take any load. When the light is on the heat from LED will cause the acrylic tube to expand and this effect also had to be taken into account when dimensioning the tube and end cap.

The stresses in the wires press the end cap strongly against the aluminium core, yet during the installation there could possibly be unexpected lift-up forces that might separate them. Thus the end cap and the aluminium core were fixed together by a screw.

5.2 Grip glider

A grip-glider is a device that grips the tension cable and connects it to the compression bars. The specific type used for the chandelier had the pivot joint connection, which could accommodate the rotational movements of the cables. There was the demand to make the detail as slim and neat as possible, and it was important that the grip-glider allows the adjustment for the cable length during the tensioning process.

A simple experimentation test was set up to verify the moment capacity of the grip-glider; more precisely it is the screw-end that was tested for the capacity. The test was necessary because at some locations the grip-gliders were not completely screwed into the end cap causing the screw-end to experience high bending stresses. Hence the test was to prove that the capacity was sufficient to sustain such levels of stress. (Figure 6) The experimental test results showed that the screw-end could sustain more than the maximum predicted load, and the deflection was minimal.

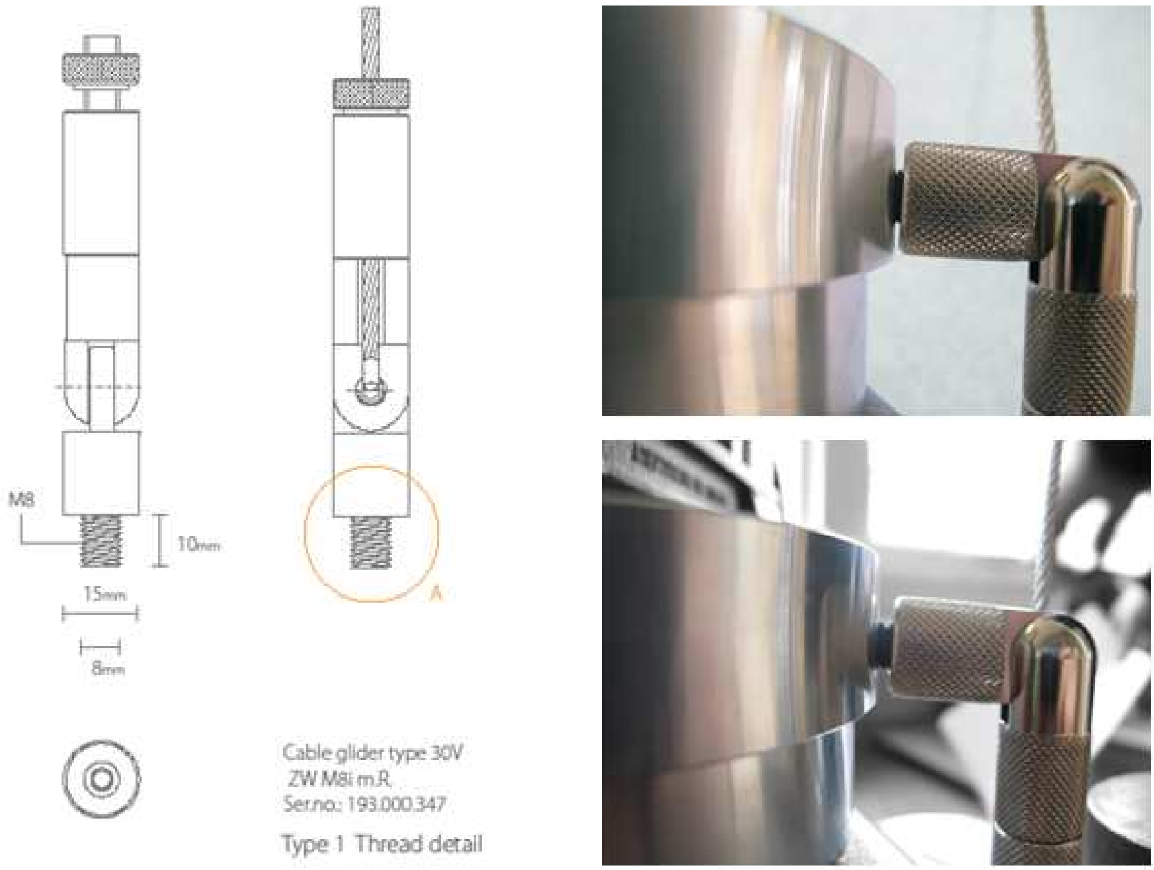

Figure 6: Grip-glider drawing (left) and Load testing of the screw-end for bending and deflection (right)

6. Conclusion

This project had many untested novel ideas, beginning with the asymmetrical geometry, defining the structural behavior, rationalizing and optimizing the geometry, achieving a minimal structure with elegant fixings, the lighting solution and the overall aesthetics. Issues that bridged several disciplines had to be resolved, which meant that the design team had to work well together and support each other. The lighting consultant Cinetech, 3xN and the BÆK group worked closely together in achieving the final design for this lightweight structure. The design meetings involved architects, engineers, lighting specialists and the project was completed on a very tight budget and in a very short time. Although it would be fair to say that at times it was nerve-wrecking because the input of every member of the team had to be on time and very precise, this project would have not been possible without the respect and collaboration of each and every member of the team. All the different professional cultural differences were overcome by the mutual respect and collaboration.

References

[1] Motro R, *Tensegrity: Structural Systems for the Future*, Kogan Page Science, London, 2003

[2] Nervi, P. L., *Aesthetics and Technology in Building,* Harvard University Press, 1965

[3] Nuhoglu, A., Korkmaz, K. A., ”A practical apporach for non-linear analysis of tensegrity systems”, *Engineering with Computers,* Springer-Verlag London Limited, 2010

[4] Oppenheim, I. J., and Williams, W. O., “Geometric Effects in an Elastic Tensegrity Structure”, *Journal of Elasticity,* Vol. 59, 2000, pp. 51-65

[5] Popovic Larsen, O., and Tyas, A., *Conceptual Structural Design: Bridging the Gap between Engineers and Architects*, Thomas Telford publishing, London, 2003

[6] Prouve, J., *The Poetics of the Technical Object,* Vitra Design Museum, 2005

[7] Sakantamis, K., and Popovic Larsen, O., “The cocoon method: A physical modelling tool for designing tensegrity systems”, *Journal of the International Association for Shell and Spatial Structures,* Vol. 19, No.1, 2004, pp. 11 - 20

[8] Sakantamis, K., and Popovic Larsen, O., “A Novel approach to physical modelling - formfinding of tensegrity systems”, *Journal of The International Association for Shell and Spatial Structures,* Vol. 44, n.1 April, n. 141, 2003, pp. 15-24

[9] Sultan, C., Coreless, M., Skelton, R. E., “The prestressability problem of tensegrity structures: some analytical solutions”, *International Journal of Solids and Structures,* Vol. 38, 2001, pp. 5223-5252

[10] Williamson, D., Skelton, R., Han, J., ”Equilibrium conditions of a tensegrity structure”, *International Journal of Solids and Structures,* Vol. 40, 2003, pp. 6347-6367

[11] Zhang, J. Y., Ohsaki, M., “Adaptive force density method for form-finding problem of tensegrity structures”, *International Journal of Solids and Structures,* Vol. 43, 2006, pp. 5658-5673