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New load monitoring method for pretensioned Structures

Thomas Prang

Civil Engineer, EWE, Pfeifer Seil- und Hebetechnik GmbH, Memmingen, Germany

ABSTRACT: Cable structures are very sensitive regarding design, calculation, manufacturing and installation methods. All elements have to work together to receive a proper result at the end. To eliminate one more point of inaccuracy in this chain, a new method for measuring and monitoring of the Cable forces was developed. The ultrasonic load monitoring method with a pin equipped with ultrasonic sensors and an unique id chip. Accuracy of measuring the cable forces raise to an exactness of +/- 1.5%. New applications for monitoring of all kind of structures can be developped.

1 INTRODUCTION IN CABLE STRUCTURES

Cable structures are to be found all over the globe. Since the construction of the Munich Olympic Parc, the amount of cable related structures increased over the years. The projects are impressive examples for the aesthetics and grace of modern cable structures and provide insight into the variety of possibilities that are at the disposal employing cables in architecture. Both the profound knowledge of the use of cables and years of hands-on experience provide the basis for successful projects – for every building requires the highest dimensional accuracy when it comes to construction, production and installation.

It is necessary to install an experienced sales team, designers with specialist knowledge of construction and mechanical engineering, qualified project management and an efficient assembly team support and look after the launching of a project from the early planning phase up to the safe and reliable assembly. Working out realistic schedules and budgets before the start of construction are just as much a part of the necessary scope of services as the construction of detailed solutions relating to the project. A specialized team of ropemakers are experts in all the techniques that are necessary for economically manufacturing ready-to-use ropes within the narrowest tolerances. The rope end fittings that are used for this should be continually optimised according to architectural and technical requirements. The realized structures have the following characters:

- Sports facilities
- Bridges
- Glass facades
- Roof structures
- Widespan structures

- Zoological and botanical gardens



(a)Durban Stadium (b)Bridge in Austria (c) glass wall

2 DESIGN AND CALCULATION OF CABLE STRUCTURES, FORCES AND GEOMETRIE

The structural calculation of cable structures is carried out with 3D FEM programms like R-Stab or Sofistik. Because of the big movements in the calculated structures it is necessary to run the calculations with Theorie 3rd order. The formfinding of the structure is done by a virtual pretension in the structural calculation.

For the structural element "Cable" it is necessary to use the correct technical values given by the Cable manufacturer. For example for a fully locked Cable the values are like following:

Cable Ø: 70mm

Characteristic breaking load: 4890 kN

Limit tension: 2964 kN

Metallic cross section: 3390 mm²

Weigth: 27,9 kg/m

Construction: VVS3

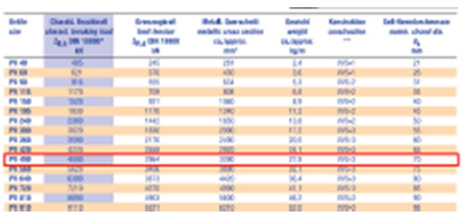
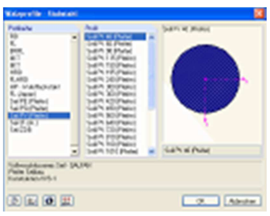
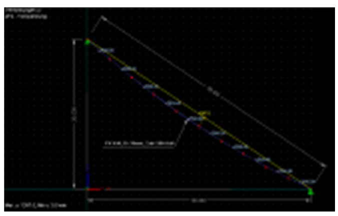
Modulus of elasticity: 16000 kN/cm²

Shear Modulus: 6154 kN/cm²

Poisson`s Ratio: 0,300

Coefficient of thermal expansion: 1,2000E-05 1/°C

After running the structural calculation with all necessary loadcases the form of the structure is found. With this geometrie and the corresponding force in the load case self weigth and pretension the Cable element can be manufactured.

(a)Technical Values 1 (b)Technical values 2 (c)Structural calculation

3 DETERMINATION OF MANUFACTURING CABLE LENGTH

The exact cutting of cables to length requires also the consideration of:

- seating of the cone in the cable socket after cooling down and loading cable
- cable creep
- cutting temperature and design temperature
- additional elongation due to cable fittings or clamps

The seating of the cone is related to the shrinkage of the socketing material (Zamak or Epoxy), the roughness of the inner surface of the socket, the size of the socket and the level of loading. This value has to be determined by the Cable manufacturer and shall be considered in the manufacturing drawings.

The Cable creep is an elongation effect due to the level of loading, number of loading intervals, the duration of loading, construction of the Cable, diameter and number of wires, kind of inner filling and the temperature. An experienced Cable supplier is able to use the correct values. If there is a more accurate value necessary a 100 hour test can be performed.

Also the cutting temperature has to be taken into account. Most of the times the temperature in the structural calculation and the manufacturing temperature is different. This delta L has to be considered during cable manufacturing.

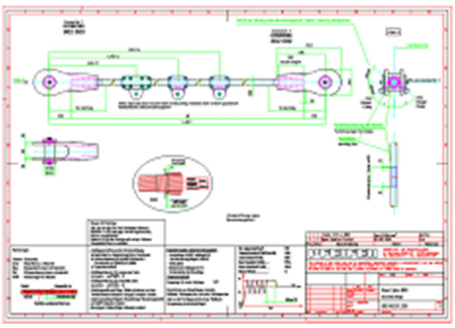
Special structures like cable nets and glass curtain walls often contain swaged fittings or bolted clamps. The clamping force is reducing the cable diameter and thus elongating the cable. Very small elongations per unit can have a large impact on the geometry of the structure if a large number of fittings or clamps are applied on a cable member.

Untensioned cables show nonlinear elongation behavior. Cables of the same construction and diameter show different length under lower loading. Only after prestretching of the cable, the elongation under working load can be calculated. Therefore all cables for buildings shall be prestretched and length measured above nonlinear elongation level in the fabrication plant. Required geometry and load should be calculated by experienced cable specialists.

There is no structural system without tolerances. Modern structural analysis software calculate geometry and forces three digits behind the decimal point. Each item discussed above naturally underlies small fabrication tolerances. The creep value is assumed based on tests in the past and the actual value differs. Even the measuring device has a measuring tolerance. Therefore the following fabrication tolerance for structural spiral strand and locked coil cables is recommended.

$$\Delta L = \pm\sqrt{L\,[m]} + 5\ mm$$

In general these values are smaller than in conventional steel structures and concrete structures. Nevertheless, when structures are sensitive to deviation from nominal geometrical values, adjusting devices shall be provided.



(a)Cable confectioning drawing

(b) Cable length calculation sheet

4 INSTALLATION OF PRETENSIONED CABLE STRUCTURES

Cables come to site shorter than in the prestressed situation, because of that they have to be elongated by pretension equipment. The elastic elongation can be determined with following equation:

$$\Delta L_{elast} = (F_{sys} * L_{sys})/(E*A)$$

ΔL_{elast} : Elastic elongation (mm)

F_{sys} : System force of the cable (kN)

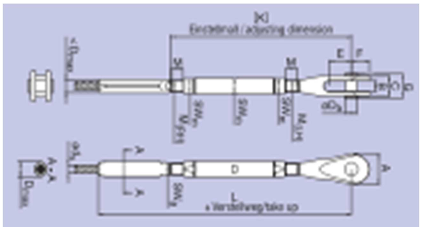
L_{sys} : System length of the cable (mm)

E: Modulus of elasticity (kN/mm²)

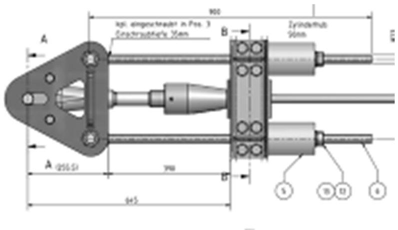
A: Metallic cross section (mm²)

There are a number of possible methods to pretension cables on site:

- Turnbuckle with thread or threaded end terminations (max. 10% of ZRd)
- Chain hoist equipment with clamps and anchor points at steel structure (max. 12 to, 2x6 to chain hoist)
- Hydraulic jacking systems with clamps and anchor points at steel structure (max. 200 to then handling problems)
- Heavy lifting systems (for complex structures)



(a)turnbuckle



(b)hydraulic jacks

(c) chain hoist

(d) heavy lifting system

5 LOAD MEASURING OF PRETENSIONED STRUCTURES

The load measuring method has to be chosen according to the maximum tension forces who have to be allied on the cable structure. Common methods are:

1. Rope Tension meter (max. 200 kN)
2. Hydraulic jacking systems (max. 2000 kN)
3. Heavy lifting systems
4. Vibration method
5. New system with ultrasonic load measurement technology.

A **rope tension meter** is an equipment where by means of the tightening device of the centre support the rope is forced to decline according to figure 4:1. The angle will always be the same, as the rope is pressed against the fixed centre support by means of the clamping jaw. Even if the rope diameter is changed, the angle will stay the same. A resultant force is then obtained, perpendicular to the main direction of the rope, see

figure 4:2.

sin X/2 x 1/F

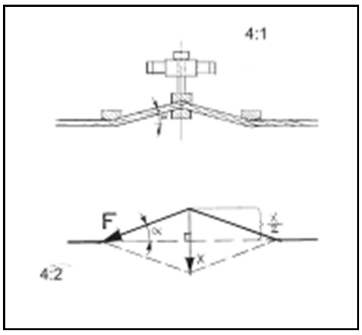
X = sin x 2F

Angle = 1.43°, gives:

sin = 0.0250 = 1/40

X = 1/40 x 2F X = 1/20 x F

i.e. ratio 20:1



The resultant force affects the pull rod which is firmly connected with the flat centre support. The pull rod affects in its turn the load cell, which gives an electrical signal which is proportional to the force. The signal is amplified, converted and indicated on the LCD display of the instrument.

Hydraulic jacking system are dependent on the size of the jacking cylinder, the possibility of installing anchor points because of technical and architectural reasons and the possibility to install this systems every time when you need the forces measured. The biggest disadvantage is the handling problem. Lifting equipment and scaffold is always necessary.

The same problems occur by using **heavy lifting systems**, special anchor points have to be designed and they have big influences in the steel structure.

Vibration method is just successful in the application with very long cables, as otherwise influences of flexibility of anchorages, the short length, low tension and bending effects are too big. A combination of high quality vibration measurements with finite element analysis of individual cables was used for the installation of the London 2012 Olympic Stadium Roof.

6 ULTRASONIC LOAD MONITORING METHOD

The new method is an ultrasonic load monitoring technology that uses a well known physical phenomena called the ‘acoustoelastic effect’. This phenomena has been widely used to measure the effect of stress on materials for decades. An example of this is the measurement of bolt tension using ultrasonic sensors. These measurement techniques have gained approvals in the aerospace industry and are used by several aerospace manufacturers.

Methods were developed to instrument the pins from fork and plate connections used in structural bar and cable products and can monitor the load through these components when used in a variety of applications. (Pinned Connections, Tie Bars, Cable Stayed Structures, Suspended Structures, Compression Struts). Once instrumented the pin is calibrated against a known load cell and the calibration is stored on the pins ID chip.

The new ultrasonic load measuring technology has been tested at the university of Leeds, UK and Braunschweig, Germany as well as in the Pfeifer testing laboratories. During this testing it has achieved an accuracy of ±1.5% of the design loads.

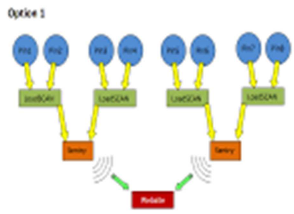
For temporary monitoring a handheld load monitoring device has been developped. This device allows quick and easy plug and play measurements and is an excellent tool to aid in the installation of assemblies and stressing operations. It offers a quick and easy method for the validation of load on these structural assemblies at any time during the structures life.

For Permanent Monitoring electronics were developped that can be permanently installed to monitor the Load on components. The electronics record the measurements of load and can be programmed to report as often as required over a GSM network allowing the user to access the data via a website.

This components allow to develop cost effective and reliable installation/maintenance concepts for nearly all pretensioned structures.


(a)instrumented pins


(b)measuring equipment

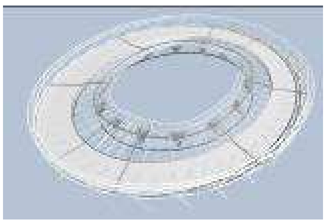

(c)measuring concept

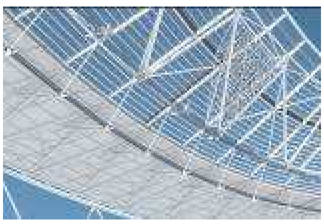
7 PROJECT EXAMPLE, LONDON OLYMPIC STADIUM

7.1 Introduction

The London 2012 Olympic Main Stadium was originally meant to be a temporary item, at least for the most parts of it. Now the City of London has suceeded in finding a user for the stadium and has also secured the Rugby World Championship 2015 and the track and field world championship 2017. For these reasons the stadium have been refurbished according to the valid regulations. Which means that there has to be a new, wider roof on it.


(a)Olympic Stadium


(b)Reconstruction 1


(c)Reconstruction 2

7.2 Overview in Figures

The Olympic Stadium in original configuration holds 80,000 seats and will also, after refurbishment. The old roof did not offer shelter for enough seats. The refurbished stadium was a versatile one, with seating moveable up to the pitch. So the new roof will have the longest cantilever ever of nearly 80 meters, to cover all seats. The covering area of 45.000 sqm will comprise of an inner, transparent polycarbonate ring and the outer area covered by sandwich panels with membrane sealing.

Title:	London Legacy Olympic Stadium
Schedule dates:	General Works: October 2013 – March 2015
	Cable Net: on site February 2014 – August 2014
Contract value:	General Works: 45 Mio GBP / 60 Mio EUR
	Dismantling Works and new Cable Net:
	12 Mio GBP / 15,8 Mio EUR
Client:	Balfour Beatty plc
Contract Type:	NEC
Additional Steel:	3400 tons of steel
Cable Structure:	Fully locked cables 60mm – 110mm,
	9 km in length, 890 tons weight cables and castings
Roofing Solid Polycarbonate:	18,000 sqm / 194,000 sq ft
Roofing Composite Panels:	27,000 sqm / 292,000 sq ft

7.3 The dismantling works

After installation of temporary bracings between two lighting masts, they were dismantled in pairs. Movements of the ring cables were controlled. The old fabric was cut out. As many as necessary of the old walkways were de-installed for re-use.

The hydraulic equipment was installed at the original lifting locations. After taking over the forces from the old cable net, it was released and lowered in a sequenced manner to the pitch. As the last step the tripods on the outside of the stadium, originally supporting the Ceremony Cables in Olympic mode, were picked from the structure. This way access is free for the strengthening works to the compression ring.

7.4 The New cable Net

Erecting the new roof for the London Legacy Stadium was a multi-discipline process. It started with the installation of the outer steel panels with attached outer radial cables. Hydraulic lifting equipment was connected then to this first parts of the roof in all grid lines.

This was followed by a full big lift operation for the inner cable net. After pinning the front radials in the engineered sequence further steel beams and girders were built on the top of the Cable net to complete the structure, using a 600 to crawler crane.

Before installing the steel structure a defined geometrie of the Cable net had to be adjusted and force controlled over the complete installation period.

For controlling the forces the **new ultrasonic load monitoring system** was installed and successfully used.

(a)Tie down

b)load scan system

The load monitoring could be done after every installation step of the steel structure without holding available the complete hydraulic jacking system and without installing and reinstalling the jacking system at the required positions. There was just one cable specialist necessary who walked around the stadium and measured and monitored the forces in the Tie Down Cables. All in all it was a reliable and cost saving solution for the client.

As a **conclusion** following points can be pointed out for the new system:

- Robust
- Without invasive works
- Removes many access issues
- Continuous monitoring
- Embedded permanently installed sensors
- Low cost
- Wireless measurement
- Very fast setup to measurement time
- Improved understanding of structural loads
- Dynamic loading environments
- Traceability through unique identifier

There are much more applications who can be developed for each single project together with the architects, structural engineers, clients and carriers.

References:

- Assessment of Cable Forces at the London 2012 Olympic Roof, Structural Engineering International, Volume 23, Number 4, November2013, pp. 489-500(12)
- Bestimmung der Seilkräfte durch Schwingungsmessung und rechnerischem Vergleich mit den Seilgleichungen, Diplomarbeit Janusz Klichta 2006, FH Augsburg
- Bauteilversuche: Frequenzmessungen am Schrägseil Versuche VVS – PV90, IMB Karlsruhe, Univ.-Prof. Dr.-Ing. Lothar Stempniewski