A Method Of Measuring and Ensuring Correct Cable Tension On Cable Stayed Structures – A Case Study

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INTRODUCTION

With the advent of superior high performance materials and computer aided design and analysis techniques, structural engineers are now capable of designing and building lighter and highly efficient structures. The typical structural elements previously used in airframes and other sophisticated structures are now being applied to building and bridge construction. A multi-strand cable in tension can act as a very efficient structural element due to its high strength-to-weight ratio. With the current manufacturing techniques and available materials, such a high tensile cable can be fabricated economically.

As the above lean design principles are highly reliant on the accuracy and tolerances of the structural system, appropriate manufacturing, fabrication and installation techniques need to be developed and used in order to assure reliability. Furthermore, with smart designing some tolerance absorption may be incorporated into the structural system; hence not requiring the same level of fabrication tolerances common in expensive aerospace applications. Greater economies can be achieved by the introduction of such measures.

In order to achieve a reliable tension cable stayed structure, each cable needs to be pre-tensioned to a designed tension load. This tension load should be sustained in the cable through the life span of the structure. Hence, a method of reliably measuring cable tension during installation as well as regular maintenance intervals becomes a necessity.

It is also common knowledge that any structural system - especially a tensioned cable system - relaxes with time. The friction interfaces between strands and other structural components generally contribute to this relaxation. In general, most of the relaxation is noticeable within the first 24 hours and will reduce with time. Therefore, it is very important to monitor the system after 24 hours and to re-tension if required. Further monitoring at one week, one month and six month intervals are also advisable to make sure that no detrimental relaxation is taking place.

Due to the cable lengths associated with typical cable stayed structures, thermal expansion of cables may also contribute to variations in design tension loads. Although some of these effects can be analysed using mathematical modeling techniques, it is not possible to determine these effects with certainty due to the number of unknowns associated with such situations. A cable tension measurement system would be useful in understanding and controlling these effects.

In general, almost all of these cable stayed structures are subject to cyclic loading. Improper connection design may lead to fatigue failure in structural components. Therefore, it is necessary to carry out a fatigue analysis and to make sure that the bolts and other similar structural components are not subject to large cyclic loads.

This paper introduces a structural concept that can be incorporated to any tensioned cable in order to measure and monitor the tension of the cable at installation and during its life span. With minor variations this system can be adopted to almost any tensioned cable system. A case study of one application is included.

PROBLEM DEFINITION

Let’s assume a particular cable stayed structure requires a design tension T (kN) on one of its cables. This cable is anchored at either end using pin connections (Figure 1). There is a need to absorb some manufacturing and operational tolerances in terms of length variations.

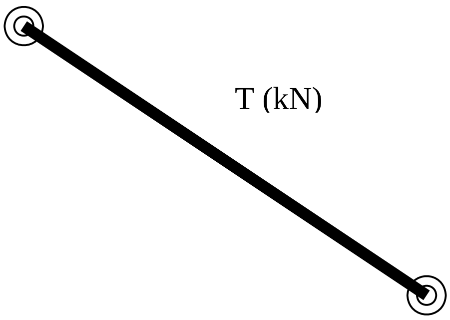

Figure 1: Schematic of the Cable System

In general the design tension load consists of two components namely, the static or dead load component ($\overline{T}$) and the dynamic or live load component ($\hat{T}$). The total load (T) is;

$$T = \overline{T} + \hat{T}$$

In the erection of the structure it is very important to make sure that the designed cable pre-tensions are achieved. In general, the pre-tension of the cable will be equal to the designed static tension load on the cable.

PROPOSED SYSTEM

Configuration 1

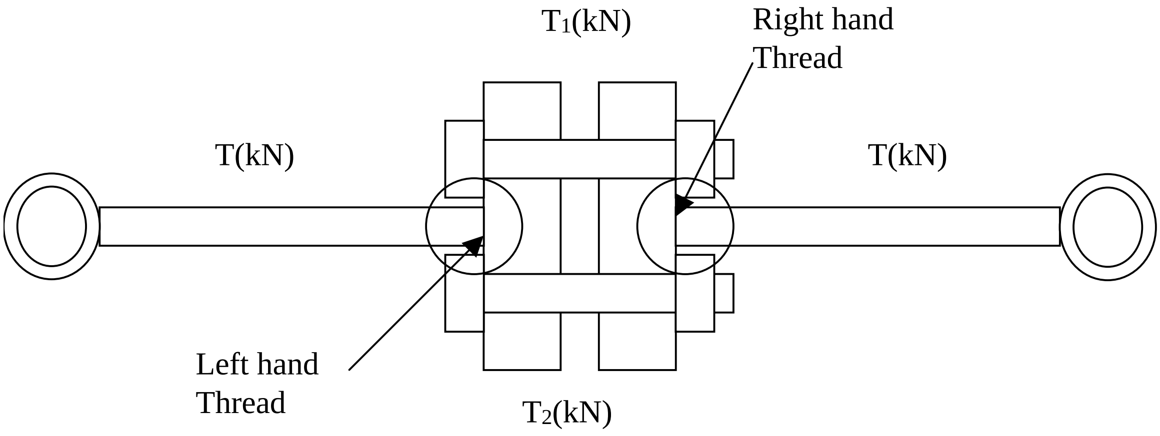

Figure 2: Proposed Configuration 1

The conceptual system shown in Figure 2 comprises a turn-buckle arrangement with left and right hand threads connecting two eye bolts or similar structural elements to two thick flanges. The flanges are connected together using a symmetrical arrangement of number of bolts (n). Assuming all the bolts are on equal tension then the required tension on each bolt is;

$$T = nT_i$$

or if they are not equal

$$T = \sum_{i=1}^{n} T_i$$

Now if the tension on each bolt can be measured with adequate accuracy the tension on the cable can be measured. The turn buckle and the bolts in combination can be used to increase or decrease tension while the tension is measured using the tension sensing bolts.

Although the above proposed system is capable of measuring and monitoring tension on the cable it is not a reliable bolted joint. The main disadvantage of the above configuration is that any cyclic loading on the cable system will be directly seen by the bolts. In general cables in tension behave much better in fatigue compared to bolts. Due to stress concentrations created by thread geometry a bolt on its own is not a robust structural member especially in a fatigue environment. A fatigue analysis using S-N curves need to be carried out in order to establish the fatigue life of the bolts. This procedure is explained in detail elsewhere [1]. Secondly the proposed system provides a discontinuity in flexural modulus of the cable hence producing bending stresses on the bolts. This will be worsened by the length of the proposed arrangement. When subject to cyclic loading combined tensile and bending stresses on the bolts make them more susceptible to fatigue failure.

In order to overcome above disadvantages the same system can be utilised in a slightly different manner.

Configuration 2

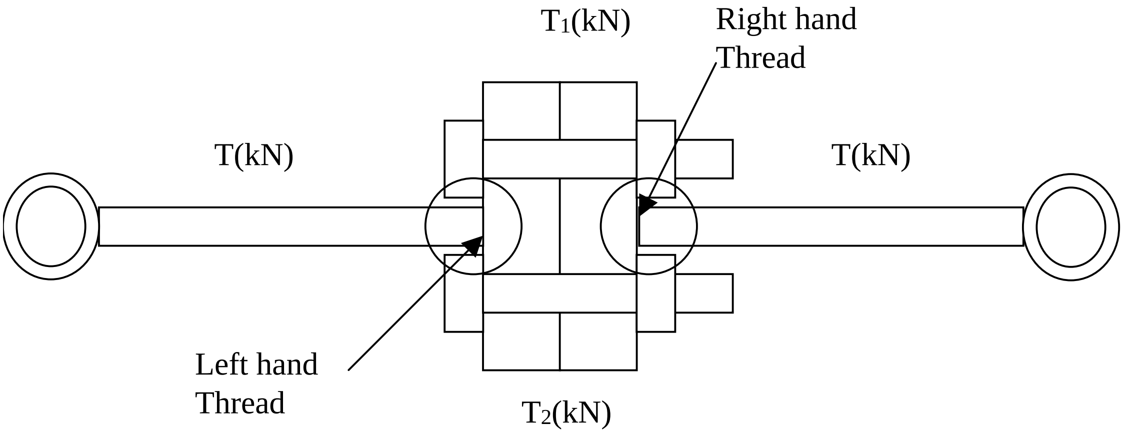

Figure 3: Proposed Configuration 2

In this arrangement (Figure 3) the bolted joint becomes a closed pre-tensioned joint. In practice this can be achieved by firstly tightening the system to achieve desired static load on the cable as per previous case. Once this is established through the measurement of individual bolt tensions, the remaining gap between the two flanges should be measured. Now loosen the turn buckle so that a displacement equal to the measured gap is added to the cable system. When the bolts are tightened to close the gap between flanges the system will now produce the necessary tension on the cable. This can be verified by measuring the bolt tensions just before the flanges come into contact. Now apply further pretension (clamp load) between the flanges by further tightening the bolts. As the movement involved in this process is extremely small (after the flanges come into contact) this will not alter the resulting tension in the cable system. Hence the relationship between tensions of the bolts and the tension of the cable becomes;

$$T < \sum_{i=1}^{n} T_i$$

$$T + F_c = \sum_{i=1}^{n} T_i$$

Where F_c is the clamp force between the two flanges. In this case the respective bolt tensions are larger than that for the previous case. However, the contribution of the dynamic load in to the bolt will be less than that for the previous case. The following analysis establishes the advantages in fatigue performance achieved by the use of this system.

DYNAMIC LOADING

The tension T on the cable can be represented by;

$$T = \overline{T} + \hat{T}$$

where $\overline{T}$ is the static component and $\hat{T}$ is the dynamic component of the tension on the cable. The dynamic component is mainly due to wind loads and live loads.

In the above configuration 1, assuming all the bolts in the joint share the tension equally the static and dynamic components of the tension on the bolts are;

$$\overline{T}_i = \frac{\overline{T}}{n}$$

$$\hat{T}_i = \frac{\hat{T}}{n}$$

This indicates that the bolts will see the total mean and fluctuating components of the load.

In the second configuration the main criterion is to keep the joint from separation. To marginally satisfy this condition the required minimum pre-tension load required on each bolt is (assuming equal distribution) [1];

$$F_i = \frac{k_c}{k_b + k_c}\left(\frac{\overline{T} + \hat{T}}{n}\right) \longrightarrow (1)$$

where k_c and k_b are the stiffness of the clamp and the bolt respectively. This is less than the maximum bolt tension experienced in the configuration 1.

$$F_{a,\max} = \frac{\overline{T} + \hat{T}}{n}$$

Using the same analysis described in [1] the bolt tension at a given applied load F_a can be given by;

$$\begin{aligned} F_b &= F_i + \frac{k_b}{k_c + k_b} F_a \\ &= \frac{k_c}{k_b + k_c}\left(\frac{\overline{T} + \hat{T}}{n}\right) + \frac{k_b}{k_c + k_b} F_a \longrightarrow (2) \end{aligned}$$

The static bolt load under static loading of the cable can be given by;

$$\begin{aligned} \overline{F}_b &= \frac{k_c}{k_b + k_c}\left(\frac{\overline{T} + \hat{T}}{n}\right) + \left(\frac{k_b}{k_c + k_b}\right)\frac{\overline{T}}{n} \longrightarrow (3) \\ &= \frac{\overline{T}}{n} + \frac{k_c}{k_b + k_c}\left(\frac{\hat{T}}{n}\right) \end{aligned}$$

As seen in the above equation the static tension load on the bolt is larger than the static tension load in the previous case (configuration 1).

When the dynamic component of loading $\hat{T}$ is applied the contribution on the bolt tension is;

$$\hat{F}_b = \left(\frac{k_b}{k_b + k_c}\right)\left(\frac{\hat{T}}{n}\right) \longrightarrow (4)$$

As k_c is significantly larger than (approximately 4 – 8 times) k_b the dynamic component experienced by the bolt is significantly smaller than that in configuration 1. However, the maximum load experienced by the bolt will be same as the previous case.

$$\begin{aligned} F_b &= \overline{F}_b + \hat{F}_b \\ &= \frac{\overline{T} + \hat{T}}{n} \end{aligned}$$

In order to achieve a robust bolted joint it is necessary to apply a bolt pre-tension load larger than F_i given in Equation 1. The excess pre-load will contribute to the prevailing clamping force on the joint when the cable experiences the maximum working tension. This will make sure that the joint will not be separated and the bolts will not be subject to undue bending moments.

THE CASE STUDY

Aluminium Business Resources (ABR) designs and constructs complex glazed structures. ABR has been successful in creating series of dramatic structures that incorporate leading edge technologies to solve particular problems.

A recent project at 207 Pacific Highway, St Leonards in Sydney (Plate 1) called for glazed feature lobby walls, seven metres square, with minimal secondary support to maximise transparency. An in plane pre-tensioned rod system with two horizontal rods was selected. To keep the glass wall deflections within acceptable limits under wind load, a pretension of 175 kN was required in each rod. A maximum rod tension of 305 kN is developed under the design wind load of 1.0 kPa.

Plate 1: 207 Princess Highway, St Leonards, Development

To resist these loads against the face of 600 mm x 600 mm supporting concrete columns, an innovative solution was required. For structural reasons it was not possible to penetrate the columns. A zone of 150 mm from the column face was available to conceal all support, anchorage and stressing mechanisms. A collar around the column was designed to anchor the stressed rods. The collar incorporated a screw plate mounting four M20 x 90 Class 8.8 SMARTBOLT™ to tension the rods.

ANALYSIS

Static Cable Load	175kN
Dynamic Cable Load	130kN
Maximum Cable Load	305kN
Stiffness ratio (k_c/k_b)	6 (estimated based on the geometry)

Use four (4), Direct Tension Measuring Bolts (eg. SMARTBOLT™) M20 PC8.8 which has a design proof load of 147kN.

Configuration 1

Now the required pre-tension on each bolt in configuration 1 is;

$$\overline{F}_b = \overline{T}_i = 175/4 = 43.75\text{kN} = 43.75/147\text{x}100\% = 29.76\% \text{ Proof Load}$$

Under a dynamic load of 130kN on the cable this bolt will experience a dynamic load of;

$$\widehat{F}_b = \hat{T}_i = 130/4 = 32.5kN = 22.1\% \text{ Proof Load}$$

Hence the maximum load on the bolt is 51.86% Proof Load and the ratio between dynamic and static bolt load is 22.1/29.76 = 0.74. Based on Goodman or S-N diagrams this will have a higher potential for fatigue failure.

Configuration 2

As per analysis detailed in the previous section (Equation 1) the minimum pre-tension load required on the bolts to avoid joint separation is;

$$\begin{aligned} F_i &= \frac{6}{6+1}.\frac{305}{4} = 65.3514kN \\ &= \frac{65.35}{147}.100\% = 44.46\% \text{ Pr oofLoad} \end{aligned}$$

When the cable is at its static load the corresponding bolt tension (Equation 3) will be;

$$\begin{aligned} \overline{F}_b &= F_i + \frac{1}{1+6}\left(\frac{175}{4}\right) = 65.35 + 6.25 = 71.60kN \\ &= \frac{71.60}{147} * 100 = 48.71\% \text{Proof Load} \end{aligned}$$

Compared to 39.6% of the proof load in configuration 1 this is significantly larger. Now the dynamic contribution on the bolt tension (Equation 4) will be;

$$\begin{aligned} \hat{F}_b &= \frac{1}{1+6}\left(\frac{130}{4}\right) = 4.64kN \\ &= \frac{4.64}{147}.100\% = 3.15\% \text{Proof Load} \end{aligned}$$

In the second configuration the distribution of static to dynamic load on the bolt will be 48.71% to 3.15% where as in the previous configuration it was 29.76% to 22.10%. Even though the maximum load experienced by the bolt is identical in both cases (51.86% proof load) the fatigue performance of the bolt is much favorable in the second configuration as the ratio of dynamic to static load is significantly smaller (0.06 compared to 0.74). Typically as characterised in the S-N diagrams smaller fluctuating component will always provide a better fatigue performance.

Although the calculated minimum pre tension requirement was 59.3% of the proof load it was decided to pre-tension the bolts to 65% of the proof load as there was enough capacity left on the bolts. Now the distribution of static and dynamic bolt loads as a percentage of the proof load will be;

$$\overline{F}_b = 65\% + 4.25\% = 69.25\%$$
$$\hat{F}_b = 3.15\%$$
$$F_b = \overline{F}_b + \hat{F}_b = 72.40\%$$

The ratio between dynamic and static components is further reduced and hence the fatigue performance is further improved. When the structure is subject to the maximum load condition still the joint will be held together by a clamping force of 20.54% of the proof load making it a robust joint.

In addition as the joint is not separated the possibility of bending loads applied on the bolts is eliminated.

APPLICATION

Tensioning the rod was achieved by tightening four M20 SMARTBOLT™ , connected to the rod end, against a backing plate (Plate 2). The bolts were incrementally tightened in sequence until the sum of all the loads in all the SMARTBOLT™ equaled the 175 kN rod pretension required. The quick direct digital readout of percentage proof load allowed very rapid tensioning of the rods. Following completion of the tensioning, the screw plates were repositioned and the SMARTBOLT™ tightened to 65% proof load to reduce the effects of fatigue loading on the SMARTBOLT™ .

The use of Ajax SMARTBOLT™ fastening technology provided ABR with a straightforward and reliable method of tensioning and monitoring a stressed cable system with access from one side only.

If at a later stage it is necessary to evaluate the tension on the cable the bolts should be loosened until the joint is just separated. The sum of the bolt tensions at this stage will be the tension on the cable. If required further adjustments to the tension can be made using the turn buckle arrangement.

Plate 2: Arrangement of SMARTBOLT™ in use

If it is necessary to monitor the variation in cable tension under applied loads or environmental conditions, again, the bolts should be loosened until the flanges are just separated and continuously monitor the bolt tension with varying applied loads or environmental conditions.

In the second configuration although the bolt will see a component of the applied dynamic load, measurement of this component may not give adequate accuracy as the sensitivity of this component is significantly lower.

Although the above configuration 1 may provide adequate fatigue life for the bolts this is not the preferred configuration due to lack of robustness.

CONCLUSIONS

- Tensioned cables are useful in designing economical and efficient structures.
- Achieving and maintaining desired cable tension is essential in guaranteeing the performance of the structure.
- A method of using accurate direct tension measuring bolts such as SMARTBOLT™ in achieving and maintaining correct cable tension is established.
- The concepts presented are successfully used in real life applications.
- Improvements to the fatigue life of a bolted joint can be achieved by carefully selecting the bolt pre-tension.
- The concepts presented may be incorporated in to the design of tensioned cable stayed structures in order to achieve higher efficiency and reliability.

BIBLIOGRAPHY

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