FULL LOCKED COIL ROPE HANGERS FOR ARCH BRIDGES - PRODUCT PROPERTIES, PRODUCT POTENTIAL AND INSTALLATION EXAMPLES

M. Bechtold[1], A. Zielinski[2]

[1]FATZER AG, Romanshorn, SWITZERLAND.
[2]Liny Stalowe Brugg Sp.z.o.o. Sp.K., POLAND.

e-mail: Martin.Bechtold@fatzer.com, az@brugg.com.pl

SUMMARY

The use of full locked coil ropes as hangers in arch bridges has a long tradition. EN 1993-1-11 [1] provides the design basis for the dimensioning and the use of structural ropes. However, the successful completion of a project requires detailed additional product knowledge and installation expertise.

The authors have extensive experience and track record in manufacturing and installing full locked coil ropes for arch bridges. They have worked together on numerous projects in- and outside of Poland and so to speak build a Polish-Swiss rope alliance.

Firstly, this paper describes the properties of full locked coil rope assemblies in respect to their use as hangers in arch bridges. Fatigue properties, stiffness, critical manufacturing steps such as prestretching, the build in redundancy of ropes made from numerous individual wires, architectural experience and inspection issues are discussed amongst other aspects. The paper also refers to a recent study about the fatigue resistance of full locked coil ropes and describes the pros and cons of full locked coil ropes in comparison to steel bars and parallel wire strands.

Secondly, the subject of installation is addressed with practical application examples. Whilst regardless of their length rope assemblies conveniently arrive at site ready for installation, they require particular care in handling for example during uncoiling and tensioning. Their flexibility is different to other construction products such as steel bars and profiles or concrete and wooden structural members.

Keywords: *Full locked coil rope, hanger, installation.*

1. INTRODUCTION

Full locked coil ropes were invented in 1884 for mining applications where they are still used today. Already in the early 19 hundreds they found their way into structural applications mainly due to the protection of the inside of the ropes by the interlocking z-shaped wires.

Full locked coil ropes have now been used in countless major structures for about 100 years. Although the basic and established product remains unaltered considerable progress and developments have been made over the decades. Their well thought out build-up and corrosion protection consisting of a stable helical arrangement of wires, Zn95Al5 galvanising of the wires, the locked surface with interlocking z-shaped wires and the zinc pigmented active inner blocking compound make them fit for years to come. Recently presented work sheds additional light on their fatigue performance in the context of structural misalignments and bending effects at the connections to the bridge deck of arch bridges.

2. FULL LOCKED COIL ROPES

2.1. Description

2.1.1. Rope Build-Up

Full locked coil rope assemblies are prefabricated tension components for structural applications. They consist of full locked coil ropes and permanently attached sockets. Full locked coil ropes are a special type of spiral strand rope. They are made using a core of helically spun round wires in several layers onto which covers of helically spun z-shaped wires in one or more layers are placed (Fig. 1 and Fig. 2). They are manufactured in a factory, layer by layer (Fig. 3). The layers are usually spun in opposite directions to minimize the residual torque.

Fig. 1. *Round and z-shaped wire.*

Fig. 2. *Full Locked Coil Rope.*

Fig. 3. *Full Locked Coil Rope Manufacture. Final z-shaped layer on a 100mm rope.*

Full locked coil ropes are made to the product standard EN 10285-10 [2] and the wires conform to EN 10264-2 [3] (round) and EN 10264-3 [4] (z-shaped).

2.1.2. Sockets

Full locked coil ropes are terminated with spelter sockets which are designed to be stronger than the rope. Fig. 4 shows the most common sockets used in arch bridges. The open sockets are easily attached to a connecting plate via a pin. They can have an adjustability build in via a left hand/right hand threaded connector. The cylindrical socket has a bearing nut which can be adjusted along the thread length of the cylinder. The fixed open socket is typically used at the arch whereas the adjustable open socket and the cylindrical socket are located at the bridge deck for ease of access.

3D modelling software and finite element software (Fig. 5) are state of the art in the design process. The external shape can be altered to provide a level of aesthetics not normally associated with this type of product. The 3D model can be incorporated into the overall design to check for proper interface with connecting steelwork.

Fig. 4. *Sockets used in arch bridges.*

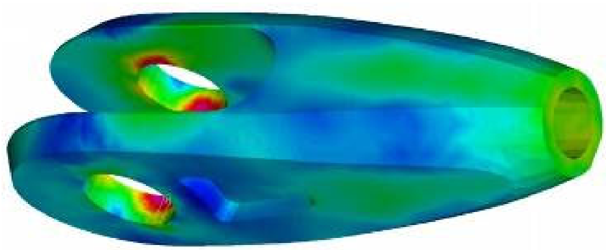

Fig. 5. *Finite Element Analysis on an open socket.*

2.1.3. Socketing

Full locked coil ropes are always anchored inside their conical socketing area. The rope is opened into a brush and the area is filled with a molten zinc alloy or a resin (Fig. 6 and Fig. 7). Fig. 8 shows an isolated zinc socket cone for demonstration purposes The process follows EN 13411-4 [5]. This type of socketing does not weaken the rope assembly. It transmits the full rope force.

Fig. 6. *Brush inside an open socket.*

Fig. 7. *Socketing of an adjustable open socket with hot metal.*

Fig. 8. *Socket cone – isolated from the socket for demonstration purposes.*

2.1.4. Assembly Length

The particular design of the structure in question determines how accurate and how stable the final rope assembly length needs to be.

In any case full prestretching of the rope and length marking under load is recommended. This makes the elongation properties and the assembly length more accurate and stable right from the start. The prestretching and marking should take place in controlled climate conditions inside a factory to avoid influence from the weathers. In the prestretching procedure the constructional stretch is taken out of the rope. This is done by loading and unloading the rope 5 to 10 times between 10% and 50% of the MBL. The rope than behaves elastically and can be marked under load to the specified length. Load and length at a given temperature need to be taken from the static calculation of the structure.

A prestretched rope will still show some additional permanent elongation once it is under load in the structure. This phenomenon is usually referred to as rope creep. For a prestretched rope it will usually be approximately 0.35 mm/m. Additionally, during initial loading of the structure, some socket seating will occur when the zinc or resin cone is fully drawn into the socket. The magnitude depends on the size and type of socket and will usually be around 1-5mm per socket. Both effects creep and socket seating need to be considered by the rope manufacturer. This is done by producing the assembly length shorter.

Current manufacturing techniques and prestretching in controlled climate conditions enable tight length tolerances to be achieved. The following tolerance for rope assembly lengths are stated in EN 1993-1-11 [1]. They are sufficient for most structural applications and can be confidently used for arch bridges.

$$\begin{gathered}\Delta L[mm] = \pm\left(5mm + \sqrt{L[m]}\right) \\ with\ \ L = rope\ assembly\ length\end{gathered} \tag{1}$$

2.1.5. Architectural Properties

Full locked coil ropes with two layers of z-shaped wires have a metallic cross section of minimum 84% compared to the circumscribed circle. This value is considerably higher than the value for all other wire based tension components.

Full locked coil ropes with their high tensile wires are therefore the tension components with the greatest ratio of load capacity over diameter. They also have the highest axial stiffness to diameter ratio of all tension members apart from solid steel bars. The small diameter has a direct impact on the size of the sockets. Some sockets have been designed to reflect the flow of forces in the architectural appearance (Fig. 4).

Wherever aesthetics and the transparency of a bridge play a role full locked coil ropes are first choice.

2.2. Properties

2.2.1. Load Carrying Capacity

With the build-up from individual wires in helixes and the sockets designed stronger that the rope itself full locked coil ropes have a high level of structural redundancy.

EN 1993-1-11 [1] refers to the following two expressions in respect to the breaking load:

Characteristic Breaking Strength or Minimum Breaking Load (MBL): The load which will be achieved in a physical breaking load test on an undamaged rope. Its calculation is based on the nominal wire tensile strength and a spinning loss. Manufacturers of full locked coil rope state the MBL of their ropes in their brochures.

Calculated Breaking Strength: This is a theoretical value based on the sum of all wires with their nominal wire tensile without considering the spinning loss.

2.2.2. Load Elongation Characteristic

The axial stiffness is the product of the elastic rope modulus and the metallic cross sectional area. The elastic rope modulus is not a material property in its pure sense but a phenomenological property which describes the elongation characteristics of the rope as a whole. It considers the material elastic modulus of the wires as well as the geometrical arrangement of the wires in the rope.

The product standard 12385-10 [2] does not give values for the elastic rope modulus. EN 1993-1-11 [1] as the design code states 160'000 N/mm^2 with a tolerance of ±10'000 N/mm^2 which covers usual designer needs and product characteristics reasonably well.

2.2.3. Corrosion Protection

Full locked coil ropes have a combination of several corrosion barriers which complement each other.

In the rope interior a blocking compound with zinc dust or aluminium flakes is added during stranding. By coating the wires inside the rope it prevents the intrusion of corrosive media and is itself a corrosion inhibitor. Dosage and composition of the blocking compound need to be such that emerging to the rope surface is minimized. Therefore the two outer layers will not have a blocking compound applied.

All wires are class A hot dip galvanized in a 99.9% zinc bath to EN 10264-2 [3] (round wires) or EN 10264-3 [4] (z-shaped wires). For improved corrosion resistance by approximately factor 3 the wires of the two outer layers are class A hot dip galvanized with Zn95Al5. Zn95Al5 is applied in a double dip galvanizing process and is also known under the brand names Galfan®, Crapal® and Bezinal®. The corrosion mechanism is similar to that of pure zinc. However the aluminium oxide that develops over time sticks to the surface better than zinc oxide. Considering this it is beneficial to use Zn95Al5 galvanizing in the two outer layers of a locked coil rope.

The z-shaped wires themselves provide an effective surface barrier against the penetration of corrosive media because of the interlocking of the z-shaped wires. Additionally the even surface has less exposed area in comparison to round wires.

If additional protection is required this can be provided by a paint, by wrapping with a butyl rubber tape or by a plastic sheathing. The first two methods are applied on site which means that they can also be fitted retrospectively whereas a sheathing is applied before delivery on site. However the basic corrosion protection does not rely on any of these additional measures. One needs to consider that both the wrapping and the sheathing take away the most straight forward and easy to apply inspection method, the visual inspection, on a product that has great structural redundancy build in.

2.2.4. Fatigue

Hangers in vehicular bridges are submitted to fatigue loads from traffic. EN 1993-1-11 [1] assigns the detail category $\Delta\sigma_c$ = 150 N/mm² to full locked coil ropes. However the failing of ropes submitted to fatigue loading is fundamentally different to that of conventional structural components where almost the whole fatigue life is related to the period before the first crack occurs. In contrast to this the first crack in a wire in a rope has no relation to the much later failing of the complete rope. In full locked coil ropes the interlocking z-shaped wires avoid the popping out of a broken wire in the outer layer. Due to the helical arrangement a broken wire will carry the full load again after approximately three lay lengths (~ 3 x 10 x rope diameter).

The fatigue detail category of welded hangers are dominated by the connection to the arch and the deck. An optimized configuration is proposed in [7] with a value of 90. Tension rod systems are dominated by the threaded end of the bars which need to be assessed with EN 1993-1-9 with a fatigue detail category of 30 minus a deduction depending on the size. Parallel wire bundles have a fatigue detail category of 200 however without the build-in redundancy of a full locked coil rope.

EN 1993-1-11 [1] does not provide clear guidance regarding bending effects on tension components and instead recommends structural measures to limit bending effects. Calculation methods for bending stresses have been developed and suggested outside of the code. Due to the complex rope geometry with wires in helical arrangement and due to the combined effect of 100s of wires these methods are very complicated and not established for design purposes.

On the positive side wires in a helical arrangement travel from tension side to compression side along the length of a rope. This means that the wires are able to alleviate bending stresses. Also the number of reported damages due to bending are relatively small which supports the assumption that current design rules seem to cover also some degree of bending.

In order to shed more light onto the subject additional research regarding the fatigue performance of full locked coil ropes in arch bridges has recently been done by Schmidmeier [8] as part of a research initiative of the German waterways authorities (Bundesanstalt für Wasserbau, Karlsruhe).

Schmidmeier performed fatigue tests on several full locked coil ropes with diameters of up to 45 mm and examined the bending effects that occur in hangers of arch bridges at the connection to the arch and to the deck. These bending effects are caused by the deformation of the bridge and of the arch due to the traffic. Especially steel hangers that are welded to the deck and arch suffer from cracks in the welds and in the geometric transition points.

A rough overview of the findings was presented at a conference in Munich “Münchner Stahlbautage” in 2015. A more detailed presentation of the work will follow most likely before the end of 2016. It will include an engineering model which takes into account the combination of theoretical bending angles at the sockets and rope forces together with the number of cycles to assess the fatigue life of full locked coil ropes under bending.

Due to the positive findings of this work the rehabilitation of “Gelmer Brücke” in Germany was done with full locked coil ropes instead of the original bars which were welded to the bridge deck and the arch.

3. INSTALLATION

3.1. Arch Bridges

Arch bridges usually cross up to 150 m but exceptional cases exceed 200 m. In those spans they have cost advantages over the longer span structures such as cable stayed bridges and suspension bridges.

Hanger arrangements vary from vertical to inclined to single crossed to multiple crossed with constant or varying incline depending on the span (Fig. 9). The largest spans and the minimum arch dimensions can be achieved with network arch bridges with multiply crossed inclined hangers [7].

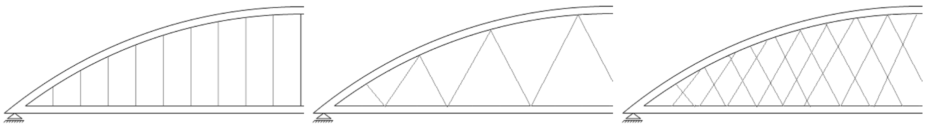

Fig. 9. *Various hanger arrangements from [7].*

3.2. Transport

Depending on the size ropes can consist of several 100s of wires. The helical arrangement of the wires makes the overall rope construction stable whilst still being flexible to bend. This goes as far as that they can be coiled which takes away length limitations for transport or joints on site (Fig. 10).

The rope diameter determines the inner coil diameter (e.g. 30 times rope diameter) whereas the height of the coil and the overall length of the rope determines the outer diameter of the coil. Standard truck widths or oversize transport need to be considered accordingly.

Fig. 10. *Delivery at site.*

3.3. Equipment

Uncoiling needs to be done horizontally. Lifting a rope end vertically from a horizontally placed coil can lead to a permanent kink and wires can come out of lock. Smaller rope coils can be uncoiled manually. The rope needs to be placed on movable supports to allow for movements and to avoid contact to the ground (Fig. 11).

Fig. 11. *Manuel uncoiling of the ropes.*

Longer rope coils need to be uncoiled with a turntable which ideally should have breaks to control the uncoiling speed.

The site needs to offer enough space to lay out the ropes straight. Ideally this could be the bridge deck. From the straight position the ropes can subsequently be lifted with a crane. An aerial platform provides access to the connection points at the arch.

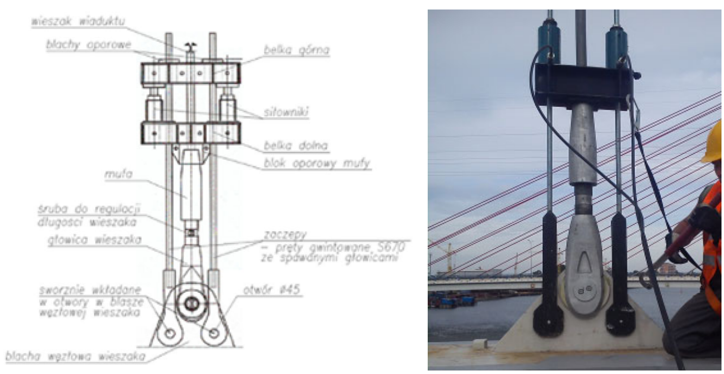

Fig. 12. *Tension equipment for an adjustable open socket.*

Unlike solid steel components ropes have their final length under load. Most rope tension components need to be tensioned for installation. A typical tension tool for an adjustable open socket is shown in Fig. 12.

3.4. Installation of Bridge on the river Dead Vistula in Gdansk in 2015

The centenarian rotary railway bridge has been replaced by a new arch bridge in 2015. Fig. 13 shows an aerial view of the location.

Fig. 13. *Aerial view of River Dead Vistula in Gdansk.*

The new arch bridge accommodates two railway tracks. The arch is 124 m long and 21.5 m high. The fairway is 50 m wide with a 9 m water depth. The bridge was assembled in the ship dock in Gdynia and then shipped to the site. During transport the bridge had temporary supports for the arch (Fig. 14). The hanger ropes were installed and tensioned after the bridge was at its final destination.

Fig. 14. *Swimming in of the arch.*

A future bridge with destination Norway is planned in the same way. Loftesnes bridge will be assembled in the ship dock in Szczecin, Polen before it is sent on its journey to Norway to bridge a Fjord.

Fig. 15. *Positioning of the ropes between temporary support of the arch.*

Fig. 16. *Positioning of the remaining ropes.*

The full locked coil ropes were delivered in coils on wooden pallets (Fig. 10). Because of the relatively short ropes and the good surface of the steel deck the ropes could be uncoiled on the deck manually (Fig. 11). In a first step the cables were installed in between the temporary supports (Fig. 15). Before removing the temporary supports the ropes were tensioned. Finally the remaining ropes were positioned and tensioned (Fig. 16). In this step always 6 ropes were tensioned simultaneously.

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