Wire rope and strand assemblies in bridge applications

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ABSTRACT: The revitalization of historic landmark bridges is an important topic for discussion in many circles today. This paper compares the current and past engineering knowledge and technology used to design bridge wire rope and strand assemblies. This paper looks at strand and rope development including socketing and fabrication procedures for assemblies. Major advancements in these fields along with advanced manufacturing technologies provide higher strength materials for assemblies. Topics discussed will be the advancements in corrosion inhibitive materials available for hangar assemblies along with their advantages and disadvantages. The reader will also be informed of the importance of proper assembly fabrication including prestretching and proofloading techniques and why this must be done to ensure proper installation of the completed assembly. Socket selection and attachment style will affect the fabrication tolerances and provide simple installation and tensioning onsite.

1. INTRODUCTION

The use of carbon steel wire in the fabrication of long span bridges has been practiced for roughly 150 years. The basic concepts and ideas incorporated into those structures are still practiced today in the construction of modern bridges. The same holds true to the structural wire rope and structural strand used today. These materials are distant cousins to the materials first incorporated in the developing bridge world. While combining higher strengths, better abrasion, and greater resistance to corrosion one item that has remained a constant is the use of carbon steel in the wire making process. The requirements of the steel industry today take full advantage of the available technologies while pushing the limits of the current manufacturing capabilities.

2. WIRE PRODUCTION

The building block of structural bridge rope and bridge strand is galvanized wire. The current ASTM A603 and A586 specifications for these items mandate the physical requirements for the wires. The requirements include the mechanical properties, stress under load, elongation, tensile strength, ductility, zinc coating weight, coat adherence, and wire surface finish. Typically to improve on one property another must be sacrificed.

The process of producing galvanized wires has seen several improvements and refinements over the past ten years leading to increased strengths and improvements in quality. Some of the processes once thought to be necessary have been removed or replaced to reduce cost and stream line the manufacturing. The manufacturing begins with the rod production. Carbon is the major steel element in the rod used for wire production. Higher carbon elements directly correlate to higher tensile strengths as well as the resistance to abrasion. The negative side of this relates to the elongation and ductility of the wire. The rod production begins with continuous cast blooms rolled to diameter and control cooled to provide a clean homogenous pearlitic grain structure suitable for direct drawing. The controlled cooling eliminates the need to patent the rod prior to drawing the wire. The drawing process is next. Drawing is the process to reduce the diameter of the rod by passing through a number of successive dies. The drawing process aligns the grain structures into a fiberous geometry substantially increasing the tensile strength of the wire. This process requires clean steel without inclusions to ensure cupping and ductility to not become a factor. Since the drawing process is a cold working process the amount that can be performed is limited by the steel. Tensile strength increases dramatically but the ductility of the wire becomes very poor. With the quality of the steel available some rod maybe reduced up to 95% of its original area. However in some cases the wire must be patented. During patenting the steel grain structure becomes more uniform and ductile making the wire suited for further drawing. Several advancements in the patenting of wire have been introduced and incorporated in to the process. The use of lead to quench the steel is no longer a viable solution in the United States due to stringent EPA regulations. Out these regulations have come new methods using salt, sand, and steam as viable quenching methods. These methods provide superior refinement of the wire grain structures without the harmful environmental effects that are associated with the use of lead.

The last step in the wire production process is galvanizing. The majority of the wire supplied for bridge strand and structural bridge rope are galvanized by the hot dip method. Meaning the wires are submerged in molten zinc to provide the coating. The main drawback to this type of coating method is strength loss due to the annealing of the wire while submerged in the molten zinc. Approximately 10% of the wire strength will be lost during the hot-dipped coating process. Drawing the wires after coating will regain most of the strength due to the cold-working effect. It is possible to produce wires in the 340-350 ksi range by drawing after galvanizing. The other means of coating the wires is electroplating the zinc to the surfaces. This provides a clean coated surface that is acceptable for use in static and dynamic applications.

3. STRAND AND ROPE PRODUCTION

The stranding and closing portions of the cable manufacturing process becomes one of the most critical steps. The ASTM specifications allow each manufacturer the latitude to determine their design as long as the mechanical properties are met as specified. Several of the steps in these processes can help the cable perform better in fatigue application as well as greatly affect the tensile strength.

4. ASTM A586 STRUCTURAL STRAND

The ASTM title for this type of strand is *Zinc Coated Parallel and Helical Steel Wire Structural Strand*. This specification also covers *Zinc Wires for Spun-In-Place Strand*. The process of manufacturing structural strand consists of laying consecutive layers of wires around a center, changing the direction of the lay of each layer. The opposing lay direction increases tensile strength and Modulus of Elasticity while providing a balanced rope. The wires used in each layer may or may not be preformed. The performing of wires consists of mechanically forming the wire. This ensures the wires form in a tight layer around the core or base layer. Some strand constructions will have multiple wires laid to form a unitized center, sometimes referred to as the Parallel Contact Core, to increase the static fatigue of the cable. Tension-tension fatigue testing has shown this construction reduces internal nicking and bending stresses which occur in conventional cross lay designs. This testing shows cracks to initiate at the cross-wire contact point of inner wires, eventually leading to tear in shear. Increasing the number of wires in the strand, smaller diameter wires, has also been shown to increase the fatigue life of structural strand. This can be related to less contact area and ductility of the wires. However it has also been shown that wire grade and mean loading have little or no effect on the fatigue life of the strand. Structural strand is designed to be used in straight tension only. Deflections in structural strand could reduce the strength and severely reduce the fatigue strength of the strand if not tensioned properly.

5. ASTM A603 STRUCTURAL WIRE ROPE

The ASTM title is *Zinc Coated Steel Structural Wire Rope*. This is also commonly referred to as Structural Bridge Rope. Due to the mechanical requirements of the specification structural wire rope is made differently from traditional six or eight stranded running ropes. The individual outer strand lay and rope lays are lengthened to provide increased strength and Modulus of Elasticity. Since they are being utilized in static tension there is a core option for these style ropes. A single strand core or independent wire rope core can be provided without a reduction in the mechanical properties of the rope. The strand core provides a simpler more traditional style rope which on average will have an increased Modulus of Elasticity. This also allows the producer the option of varying the manufacturing process.

6. CORROSION RESISTANCE

By looking around us today at the ageing structures everyone is fully aware of the need to protect the steel from the harsh environment. Countless studies have been conducted to measure the corrosion resistance ability of zinc coated steel. In the ASTM A586 and A603 specifications there are three levels of zinc coating available for the wire. These levels consist of Classes A, B, and C which increase the amount of zinc weight per foot, Class C being the heaviest. These coatings may be applied by the hot-dip method or electroplating process.

Aside from the zinc coating applied to the wire surface there are numerous additional types of coatings that may be applied to the rope or strand to increase the corrosion resistance of the assembly. Studies have been performed to find alternatives to painting or coating the cables onsite after installation. Greases, pastes, and preservatives applied internally to the cable during the manufacturing process work to protect the wires from corrosion during the life of the cable. Testing done by the State of California Department of Transportation compared wires coated with Gri-Kote Z-Complex 2C, manufactured by Grignard Company LLC, bare wires, and various other coatings after 6 months of accelerated corrosion testing in an ASTM B117 salt fog chamber. The obvious signs of severe corrosion are present in Figure 1 of the bare wire while oxidation of the wires in Figure 2 is the result of the wires coated with Gri-Kote Z-Complex 2C.

Figure 1. Corrosion of bare wire.

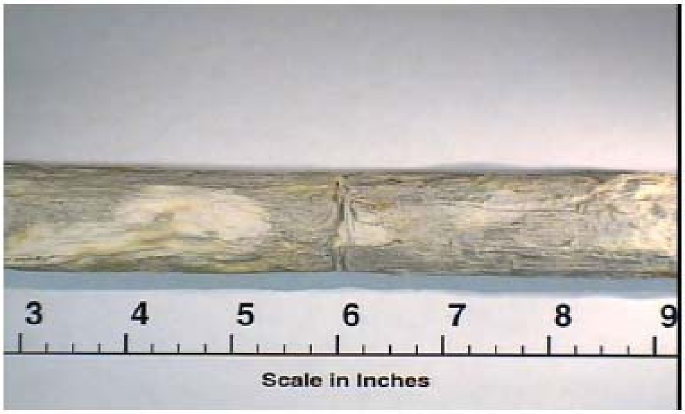

Figure 2. Corrosion of coated wire.

The coating applied to the wire for testing purposes incorporates a combination of 45% zinc dust and 45% zinc oxide in a blend of vegetable oil, with additional corrosion inhibitors. These types of corrosion inhibitors can increase the life of the cable substantially by protecting the wires as a sacrificial anode as well as repel water away from the surface. They must remain flexible during the life of the cable to adjust and deflect as the cable operates. Grease type corrosion inhibitive treatments can be used to prevent moisture from entering the cable and provide reduced friction between the wires during its operating life. The main drawback to these types of treatments is the appearance of the material on the exterior of the strand. Figure 3 shows the application of Syncan Grease preservative, supplied by the Grignard Company LLC, to galvanized structural strand during the manufacturing of the cable.

Figure 3. Application of preservative.

The coating or jacketing of cables as a means of providing corrosion resistance is not recommended. These types of coatings not only conceal the wires from external inspection but could act as a water trap. Although UV inhibitors are included in the coating material these become susceptible to cracking. These cracks will then work to draw in moisture which has no outlet. It is also critical that individual wires be allowed to move and adjust freely during the operating life of the cable.

7. FABRICATION OF ASSEMBLIES

Once the strand has been produced and the socket selected the assembly work begins. Depending on the application and installation procedures the final length tolerance may be become a very critical point. Several procedures need to be done to ensure the assemblies fabricated in a shop environment can be installed in a field environment without adjustment.

Prestretching the wire rope or strand should be the first step. This operation is critical to remove the constructional stretch of the cable providing length stabilization during assembly fabrication process. The ASTM specifications do not state what procedures or steps are to be used to establish this they do specify the minimum Modulus of Elasticity, E, for the cable. The ASTM A586 Structural Strand specifies the limits at 24,000 ksi while ASTM A603 Structural Wire Rope is slightly lower at 20,000 ksi. The prestretching operation is carried out by loading the cable to a specific percentage of the cables minimum breaking force and holding it for a set time period. In some cases the cable may be cycled up and down.

Directly after prestretching the cable it should be measured for assembly length. During the prestretching operation the zinc coated wires will seat onto one another slightly displacing the zinc coating, this is more prevalent with heavier coated wires. Moving or handling of the cable prior to measuring will cause disturbances which will reintroduce some of the constructional factors of the cable. Typically the assemblies are measured for cutting at the calculated dead load tension of the structure. This enables production of the assemblies to the desired tensioned field length of the cables. It is highly recommended that all measurements be performed in controlled environments under cover to ensure undesirable weather or temperature changes do not affect the assembly performance. All measuring should be performed with calibrated tapes. The standard temperature specified by the National Institute of Science and Technology is 68 degrees Fahrenheit. Should the design temperature of the bridge vary widely from this temperature it will be necessary to accommodate these length changes prior to beginning measuring operations.

The prestretching and measuring procedures lead to the final operation of socket installation. The most common type of end termination is the speltered socket. Swaged and wedge style sockets are available but efficiency losses and unfamiliarity with the products are still present. In speltering operations the brooming and cleaning of the cable ends need to be performed to ensure proper adhesion of the wires to the socketing medium. The prepared end is then suspended vertically. This is required to minimize the curvature of the strand and ensure equalization of the stresses in the wires. The larger the diameter of the cable the higher the cable must be suspended to ensure the cable lie true during the socketing operation. Figure 4 shows a multi leveled socketing tower for speltering large diameter structural strand.

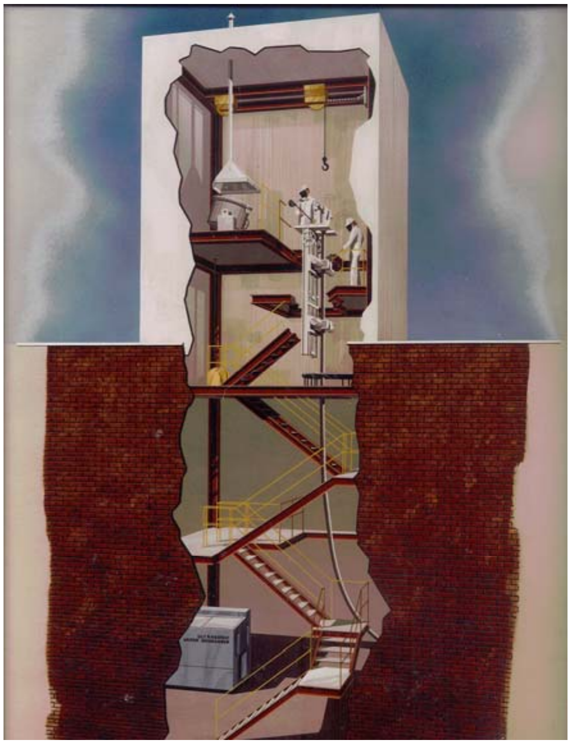

Figure 4. Socketing tower

The broomed end is then closed and inserted into the socket splaying the wires evenly to allow flow of the socketing medium around each wire. The axial alignment of the socket with the strand should be checked. In addition, the concentricity of the strand within the socket should be checked. Proper socket alignment assures maximum service life for any socketed assembly, by distributing stresses to all wires in the strand in equal proportion. The socketing medium is then added to the socket. The two common types of medium are resin and zinc. With each having positives and negatives to the installation and long term assembly the zinc medium is the most common found today. Several other mediums including Zinc-Aluminum and Zinc-Copper are becoming present on the market. The final operation of the socket attachment process is proofloading the socket. The proofloading of the socket serves to test the pouring operation of the assembly manufacturer. It also serves to seat the socket. Spelter sockets work on a wedge action to develop the strength of the socket. The wedging seats the cone in the socket causing some elongation of the assembly. This elongation should be accounted for in the layout of the assembly.

The previous paragraphs have only spoken of spelter sockets. It should be pointed out to the reader that a swaged style socket may also be applied to the cable types spoken of in this paper. Swaged sockets are mechanically pressed on to the cable. However since these are forged pieces the size and design of the socket may be limited to smaller diameter cables.

8. BRIDGE ROPE FATIGUE

Axial fatigue testing of Galvanized Structural Bridge Rope is a time consuming process. The fatigue data acquired from these types of tests is crucial in determining periodic maintenance and load effects on suspenders. Open strand sockets were speltered onto all of the samples with Prime Western grade zinc. The cyclical frequency of the loading was approximately 100 cycles per minute. The tests were performed on four 2-3/4" diameter 6x25FW IWRC galvanized bridge ropes. The rope was produced in accordance with the ASTM A603 specification.

Samples 1 and 2 were cycled from 90 to 170 kips during the tests. Sample # 1 performed the best of all samples. Table 1 shows the results of all samples tested. It has been known for some time that the failure of wire rope subjected to axial load is fretting. This is a form of fatigue in which the damage is accelerated by the rubbing of surfaces. To reduce the fretting action pure boiled linseed oil was applied directly to the rope during cyclic loading to simulate the lubricity which would be provided by the protective paints applied in a preventative maintenance program. This also occurs naturally due to the oxidation of the zinc coating. Sample # 2 was painted will linseed oil only at the beginning of the testing. This sample approached the 40 broken wire at approximately half the cycles of sample #1. Samples 3 and 4 were cycled from 102 to 193 kips. Sample # 3 was not painted and was the only sample allowed to be cycled to complete failure. Sample # 4 was cycled to 100,000 cycles and removed for destructive testing. Sample # 4 broke at approximately 4% over the nominal strength. Open strand sockets were speltered onto the samples with Prime Western grade zinc. The cyclical frequency of the loading was approximately 100 cycles per minute.

Table 1.Wire Rope Fatigue Results

Sample # 1		Sample # 2		Sample # 3		Sample # 4	
# Broken Wire	# of Cycles	# Broken Wire	# of Cycles	# Broken Wire	# of Cycles	# Broken Wire	# of Cycles
1	1309900	4	1016800	64	456931	20	466000
4	1869400	10	1168860	86	483700		
17	2142900	19	1323400	160	587000		
28	2688500	37	1452900	260	859000		
42	3193263			Failure	1670000		

The result of the testing was as expected. The number of wire breaks increases as the cycles increase. There is no retirement criteria specified for wire rope and structural strand components. For the tests an initial value of "six broken wires in one rope lay" was established to determine the fatigue failure of the rope. The testing soon pointed out that this number was not a realistic value. Therefore the fatigue failure criterion was increased to approximately "40 broken wires in one rope lay" to establish the actual life of the cable. With the exception of one sample, all were able to carry the loading despite the large number of wire breaks. Due to the nature of fretting fatigue wire breaks tend to raise up and out of the rope, "porcupine". Due to the increased contact stresses in the wire at the raised point, failure will occur rapidly causing the wire to complete break from the rope and fall out of the sample. However the loss of the wire does not reduce the strength of the sample for two reasons. Wire ropes are composite structures that are redundant at any section. The second is due to frictional forces. A broken wire will regain load carrying ability several rope diameters away from the failure. Figure 5 shows fretting on the suspenders of the Manhattan Bridge in New York City.

Figure 5. Fretting of suspender ropes.

Because of the lubrication effect, the fatigue life seen of the standard un-lubricated samples as received from a rope mill should not be compared directly with that of samples 1 and 2.

CONCLUSION

This paper was written with the intent of educating the bridge community on the advancements and process used to properly manufacture cable assemblies. The amount of time and effort exerted by the steel community over the past 10 years to advance the mechanical properties of galvanized steel wire used in all types of cables has been tremendous. The processes used today to produce these items domestically are very restrictive but with the introduction of fine grain steel rod and advanced manufacturing processes a higher strength galvanized wire is being produced. The current ASTM specification covering these types of cables allows the manufacture the latitude to produce cables without restrictive manufacturing parameters. Innovative materials are now available to increase the corrosion resistance of the cable. Some of the materials are applied during the manufacturing of the strand to individually coat wires and some are applied to the cable once it is installed and tensioned onsite. The fatigue tests presented in this paper show that standard preventative maintenance on bridge cables can significantly extend the life of cable. Variations in the construction of the cable have also been shown to increase the life cycle of the cable.

The amount of information provided in this paper only begins to describe some of the ideas and trends of the wire rope and strand industry. The ultimate goal is higher strength materials that provide safe and efficient structural members for bridges.

REFERENCES

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