THE SECURITY ASSESSMENT OF CABLE ASSEMBLIES IN MOVABLE STRUCTURES

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Abstract:

The ability to provide a secure environment in the bridge community today is a daunting task being undertaken by many engineers worldwide. One of the key structural components identified in vertical lift bridges is the wire rope assembly. The paper focuses on identifying the vulnerability of the cable assembly in the event of an accident, disaster, or attack. The paper describes the response of traditional and experimental cable assemblies to moderate and extreme heat. The results from high temperature testing performed on mock cable assemblies under load in controlled test environments will be presented and discussed. The paper also looks at new practices being developed in the wire rope industry to increase the security and functionality of cable assemblies currently used in vertical lift bridges. New high performance materials have been shown to drastically increase the functional operating temperature of the cable assemblies without affecting the mechanical properties of the wire rope. The paper will also discuss the theoretical and experimental work regarding the operating mechanisms of wire rope held in conventional tapered sockets.

Security is a topic of discussion in all fields especially with structures due to their accessibility. Information provided on the heat affects of key structural elements on bridges will provide useful information for the design and retrofit of bridges around the world.

Introduction

Vehicular accidents involving volatile materials are considered dangerous but when mixed with bridges they may they could become devastating. One such accident that took place on August 15, 2003 had this effect on the surrounding community. The passenger side of a tractor trailer truck traveling over a traditional cable supported arch structure hit a bridge abutment, rupturing the gas tank and ripping open the side of the trailer. The gasoline from the tank caught fire, as did the 15,000 pounds of garlic powder in the trailer when both spilled onto the bridge deck. It was estimated that the fire burned at temperatures reaching 1,500 degrees Fahrenheit for several hours. The effects of the heat took its toll on various areas of the bridges raising the concerns of many people in the bridge engineering community. Fortunately no one was injured in the accident. It was also fortunate that the fire do not occur near to the cables supporting the structure.

The ability of a cable supported structure to withstand damage during a high intensity fire or blast contains a multitude of variables. It is estimated that a fuel fire could burn in excess of 2,000 Fahrenheit. This paper focuses on the ability of the structural cable assembly to operate in high-temperature environments. To substantially increase the operating temperature of the cable assembly the socketing medium of the cable needed to be evaluated and tested. Additional options include fire protection methods for the cable assemblies that are capable of resisting and deflecting blast impacts, as well as deflect heat away from critical areas of the assemblies.

Description

The cable assemblies on bridges work as a tension member transferring the load of the roadway deck to a counterweight used to lift the structure. The connection of the cable assembly requires a termination socket be permanently attached to the end of the cables. This is typically done by speltering open cavity sockets on to the cable with socketing mediums.

The speltering process requires the individual wires of the cable be separated into a broom configuration as shown in photo 1. The broomed wires are cleaned and inserted into the cone of the termination as shown in photo 2. The socketing medium is cast in to the cavity and allowed to solidify forming a solid composite of socketing medium and wires. The most widely used socketing medium material is ASTM B6 High Grade Zinc. It is an inexpensive product that provides an efficient end termination while protecting the cable from corrosion. The assemblies are proof-loaded to seat the wedge and prove the bond between the wires and the socketing medium.

Photo 1

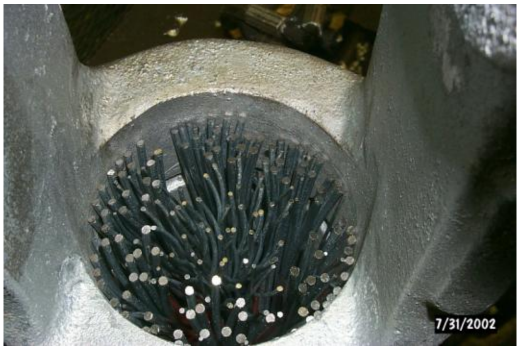


Photo 2

Socketing Mediums

The temperature resistance of cable assemblies produced with traditional methods will be limited by the melting temperatures of the socketing mediums. Zinc has a melting temperature of approximately 600 degrees Fahrenheit and Resin will begin to lose mechanical properties at approximately 250 degrees Fahrenheit. The need for an alternative socketing medium for cable supported structures is becoming prevalent in the market today due to increased security needs. New socketing mediums have been developed that will increase the working temperature of the socketed connection to above 2,500 degrees Fahrenheit. At these temperatures the weak link of the assembly will actually be the steel itself. High Temperature socketing mediums ensure the safety of the suspended structure in the event of a moderate fire or accident on the roadway that may directly affect the cable assemblies.

Analysis of the Socketed Connection

Cables are linked by shape and force to the termination due to the conical shape which the medium forms with the steel wires. The composite material formed from the wires and socketing medium needs to be an efficient connection. An evaluation of the working properties of the conical shape of the termination as well as the medium used for socketing was fully investigated to determine the stresses developed on the socket walls. Socketing mediums are required to adhere to the carbon steel wires as well as provide the compression strength needed for transmittal of the force through the cable end terminations.

The first step in the assessment of an alternative socketing material required an evaluation of the stresses of the socket. A mechanical model of a wire rope termination is shown in Figure 1. In this model the individual wires are not shown dispersed in the cone since the evaluation is focused on the socketing medium.

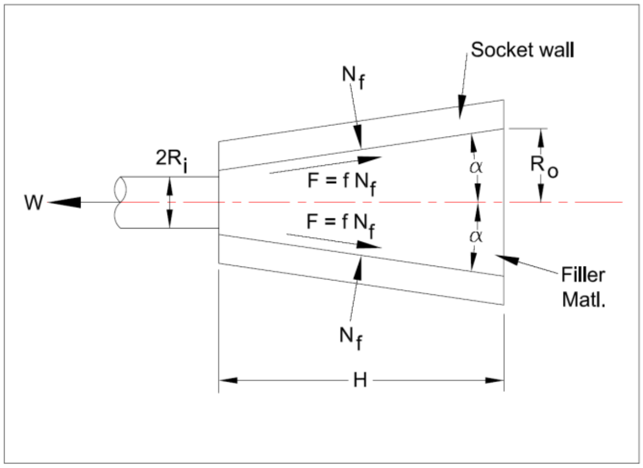


Figure 1, Socket Body Free Diagram

The equilibrium of forces allow the following Equation 1 to be formulated,

$$W = Nf\ (\sin \mathbf{a} + f \sin \mathbf{a})$$
(Eq. 1)

When **a**=0, W=Nf, representing only the frictional effect of the joint when assembled with sufficient compression between the wire matrix and the socket wall. In reality the external load has to overcome additional adhesion forces.

The contact pressure, P, from the socket will theoretically be dispersed throughout the socketing along the wall in contact with the socketing medium. The geometry of the conical socket depicted in Figure 1 is shown in Equation 2 below.

$$A = \mathbf{p(}Ro+Ri)\ [\ (Ro+Ri)^{2} + H^{2}\ ]^{(1/2)}$$
(Eq. 2)

Postulating that P = Nf / A, Eq. 3, the contact pressure may now be used to estimate the typical stresses applied to the socketing medium.

$$P = W / (\mathbf{p(}Ro + Ri)(Ro - Ri + fH))$$
(Eq. 3)

In the calculations above the cone represents an infinite stiff object applying an equally distributed pressure load on the interior socket wall. Studies performed on sockets have shown the pressure loading, P, in the socket is not equally distributed throughout the socket body. At the base of the socket the internal pressure may be up to four times greater than initially estimated. Figure 2 shows the distribution curve of the forces applied to the interior of the socket.

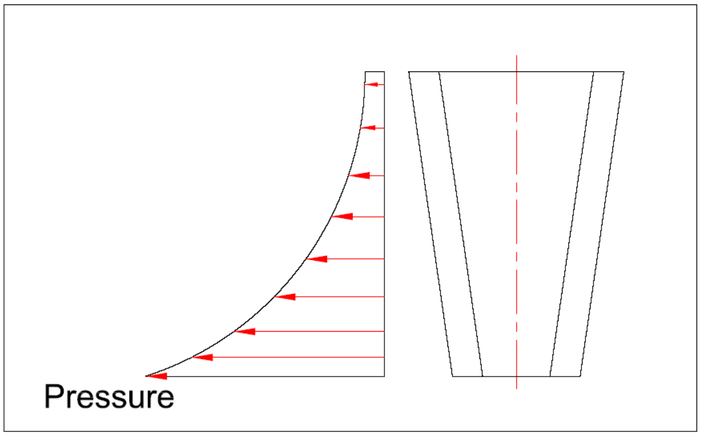


Figure 2

Using the minimum breaking forces specified for ASTM A603 Structural Bridge Rope the theoretical average pressure the socketing medium will need to withstand is approximately 9,000 psi. This value does not take in to account the extreme pressures at the base of the socket. As in all cases the reliable magnitude of the equations can only be established experimentally.

Testing

A Composite Material, CM, was selected for testing as an alternative socketing material. The major components and mechanical properties of the CM material are specified below.

Mechanical Properties at temperatures up to 2,500 degrees Fahrenheit.
Compressive Strength – 15,500 psi
Modulus of Rupture – 1,160 psi

The initial destructive testing conducted with the CM socketing medium was successful providing 100% efficient end terminations. Destructive testing was performed on the 10th day after pouring. This ensured all samples had adequate time to cure thoroughly. The samples failed clear of the end terminations. This type of failure is critical to ensure the socketing medium did not affect the efficiency of the test sample. No signs of slippage or disruption were detected in the socketing medium.

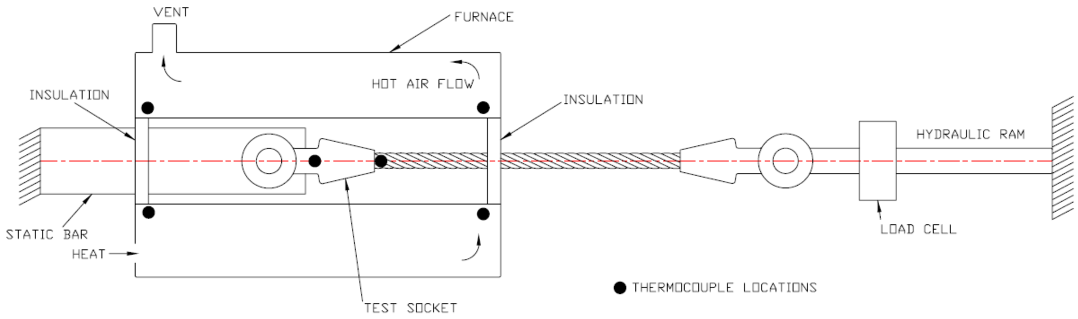
High Temperature Testing

A total of seven tests were performed at two target temperatures to determine the mechanical effects of the socketing mediums under tension. Table 1 below shows the Sample Number, Socketing Medium, Strand Diameter, and Tension Load during test. Each sample was socketed with the corresponding medium and exposed to an elevated target temperature environment while under a tension load equaling 20% of the cable assembly minimum breaking force.

Sample #	Socketing Medium	Strand Diameter	Tension Load (lbs.)
1	CM	1-1/2"	56,000
2	CM	1-1/2"	56,000
3	CM	1-1/2"	56,000
4	Zinc	1-1/2"	56,000
5	Resin	1-1/2"	56,000
6	CM	1-3/4"	76,000
7	CM	1-3/4"	76,000

Table 1 – Test Matrix

The test schematic as shown below consisted of a single sample enclosed in an insulated oven. Inside the oven the test socket was pinned to a fixed steel connection plate. The opposite end of the sample was attached to a load cell which connected to a hydraulic ram keeping the specified load constant during the testing. Propane was used to fuel the burner on the oven. Once the target temperature was reached a smaller nozzle was attached and the control mode was initiated to hold the temperature constant. The nozzle switch point will be evident in the time-temperature curves. Four thermocouples were inside the oven to accurately monitor the oven chamber.



Testing Schematic

The first samples to be tested were socketed with the CM socketing material. The strand for both samples was 1-1/2” diameter ASTM A586 Grade 1 galvanized strand. The target temperature for samples #1 and #2 was 1,000 F (538 C). A static tension of 56,000 lbs. was applied to the samples during the heating.

Sample # 1 was prepared with a 1/8” diameter well tube inserted into the socketing material to allow the placement of a thermocouple into the socket basket. The second thermocouple was attached to the inside of the socket ear, see photo 3 and 4.

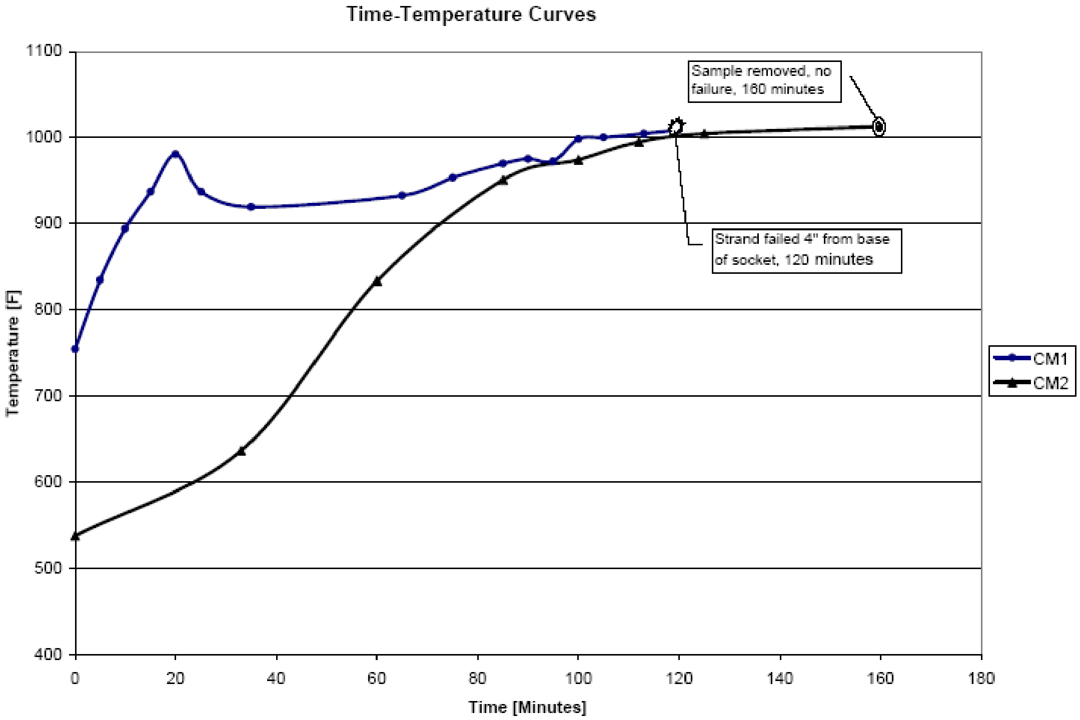
Photo 3, Test # 1

Photo 4, Test # 1

The results for test # 1 are shown below. The total test time inside the oven was 160 minutes at an average oven temperature of 987.6 F (530.9 C). The socket temperature and well temperature came close to the oven temperature due to the time exposed in the oven. The test was completed at 160 minutes after the strand failed 4” from the base of the socket as shown in photo # 2. An examination of the socket showed no movement of the wires in the socket basket. The strand failure was due to the annealing of the wires. The socketed assembly was exposed to temperatures in excess of 900 F for 150 minutes prior to failure.

Sample # 2 had one thermocouple attached to the inside ear of the socket with the second thermocouple attached to the galvanized strand 4” from the base of the socket. The remaining test samples were monitored using this thermocouple placement procedure. The test time inside the oven for test # 2 was 120 minutes at an average oven temperature of 990.3 F (532.4 C). The test was terminated without the strand failing. The sample was removed and examined. No movement had occurred in the socket basket. Test sample # 2 was then tensile tested producing an ultimate tensile strength of 238,970 lbs. This is approximately 75% of the nominal catalog strength of 318,000 lbs. The tensile strength of the structural strand was reduced due to the heat exposure. Most importantly the failure occurred in the middle of the sample indicating the ability of the socketed connection to develop the strength of the structural strand after the exposure at temperatures is excess of 900 F for 100 minutes,

A graph of test # 1 and # 2 is shown below. The Time-Temperature curves vary due to the time required to heat the oven. Test # 1 was performed in the midday and Test # 2 was performed in the early morning. Both samples were in the 900-1000 F range for approximately 100 minutes prior to terminating the tests. The temperature on the graph is the average oven temperature.



Tests #1 & #2, CM Socketing Material

Tests #3 and #4 were performed with traditional socketing material of zinc and resin respectively. The strand for both samples was 1-1/2” diameter ASTM A586 Grade 1 galvanized strand. The target temperature for samples #3 and #4 remained at 1,000 F (538 C). Sample # 3 was socketed with zinc material and failed after 47 minutes of exposure never reaching the desired set point temperature. The zinc partially melted from the socket basket losing the mechanical properties required to maintain the load ultimately releasing the strand. Photos 5 and 6 below show the zinc socket sample after failure.

Photo 5, Zinc Test # 3

Photo 6, Zinc Test # 3

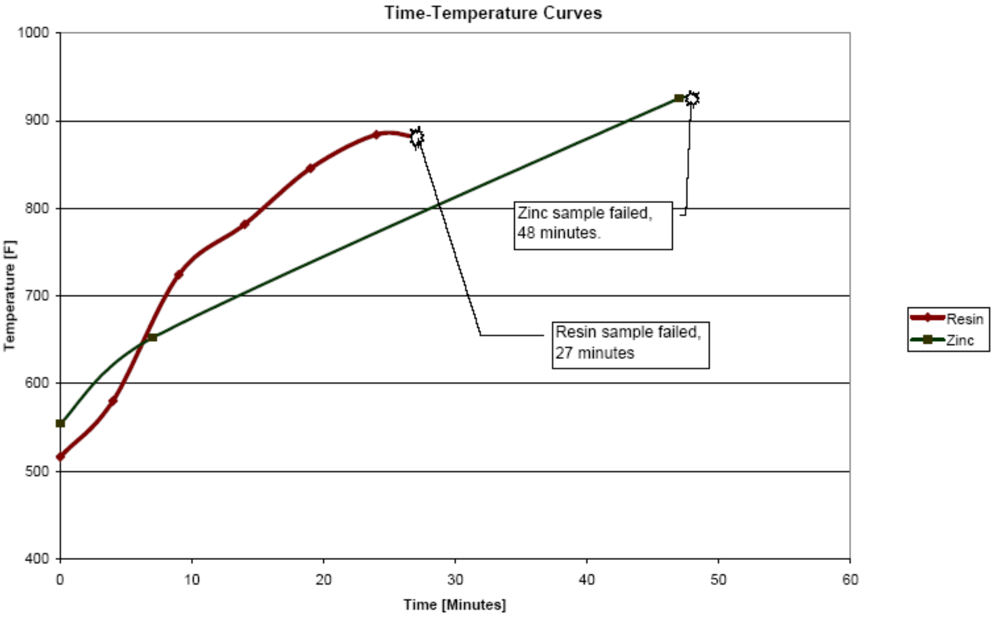
Sample # 4 was socketed with resin material and failed after 27 minutes of exposure without reaching the 1,000 degree target. The resin material combusted and began to burn after 15 minutes of exposure in the oven. At the time of failure the socket had only reached 521.6 F (272 C).

Photo's 7 and 8 show the resin sample after removal from the oven. The strand had slipped approximately 5" from the socket. The resin lost all mechanical abilities turning the socket medium into a fine particle.

Photo 7, Resin Test # 4

Photo 8, Resin Test # 4

The graph below shows the Time-Temperature curves for test 3 and 4. Neither sample reached the target temperature of 1000 F (538 C) prior to failure. Both tests resulted in failure due to the socketing material weakness. The temperature on the graph below is again the average oven temperature. The temperature of the sockets at the time of failure was significantly less.



Test #3 & #4, Resin and Zinc Socketing Material

Additional testing of the CM socketing material was conducted with tests #5, #6, and #7. The strand for test samples #5 and #6 was increased to 1-3/4" diameter ASTM A586 Grade 1 galvanized strand. The target temperature for samples #5 and #6 was 1,000 F (538 C) and 1,200 F (649 C) respectively. A static load a 76,000 lbs. was applied to the strand samples during the heating cycle.

Test #5 was heated in the oven for a total of 100 minutes before terminating the test. More importantly the sample was above 900 F (482 C) for more than 60 minutes during the testing. The sample was removed and inspected. No movement or slippage was measured in the socket basket. The sample was tensile tested with an ultimate tensile strength of 325,395 lbs. This is approximately 75% of the nominal catalog strength of 432,000 lbs. The tensile strength of the structural strand was again reduced due to the heat exposure. The failure occurred approximately 4" from the socket base, see Photo 9. This indicates the ability of the socketed connection to develop the strength of the structural strand after the exposure at temperatures is excess of 900 F for 60 minutes,

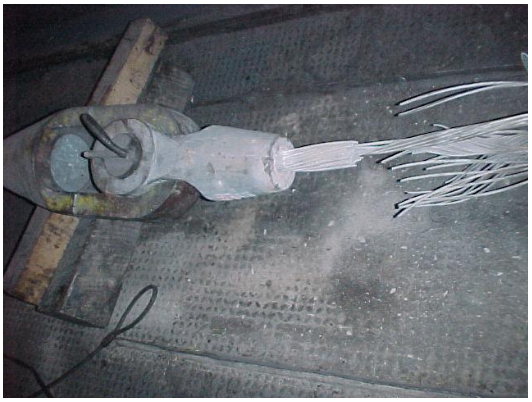


Photo #9, Tensile test of sample # 5

Test # 6 increased the target temperature to 1,200 F (649 C) for the sample. After 73 minutes in the oven the strand failed 4" from the base of the socket prior to reaching the target temperature.

The oven was not capable of heating the sample quickly causing the strand to anneal prior to reaching the target temperature. Photos 10 and 11 below show the failed sample. The high temperature exposure resulted in necking and ultimate failure of the strand.


Photo 10, Test # 6


Photo 11, Test # 6

Due to the previous results for test # 6 the strand in test # 7 was insulated to deflect the heat away from the strand. 1” insulation was wrapped around the strand for approximately 12” from the base of the socket as shown in photo # 9. The socket body remained exposed to the heated environment. The strand for test # 7 was 1-1/2” diameter ASTM A586 Grade 1 galvanized strand. The target temperature for sample was 1,200 F (649 C). A static tension of 56,000 lbs. was applied to the sample during the heating.


Photo # 12, Test 7

The results of test # 7 showed the materials ability to withstand temperatures up to 1,200 F (649 C) without losing the mechanical properties required to sustain loading of the sample. The total exposure time of the sample was 135 minutes. The total exposure time of the sample in range of the target temperature was approximately 90 minutes. The temperature of the socket body was 1,056 F at the time of failure. At 135 minutes the strand failed at the base of the socket. As before the strand failed due to annealing of the wires. Photos #13 and #14 show the necked condition of the wires at the failed connection. A close examination of the socket showed no movement or distortion in the socketing medium up to the time of failure. An examination of the face of the CM socketing medium showed no cracks or distortion.

Photo 13, Test # 7

Photo 14, Test # 7

Conclusion

The testing as a whole was successful in answering many questions regarding the effectiveness of traditional socketing mediums when exposed to elevated temperatures while under a load equaling 20% of the structural strand minimum breaking force. The composite socketing medium was successful in sustaining the test load for an extended period of time while exposed to the target temperatures set forth in the testing parameters. The final test # 7 showed the socketing medium to be effective at 1,200 F (649 C) for up to 90 minutes. The traditional socketing materials, zinc and resin, were shown to have very poor characteristics in elevated temperatures. Neither zinc nor resin socketing mediums could provide the mechanical properties at temperatures near 1,000 F (538 C). Both samples failed without reaching the target temperatures specified in the test. It should be pointed out that the temperatures graphed in the all of Time-Temperature curves are the averages based on the temperature measurements of four thermocouples inside the oven. During the testing of the traditional zinc and resin socketing material the oven temperatures shown on the graphs was much higher than the measured temperature of the strand and socket at the time of failure. Tests # 3 and # 4 were unsuccessful in reaching equilibrium with the oven temperature nor did they reach the target temperatures of the test due to the short test time.

The tests that have been conducted thus far have shown the CM socketing material to be efficient in high temperature environments. In each of the five tests conducted with the CM socketing material no movement was detected in the socketed connection despite failures occurring in the component body of the structural strand. The material remained solid and retained all mechanical properties despite the exposure time to the target temperatures. The material has also be through several testing cycles at ambient temperature and proven to be effective in terminating the cable with 100% efficiency. The CM socketing material has shown to be an efficient and future replacement for the traditional materials currently being used in the market place today.