Appendix N
Socket Load Test

1.0 Introduction

The cables of the telescope are terminated at both ends with zinc-filled spelter sockets, which are commonly used to connect large structural cables. The first two cable failures in August and November 2020 occurred near or within their sockets at Tower 4. In addition, significant displacements of other cables with respect to their sockets (cable slips) were observed before the cable failures. As part of the investigation of the cable slips and socket failures, a socket recovered from the collapsed telescope was load-tested at Lehigh University's Fritz Laboratory. During the test, the socket-cable assembly was subjected to sustained and cyclic loads of different amplitudes, before being pulled to failure. The setup and results of the test are presented in this appendix. The laboratory analysis of the failed socket after the load test is covered in Appendix M.

2.0 Test Specimen

2.1 Socket B4S_G

The socket selected for the load test is B4S_G, which was recovered from the ground end of an auxiliary backstay stabilizing Tower 4. On December 1, 2020, the collapse started with with the failure of multiple main cables at the top of Tower 4, which caused an immediate force release in the Tower 4 backstays. As a result, socket B4S_G did not experience any impact loading during the collapse. The socket was in good general condition, had no visible wire breaks, and exhibited a cable slip of 0.875 inch. This cable slip is intermediate compared to the other auxiliary sockets of the telescope, where cable slips between 0.375 inch and 1.875 inch were observed. Like the first two sockets that failed (M4N_T and M4-4_T), socket B4S_G had a shoulder. B4S_G was recovered with 15 feet of cable B4S still attached (Figure 1).

Figure 1: Recovered B4S_G cable-socket assembly.

2.2 Free End Socketing

The free end of the cable segment recovered with socket B4S_G was connected to a new socket, such that it could later be installed in the load testing fixture. Like the telescope's sockets, the new socket is a zinc-filled spelter socket. However, contrary to most of the telescope's sockets, the new socket is of a design without a shoulder. As shown in Figure 2, a spelter socket is a steel block with a cone-shaped cavity where the cable's wires are inserted and spread out before being filled with molten zinc.

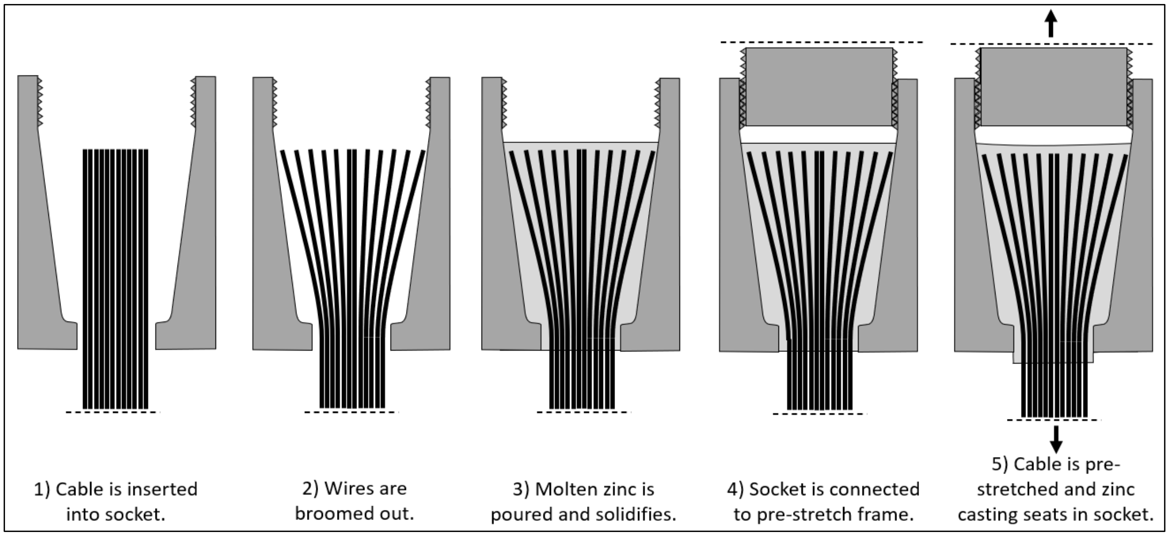

Figure 2: Cable socketing amd pre-stretching process.

The socketing procedure was performed by Wirerope Works in Williamsport, PA, and key steps are shown in Figure 3 to Figure 6. As a first step, wires are bent manually in a broom made wider to access and bend the inner wires (Figure 3). The wires are then chemically cleaned from paint and grease residues using the Tergo metal cleaning solution, and flux treatment is used to improve the wire-zinc bonding. The clean broom is then temporarily closed to allow socket installation (Figure 4). The broom is then released into the socket, and molten zinc is poured to fill the gaps between the wires (Figure 5). After initial solidification of the zinc, the socket is submerged in water to accelerate the cooling process (Figure 6).

Figure 3: Manual wire brooming.

Chemical cleaning to remove paint and grease.

Flux treatment to improve wire-zinc bonding

Clean broom temporarily closed to allow socket installation.

Figure 4: Wire broom cleaning.

The cable is hung from the end to be socketed.

The broom is accessible through an elevated platform.

The socket is installed.

The broom is released in the socket.

Figure 5: Socket installation.

Zinc melting.

Zinc poured into socket.

Socket cooling in water.

Figure 6: Zinc casting and socket cooling.

3.0 Test Setup

3.1 Testing Machine

The cable test was conducted at Lehigh University's Fritz Laboratory using a 5,000-kip universal testing machine (Figure 7). The new socket was connected to the fixed top of the machine, and the B4S_G socket was connected to the moving table below. The load applied to the specimen is controlled by adjusting the vertical position of the moving table.

Figure 7: Cable test at Fritz Laboratory using a 5,000-kip universal testing machine.

3.2 Instrumentation

The ends of the specimen were instrumented as shown in Figure 8. At both ends, four displacement sensors (LVDTs - linear variable displacement transducers) were installed to measure the cable slip, and strain gages were installed on four of the cable's outer wires. Extensometers were also installed at the middle of the specimen to measure cable strain away from the sockets. The load applied to the cable is provided through a gage on the testing machine's control panel.

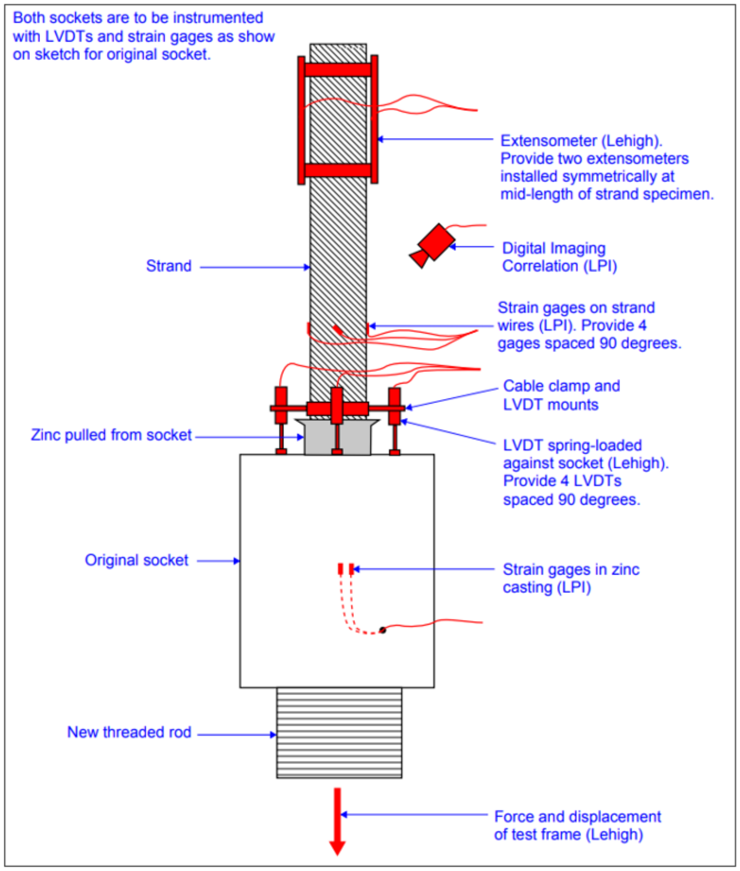

Figure 8: Instrumented cable assembly.

3.3 Load Sequence

The load test was performed over four days starting on October 18, 2021. With the objective to observe the specimen's response to sustained and cyclic loads of different magnitudes before loading to failure, the precise loading sequence was adjusted during the test based on the observed response. The time history of the applied load is shown in Figure 9.

The specimen was first loaded to the service load of 675 kip. This is the tension that cable B4S and socket B4S_G experienced during most of their lifetime, as determined through sag survey and analysis. After holding overnight, the load was cycled 150 times between 675 kip and 625 kip. This amplitude of 50 kip is similar to the largest tension cycle that the telescope experienced during hurricane Maria per our analysis (Appendix J). Each cycle was performed in approximately one minute. The load was then increased to 125 percent of the service load (825 kip), and the same 50-kip cyclic loading process was repeated before holding overnight. The load was then cycled three time between the service load (675 kip) and 150 percent of the service load (1000 kip), and that higher load was held overnight. Finally, after a few intermediate holds, the specimen was loaded to failure. We ended the test after seven outer wires had fractured in the B4S_G socket, while no wire fractures were observed at the new socket. The test was ended to avoid pulling the cable out of the socket completely, such that we could observe the condition of the socket on the brink of failure. Just before the last few wire failures, a maximum load of 1647 kip was reached. This load is two percent higher than the cable's minimum breaking strength.

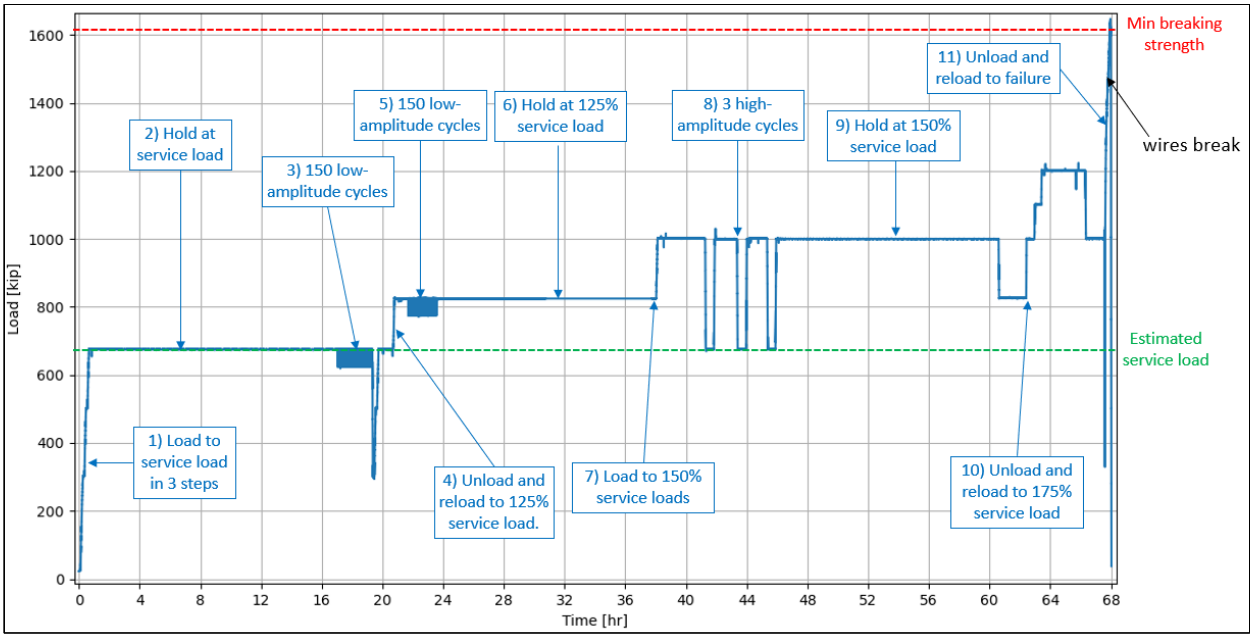

Figure 9: Loading time history.

4.0 Results

4.1 Cable Slip under Static Load

The average cable slip measured throughout the test is shown for both sockets and compared to the applied load in Figure 10. At each socket, the average cable slip is calculated by taking the average of the four displacement sensors installed between the cable end and the socket. The displacement sensors were zeroed at the start of the test, such that the pre-existing cable slip of socket B4S_G (0.875 inch) is not included in the average cable slip shown in Figure 10.

The specimen was loaded and held overnight at three different load levels corresponding to 100, 125 and 150 percent of the cable's service load. During the initial loading, the cable slipped by 0.35 inch at the new socket, an order of magnitude more than for the B4S_G socket. This is due to the zinc casting of the new socket experiencing some degree of elasting and plastic deformation as it is engaged and wedged into the socket for the first time. The cable slip increase caused by the next two load levels is also more significant at the new socket. For each of the three load levels, the cable continues to slip after the load is applied, at a rate that gradually decreases. This delayed response is observed at both sockets.

A close-up of the same data is shown in Figure 11 for the last 25 minutes of the test, when the specimen was loaded to failure. During this last step, the cable slip increases more at the B4S_G socket (+0.4 inch) than the new socket (+0.25 inch). This is consistent with the B4S_G socket failing first, with multiple wire fractures within the socket. The final cable slips at the BS_G socket is 0.53 inch, or 1.41 inch when including the pre-existing slip that occurred during the socket's service life on the telescope. The final cable slip at the new socket is 0.84 inch (Figure 12).

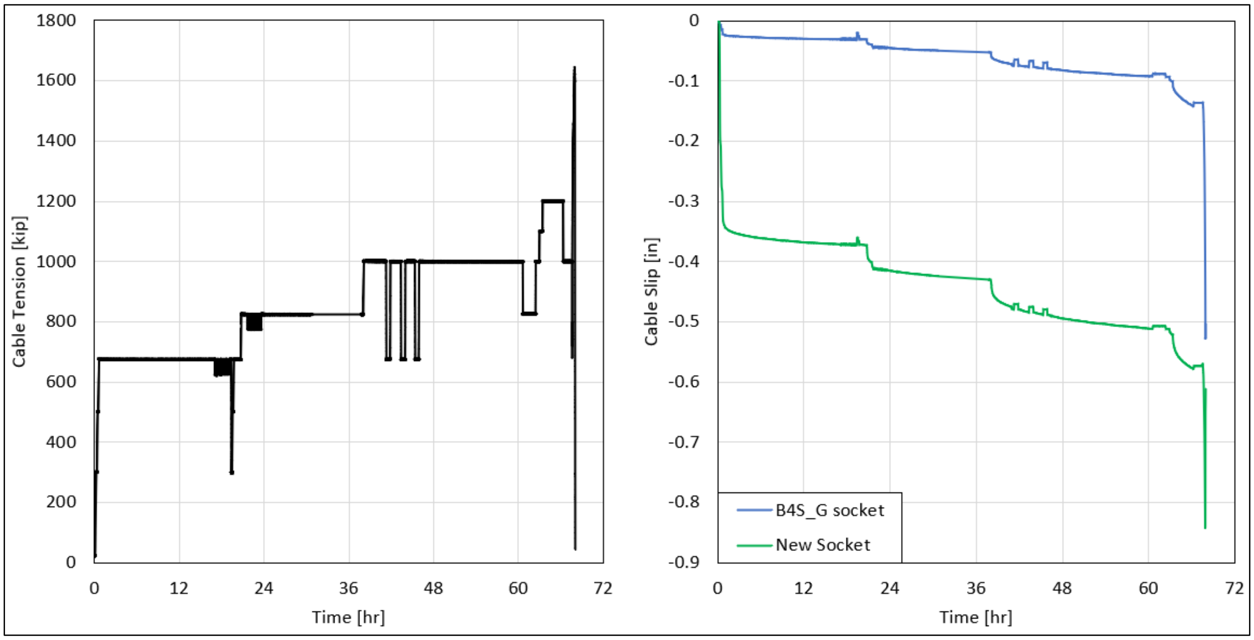

Figure 10: Cable tension and slip at both sockets during full load test.

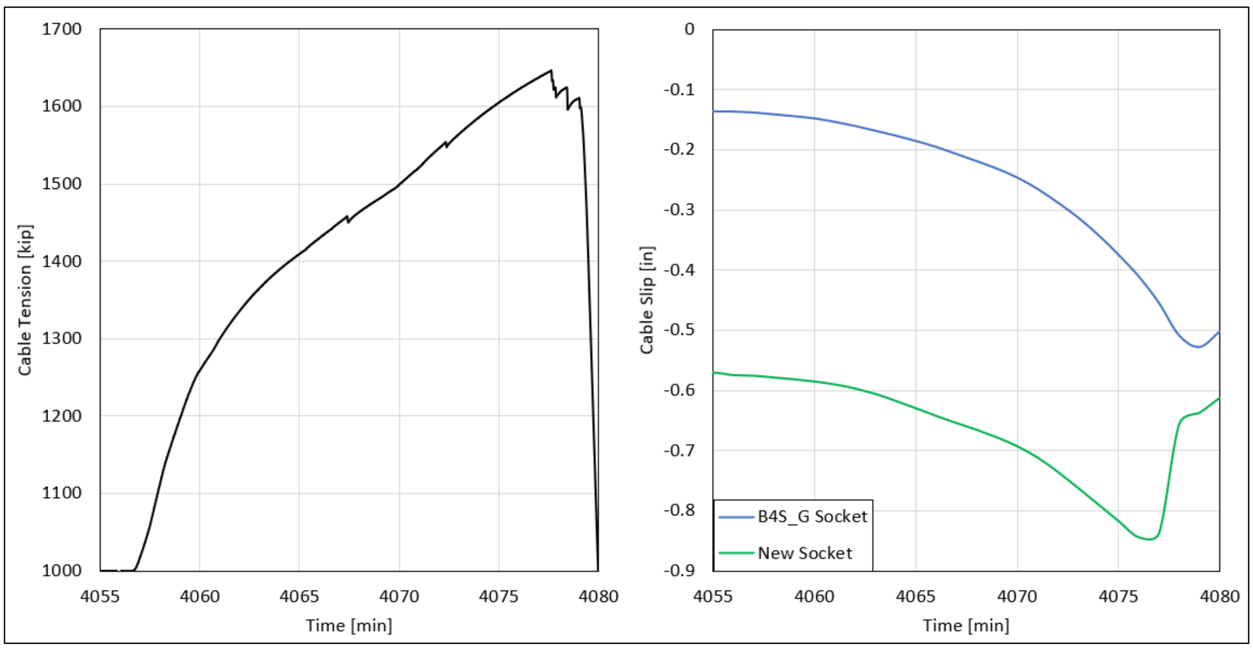

Figure 11: Cable tension and slip at both sockets during final loading to failure.

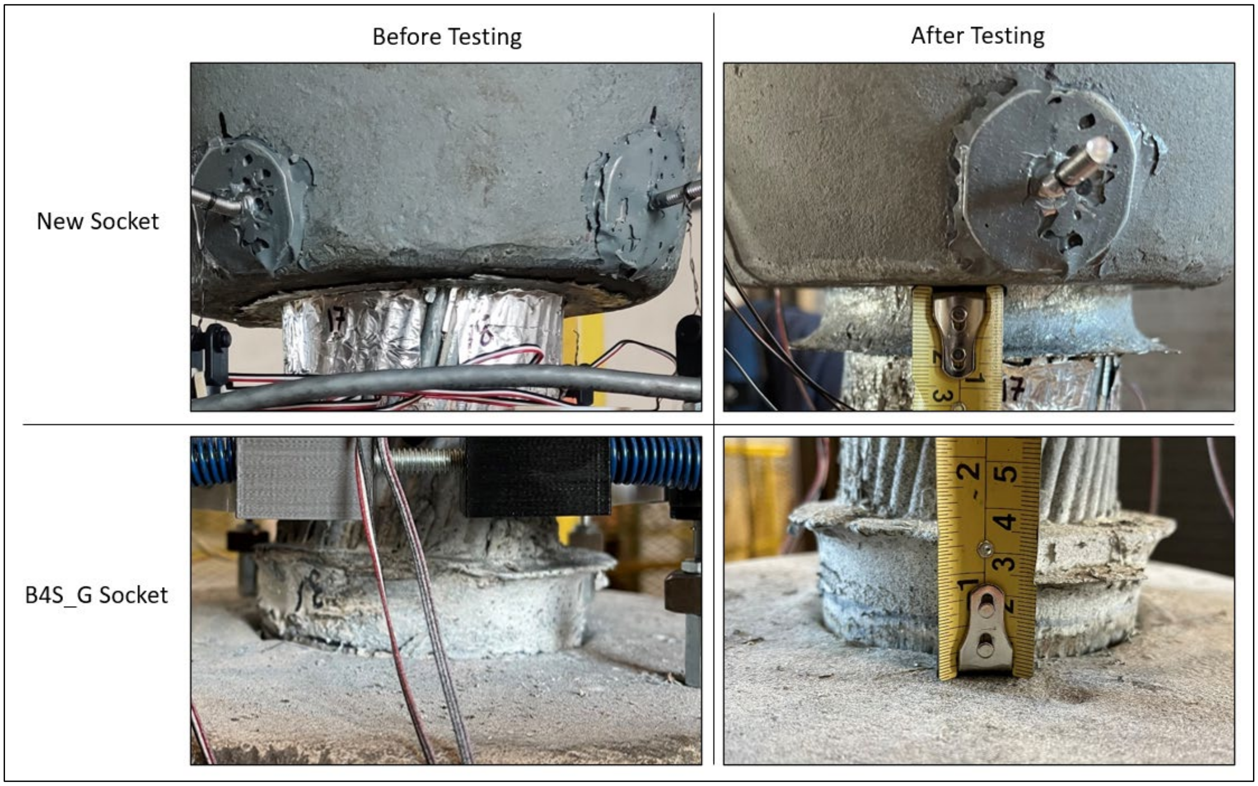

Figure 12: The cable slip for each socket before and after the test.

4.2 Cable Slip under Cyclic Load

The test sequence includes two series 50-kip load cycles, centered on 650 kip for the first series and 800 kip for the second series. Each series consists of 150 cycles performed at a rate of approximately one cycle per minute. The average cable slip at each socket is plotted against the load for the first and last cycle on Figure 13 (first series) and Figure 14 (second series). Similar observations are made for both series. First, the force-displacement loops are narrower for socket B4S_G and wider for the new socket. This indicates that the new socket is experiencing more plastic deformation during the load cycles. Then, for the same reason, the non-recovered cable slip increase between the first and last cycle is larger for the new socket.

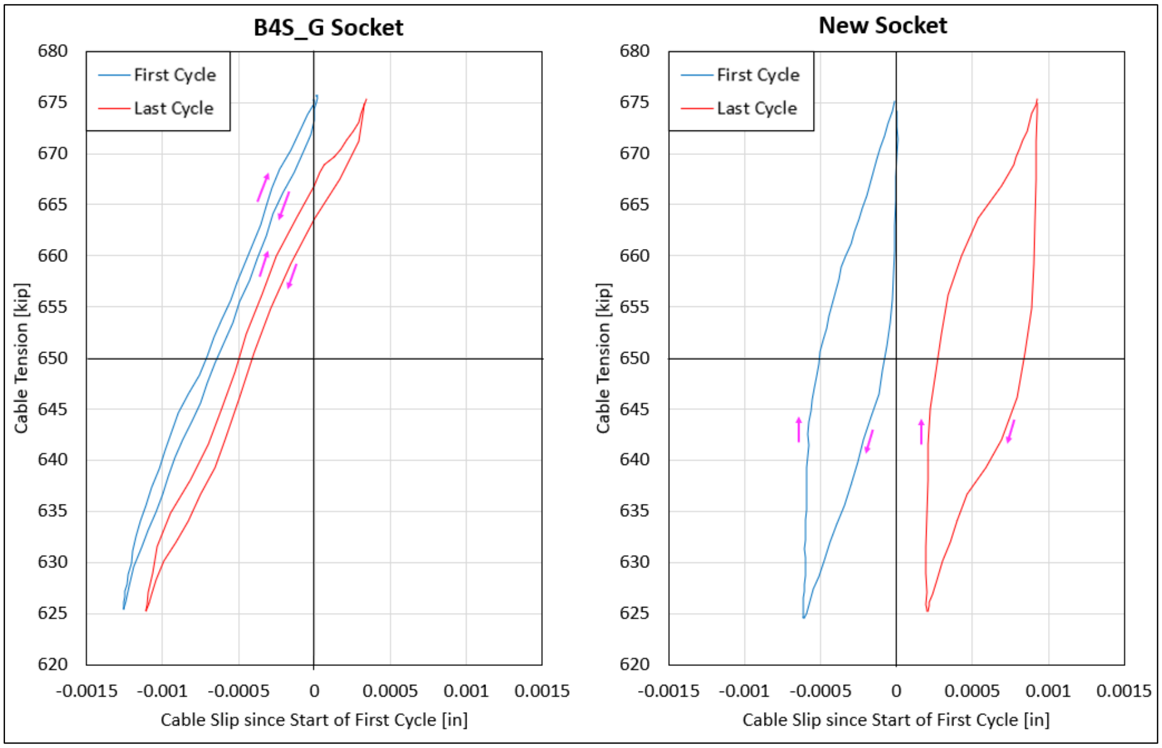

Figure 13: First and last of 150 cycles at 650 kip +/- 25kip.

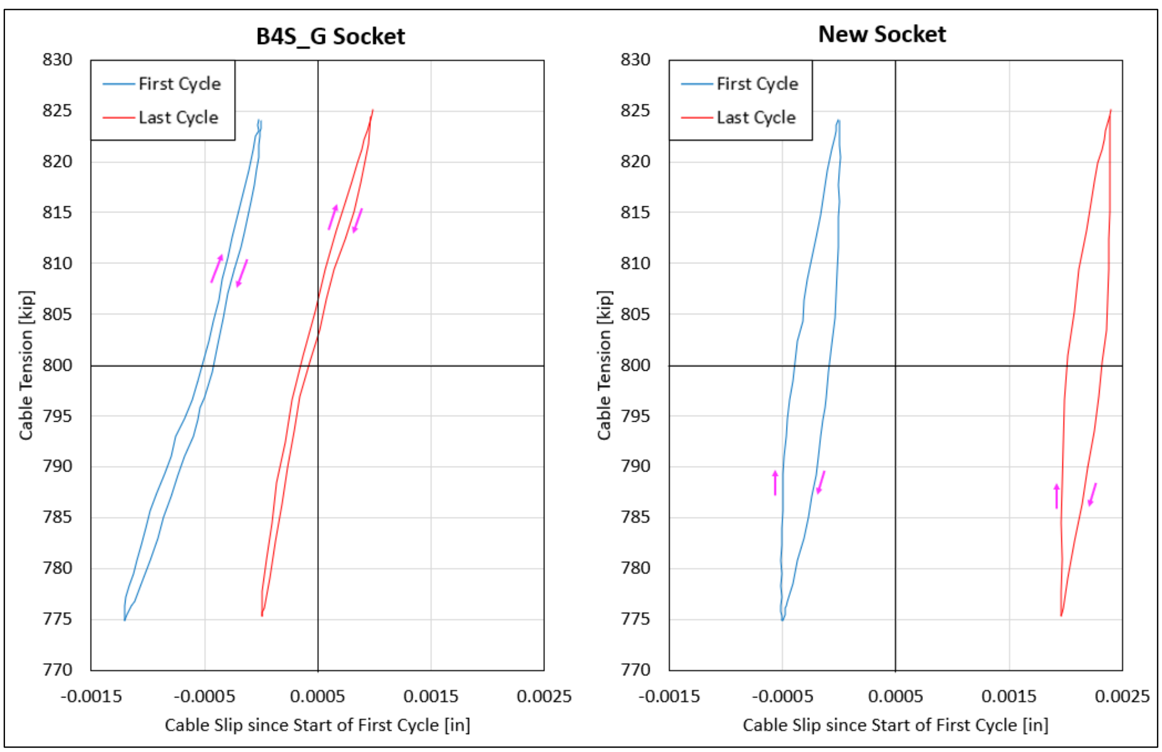

Figure 14: First and last of 150 cycles at 800 kip +/- 25kip.

4.3 Wire Stress Distribution

Figure 15 compares the outer wire stress near each socket with the average wire stress in the cable throughout the load test. The outer wire stress near a socket was calculated from the average of the four outer wire strains measured just outside of the socket with strain gages. The average wire stress in the cable is calculated directly from the known cable tension and metallic area.

The outer wire stress is higher that the average wire stress near both sockets, and the difference is more significant at the new socket. At both sockets, the relative difference between outer and average wire stress increases with the load. This indicates that as the sockets are experiencing cable slip, more load is transferred to the outer wires.

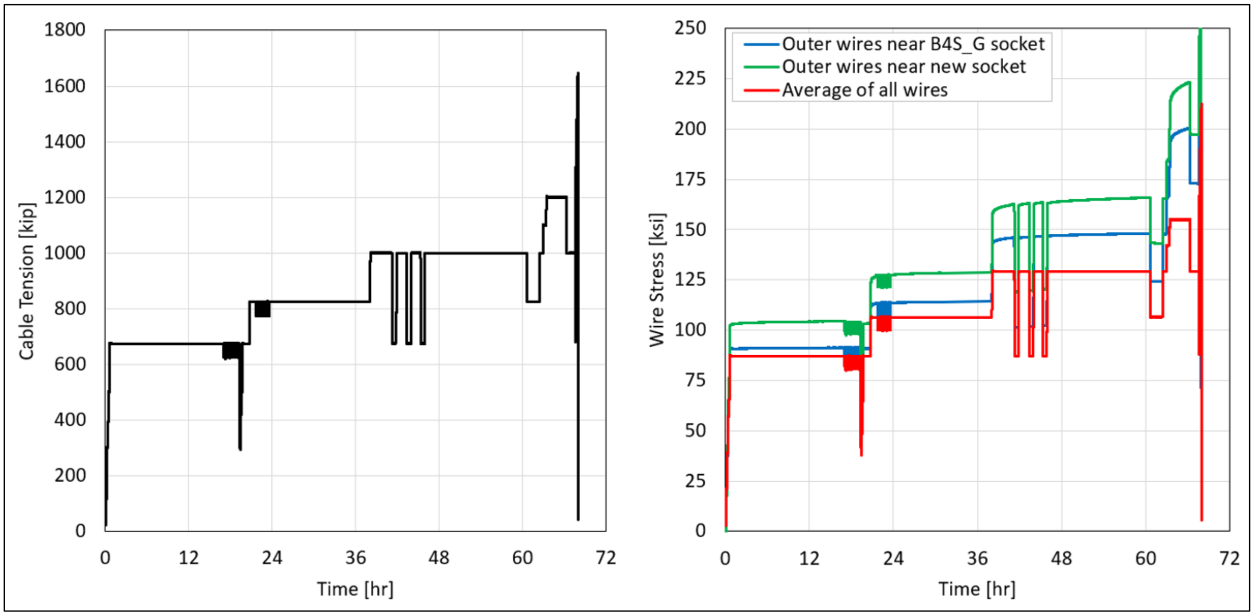

Figure 15: Loading and wire stress distribution time histories.

4.4 Socket Failure Mode

As the cable was being loaded to failure, several wires fractured inside the B4S_G socket. As shown in Figure 16, the first two fractures occurred at cable tensions of 1,454 kip and 1,552 kip. The cable tension was then increased past the minimum breaking strength of 1,614 kip, and reached a maximum of 1,647 kip before three wires fractured simultaneously. As the testing machine attempted to increase the load again, two more wires fractured at cable tensions lower than the maximum previously reached. This suggested that a complete failure of the cable-socket assembly was imminent, and the test was therefore terminated by rapidly unloading the cable.

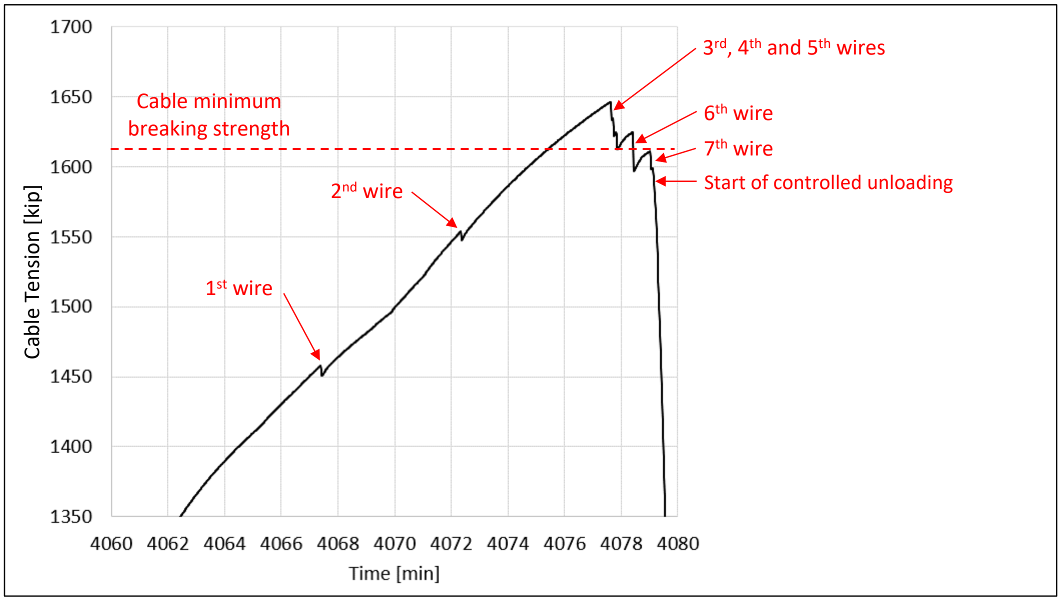

Figure 16: Cable tension drops due to wire fractures.

The condition of the specimen at the end of the test is shown in Figure 17. The seven fractured wires exhibit a cup-cone failure surface characteristic on tensile overload, and all of the fracture occurred within the B4S_G socket. The specimen was later moved to Socotec's laboratory, where the zinc casting of socket B4S_G was cut open for analysis. As shown in Figure 18, a central core has shifted with respect to the rest of the casting. The laboratory test results are covered in M.

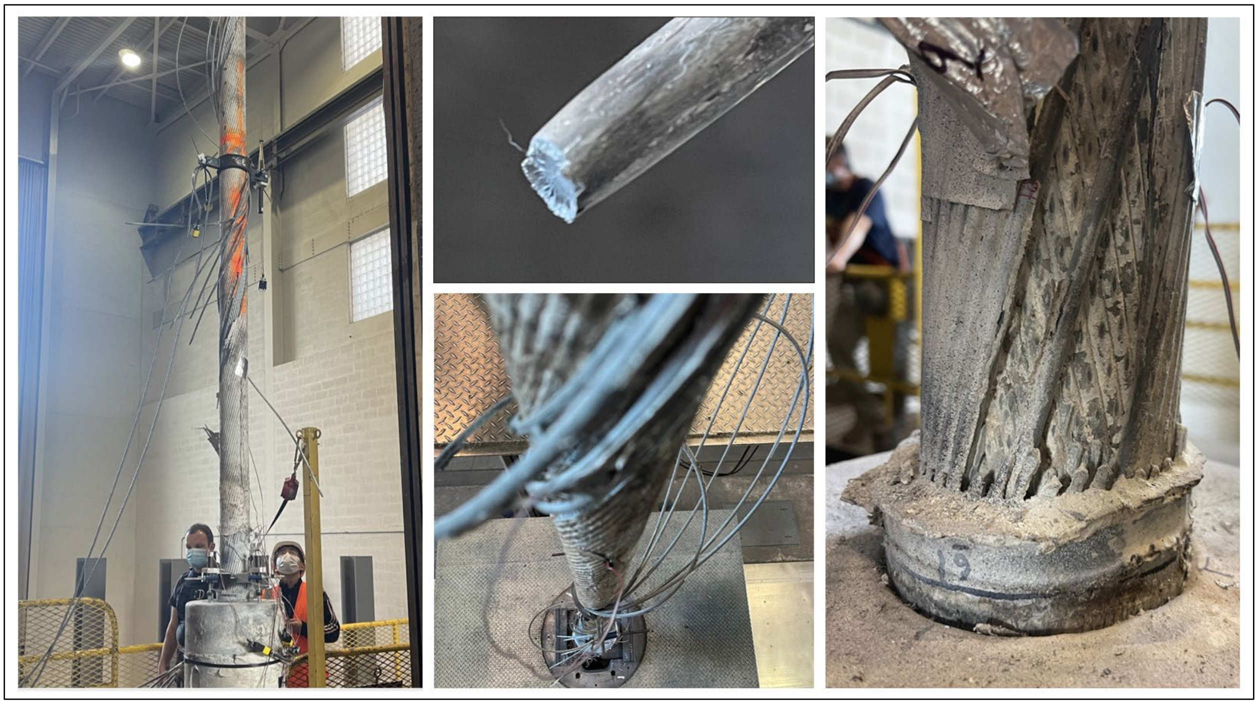

Figure 17: Specimen condition at end of load test.

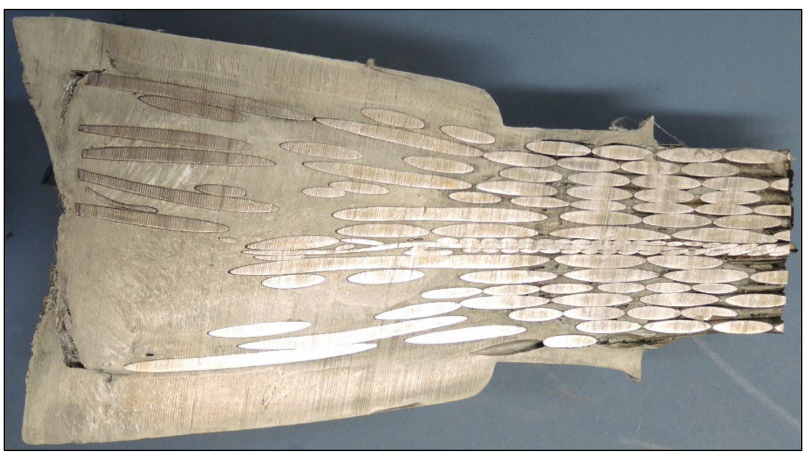

Figure 18: B4S_G casting cut open after load test to *(photo: Socotec).*