Appendix L
Cable Laboratory Analysis

1.0 Introduction

After the telescope's collapse, samples were cut from the steel cables and sent to Socotec's laboratory for analysis. The objective was threefold: determine whether the cables satisfied the design requirements, evaluate the cables' condition after years of service, and investigate how some of the cables failed near the socket connections.

2.0 Cable Samples

On December 1, 2020, the telescope's platform lost stability and collapsed when the three remaining M4 cables failed in rapid succession at the top of Tower 4. After the collapse, the failed end of each cable was cut from the rest of the cable and sent to Socotec's laboratory for analysis (Figure 1). These samples are referred to as *failed cable end 11M*, *12M* and *13I* in this appendix.

Another M4 cable, M4-4, failed three weeks before the collapse. Some of the cable's wires fractured within socket M4-4_T, while others fractured outside of the socket. Socket M4-4_T was recovered and sent to Socotec's laboratory for analysis, and the fractured wires still attached to the socket are considered as *failed cable end M4-4* in this appendix (Figure 2).

An additional segment was cut from each of the four M4 cables and sent to Socotec's laboratory for analysis (Figure 3). Each segment was cut away from the cable failure point and had no visible wire break. These samples are referred to *intact cable segment 10H*, *11I*, *12G* and *13GH* in this appendix.

Failed cable end 11M

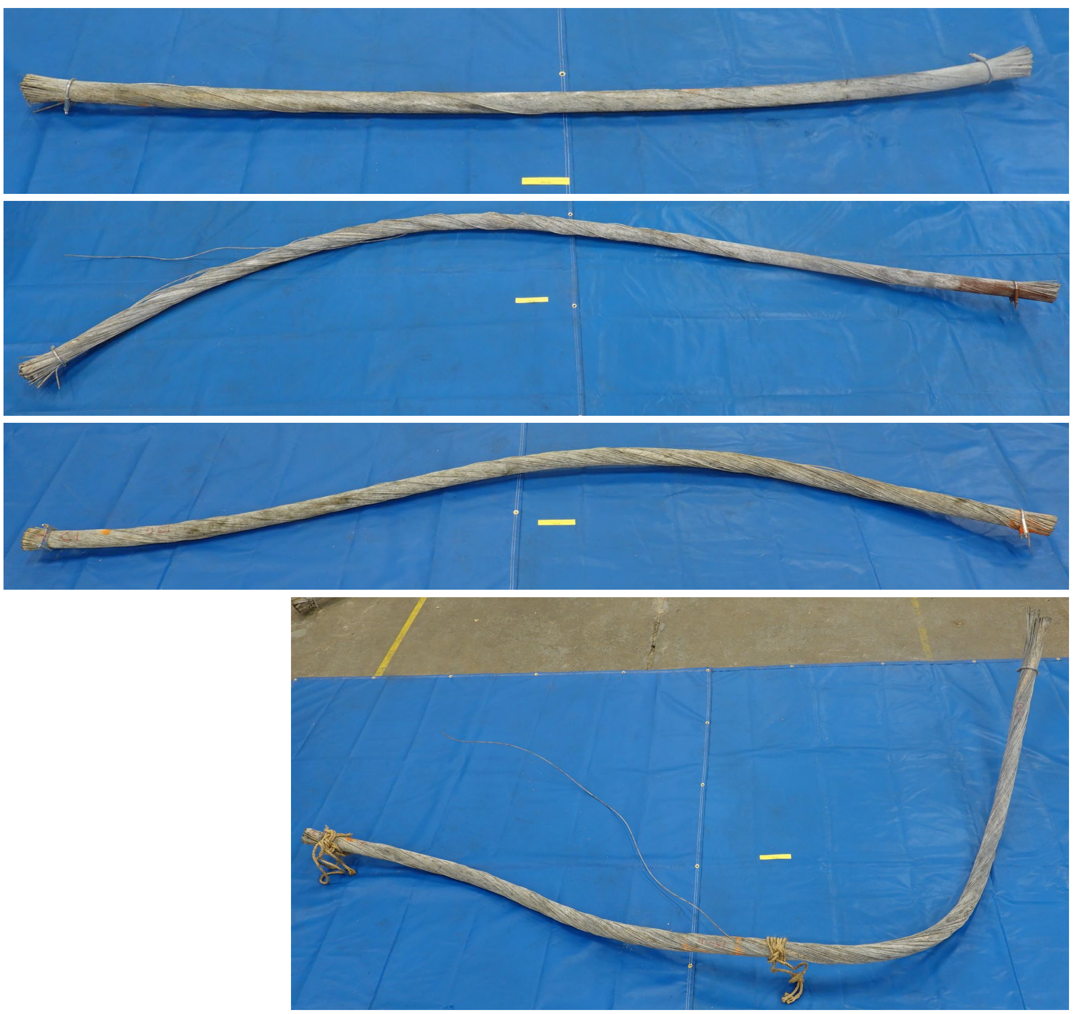
Failed cable end 12M

Failed cable end 13I

Figure 1: Failed ends of three M4 cables *(photos: Socotec).*

Failed cable end M4-4

Figure 2: Socket M4-4_T with multiple M4-4 wires fractured outside of socket *(photo: Socotec).*



Intact cable segment 10H

Intact cable segment 11I

Intact cable segment 12G

Intact cable segment 13GH

Figure 3: Intact segments of four M4 cables *(photos: Socotec).*

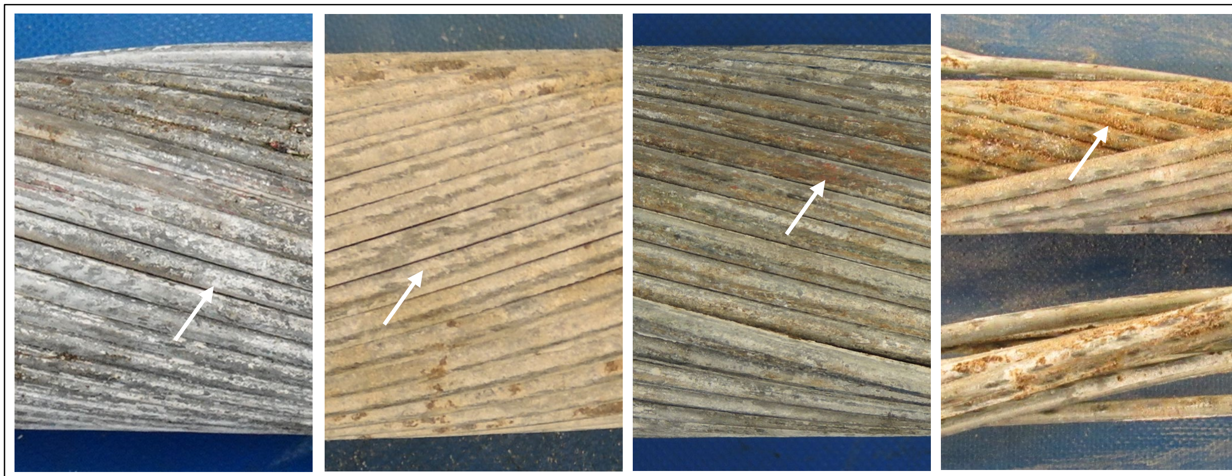
3.0 Cable Condition

3.1 Corrosion Deposits

Each M4 cable consists of 7 concentric layers of galvanized steel wires. The outermost layer is referred to as the first layer, while the innermost layer is the seventh layer. The four intact cable segments were taken apart layer by layer to observe the condition of each layer, and two types of corrosion deposits were observed in the first five layers (Figure 4). A white powdery deposit is generally present on the entire length of the cable segments and is characteristic of galvanizing zinc corrosion. Red/brown deposits are also present but more localized, and indicate that the steel of the wires started to corrode at some locations.

Four samples of corrosion deposits were analyzed with energy dispersive x-ray spectroscopy (EDS) to determine their chemical composition (Figure 5, Table 1). The white deposits consist primarily of oxygen of zinc, and contain very little iron. This confirms that the white deposits are due to corrosion of the galvanizing zinc, while the wires' steel remained protected. The red/brown deposits, however, consist primarily of oxygen, zinc, and iron. This confirms that at the locations of the red/brown deposits, the wires' steel started to corrode.

The other elements present in the deposits may have been part of the corroded steel or the paint(s) applied to the cable, or come from the environment.



White deposit on first layer of intact cable segment 11I

White deposit on second layer of intact cable segment 12G

Red/brown deposit on first layer of intact cable segment 10H

Red/brown deposit on fourth layer of intact cable segment 10H

Figure 4: Corrosion deposits tested for chemical composition *(photos: Socotec).*

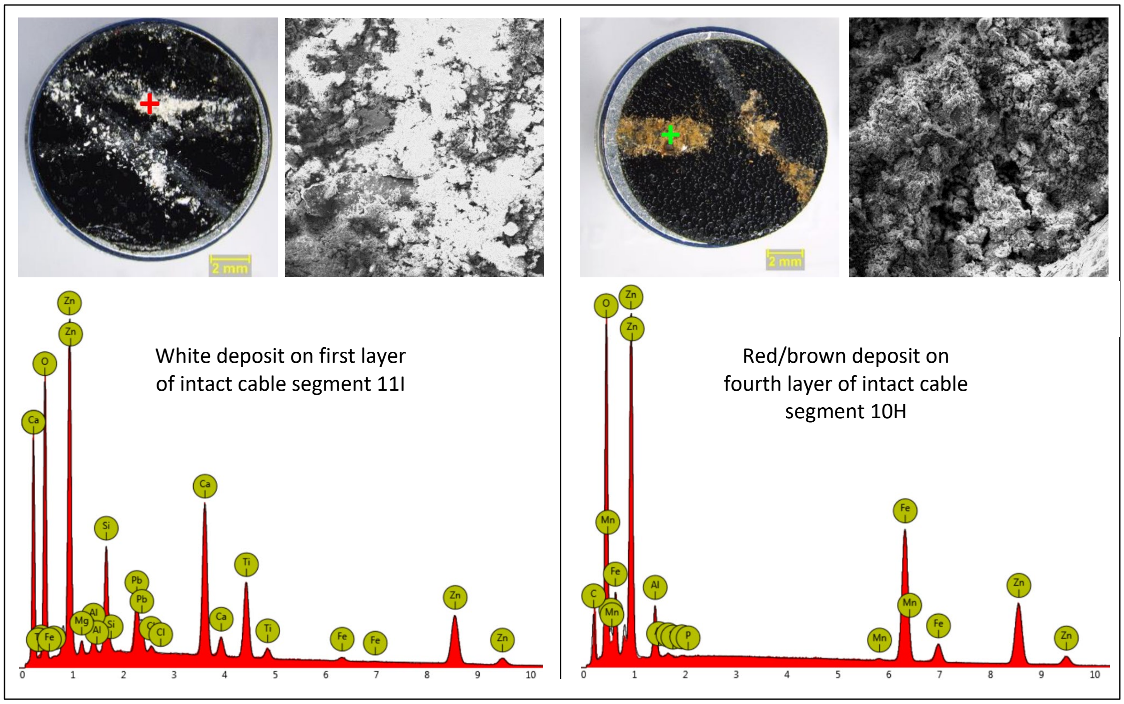


Figure 5: Representative EDS spectra from white and red/brown deposits *(photos and figures: Socotec).*

Table 1: Corrosion deposit composition by element weight.

			Intact Cable Segment 11I	Intact Cable Segment 12G	Intact Cable Segment 10H	
			Wire Layer 1[A]	Wire Layer 2[A]	Wire Layer 1[A]	Wire Layer 4[A]
Deposit Color			White	White	Red/brown	Red/brown
Weight Fraction [%]	**Oxygen**	**O**	34.2	22.3	24.7	24.3
	Zinc	**Zn**	30.6	75.4	52.6	42.1
	Iron	**Fe**	0.8	0.6	21.6	28.8
	Aluminum	**Al**	1.0	0.3	0.2	3.3
	Calcium	**Ca**	10.6	0.7	0.2	
	Carbon	**C**				1.0
	Chlorine	**Cl**	0.2			
	Lead	**Pb**	10.1			
	Magnesium	**Mg**	0.9			
	Manganese	**Mn**				0.3
	Phosphorus	**P**		0.3	0.2	0.1
	Silicon	**Si**	4.1	0.2	0.3	0.1
	Sulfur	**S**			0.3	
	Titanium	**Ti**	7.7	0.3		

[A] Layer 1 is the outermost layer.

3.2 Remaining Galvanizing Zinc

The galvanizing zinc weight was measured on 27 wires taken from the first two layers of three failed cable ends. The amount of galvanizing zinc on a steel surface is typically expressed as a weight of zinc per surface area, in this case in ounces per square foot (oz/ft^2). Measurements were performed according to the ASTM A90 standard[1] on wire lengths ranging from 18 to 27 inches.

The results are provided in Table 2, where five measurements are flagged for being less than one oz/ft^2. One oz/ft^2 is the minimum required for Class A wires in the ASTM A586 standard,[2] which was prescribed for the auxiliary cables of the telescope installed in 1997. The M4 cables tested at Socotec's laboratory are part of the original cables installed in 1964, and the requirement on galvanizing zinc weight is not known for those cables. Yet, after 57 years of service, over 80 percent of the wires tested still have more galvanizing zinc than required in a standard applicable to the fabrication of new cables. For the five wires that no longer meet that standard, the average and minimum galvanizing zinc weight are respectively 88 percent and 85 percent of the standard's requirement.

Table 2: Galvanizing zinc weight measured on cable wires.

		Failed Cable End 11M	Failed Cable End 12M	Failed Cable End 13I
Zinc Coating Weight [oz/ft^2]	**Wire 1**	1.11	0.85	0.85
	Wire 2	1.51	1.32	0.91
	Wire 3	1.45	1.35	0.87
	Wire 4	1.19	1.23	1.18
	Wire 5	1.11	1.20	1.24
	Wire 6	0.94	1.22	1.42
	Wire 7	1.19	1.06	1.21
	Wire 8	1.04	1.11	1.49
	Wire 9	1.04	1.10	1.17
Average Zinc Coating Weight [oz/ft^2]		1.18	1.16	1.15
Zinc Coating Weight CV		15%	12%	19%

3.3 Fractured Wires

Visual examination of the four intact cable segments revealed three fractured wires in the second layer of one segment (11I). The wire fracture surfaces are flat transverse planes with thumbnail-shaped regions covered with a dark layer of oxide deposit (Figure 6). Scanning electron microscopy (SEM) of the fracture surfaces shows a morphology with micro void coalescence indicative of ductile overstress fracture (Figure 7). Additional stereomicroscopic examination revealed multiple cracks on the surface of two of the fractured wires parallel to the fracture surface. Finally, a cross-section through the length of the wire cutting through the crack revealed multiple branched cracks parallel to the primary fractured surface (Figure 8). This indicates that the wires fractured to stress-corrosion cracking.

[1] American Society for Testing and Materials (ASTM). *ASTM A90/A90M-21. Standard Test Method for Weight [Mass] of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings*. 2021.

[2] American Society for Testing and Materials (ASTM). *ASTM A586-18. Standard Specification for Metallic-Coated Parallel and Helical Steel Wire Structural Strand.* 2018.

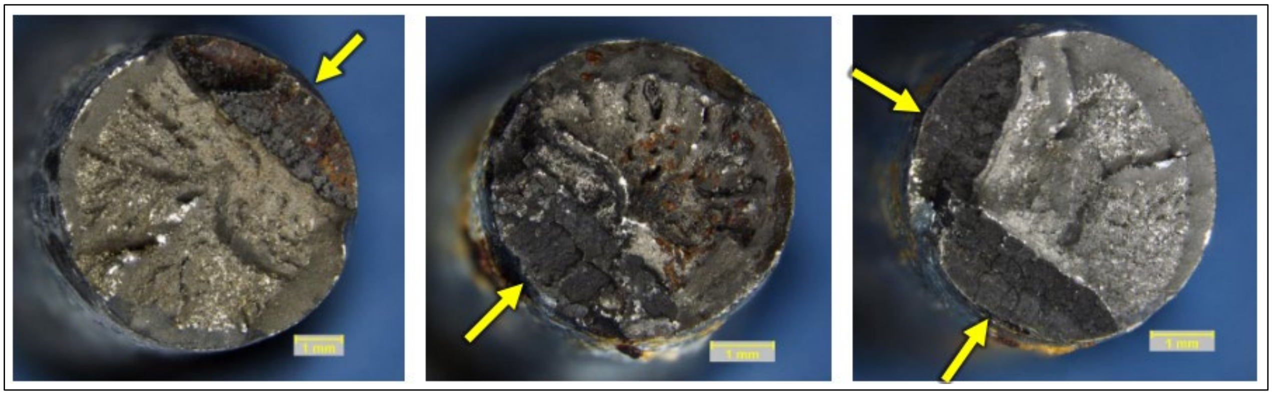


Figure 6: Stereomicroscopic images of three fractured wires of intact cable segment 11I, showing thumbnail-shaped areas covered with an oxide layer *(photos: Socotec).*

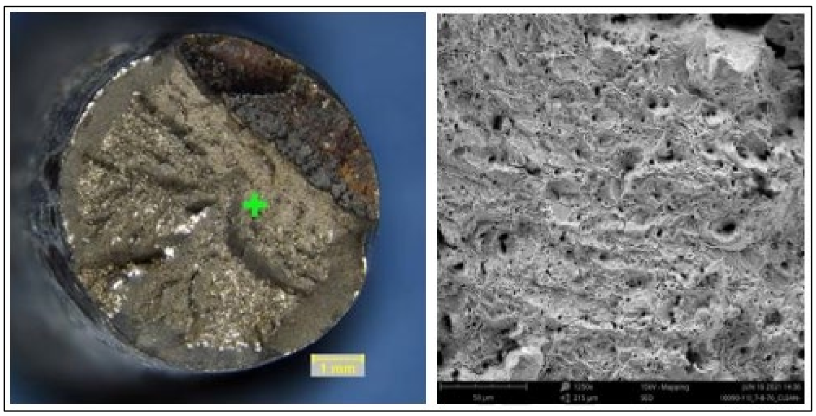


Figure 7: SEM image of a fractured wire of intact cable segment 11I, showing fracture morphology consistent with microvoid coalescence *(photos: Socotec).*

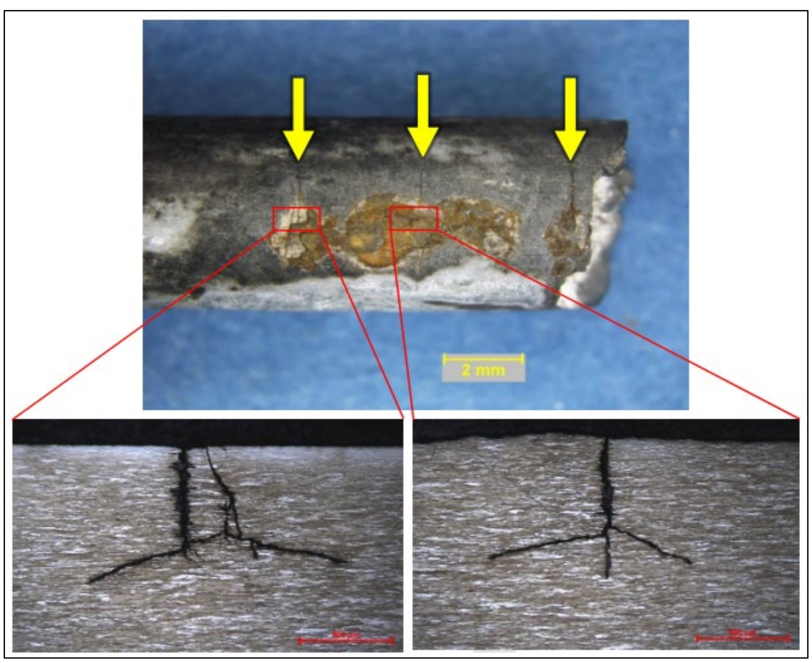


Figure 8: Metallographic images of branched cracks near fracture point of a wire of intact cable segment 11I *(photos: Socotec).*

4.0 Wire Properties

4.1 Wire Diameter

The diameter of 10 wires were measured on each of the three failed cable ends, which were part of three original main cables. Additional wire diameter were measured on two other cable types: an auxiliary main cable, and an auxiliary backstay cable. Segments of those cable types were still attached to the sockets sent to Socotec's laboratory for analysis (Appendix M).

The nominal wire diameter is 13/64 (= 0.2038) inch in the original main cables. It is 1/4 (= 0.25) inch in the auxiliary main and backstay cables, except for the fifth layer of the auxiliary backstay cables, which uses 3/16 (= 0.175) inch diameter wires. As shown in Table 3, the measured wire diameters are consistent with the nominal values.

Table 3: Cable wire diameter measurements.

		Failed Cable End 11M	Failed Cable End 12M	Failed Cable End 13I	Auxiliary Main Cable	Auxiliary Backstay Cable	
						Layers 1-4 and 6-7[A]	Layer 5[A]
Wire Diameter [in]	Wire 1	0.2045	0.2030	0.2035	0.2460	0.2505	0.1890
	Wire 2	0.2030	0.2025	0.2000	0.2455	0.2555	0.1890
	Wire 3	0.2060	0.2015	0.1985	0.2460	0.2510	
	Wire 4	0.2170	0.2000	0.1970	0.2435	0.2500	
	Wire 5	0.2045	0.2020	0.2010	0.2500	0.2515	
	Wire 6	0.1985	0.2020	0.2000	0.2450	0.2500	
	Wire 7	0.2025	0.1975	0.1975	0.2440		
	Wire 8	0.2010	0.2010	0.1965	0.2460		
	Wire 9	0.2045	0.1990	0.1985	0.2445		
	Wire 10	0.1965	0.1990	0.2005	0.2480		
Average Wire Diameter [in]		0.2038	0.2008	0.1993	0.2459	0.2514	0.1890
Wire Diameter CV		2.56%	0.85%	1.01%	0.74%	0.76%	0.00%
Nominal Wire Diameter [in]		0.2031	0.2031	0.2031	0.2500	0.2500	0.1875
Average / Nominal		100%	99%	98%	98%	101%	101%

[A] Layer 1 is the outermost layer.

4.2 Wire Chemical Composition

The steel's chemical composition was determined for nine wires taken from three failed cable ends using optical emission spectroscopy (OES). As shown in Table 4, the results indicate that the wires meet the requirements of 1080 carbon steel (AISI 1080, or UNS G10800).

The three failed cable ends whose chemical composition was tested are from cables installed in 1964 as part of the original structure. The original structural drawings only prescribe a minimum tensile strength on 220 kilopound per square inch (ksi) for the cables, with no reference to any specific material standard. However, a strength of 220 ksi is consistent with the requirements of ASTM A586, which requires the wires' steel to be carbon steel.

Table 4: Cable wire composition by element weight (iron excluded).

			AISI 1080 Limits	Failed Cable End 11M				Failed Cable End 12M		Failed Cable End 13I		
				Wire 1	Wire 2	Wire 3	Wire 4	Wire 1	Wire 2	Wire 1	Wire 2	Wire 3
Element Weight Fraction [%]	Carbon	C	0.75-0.88	0.80	0.82	0.81	0.82	0.81	0.82	0.79	0.79	0.82
	Chromium	Cr	-	0.036	0.026	0.045	0.032	0.029	0.027	0.026	0.027	0.030
	Manganese	Mn	0.60-0.90	0.82	0.69	0.75	0.75	0.63	0.65	0.60	0.60	0.74
	Phosphorus	P	0.030 max	0.024	0.020	0.025	0.027	0.016	0.016	0.011	0.014	0.019
	Sulfur	S	0.050 max	0.021	0.021	0.019	0.020	0.023	0.021	0.022	0.023	0.020
	Silico	Si	-	0.21	0.068	0.26	0.18	0.20	0.16	0.20	0.20	0.20
	Vanadium	V	-	0.005	0.003	0.005	0.004	0.003	0.003	0.002	0.003	0.003

4.3 Wire Strength

A total of 12 wire samples taken from three intact cable segments were tested to failure in conformance with the ASTM A586 standard.[3] Per the original structural drawings of the telescope, these wires were required to have an ultimate tensile strength of at least 220 ksi. The test results indicate that every tested wire meets this requirement (Table 5). Moreover, every tested wire meets the strength and ductility requirements of ASTM A586, which was prescribed for the auxiliary cables installed in 1997. Photographs of the fracture surface of each tested wire are provided in Figure 9.

Table 5: Wire tensile test results.

		Ultimate Tensile Strength [ksi]	Yield Strength [ksi]	Elongation in 10 inches [%]	Area Reduction [%]
Intact Cable Segment 11I	Wire 1	233	186	5	22
	Wire 2	221	170	5	15
	Wire 3	227	171	4	29
	Wire 4	222	166	5	29
Intact Cable Segment 12G	Wire 1	236	185	4	21
	Wire 2	227	176	4	25
	Wire 3	224	174	5	28
	Wire 4	231	177	5	21
Intact Cable Segment 13GH	Wire 1	233	179	5	26
	Wire 2	225	175	6	6
	Wire 3	233	179	4	30
	Wire 4	227	169	4	23
Average		228	176	5	23
CV		2.0%	3.3%	13.4%	28.8%
ASTM A586, Class A Limits		220 min.	160 min	4 min.	-
Average / ASTM A586		104%	110%	117%	-

[3] American Society for Testing and Materials (ASTM). *ASTM A586-18. Standard Specification for Metallic-Coated Parallel and Helical Steel Wire Structural Strand.* 2018.

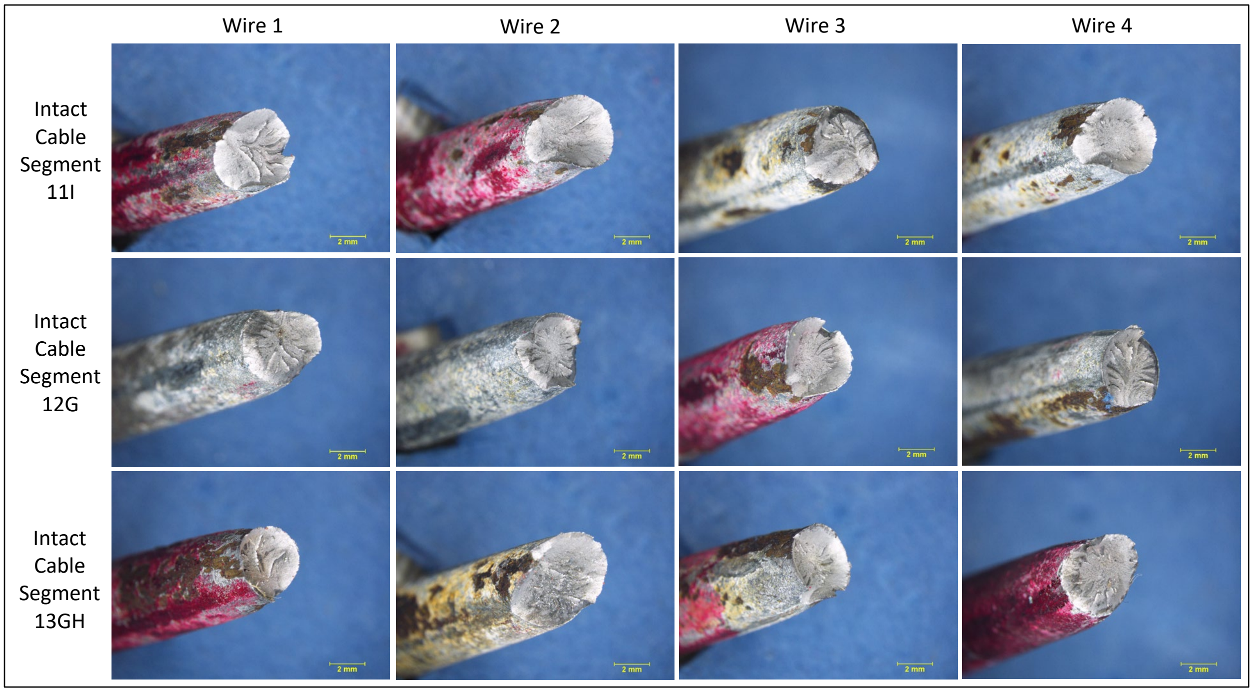


Figure 9: Fracture surfaces after wire tensile tests *(photos: Socotec).*

5.0 M4 Wires Failure Mode

On the four failed cable ends, each wire was examined to determine its fracture mode. Each wire was initially assigned a fracture mode based on the shape of the wire end and fracture surface: a "cup and cone" shape indicates axial overstress, a 45 degree slant indicates shear overstress, and a flat fracture surface indicates potential brittle fracture. Brittle fracture can be due to several causes, such as stress corrosion cracking, hydrogen embrittlement, or fatigue. For the wires categorized as potential brittle fractures, the fracture mode was verified through scanning electron microscopy (SEM) of the fracture surfaces after cleaning. This second examination revealed that many of these wires actually failed due to axial or shear overstress.

The final count of each fracture mode is provided in Table 6 and indicate that more than 90 percent of the wires fractured due to axial or shear overstress.

Each original main cable includes 168 wires arranged around a core made of seven smaller wires. Both the wires and core wires were examined in the failed cable ends, but the total number of wires examined varies between cables as some wires were missing or not examinable. The number of wires examined is significantly lower for M4-4, as many wires in that case failed within the socket.

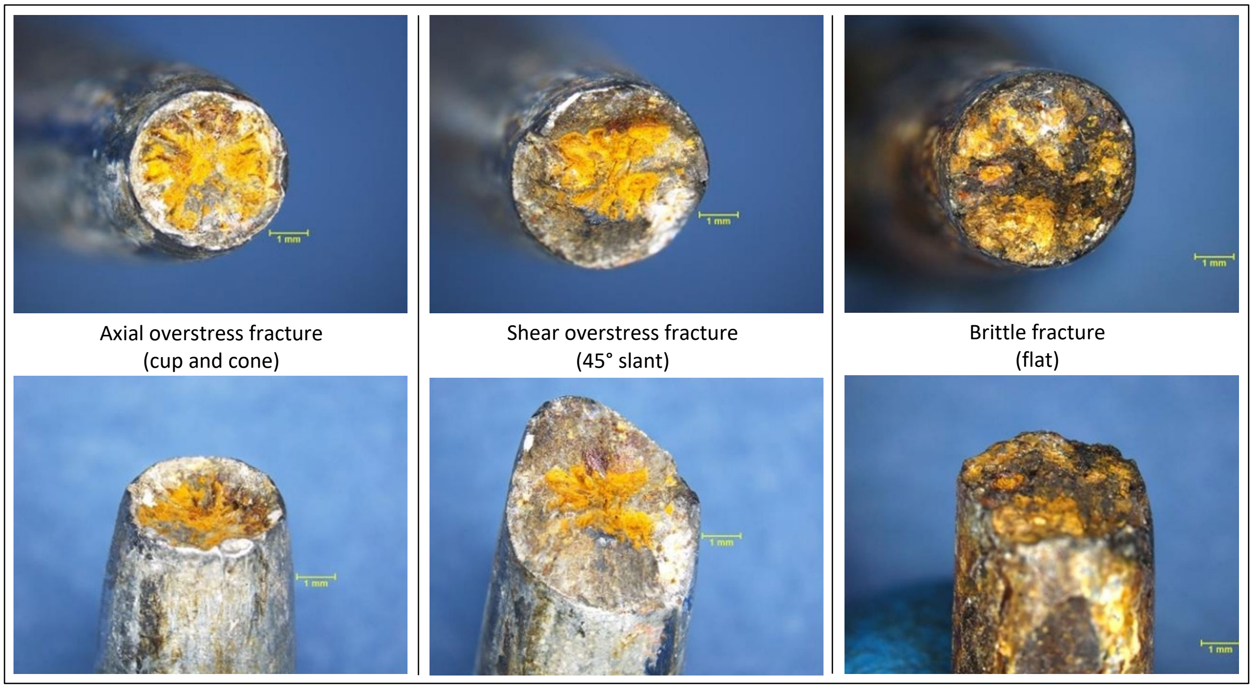


Figure 10: Representative images of axial overstress, shear overstress, and brittle fracture surfaces on wires of the failed cable ends *(photos: Socotec).*

Table 6: Wire fracture mode counts on failed cable ends.

		Failed Cable End 11M	Failed Cable End 12M	Failed Cable End 13I	Failed Cable End M4-4
Number of Wires	**Axial Overstress Fracture**	133	130	154	34
	Shear Overstress Fracture	18	37	9	1
	Brittle Fracture	10	3	6	4
	Total Examined	161	170	169	39
Fraction of Wires	**Axial Overstress Fracture**	83%	76%	91%	87%
	Shear Overstress Fracture	11%	22%	5%	3%
	Brittle Fracture	6%	2%	4%	10%
	Total Examined	100%	100%	100%	100%