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Root cause analysis of damaged ACSR conductors during construction of a 500 kV transmission line

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SUMMARY

Recently during the stringing of phase conductor on a 500 kV transmission line with triple bundle configuration, Manitoba Hydro discovered "black marks" and cable damage along the phase conductor at various locations near the suspension clamps. These damages were characterized as broken strands, flattened wires, and cut marks. In addition, some uninstalled spacer-dampers were found hanging on the conductors and were not installed in accordance with contract requirements.

This paper presents a step-by-step root cause analysis on the damaged conductor including forensic analysis, full scale inspection, industry survey, and recommended mitigation solutions. The lessons learnt from this project have been shared with the IEEE standard 524 committee (IEEE Guide for the Installation of Overhead Transmission Line Conductors) and propose changes to design and construction procedures that might benefit other electric utilities companies on future projects with bundled conductor configurations.

KEYWORDS

Transmission Line Conductor, ACSR, root-cause-analysis.

1. INTRODUCTION

As an overhead line relying on the conductor to carry electric power from one point to another, it is often considered the most important component of a power line. Other line components such as insulators, structures, and foundations are accessories to support this function. In addition to the importance of this technical function, the conductor also constitutes a major cost of an overhead line, accounting up to 40% of the overall costs of an EHV line. Therefore, it is crucial to select an appropriate conductor or conductor bundle to meet electrical, mechanical, and environmental load requirements.

Presently, Aluminum Conductor Steel Reinforced (ACSR) is the most commonly used conductor type in Canada. The form of ACSR conductors is that layers of round wires are stranded, first, around the core, and then around each other. In order to keep the integrity of this construction, the stranding takes place in alternating directions from layer to layer. In Canada, for aluminum conductors, the usual convention is to wrap the outer layer with a right-hand lay and the construction of ACSR conductor need to be compliant to several CSA Standards [1]-[3].

Manitoba Hydro has used ACSR conductors on most of its transmission line systems. During the stringing of ACSR conductor on a recent 500 kV transmission line, our field line inspectors identified multiple damaged locations and “black marks” along the phase conductor near the suspension clamp. Some locations experienced severe damage such as broken strands and some other locations have flattened wires or cut marks. These unanticipated damages raised a major concern on the lifespan of the conductor and required a detailed investigation and root cause analysis.

2. BACKGROUND

Transmission line conductors may be subjected to a wide range of tensions due to changes in loading and temperature. Exact maximum design limit depends on the importance and the exposure of the line, on the safety factors, as well as on the type of conductor material. The appropriate selection of sags and tensions considers its effects on ground clearance, support clearance, insulator swing clearance, conductor separation, line economy and operation, conductor vibration fatigue, permanent stretch, elastic limit, and structural and equipment stresses. The initial tension criteria used to string ACSR conductor at Manitoba Hydro is based on CSA standards [4] [5] and CIGRE Technical Brochure 273 [6]. For most projects, the tension limit due to aeolian vibration is the governing factor. The initial tension limit at average temperatures during the coldest month (January) should not exceed a catenary parameter of 2000 m for single conductor spans properly equipped with vibration dampers. In the case of bundled conductors, the catenary parameter may be increased to 2200 m [4].

During a recent 500 kV transmission line projects, a triple bundle configuration with ACSR conductor had been selected as phase conductor, and a 2200 m catenary parameter was adopted for conductor tension criteria. Spacer-dampers were also required for protection against aeolian vibration and sub-span oscillation. During stringing and sagging the conductor, the conductor was loaded for a minimum of one hour to accelerate initial set and creep immediately before sagging. The phase conductor was then tensioned in the travelers to 95% of the sag shown on the sag data sheets. The maximum time allowed for phase conductor to be held in the pre-loaded condition shall be five (5) hours. After sagging the phase conductor, the conductor shall not remain in traveler for a period exceeding 72 hours before clipping and installing the spacer-damper.

Temporary safe grounding is another requirement during stringing of conductor for this project. When new conductors are installed in an area remote from other energized lines, and with no thunderstorm activity present, the minimum earthing requirements can be used. These minimum requirements include bonding and earthing of all equipment involved at pull and tension sites. In addition, running earths should be installed on all metallic pulling or pilot ropes, and on the conductor in front of the pulling and tensioning equipment. In contrast to the above, for a project located in a congested area involving exposure to energized parallel lines or the crossing of existing energized lines, the maximum earthing requirements shall be used. Such maximum earthing requirements include bonding and earthing of equipment, the use of running earths, earth mats at work sites, and stringing block earths. The project site included both remote and congested sites and therefore required appropriation selection of grounding methods during stringing.

In most section of this project, ground travelers were installed every 3rd structure and each pull section is approximately 6 km.

3. FAILURES AND UNFORESEEN DAMAGE

During the routine construction inspection, the field inspectors identified several “black marks” along the phase conductor in random locations near the suspension clamp, which was flagged by quality control and resulted in a quality nonconformance report being submitted to the Line Design group. To facilitate confirmation of the damage, a crew was sent to examine the damage at a close distance. Figure 1 shows examples of sections of damaged phase conductor along the line.

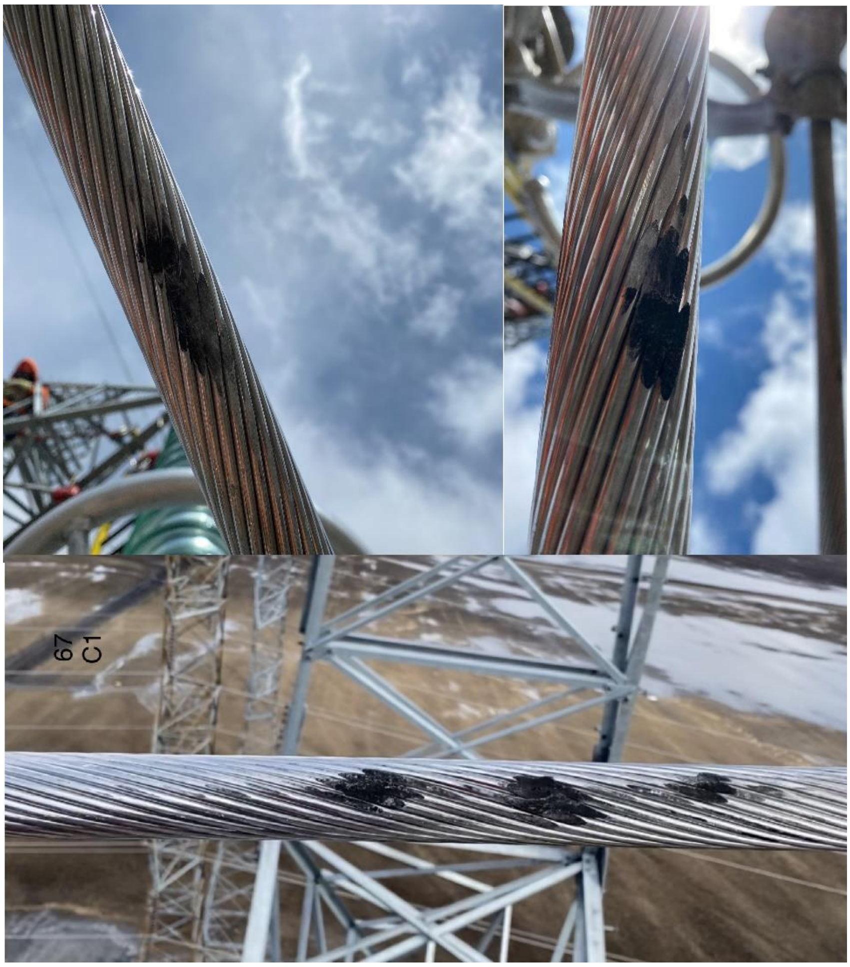


Figure 1, Examples of Damaged Locations on Phase Conductor

4. DETAILED INVESTIGATION AND ROOT CAUSE ANALYSIS

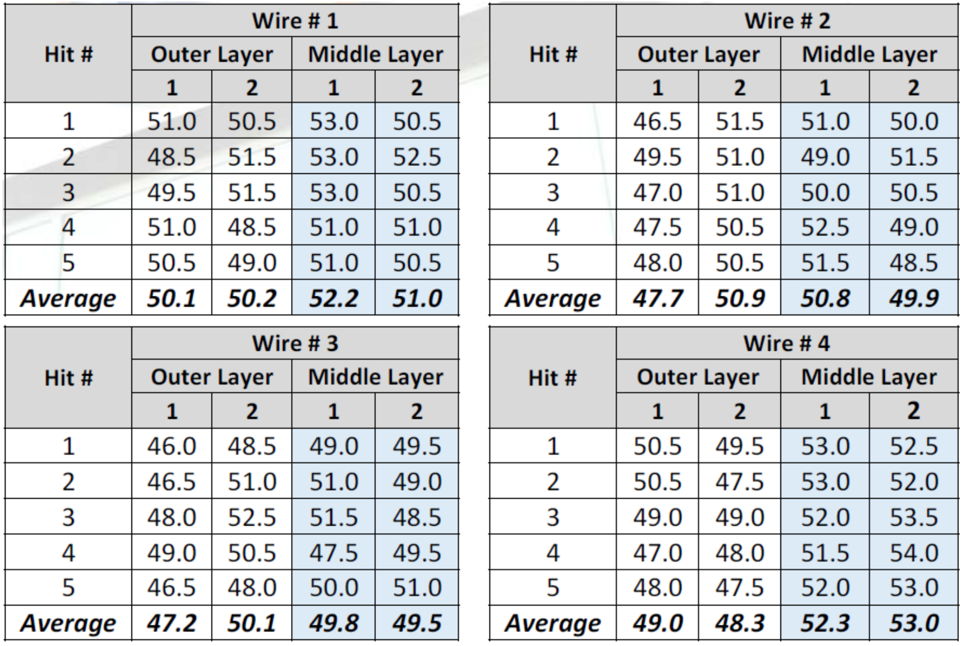
Based on the type of damage and preliminary examination of damaged conductor, possible root causes were theorized as possibly including poor quality of conductor, damage caused during transportation, poor handling, or other construction related damage. This section will discuss the process Manitoba Hydro adopted to conduct the root cause analysis for this particular issue.

4.1 Quality of Conductor

As it was possible the conductor damage resulted from poor quality control during the manufacturing process, several brand new reels of conductors from Manitoba Hydr's received stock in its material yards were randomly selected for visual and full lab testing. This testing quickly eliminated poor quality control as a possible cause of the damage as confirmed by the acceptable visual inspection and full type tests completed at a 3rd part lab. The sample of conductor was confirmed to fully conform to Manitoba Hydro's technical specification and relevant CSA/ASTM standards. While a unacceptable low aluminum strand hardness in Manitoba Hydro's received batch of conductor was theorized as a possible cause, a hardness comparison between different sources of same ACSR conductor completed by a 3rd party tested lab disproved that theory. As shown in Table 1, all samples have similar Rockwell hardness reading. (Wire #1 is the conductor used on this project).

Based on the test results, the damage on the conductor was confirmed as not being caused by poor quality ACSR conductor.

Table 1, Hardness Test Results – Rockwell Hardness



Hit #	**Wire # 1**				**Hit #**	**Wire # 2**			
	Outer Layer		**Middle Layer**			**Outer Layer**		**Middle Layer**	
	1	**2**	**1**	**2**		**1**	**2**	**1**	**2**
1	51.0	50.5	53.0	50.5	1	46.5	51.5	51.0	50.0
2	48.5	51.5	53.0	52.5	2	49.5	51.0	49.0	51.5
3	49.5	51.5	53.0	50.5	3	47.0	51.0	50.0	50.5
4	51.0	48.5	51.0	51.0	4	47.5	50.5	52.5	49.0
5	50.5	49.0	51.0	50.5	5	48.0	50.5	51.5	48.5
Average	***50.1***	***50.2***	***52.2***	***51.0***	***Average***	***47.7***	***50.9***	***50.8***	***49.9***

Hit #	**Wire # 3**				**Hit #**	**Wire # 4**			
	Outer Layer		**Middle Layer**			**Outer Layer**		**Middle Layer**	
	1	**2**	**1**	**2**		**1**	**2**	**1**	**2**
1	46.0	48.5	49.0	49.5	1	50.5	49.5	53.0	52.5
2	46.5	51.0	51.0	49.0	2	50.5	47.5	53.0	52.0
3	48.0	52.5	51.5	48.5	3	49.0	49.0	52.0	53.5
4	49.0	50.5	47.5	49.5	4	47.0	48.0	51.5	54.0
5	46.5	48.0	50.0	51.0	5	48.0	47.5	52.0	53.0
Average	***47.2***	***50.1***	***49.8***	***49.5***	***Average***	***49.0***	***48.3***	***52.3***	***53.0***

4.2 Chemical Analysis

The sample of damaged conductor was also sent to a chemical lab for future analysis. A portion of the outer surface of the conductor containing wire strands was cut out for the Scanning Electron Microscope (SEM) examination / Energy Dispersive X-Ray (EDX) Chemical Analysis of the damaged surface of the conductor. The SEM view of the "black mark" is shown in Figure 2.

SEM micrograph showing the interface between the "shiny" aluminum wire and the "black mark" damage. An energy dispersive X-Ray chemical analysis (using the scanning electron microscope / SEM) was used to determine the chemical difference between the 2 different areas on the wire strand as defined by Spectrum #1 (shiny aluminum) and Spectrum #2 ("black mark"). Based on the chemical analysis, the "black mark" on the phase conductor is aluminum oxide which could be caused by local frictional heating.

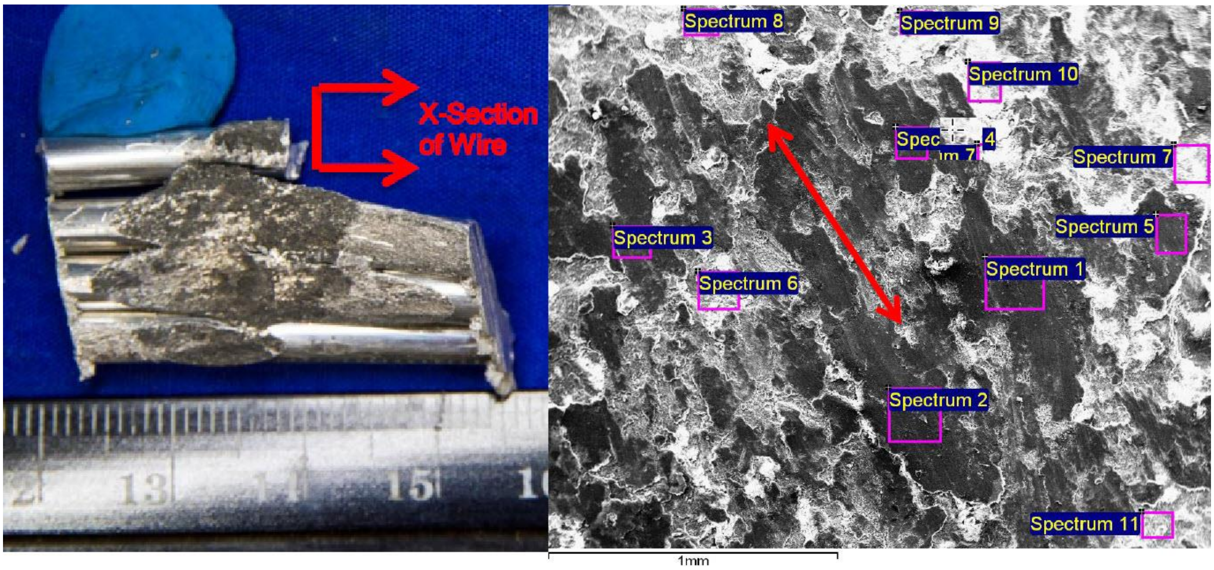


Figure 2, Scanning Electron Microscope (SEM) Micrograph

4.3 Review of the Installation Procedure

After identifying a possible cause (local frictional heating) from the chemical analysis, Manitoba Hydro reviewed and evaluated their current installation procedure and actual field construction activities for phase conductor on this project. Multiple spans were identified as violating the maximum of 72 hours requirement between sagging and clipping/installation of spacer-damper. Additionally, several spans were left without spacer-damper for more than 6 weeks. In this case, the conductors were subjected to severe aeolian vibration and sub-span oscillation damage.

During the inspection, some spacer-dampers were left hanging on the phase conductor as shown in Figure 3. The weight of the spacer dampers at the attachment point on the conductor would create another vibration node, subjecting the conductor to severe bending amplitudes due to aeolian vibration. This bending may result in fretting and other damage to the conductor.

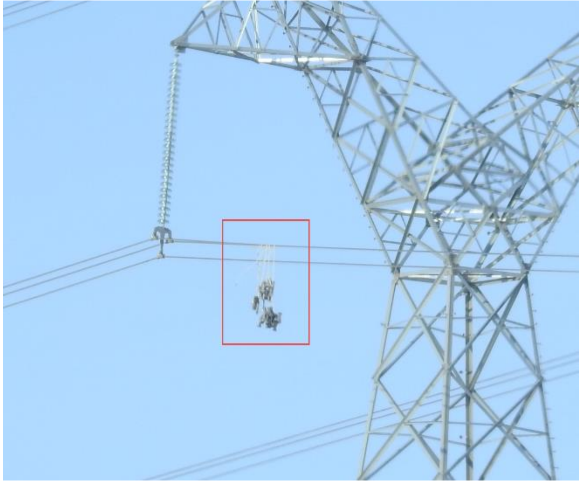


Figure 3, Improper Hanging the Spacer-Damper on the Conductor

The ground traveler was also identified as contributing to the conductor damage. The ground traveler is made of aluminum alloy and ductile iron. As the outer layer of ACSR conductor is made of pure aluminum which relatively soft compared to ductile iron or aluminum alloy, it is feasible that conductor resting on the ground travelers could deform due to the weight of the conductor, and/or be eroded by friction (and accompanying heat) damage induced by aeolian vibration. The documented delays based on construction records in stringing that allowed the conductors to sit on the ground traveler for a long period are also considered to have caused damage on the conductor surface. The installation of ground traveler is shown in Figure 4.

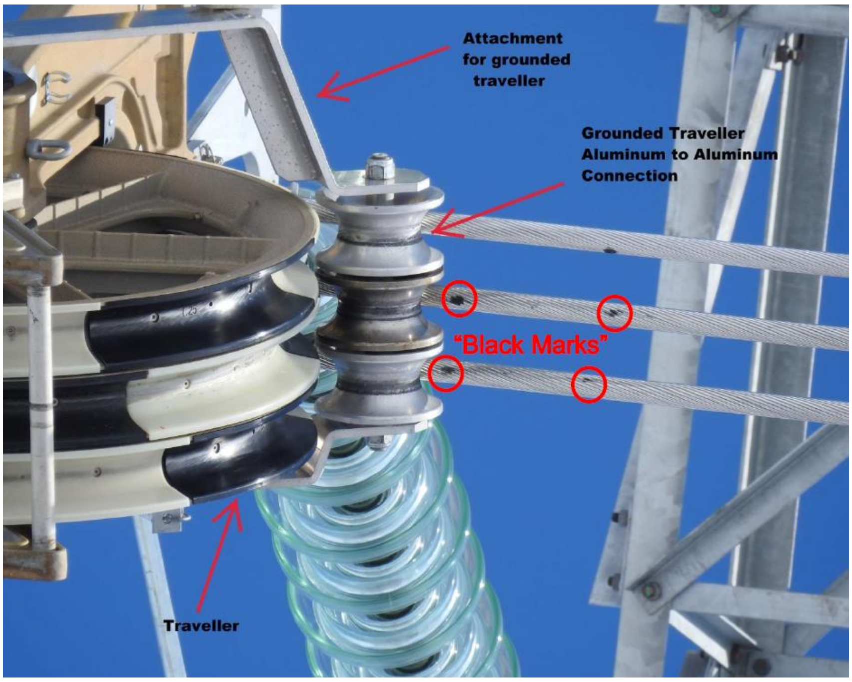


Figure 4, Typical Installation of Ground Traveler

4.4 Field inspection on damaged location

A field inspection of damaged conductor identified damage on its outer layers but could not confirm if the steel core's condition was undamaged. To acquire the knowledge of the actual physical condition of the conductor's steel core, the LineVue inspection tool made by Kinectrics was used for this project. The LineVue device is a field-based, non-destructive inspection system that "looks through" the aluminum wires and into the steel core wires. Its function is to measure the remaining cross-sectional area of steel wires and to detect any localized breaks or corrosion pits. The inspections can be performed on de-energized and energized conductors up to 500 kV. Figure 5 shows the installation of LineVue tool on the conductor. Based on the performed LineVue inspections on all identified damaged locations, no damage was found on the steel core at the inspected locations.

Figure 5, Typical Installation of LineVue Tool

Meanwhile, a mobile X-ray was used to examine all aluminum layers near the suspension clamp to confirm the condition of the aluminum strands. The X-ray inspection confirmed all the damages occurred on the outer two layers of the ACSR conductor.

4.5 Thermal Profile and Electrical Testing

In addition to mechanical strength loss, a degradation in electrical/thermal performance was also a concern and was investigated in a 3rd party lab. Two (approximately) 16-foot sections of conductor with significant abrasions were removed from the line. These two sections were placed in series within an AC circuit to test their thermal performance. Thermocouples were placed approximately 7 inches from the bolt-on NEMA pad connectors used to electrically connect the samples and the power supply. Additionally, a thermocouple was placed on the damaged portion of the conductor and a healthy portion of the conductor. The circuit was loaded with 1200 amps AC, the ambient temperature was 22.4°C. Under these conditions, Sample B operated at a significantly higher temperature where the abrasion was located (TC 6). The expected operating temperature for this conductor under these conditions was 94°C; the test results summarized in Table 2 that some damage resulted in localized heating that exceeded the design temperature and may cause annealing of the conductor.

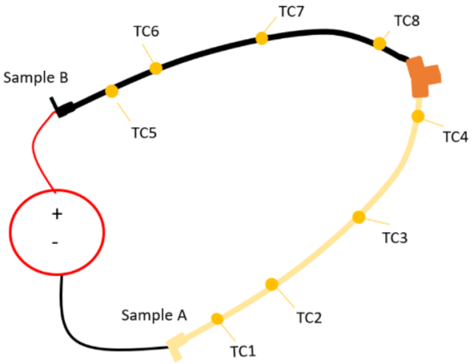


Figure 6, Thermal Performance Test Setup

Table 2, Summary of Thermal Performance Test Results

	TC #	TC Location	Temp (°C)
Sample A	1	6.5" from AC Power Supply	79.9
	2	56.5" from AC Power Supply	77.3
	3	87" from AC Power Supply (on damage)	80.3
	4	168" from AC Power Supply	80.4
Sample B	5	7.5" from AC Power Supply	77.5
	6	92.5" from AC Power Supply (on damage)	103.2
	7	123" from AC Power Supply	96.9
	8	176.5" from AC Power Supply	79.2

4.6 Electric Utilities Survey

An industry survey was conducted within Canada and some American electric utilities to confirm if similar issue was observed in other projects, and to source possible mitigation options. While the survey results did not identify similar issues of "black marks", conductor damage was commonly noted. The survey responses identified triggers for repair and repair methods that were often common between utilities. A summary of the survey is listed below.

- Almost all utilities would repair conductor even if the damage was limited to a single strand.

- Utilities had varying methods for prioritizing and scheduling the repair based on voltage and system impact of the line.
- Most utilities have guidelines similar to MH's Line Maintenance for determining the correct repair method. These guidelines were developed from manufacturer's recommendations, testing and past experience.
- It was unanimous that if there is any damage to the steel core, the damaged section of conductor should be spliced out.
- Several utilities referenced their past experience of a single strand breaking, popping loose, and starting to unravel, leading to flashovers and additional corona issue/loss.

5. MITIGATION AND REPAIR PLAN

Three possible mitigation options were evaluated for this project including compression/implosive repair sleeve, patch rod and splicing in new conductor.

The implosive/compression repair sleeves cannot be installed properly since the damaged location is too close to the suspension clamp. According to the consulted manufacturers, repair sleeves are required to be installed a minimum 5m separation distance from the suspension clamp to prevent birdcaging. All manufacturers were against using repair sleeves inside the suspension clamp.

The use of patch rods was another considered solution as it can be installed easily. Based on the manufacturer's type testing the installed patch rod on the damaged conductor can restore up to 3749.86 lbs or 16.68 kN conductor strength, which is equivalent to less than 6 broken strands. The relationship between tensile strength and number of broken strands phase conductor is given in Table 3.

Table 3, Relationship between Broken Strand and Strength Loss for Damaged ACSR Conductor

Number of Broken Strand	Strength Loss in KN	Remaining Strength in %
0	Rated RBS	100%
1	2.87	98.46%
2	5.74	96.91%
3	8.61	95.37%
4	11.48	93.82%
5	14.36	92.28%

If the damage exceeds 5 broken strands, the repair cannot be made by using patch rod, and require splicing in a new section of conductor. The proposed summary of repair plan(s) based on this information is shown in Table 4.

Table 4, Repair Plan – Damaged Conductor

Damaged Component	Severity of Damage	Mitigation Method
Wire / Individual Strand	Up to 10% of strand depth; "intact"	Smooth or polish strand
	10% - 50% of strand depth; "damaged"	Armor/repair rods required to restore conductor strength; refer to criteria for damaged conductor (below)
	>50% of strand depth; "broken"	Armor/repair rods required to restore conductor strength; refer to criteria for damaged conductor (below)
Conductor	≤5 damaged/broken strands on outer layer	Armor/repair rods required to restore conductor strength

	>5 damaged/broken outer aluminum strands on outer layer, or any damage to inner layers	Full tension splice required to restore full conductor strength

6. SUMMARY

A root cause analysis of the visibly damaged on outer strands of ACSR conductor identified extended undesirable contact between the conductor and Ground Traveler as one source of the damage. Damaged conductor strands were also identified on subconductors adjacent to subconductor splices, where failure to install spacer-dampers in a timely fashion resulted in subconductor motion, contact between subconductors, and conductor strand abrasion.

Damage to the interior strands was also identified as a risk due to unacceptable bending stresses without antivibration devices. The LineVue inspection tool and mobile X-ray was used to confirm the actual condition of the interior strands and steel cores.

Based on the test data and manufactures' recommendation, patch rods and full tension splices were used to repair the damage location.

The stringing procedure including the ground traveler application has been revised at Manitoba Hydro to minimize the possible conductor damage in future project. Manitoba Hydro's experience has been also shared within IEEE standard 524 committee (IEEE Guide for the Installation of Overhead Transmission Line Conductors) for consideration in future updates to their standard.

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