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Why Extensive Testing, Field Experience and International Standards are Key to Ensuring Grid Reliability

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INTRODUCTION

A recent power outage in Mumbai which took 2.6 GW of power off the grid, was attributed to the overloading of high voltage lines which underscores the importance of modernizing the grid with high performance conductors and devising a plan to deal with multiple contingences which may occur simultaneously. While tens of millions of people have little to no access to electricity, major efforts are underway to correct this, and efforts to build a modern and efficient grid are well underway, worldwide.

It is noteworthy that conductor technology had changed very little over the last several decades until recently. For instance, steel reinforced ACSR conductor was introduced in the early 1900's – over one-hundred years ago. In the 1970's a higher temperature version, ACSS conductor, enabled higher current flows but with greater power losses and poor sag performance.

In the early 2000's composite core conductors were introduced. These included 3M's ACCR conductor which uses ceramic fiber reinforced aluminum core strands and thermal resistant aluminum-zirconium conductive strands; and CTC Global Corporation's ACCC® Conductor, which uses a single carbon and glass fiber core surrounded by trapezoidal shaped fully annealed aluminum conductive strands or thermally resistant aluminum zirconium alloy conductive strands. While each of these technologies were designed to increase line capacity, mitigate thermal sag and improve overall conductivity to reduce electrical line losses, carbon fiber technology has been more widely accepted within the electrical transmission industry due its toughness, flexibility, and low cost.

TESTING

For good reason, Utilities are very conservative by nature. Safety, reliability and resilience are at the very top of the list. For this reason, both 3M and CTC Global in collaboration with the U.S Department of Energy, the Electric Power Research Institute (EPRI), key utility companies, and a number of international universities and laboratories conducted substantial testing to develop technologies, measure performance attributes and operating parameters, and evaluate longevity in the extremely harsh environmental conditions in which overhead conductors are expected to operate for a minimum of 40 to 50 years or more.

In addition to core testing, mechanical and electrical conductor testing and field trials (discussed in more detail below), overhead conductors are part of an overall system that include ancillary components such as splices, dead-ends, suspension clamps and jumpers. *The importance of the development and testing of suitable connectors and ancillary hardware components for new conductor technologies cannot be understated*, and the amount of energy expended on the two products described was substantial. Figure 1 offers a list of testing performed.

TEST EXAMPLES

As part of their analysis of various conductors, American Electric Power (AEP) designed and conducted a "Sequential Mechanical Test." In this series, they installed conductor samples on a load-frame with a suspension clamp mounted at a one-third span. The conductor samples were first subjected to a series of bending tests to replicate installation stresses. The samples were then subjected to 100 million cycles of vibration followed by one hundred thousand cycles of galloping, and subsequently pulled to failure.

Remnants of the ACCC Conductor were then subjected to approximately two dozen additional tests. To address concerns about the flexibility of the single strand composite core, AEP placed the Drake size conductor sample in an electrician's conduit pipe bender and bent the sample ten times to 90 degrees+. They then removed the composite core, cut it into 10 mm samples, placed the samples into die penetrant and looked for damage under a microscope. After all of this, virtually no damage was observed. This test series not only confirmed the conductor's overall toughness, it also confirmed that the single strand composite core design has excellent flexibility and is highly resistant to damage. Figure 2 highlights the observations.

"Load path redundancy" was another concern regarding single-strand composite core designs. A few engineers speculated "if you only have one core strand and it gets damaged, there is no load path redundancy, and it will fail." Lab tests proved that some 'notched edge' or

1. CTC Global

Core Testing:

2.1.1 Tensile Testing
2.1.2 Flexural, Bending & Shear Tests
2.1.3 Sustained Load Tests
2.1.4 Tg Tests
2.1.5 CTE Measurements
2.1.6 Shear Testing
2.1.7 Impact and Crush Testing
2.1.8 Torsion Testing
2.1.9 Notched Degradation Testing
2.1.10 Moisture Resistance Testing
2.1.11 Long Term Thermal Testing
2.1.12 Sustained Load Thermal Testing
2.1.13 Cyclic Thermal Testing
2.1.14 Specific Heat Capacity Testing
2.1.15 High Temperature Short Duration
2.1.16 High Temperature Core Testing
2.1.17 Thermal Oxidation Testing
2.1.18 Brittle Fracture Testing
2.1.19 UV Testing
2.1.20 Salt Fog Exposure Tests
2.1.21 Creep Tests
2.1.22 Stress Strain Testing
2.1.24 Micrographic Analysis
2.1.25 Dye Penetrant Testing
2.1.26 High Temperature Shear Testing
2.1.27 Low Temperature Shear Testing

Mechanical Conductor Testing:

2.2.28 Stress Strain Testing
2.2.29 Creep Testing
2.2.30 Aeolian Vibration Testing
2.2.31 Galloping Tests
2.2.32 Self Damping Tests
2.2.33 Radial Impact and Crush Tests
2.2.34 Turning Angle Tests
2.2.35 Torsion Tests
2.2.36 High Temperature Sag Tests
2.2.37 High Temperature Sustained Load
2.2.38 High Temperature Cyclic Load Tests
2.2.39 Cyclic Ice Load Tests
2.2.40 Sheave Wheel Tests
2.2.41 Ultimate Strength Tests
2.2.42 Cyclic Thermo-Mechanical Testing
2.2.43 Combined Cyclic Load Testing
2.2.44 Conductor Comparison Testing

Systems & Hardware Testing:

2.4.55 Current Cycle Testing
2.4.56 Sustained Load Testing
2.4.57 Ultimate Assembly Strength Testing
2.4.58 Salt Fog Emersion Testing
2.4.60 Static Heat Tests
2.4.61 Suspension Clamp Testing
2.4.62 Thermo-Mechanical Testing
2.4.63 Cyclic Load Testing
2.4.64 EPRI Longevity Assessment (1,500 cycles)

Electrical Conductor Testing:

2.3.45 Resistivity Testing
2.3.46 Power Loss Comparison Testing
2.3.47 Ampacity
2.3.48 EMF Measurements
2.3.49 Impedance Comparison Testing
2.3.50 Corona Testing
2.3.51 Radio Noise Testing
2.3.52 Short Circuit Testing
2.3.53 Lightning Strike Testing
2.3.54 Ultra High Voltage AC & DC Testing

Field Testing:

2.5.64 Ambient Temperature
2.5.65 Tension, Sag, and Clearance
2.5.66 Conductor Temperature
2.5.67 Electric Current
2.5.68 Wind Speed and Direction
2.5.69 Solar Radiation
2.5.70 Rainfall
2.5.71 Ice Buildup
2.5.72 Splice Resistance
2.5.73 Infrared Measurements
2.5.74 Corona Observations
2.5.75 Electric and Magnetic Fields
2.5.76 Wind and Ice Load Measurements
2.5.77 Vibration Monitoring
2.5.78 Typhoon Test

Fig. 1 : Examples of Composite Core Conductor Testing Performed on ACCC Conductor

Fig. 2 : ACCC Core bent to 90 degrees with no remarkable damage

'circumferential' damage will result in a loss of strength, but the degree depends upon the amount of damage, just like with multi strand core designs. In the field, a Drake size ACCC Conductor installed on a Western Area Power Administration (WAPA) trial line was shot by a hunter with a high caliber rifle. While the conductor and core were damaged and required the installation of a full-tension splice, the fact that the composite core in this size contains ~600,000 carbon fibers and ~400,000 glass fibers proved, in fact, that there was plenty of load path redundancy to prevent catastrophic failure. Figure 3 provides additional details.

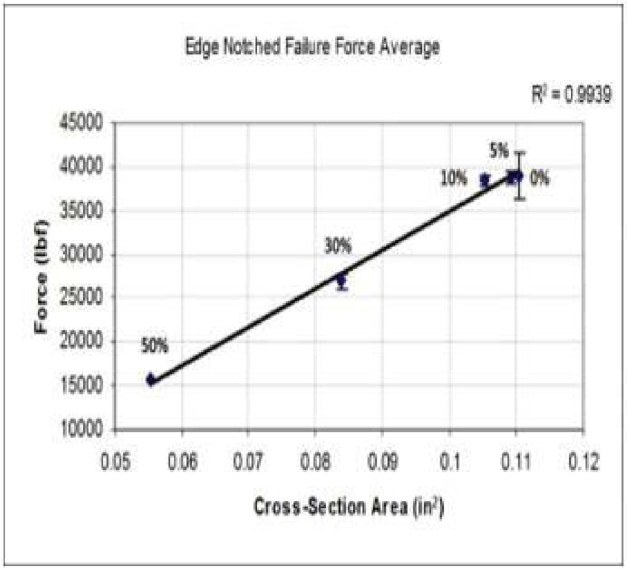

Fig. 3 - lab tests and field observation demonstrate 'load path redundancy' of ACCC Composite Core

"Galvanic Protection" is Essential with Carbon Fiber Core Conductors irrespective of types. Composite core conductors utilize a carbon and glass fiber core embedded in a toughened polymer resin matrix. The central carbon fiber core is surrounded by glass fibers of sufficient thickness to improve flexibility and create a durable barrier that prevents galvanic corrosion. Aluminum with carbon fiber composite is among the most reactive galvanic pairing possible where aluminum material is gradually corroded away. The insulation layer between

aluminum strands and carbon fiber core must be of sufficient integrity to survive the constant fretting (from conductor vibration or the differential thermal expansion with temperature) between the inner aluminum strands and the composite core over its lifetime. Aerospace structures typically require 1 to 2 layers of fiberglass insulation (~10 mil or 0.25 mm per layer) to prevent galvanic coupling of aluminum and carbon fibers. The ACCC conductor core is designed to maintain a minimum glass layer of 0.38 mm (As specified in ASTM B987) to ensure the integrity of the galvanic corrosion barrier over the conductor's service life. See Figure 4

Fig. 4 : ACCC Conductor showing galvanic barrier that meets ASTM B 987 Standard

Barrier protection is perhaps the oldest and most widely used method of corrosion protection. It acts by isolating the base metal from the environment. Like paints, the hot-dip galvanized coating provides barrier protection to steel. As long as the barrier is intact, the steel is protected, and corrosion will not occur. However, if the barrier is breached, corrosion will begin. Likewise in case of Composite Core Galvanic Protection Barrier Layer is important and breach of layer corrosion will begin between Carbon Fiber and Aluminum Strands.

FIELD EXPERIENCE

In addition to the laboratory testing process that took place over a period of several years, field experience contributed substantially to the overall knowledge gained on these novel conductors. While field trials confirmed the suitability of conventional installation equipment and safe installation procedures, there were things 'learned the hard way.' These exercises proved highly valuable to Utilities that subsequently installed these products.

Over time, additional knowledge was gained from a number of real-world events. For instance, in 2013 an EF 5 tornado crossed directly over one of these conductors and caused extensive damage to the community. In this case, a steel monopole was hit by flying debris which caused a shockwave that snapped the conductive aluminum strands. Fortunately, the single-strand composite core was not damaged and held the conductor in the air which expedited repairs. If the core failed, the conductor would have fallen to the ground which would have had to be replaced or repaired using pulling equipment that was needed elsewhere. This attribute falls under the category of 'resilience," and was a good lesson. Figure 5 shows a quick repair in process.

Fig. 5 : OG&E linemen preparing to install 4 meters of ACCC Conductor to repair tornado damage

Fig. 6 : Undamaged ACCC Conductor on the ground after wildfire. The structures were rebuilt, and the conductor quickly put back into service

In 2012, a wildfire burned wood poles (H-frame configuration) on transmission line near Reno, Nevada. Fortunately, the very small the single-strand composite core conductor was not damaged which allowed linemen, with the support of a helicopter to replace the wood poles and insulators and quickly lift the cross arms and conductor back into place and back into service. This is another good example of the toughness of carbon fiber composites and how it supports grid resilience. Figure 6 shows the downed conductor.

Though field experience and lab testing is extremely important, the significance of product quality and manufacturing consistency is hugely important to ensuring grid reliability. For this reason (and others) International Organizations such as ASTM, IEEE, ANSI, ISO, IEC and others develop standards and guidelines.

STANDARDS

Utilities world over lean over to various standards like ASTM, IEC, IS, etc. for procurement of equipment for their grids.

As per IEEE, “Standards form the fundamental building blocks for product development by establishing consistent protocols that can be universally understood and adopted. This helps fuel compatibility and interoperability and simplifies product development, and speeds time-to-market. Standards also make it easier to understand and compare competing products. As standards are globally adopted and applied in many markets, they also fuel international trade.”

As per CEA (Canadian Electricity Association), “The use of standards has been highly beneficial to the Canadian economy as well as to the design, construction, procurement, maintenance, and operating processes of the electricity industry. Updated standards are crucial at this point in time, as the industry prepares to enter into a multi-year intensive capital replacement program.”

Originally adopted in 2014 and updated / clarified in 2017 and again in 2020, ASTM B987 “Standard Specification for Carbon Fiber Thermoset Polymer Matrix Composite Core (CFC) for use in Overhead Electrical Conductors” is the only Internationally Recognized Standard for composite cores used as a strength member in overhead conductors.

ASTM B987 specifies a number of performance requirements, test methods and evaluation protocols that include, bending strength, tensile strength, elastic modulus, glass transition temperatures, density, non-conductive galvanic barrier thickness, thermal aging and more. The Standard establishes minimum acceptance criteria; design validation testing; acceptance testing; suitability of design, materials and methods of manufacture; testing frequency; test lab accreditation requirements and product batch acceptance “routine” testing. All of these elements are designed to help ensure that the product offered to the Utility meets the rigors of the product’s application over its anticipated service life. ASTM B987 is generally called out as a requirement in Tender Specifications to help engineers avoid unknowingly putting their systems at risk.

Likewise, IEEE 524 “Guide for the Installation of Overhead Conductors” (April 2017) is useful reference that shares insight into proper installation practices for most conductor types. In certain areas it recommends following ‘Manufacturer’s Recommendations.’ This statement underscores the value of installation and performance experience.

ACCC® CONDUCTOR: HIGHLY TRUSTED FOR ITS RELIABILITY

The ACCC® conductor consists of a hybrid carbon and glass fiber composite core which utilizes a high-temperature epoxy resin matrix to bind hundreds of thousands of individual fibers into a unified load-bearing tensile member. The central carbon fiber core is surrounded by high-grade boron-free glass fibers to improve flexibility and toughness while preventing galvanic corrosion between the carbon fibers and the aluminum strands. The composite core exhibits an excellent, highest-in-the-industry, strength to weight ratio, and has a lowest-in-the-industry coefficient of thermal expansion which reduces conductor sag under high electrical load / high temperature conditions. The composite core is surrounded by aluminum strands to carry electrical current. The conductive strands are generally fully annealed aluminum and trapezoidal in shape to provide the greatest conductivity and lowest possible electrical resistance for any given conductor diameter.

The ACCC® conductor is rated for continuous operation at up to 180°C (200°C short-term emergency) and operates significantly cooler than round wire conductors of similar diameter and weight under equal load conditions due to its increased aluminum content and the higher conductivity offered by Type 1350-O aluminum. Though the ACCC® conductor was initially developed as a “High-Temperature, Low-Sag” (HTLS) conductor to increase the capacity of existing transmission and distribution lines with minimal or no structural changes, its improved conductivity and reduced electrical resistance makes it ideally suited for reducing line losses on new transmission and distribution lines where improved efficiency and reduced upfront capital costs are primary design objectives.

The ACCC InfoCore™ System reduces real-world conductor installation risk experienced by utilities, contractors, and lineman across the globe. These dedicated professionals know that even with the best tools, equipment and field conditions, accidents can happen. By using a proprietary infrared light system, special fibers in the core, and a robust data-capture and recording methodology, the ACCC InfoCore™ System can confirm the integrity of the conductor in seconds.

Fig. 7 : The ACCC InfoCoreTM System taking reliability to next Level.