High Temperature Strength and Creep of an Al Conductor with a Hybrid Composite Core

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Abstract

Steel reinforced overhead conductors undergo severe sag at high temperatures, limiting both the service temperature and the ampacity. To limit sag, an alternative core material has been developed that consist of a polymer matrix/hybrid composite. The aluminum conductor-composite core (ACCC) consists of annealed aluminum trapezoidal wire (TW) strands, much like ACSS. The ACCC/TW, though, offers reduced sag and improved creep resistance. In this work, the high temperature strength and creep of the ACCC/TW is assessed. The strength of the composite core at 100° to 180°C decreased only 10% from the room temperature strength. Furthermore, under constant loads at temperatures up to 180°C, creep was insignificant, and was determined to only induce a change in sag for a typical span and load of less than 0.35 mm at 150°C. The superior mechanical properties of the composite core highlight the potential for use of composite materials to produce overhead conductors with low sag at high temperatures.

1 Introduction

The nation's electrical power grid is presently in need of upgrade and expansion to meet the growing demand for distribution capacity in the coming decades [1]. The primary factor limiting the distribution capacity of the grid during peak demand is heat, which causes expansion of metallic conductors and results in sag. The present conductor design relies on hardened aluminum (Al) wires to carry the electrical current. The Al wires are supported mechanically by a core of stranded steel wires. As the conductor temperature rises with increased electrical transmission, the conductor expands and sags. Excessive sag is unacceptable because of the risk of grounding to treetops, human injury, and property damage. To address these issues and to increase the capacity of the existing grid, high-temperature, low-sag (HTLS) conductor designs have been proposed that overcome the limitations of present designs [2-8]. One of these HTLS conductors is the aluminum conductor-composite core, trapezoidal wires (TW) (ACCC/TW) [7, 8]. The ACCC design stems from the conceptual design of the aluminum conductor steel supported, trapezoidal Al wires (ACSS/TW), but the steel core is replaced with a core of carbon/glass fiber polymer matrix composite which exhibits a coefficient of thermal expansion about 7 times less than steel. Like ACSS/TW, ACCC/TW consists of 1350 fully annealed trapezoidal (trap) wire, so it can run continuously at temperatures upwards of 200°C. But unlike ACSS/TW, the 1350-O' trap wire is supported by a pultruded hybrid composite core. A cross-sectional comparison of the ACCC/TW to ACSR is shown in Figure 1, which is an updated picture to the one shown in Figure 1 in [7].

The composite core is considered a viscoelastic material. With the intended operating temperature of the ACCC/TW being between 100° and 180°C, the mechanical properties of the matrix can vary with time and temperature [2, 9-14]. To predict long-term performance and define safe operating conditions for the conductor, changes in the mechanical properties of the composite core must be evaluated and understood. For example, creep, or time-dependent deformation of the core at high temperature, is a critical factor in the long-term performance of the conductor, contributing to sag as the material ages. The strength at high temperature is also an important factor affecting the loading conditions, span lengths, and tower design. This report endeavors to establish the effect of temperature on the high-temperature strength and creep of the composite, and to demonstrate how these properties will affect the performance of the overhead conductor.

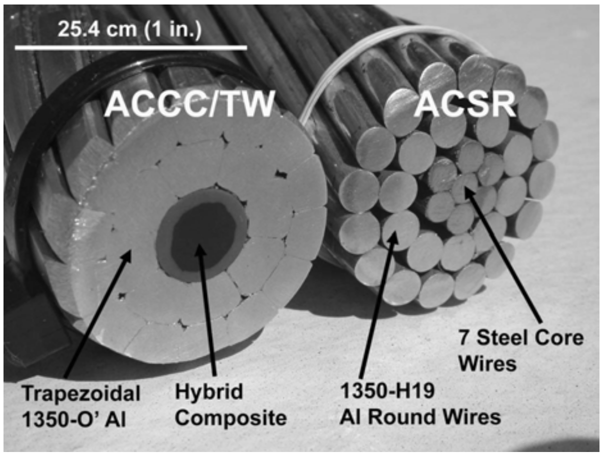

Figure 1. Comparison of the ACCC/TW to ACSR Drake.

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2 Technical Work preparation

A. Materials

The conductor core is a pultruded composite rod composed of an epoxy matrix reinforced with high-strength carbon fibers surrounded by a shell of boron-free E-glass fibers, as shown in Figure 2. The diameter of the composite core varies with the size of the conductor. Different proprietary epoxy formulations were developed and evaluated, each exhibiting different thermal characteristics that affected the composite mechanical properties [2]. One epoxy formulation, with a glass transition temperature (T_g) of 202ºC [2], was selected for evaluation with respect to composite creep and high-temperature strength. Since this report was written, a new formulation has been developed and is presently used in production which exhibits a T_g of 215°C, an exhibits improved mechanical properties [15, 16].

B. Experimental Methods

1) High Temperature Tensile Testing: Composite tensile strength was measured in air at temperatures between 25º and 250ºC. The composite samples were mounted in custom-made gripping fixtures to perform the tests [7]. Details of the tensile testing parameters have been reported [2], and are briefly described here. The gauge section of the composite was wrapped with heating tape and heated for 15 to 30 minutes prior to testing at the prescribed temperature. The samples were placed in a load frame (SATEC 135HVL 534 kN/120,000 lbf), then preloaded to 4.5 kN and held for 5 minutes to allow the load to redistribute between the epoxy cone and the composite strands inside the gripping fixture. After 5 minutes, load was increased at a constant crosshead speed of 5 mm/min (0.20 in./min.) and pulled to failure, as specified in ASTM Standard D3916, which was developed for testing reinforced plastic rods [17]. Extended thermal exposures were achieved by heating the composite at 150°C for 1 week prior to tensile testing at room temperature or 150°C, and the retained strength at these temperatures was determined.

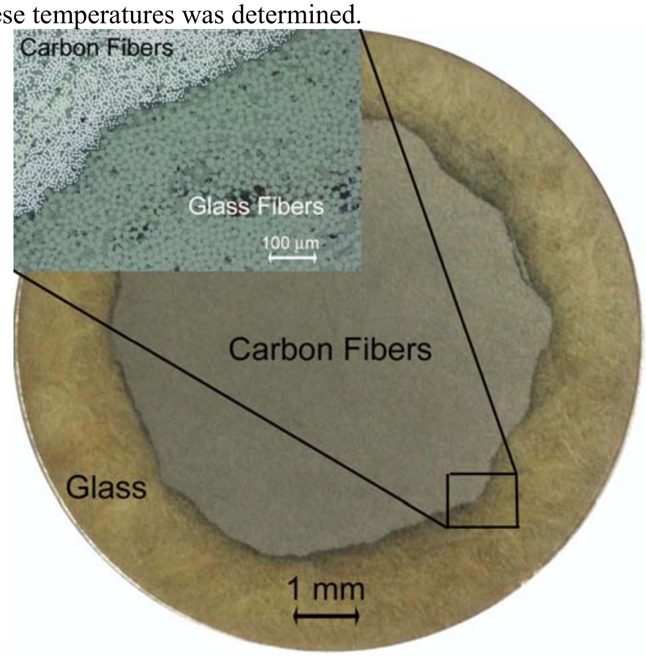

Figure 2. ACCC/TW composite core showing the carbon composite in the center and the glass composite shell around it (Drake size, diameter = 9.53 mm (0.375 in). The inset shows a magnified view of the glass/carbon fiber interface [2].

2) Dynamic Mechanical Analysis-Glass Transition and Thermal Cycling: Dynamic mechanical analysis (DMA) was performed using a dual cantilever beam clamp in a commercial instrument (TA Instrument DMA2980). The sample was clamped at both ends and in the middle of the sample. Cyclic load was applied to the beam midpoint to achieve a fixed amplitude as the temperature was increased. The stiffness (storage modulus) and the lag time between the maximum strain and the maximum force (tan δ) was calculated and recorded as a function of temperature. The composite samples were rectangular beams with approximate dimensions of 50 mm × 4 mm × 1.6 mm, and were sectioned from the carbon fiber core. Cyclic displacements of 20 μm amplitude were applied with a frequency of 1 Hz. (Larger displacements would have risked exceeding the maximum load capacity of the instrument (18 N)). The samples were heated to 250°C at a rate of 5°C/min. The glass transition temperatures (T_g) of the composite was determined from the peak in the tan δ curve. For cyclic heating tests, samples were heated to 250°C, then cooled to 45°C, and the process was repeated several times.

3) Creep of the Composite: Creep of the composite was also measured by DMA using the dual cantilever beam clamp on rectangular samples 50 mm × 1.6 mm × 0.5 mm sectioned from the carbon fiber core. The procedure used for determining creep is described by Abdel-Magid and Gates, who compared DMA measurements of creep to conventional tensile and compression creep experiments [18]. Short-term creep was measured between 150°C and 225°C in steps of 15°C. For each temperature, a stress of 600 MPa was applied for 20 minutes, followed by 20 minutes without load for recovery. Long-term creep behavior was determined by the principle of Time-Temperature-Superposition (TTS) using commercial software (TA Instruments, TTS Rheo Advantage Data Analysis). The short-term creep measurements were shifted in time around a reference temperature (T_o). Shift factors (log a_T) were determined for each short-term creep curve and were used to generate an approximate long-term creep curve for the time and temperature ranges of interest [10, 18, 19]. Creep rates (given in either year^{-1} or sec^{-1}) were calculated by determining the change in the strain between 1000 and 100,000 hours. The DMA instrument affords exceptional accuracy for measuring strain (displacements of 1 nm can be detected), exceptional control of test environment (temperatures and atmospheres), and convenience relative to conventional creep measurement techniques.

3 Results and Discussion

A. Effect of Temperature on the Strength of the Composite: Temperature affected the strength of the composite core for the ACCC/TW. The room-temperature strength was retained to temperatures of ~170°C, as shown in Figure 3. Above 170°C, the strength dropped and reached a plateau at temperatures above T_g (202ºC). The decrease in strength was attributed to (1) the phase change in the matrix, which degraded the elastic properties and (2) diminished interface adhesion, and their affect on the composites strength is discussed in [2].

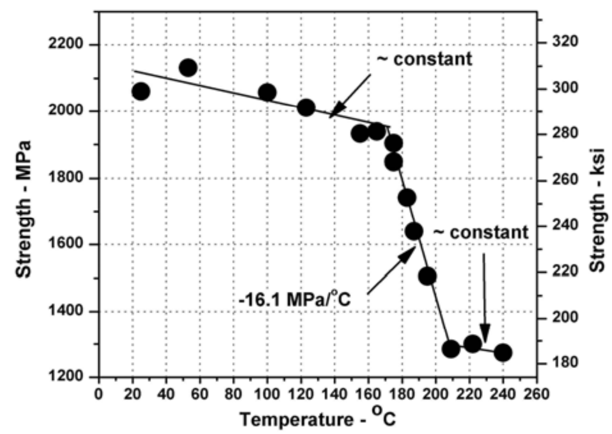

Figure 3. Effect of test temperature on tensile strength of composite core.

The effect of thermal exposure on tensile strength was investigated by heating samples to 150°C for 1 week prior to tensile testing. Samples subsequently tested at room temperature showed no decrease in tensile strength. Samples subsequently tested at 150ºC showed virtually the same strength as samples tested at 150ºC without prior thermal exposure. Thus, thermal exposure at 150°C appeared to have no significant effect on retained tensile strength.

DMA experiments were performed to detect possible chemical degradation of the matrix during cyclic heating. Previous reports have shown that the temperature dependence of the storage modulus (as measured by DMA) shows a close resemblance to the temperature dependence of tensile strength in unidirectional composites [2]. The storage modulus is primarily a reflection of the stiffness of the sample [20]. Thus, because the matrix softens with increasing temperature, the storage modulus also decreases, as shown in Figure 4. If matrix degradation were to result from thermal cycling, a shift in the T_g to lower temperatures would be expected. As the sample is heated beyond T_g, the tan δ curves, defined as the ratio of the imaginary (loss) modulus to the storage modulus [20], shows no shift in T_g, and the storage modulus is unchanged by the cyclic heating. (The difference between the heating curves (upper) and the cooling curves (lower) in Figure 4 is caused by the different rates of heating and cooling.) Thus, the matrix does not undergo a chemical change or breakdown that adversely affects the long-term strength, leaving only the two mechanisms discussed previously as possible causes for the observed strength loss at higher temperatures.

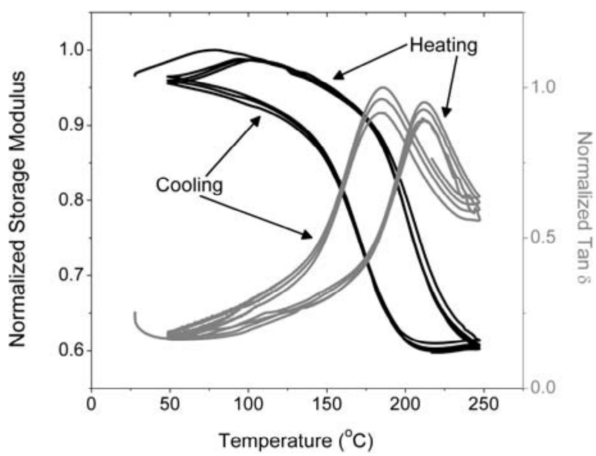

Figure 4: Normalized storage modulus and tan δ versus temperature for multiple heat cycles.

B. Creep: Two phenomenon cause permanent elongation of overhead conductors. After a heavy loading event occurs and the stresses are reduced, the conductor elongation will follow a curve parallel to the final unloading curve of the conductor and never return to its original length. Also, when the conductor is under a constant stress for a long period of time, the conductor will also elongate and is called creep elongation. In bimetallic conductors, load is shared between the Al strands and the steel core, and the temperature of the conductor will dictate the rate of creep. As the temperature rises, Al experiences less stress and the load is shifted to the steel core until a certain temperature at which all the load is carried by the core alone, called the "knee point" temperature [21]. At the knee point temperature and above, the elongation and sag are virtually dictated by the core. The knee point temperature of a service conductor can typically shift to higher temperatures depending on the pre-stresses and the amount of elongation the conductor has experienced. For a Drake ACSR conductor, the knee point temperature is typically around 75° to 90°C, and thus are operated at temperatures above and below the knee point.

Like the ACSS, the core of ACCC/TW is intended to carry the entire load at all operating temperatures. Figure 5 shows the tension vs. sag curve for Drake ACCC/TW. No pre-stress was applied to the ACCC/TW, only brought to 25% of it RTS before making the tension/sag measurements. The knee point is observed to be between 40° and 60°C, vs. ~75-90°C for ACSR, and is due to the use of tempered Al in the former and hardened Al in the latter. While the knee point appears low for the ACCC/TW, pre-stressing to higher tensions and then reducing the load could also raise the knee point temperature. But, due to the "dead soft" properties of the tempered Al used in ACCC/TW and ACSS, it is the creep of the cores that will dictate the overall high temperature creep properties of these conductors. The creep rate of the ACCC/TW core should be time-dependent, because the matrix is a viscoelastic material. Thus, at high temperatures, particularly near T_g, the core may exhibit non-linear behavior, leading to complications in predicting the long-term performance of the conductor [22].

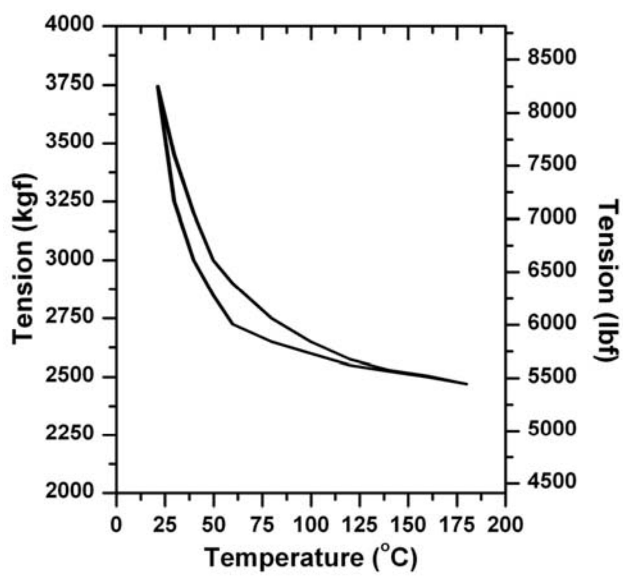

Figure 5. Tension versus temperature curve for Drake ACCC/TW [23].

Figure 6 shows short-term creep curves measured using the procedure discussed in section II B Creep of Composites. For test temperatures of 180°C and below, creep strains were extremely small, corresponding to creep rates of ~10^{-11} sec^{-1}. The short-term creep curves at 195°C and 210°C exhibited greater strains over time, corresponding to creep rates on the order of 10^{-11} sec^{-1} and $2x10^{-11}$ sec^{-1} respectively. The increase in creep strains at temperatures near T_g, is attributed to matrix softening, which accelerates load relaxation [22].

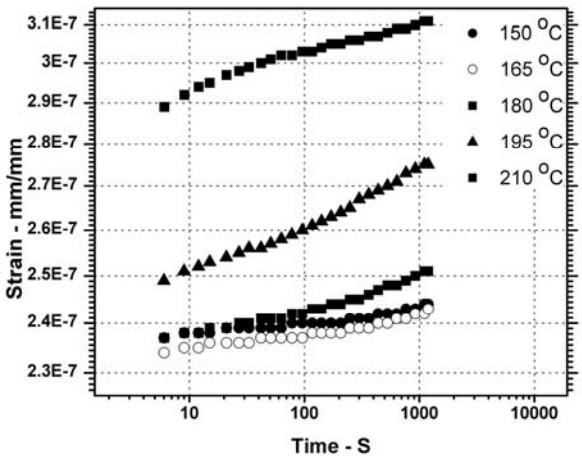

Figure 6. Short-term creep data for carbon core at 600 MPa.

Long-term creep behavior was calculated from the short-term creep curves using the TTS principle, as described in section II B Creep of Composites. First, shift factors were calculated for each short-term creep curve using a reference temperature (T_o) of 150ºC. The shift factors, shown in Figure 7, follow the William, Landel & Ferry (WLF) equation, given by [24]:

$$Log\ a_T = \frac{-C_1(T-T_0)}{(C_2+T-T_0)} \quad (1)$$

The coefficients yielding the best fit were determined to be $C_1 \approx 2.54x10^7$, $C_2 \approx 2.72x10^8$ at T_o = 150 °C. Master creep curves then were plotted on a logarithmic time scale to predict the long-term creep behavior, as shown in Figure 8. The curves show long-term creep strain and creep compliance, based on a reference temperature of 150°C. The long-term creep was then fitted with a power law equation given by:

$$\varepsilon_c = At^n \quad (2)$$

where ε_c is the creep strain of the composite, A (μm/mm) is the Y-axis intercept at the first hour, t is the time in hours, and n is the time exponent, which represents the slope of the power law curve. Using least squares fitting, the power law equation was determined to be:

$$\varepsilon_c = 0.2395t^{0.015} \quad (3)$$

The time exponent (n) was extremely small, which is consistent with the observed low creep strains over long periods.

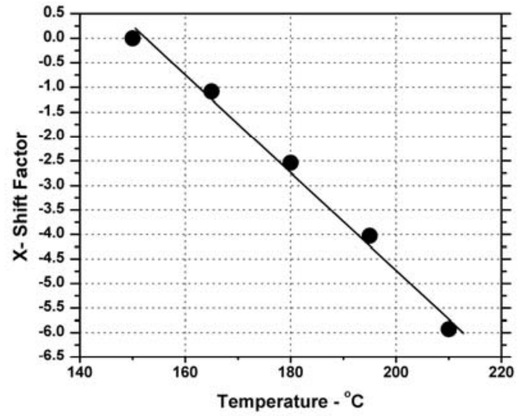

Figure 7. Shift factors following WLF model.

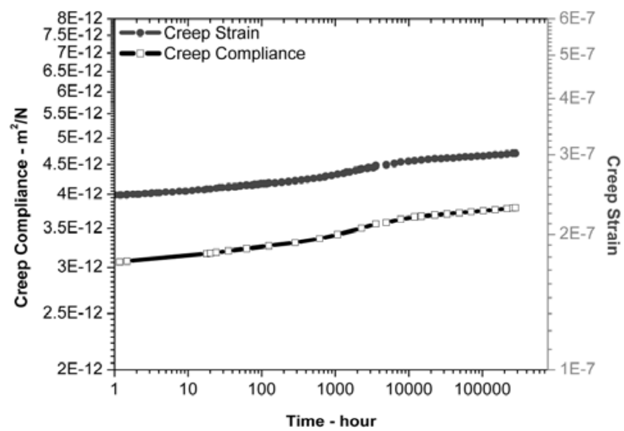

Figure 8. TTS curves for long-term creep behavior based on creep data at 150°C.

The creep rates for the composite core can be ascertained from the master creep curves shown in Figure 8. Therefore, at 150ºC and 600 MPa, the creep rate expected for the composite core is on the order of $1.5x10^{-9}$ $year^{-1}$ ($4.7x10^{-17}$ sec^{-1}). This creep rate is extremely small, and is impossible to detect using conventional extensometry. This is not surprising, however, as reports indicate that creep rates in carbon fiber composites are negligible under these conditions [25]. While these rates and strains are difficult to measure, the present results are nevertheless consistent with creep rates reported for similar composites [18, 26].

In contrast to the composite core, the creep rate for a steel core subjected to 430 MPa at 125ºC was determined to be ~$4.1x10^{-5}$ $year^{-1}$ ($1.3x10^{-12}$ sec^{-1}), measured between 10,000 and 100,000 hours [27].

This is approximately 4 orders of magnitude greater than the predicted creep rate of the composite core. When a power law was fitted to the creep strain of the ACSR conductor, the equation was determined to be:

$$\varepsilon_c = 300t^{0.125} \quad (4)$$

The large difference in the creep rates and the time exponent for the steel and composite cores was attributable to the large initial strain occurring between 0 and 1000 hours for steel creep. For the ACSR conductor steel, the strain in the first hour was 200-300 microstrain, which is attributed to strand settling [27]. In contrast, the creep strain for the carbon fiber core in the first hour was 0.24 microstrain, as shown in Figure 8.

The tensile creep of the entire ACCC/TW conductor was also measured. The conditions selected were room temperature and a stress of 62.4 MPa, corresponding to 25% rated tensile strength (RTS) [28]. Figure 9 shows the creep strain versus time for Drake ACCC/TW and Drake ACSR tensioned to 20% of its RTS. The creep was measured for 1000 hours, and a power law equation (Eq. (2)) was fitted to extrapolate the creep out to 100,000 hours for both conductors. For the ACCC/TW, the Y-intercept constant, A, was 30.65 microstrain, and the time exponent was 0.2392. These results are inconsistent with the creep data obtained for the composite core alone. The apparent discrepancy stems from the fact that the aluminum wires contribute to the room-temperature creep behavior. In fact, the strain contribution from the aluminum wires is greater than the creep of the composite core because the area of the aluminum (516.9 mm^2) is approximately 8 times the area of the composite core (71.3 mm^2). The aluminum relaxes under load, and eventually sheds load to the composite core. Therefore, the measured displacement is not pure creep elongation, but involves both elastic and plastic strain in the aluminum wires.

The data in Figure 9 allow a comparison of the creep of the steel-core and composite-core conductors at room temperature and similar loading conditions. Based on the power law equation, the creep strain of the composite core conductor (ACCC/TW) at 25°C after the first hour is approximately 30.7 microstrain. This is less than the creep strain of the steel core conductor by about a factor of 2 under approximately the same conditions (25°C and similar load). After approximately 10 years, the predicted creep of ACCC/TW under the conditions described is 500 microstrain. This compares favorably with the creep of steel-core conductors, which under similar conditions, is projected to be approximately 800 microstrain. The similarity in creep trends at 25°C for the ACCC/TW and the ACSR at approximately the same conditions derives from the similar contribution of the aluminum wires.

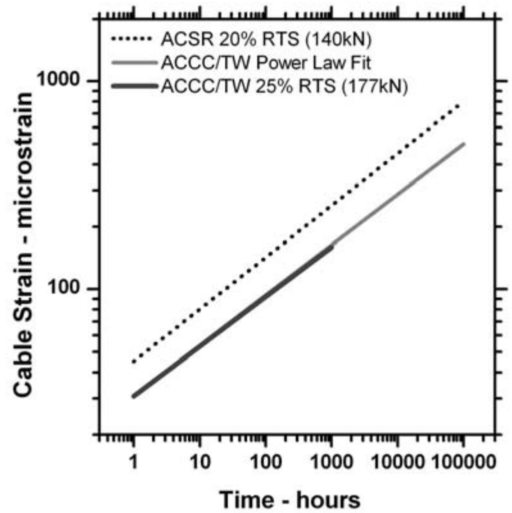

Figure 9. Creep of ACCC/TW conductor at room temperature fitted by Power Law curve and the ACSR creep curve at room temperature. Values in the parentases are the RTS values for each conductor design.

Creep at higher temperatures is expected to be significantly different for the ACCC/TW and ACSR conductors. At high temperatures, the load is carried exclusively by the core, even for ACSR conductor (above ~100°C) as shown in [27]. Thus, creep rates at higher temperatures is controlled by the core, which is distinctly different for the two conductors. Unfortunately, measurements of high temperature creep have not been reported, with the exception of one study with ACSR [27]. The main reasons for the paucity of creep data on conductors is the absence of an accepted standard test (ANSI C119.4 and Aluminum Association standards do not address high temperature creep.) New standards for testing high temperature, low sag conductors are expected within the next year, and creep tests on the ACCC/TW are presently underway using the proposed test protocols. These results will be reported separately, when completed.

C. Mechanical Properties of the Core and the Performance of ACCC/TW: Creep and the ultimate tensile strength at high temperature will affect the thermomechanical performance of the ACCC/TW conductor. For example, when the conductor is in service and under load, the applied tensile load continuously decreases with increasing temperature. This derives from thermal expansion and creep according to the sag/tension relationship, which increases the conductor sag. On the other hand, the tensile strength is essentially constant up to ~170ºC, then decreases at higher temperatures, as shown in Figure 2. At such high temperatures, the probability of failure of the ACCC/TW increases slightly.

Creep can have a profound impact on the sag characteristics of the conductor. For example, for a steel core conductor 305 m (1000 ft) in length subjected to the creep conditions assumed previously (430 MPa at 125ºC), the creep strain after 10 years would produce an additional 0.04% elongation in the conductor, producing an additional ~1500 mm of sag, most of which would occur during the first few years of service. In contrast, the composite core conductor of similar length and under similar conditions would undergo creep strain that would result in ~0.35 mm of additional sag at 150ºC over a 10 year period. These creep strains were determined by extrapolation from short-term creep measurements, and are thus subject to considerable error. Furthermore, the effects of chemical and physical aging of the composite core on the creep rates are presently unknown. Creep rates certainly could be affected by changes in the viscoelastic properties of the composite core. In spite of these uncertainties, the carbon fibers will not creep significantly under relevant conditions, so the impact of these factors on creep may be minimal.

Because of the load shedding that occurs between the aluminum wires and the core as the operating temperature increases, it is instructive to examine the ultimate strength and the applied load as functions of temperature. Figure 10 shows the ultimate tensile strength of the composite normalized to the RTS of the composite as a function of temperature, along with the normalized applied tension on the conductor and the ratio of the applied load to the ultimate tensile strength. The tensile strength of the composite is retained up to ~170°C, and drops to ~65% RTS at 200°C. It is realistic to assume that the ACCC/TW would also exhibit the same strength versus temperature curve, since at high temperatures; the Al wires will not be able to carry any load. Like ACSS, the full strength of the composite core is considered in the overall strength of the conductor, and no derating factor is used, according to ASTM B 857. Between 60° and 180°C, the applied tensile load is ≤20% of the RTS, and the ratio between the ultimate tensile strength and the tension in the line is 0.2 (Figure 10). Over the same temperature range, the strength of the composite rod decreases by only 15% of the RTS. Note however that at extreme temperatures (greater than 180°C), the decline in ultimate strength outpaces the decline in applied tensile load. Thus, the ratio of the tensile load on the conductor to the ultimate tensile strength rises, reaching a maximum of only ~ 0.3 at 220ºC. This low stress ratio is desirable for both operational safety and hardware longevity.

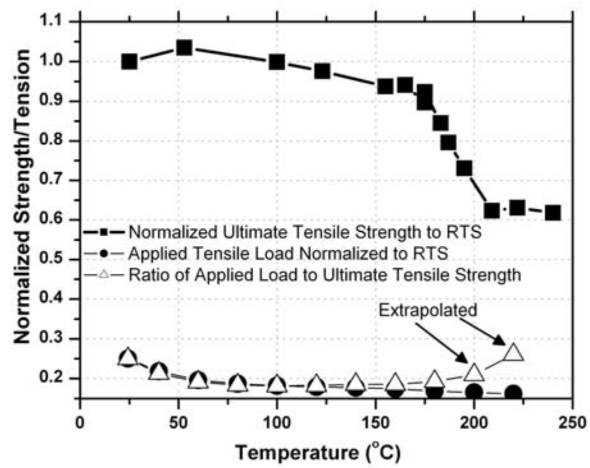

Figure 10. Tension change with temperature compared to strength change with temperature. Points at 200º and 220ºC are extrapolated.

4 Conclusions

The effect of temperature on the strength, creep and thermal cycling behavior was evaluated for a pultruded unidirectional hybrid composite intended for supporting overhead conductors. The ultimate tensile strength of the composite was retained to ~170ºC, than dropped to ~65% of the room temperature tensile strength at temperatures above T_g (202°C). Within the anticipated service temperature range of 100º-180ºC, the strength loss was not significant. Projections indicated that the composite core could withstand anticipated design loads without approaching the allowable design limits presently used for conductors.

Creep of the composite core was negligible at a reference temperature of 150°C and 600 MPa. The increase in sag caused by creep of the composite core under these stress-temperature conditions was only ~0.35 mm at which compared favorably with ~1500 mm for Drake ACSR conductor of the same outer diameter and length at 125°C and 430 MPa. The results highlight the potential for the use of composite cores to support high-temperature low-sag conductors. Of perhaps greater concern at present is the longterm durability of a polymer composite intended for decades of load-bearing service in a wide range of climatic conditions. Accelerated aging studies are presently being conducted to determine the effects of prolonged exposure to temperature, humidity, and other environmental factors on retention of mechanical properties.

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