Citation: INL, "Elevated-Temperature Stress-Strain" in Advanced Conductor Testing: Compilation of Test Results and Summaries, Idaho National Laboratory with Electric Power Research Institute, pp. 130-145, 2025. https://inl.gov/national-security/advanced-grid-solutions/

Elevated-Temperature Stress-Strain Results

Aluminum Zirconium (ACCR) Conductor

This section describes testing results obtained from Southwire ACCR C[7] conductors made of Celanese C[7] core and aluminum zirconium (Al-Zr) trapezoidal wires.

Sample Specific Test Procedure

For the high temperature testing, a current transformer was configured to provide current to increase the temperature of the test sample to 180°C. A 600V variable transformer (Variac) supplied current to the current transformer. The motor-driven Variac was controlled by a data acquisition system to provide the necessary current to increase and maintain the temperature in the sample. Additionally, a capacitor bank was connected to the primary side of the current transformer to balance the impedance of the test sample.

A schematic of the high temperature stress-strain test setup is illustrated in Figure 4-14.

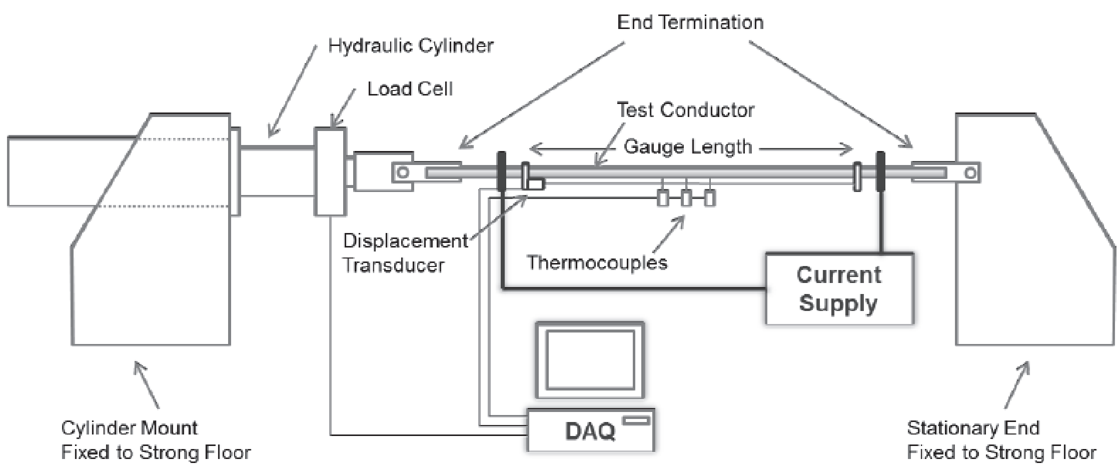

Figure 4-14. Setup for high temperature stress-strain test (schematic)

Photos of the actual Southwire ACCR C^7 samples for the high temperature test installed in the test bed are shown in

Figure 4-15.

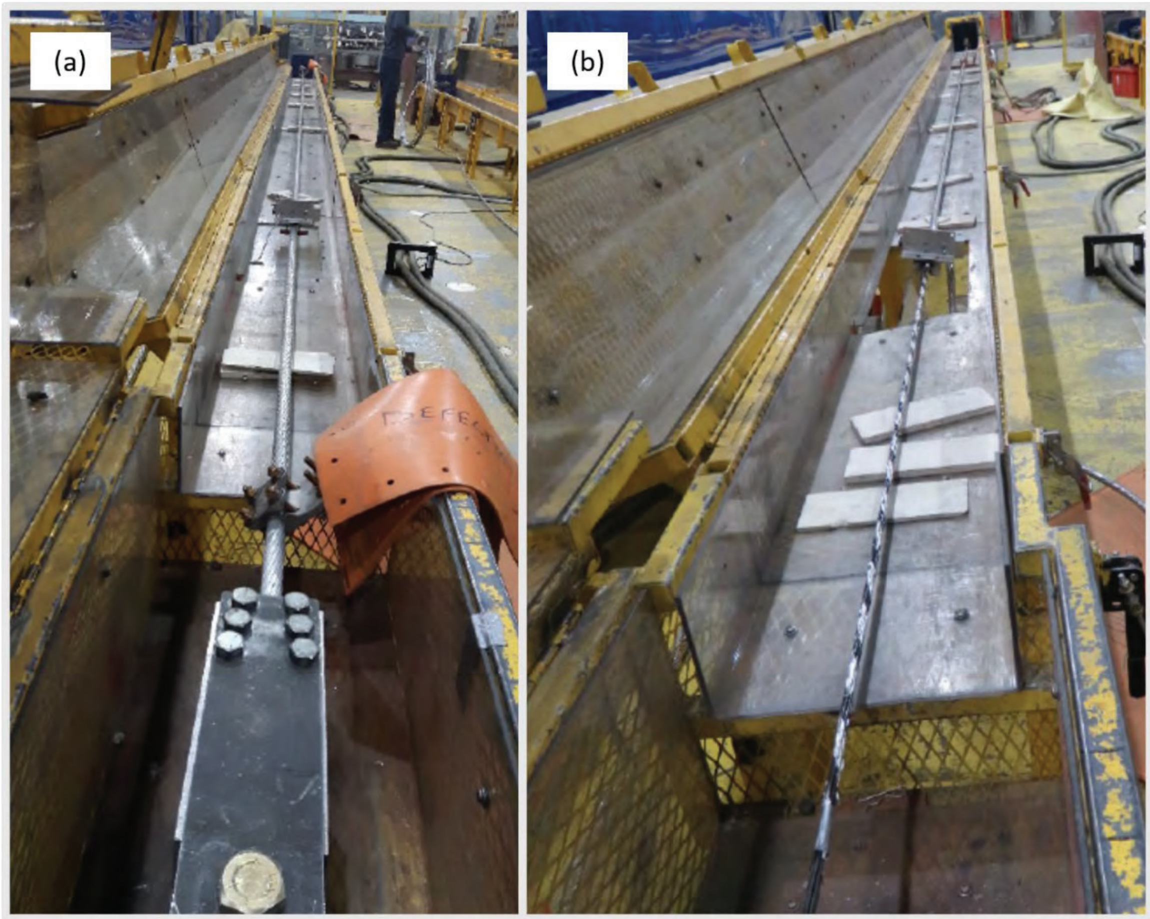

Figure 4-15. (a) Southwire ACCR C^7 conductor and (b) conductor core samples installed for high temperature stress-strain test

For the high temperature test, the Southwire ACCR C^7 conductor's UTS at testing temperature was used in place of the conductor's RBS. The following loading schedules were used when evaluating the Southwire ACCR C^7 whole conductor and core samples at room temperature. The pre-load value (2% of the Southwire ACCR C^7 conductor's UTS at the testing temperature of 180 °C) was 531 pounds, and the loading rate was 3,986 pounds per minute.

Table 4-9. Loading schedule for Southwire ACCR C^7 high temperature whole conductor sample

Whole Conductor HT UTS = 26,570 lb (118.2 kN)				
Step	% HT UTS	Load		Hold, minutes
		lb	kN	
Preload	2%	531	2.36	-
1	30%	7,971	35.5	30
2	2%	531	2.36	1
3	50%	13,285	59.1	60
4	2%	531	2.36	1
5	70%	18,599	82.7	60
6	2%	531	2.36	1
7	85%	22,585	100.5	60
8	2%	531	2.36	1

Table 4-10. Loading schedule for Southwire ACCR C^7 high temperature core sample

Step	Elongation		Hold, minutes
	inch	mm	
Preload	-	-	-
1	1.073	27.26	30
2	-	-	1
3	1.351	34.31	60
4	-	-	1
5	1.863	47.33	60
6	-	-	1
7	2.543	64.60	60
8	-	-	1

Test Results

The strain data for the Southwire ACCR C^7 conductor and core samples has been corrected because the elongation measurement was taken to be zero at the pre-load value. The samples would have zero strain only when under zero tension, so this adjustment was necessary. Using a straight-line regression of the stress-strain data during step 1 of loading, the corrected strain at pre-load for the Southwire ACCR C^7 conductor and core samples was 0.0326% and 0.0457%, respectively.

Stress plotted against strain for the Southwire ACCR C^7 whole conductor and core sample is shown in Figure 4-16 and Figure 4-17 respectively. The points contributing to the stress-strain curve are taken at the end of each hold period as described in IEC 61089, Annex B. The difference in strain from the beginning and end of the stress-strain test is smaller than for the room temperature tests. The high temperature strain after the first loading (step 1 in Table 4-12) is nearly double the room temperature strain (nearly 0.40% compared to slightly above 0.20%). The high temperature strain after the second loading (step 3) is slightly higher than the room temperature strain. However, with each subsequent loading cycle, the strain on the high temperature sample is less than that of the room temperature sample. This may be due to increased difficulty in maintaining tension as the conductor experiences high temperature sag. The stress on the Southwire ACCR C^7 conductor at each step is also lower than for the room temperature ACCR test.

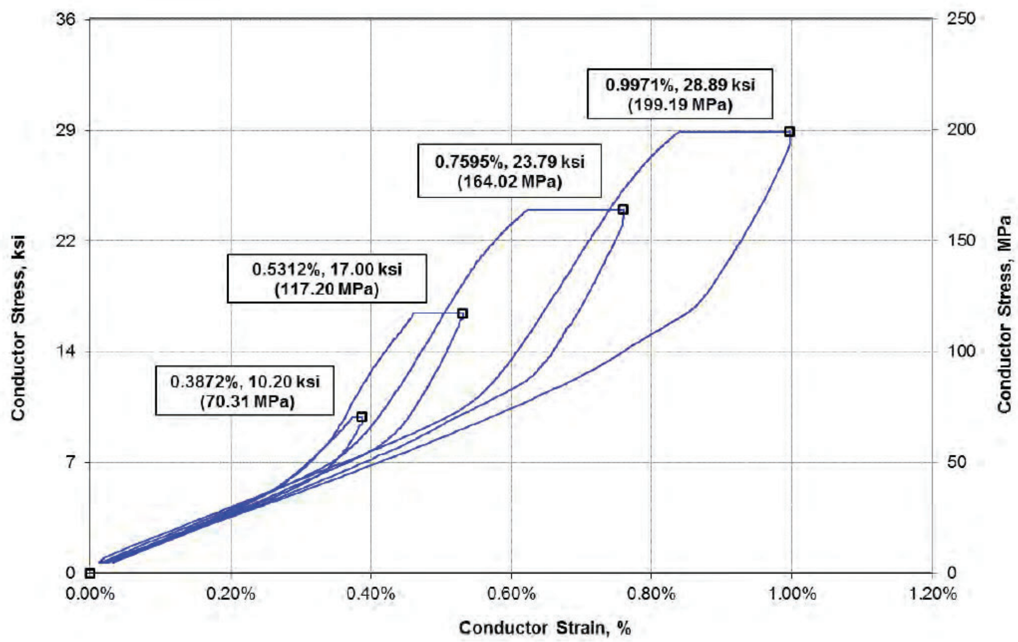

Figure 4-16. Stress vs. conductor strain during Southwire ACCR C^7 high temperature stress-strain test

The Southwire ACCR C^7 conductor core deformation is more elastic than the whole conductor, but it is more plastic than at room temperature. This suggests that the glass transition temperature T_g of the carbon-fiber composite (C^7) core is below the testing temperature of 180 °C. Raising the temperature of the core above its T_g allows its molecules to move more freely, resulting in a softer, more flexible material. It may have a lower strength, but it is also less brittle.

The Southwire ACCR C^7 core evaluated at high temperature experiences lower stress and lower strain values at each step compared to room temperature, except for step 1 and 3. Again, in step 1, the strain for the high temperature sample is higher. In step 3, the strain for the two tests is similar.

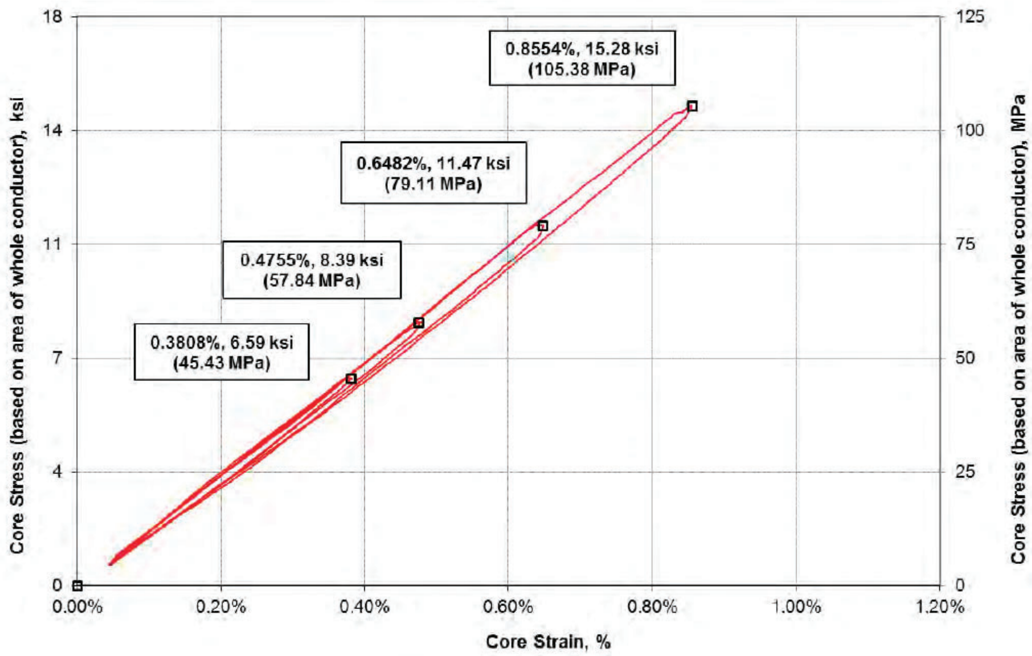

Figure 4-17. Stress vs. core strain during Southwire ACCR C^7 high temperature stress-strain test

The modulus of elasticity (MOE) can be obtained from the slope of the unloading segment from the last hold for the Southwire ACCR C^7 whole conductor and core, respectively. The MOE of the aluminum layers is calculated by subtracting corresponding data points of the Southwire ACCR C^7 whole conductor and core. The MOE of the Southwire ACCR C^7 whole conductor was found to be 8,192 ksi, whereas the MOE of the conductor core was found to be 1,854 ksi. The MOE of the whole Southwire ACCR C^7 conductor at high temperature is 1,890 ksi lower than at room temperature. The MOE of the cores is similar regardless of testing temperature.

The best fit curve of the data points gathered at the end of each hold period was a 3rd order polynomial, instead of the 4th order polynomial fit to the room temperature Southwire ACCR C^7 data. For this reason, the a_4 coefficient from Equation 4-1 was set to zero, resulting in the following equation:

Equation 4-2. General form of the stress-strain curve for the high temperature ACCR test

$$y = a_3x^3 + a_2x^2 + a_1x + a_0$$

where

y (MPa) is stress

x (%) is strain

a_3, a_2, a_1, a_0 (MPa) are the coefficients of the stress-strain polynomial

The stress-strain curve calculated from the gathered data for T13 ZTACCR/TW/C^7 components is shown in Figure 4-18.

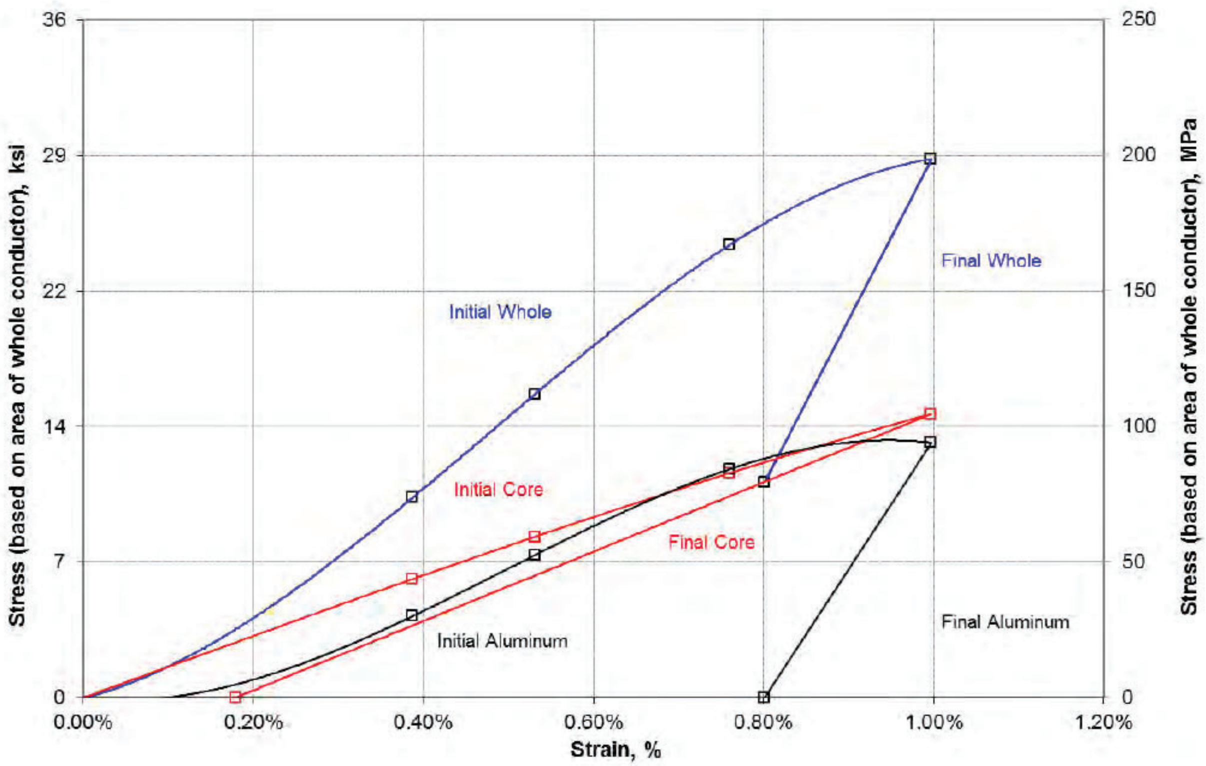

Figure 4-18. Stress-strain curve at 180 °C for T13 ZTACCR/TW/C[7] (Southwire ACCR C[7]) conductor

The calculated MOE and coefficients of the stress-strain polynomial are shown Table 4-11. The values for the aluminum components of the Southwire ACCR C^7 conductor are found by subtracting the core from the whole conductor.

Table 4-11. Summary of Southwire ACCR C[7] high temperature stress-strain test results

Value	Whole Conductor		Core Only		Aluminum Only	
	ksi	MPa	ksi	MPa	ksi	MPa
a_4 (x^4)	0.00	0.00	0.00	0.00	0.00	0.00
a_3 (x^3)	-39.11	-269.66	-1.49	-10.28	-37.62	-259.38
a_2 (x^2)	56.11	386.88	0.17	1.14	55.95	385.74
a_1 (x)	11.86	81.74	16.53	113.96	-4.67	-32.22
a_0	-0.04	-0.28	0.00	-0.01	-0.04	-0.27
MOE based on Area of Conductor	8,192	56,484	1,854	12,780	6,339	43,704
MOE based on Area of Component	N/A	N/A	14,033	96,752	7,303	50,355

Tension plotted against time for the Southwire ACCR C[7] whole conductor sample is shown in Figure 4-19. The conductor broke at 30,584 lb. (136.0 kN). The failure occurred near the center of the effective sample length as shown in Figure 4-20.

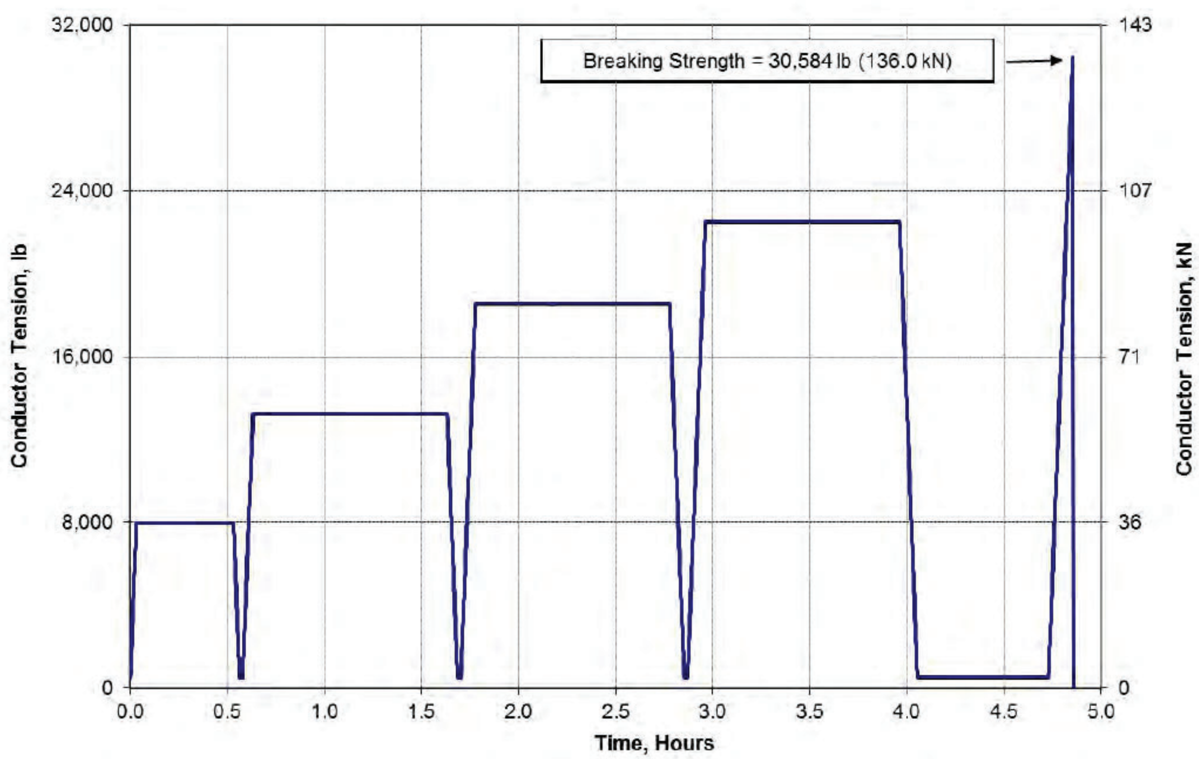

Figure 4-19. Loading history for the Southwire ACCR C[7] high temperature stress-strain test

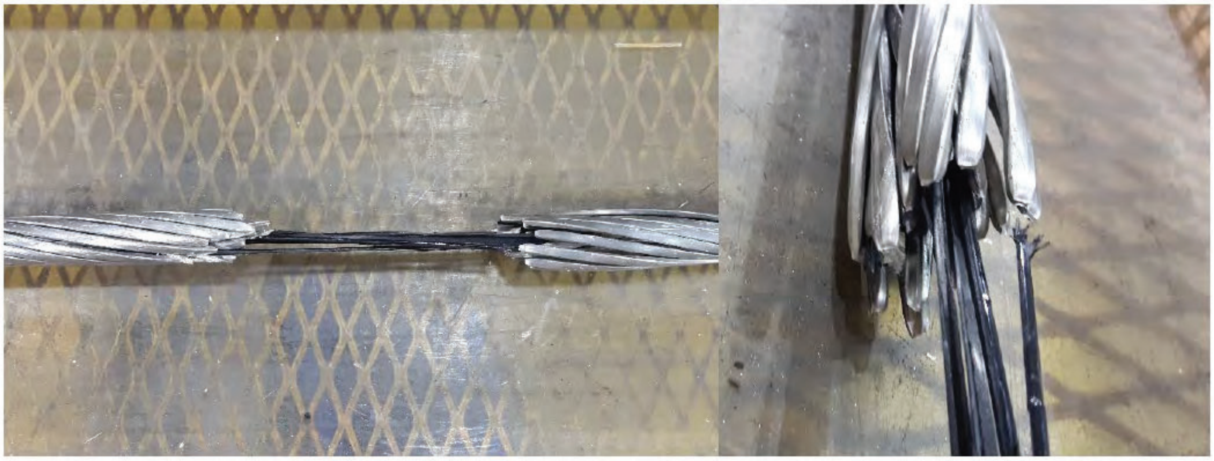

Figure 4-20. T13 ZTACCR/TW/C^7 (Southwire ACCR C^7) conductor at failure location for high temperature test

O-Temper Aluminum (ACCS) Conductor

This section contains results from testing Southwire ACCS C^7 conductors made of Celanese C^7 core and annealed aluminum (1350-O) trapezoidal wires.

Sample Specific Test Procedure

For the high temperature test, the conductor's UTS at testing temperature was used in place of the Southwire ACCS C^7 conductor's RBS. The following loading schedules were used when evaluating the Southwire ACCS C^7 whole conductor and core samples at room temperature. The pre-load value (2% of the conductor's UTS at the testing temperature of 180 °C) was 670 pounds, and the loading rate was 5,024 pounds per minute.

Table 4-12. Loading schedule for Southwire ACCS C^7 high temperature whole conductor sample

Whole Conductor HT UTS = 22,890 lb (101.8 kN)				
Step	% HT UTS	Load		Hold, minutes
		lb	kN	
Preload	2%	458	2.04	-
1	30%	6,867	30.55	30
2	2%	458	2.04	1
3	50%	11,445	50.91	60
4	2%	458	2.04	1
5	70%	16,023	71.27	60
6	2%	458	2.04	1
7	85%	19,456	86.54	60
8	2%	458	2.04	1

Table 4-13. Loading schedule for Southwire ACCS C^7 high temperature core sample

Step	Elongation		Hold, minutes
	inch	mm	
Preload	-	-	-
1	1.218	30.93	30
2	-	-	1
3	1.716	43.59	60
4	-	-	1
5	2.320	58.92	60
6	-	-	1
7	2.769	70.33	60
8	-	-	1

Test Results

The strain data for the Southwire ACCS C^7 conductor and core samples has been corrected because the elongation measurement was taken to be zero at the pre-load value. The samples would have zero strain only when under zero tension, so this adjustment was necessary. Using a straight-line regression of the stress-strain data during step 1 of loading, the corrected strain at pre-load for the Southwire ACCS C^7 conductor and core samples was 0.0317% and 0.0363%, respectively.

Stress plotted against strain for the Southwire ACCS C^7 whole conductor and core sample is shown in Figure 4-21 and Figure 4-22 respectively. The points contributing to the stress-strain curve are taken at the end of each hold period as described in IEC 61089, Annex B. The difference in strain from the beginning and end of the stress-strain test is smaller than for the room temperature tests. The high temperature strain after the first loading (step 1 in Table 4-9) is somewhat higher than the room temperature strain at the same step (0.43% compared to 0.39%). However, with each subsequent loading cycle, the strain on the high temperature sample is less than that of the room temperature sample. This may be due to increased difficulty in maintaining tension as the conductor experiences high temperature sag. The stress on the Southwire ACCS C^7 conductor at each step is also lower than for the room temperature ACCS test.

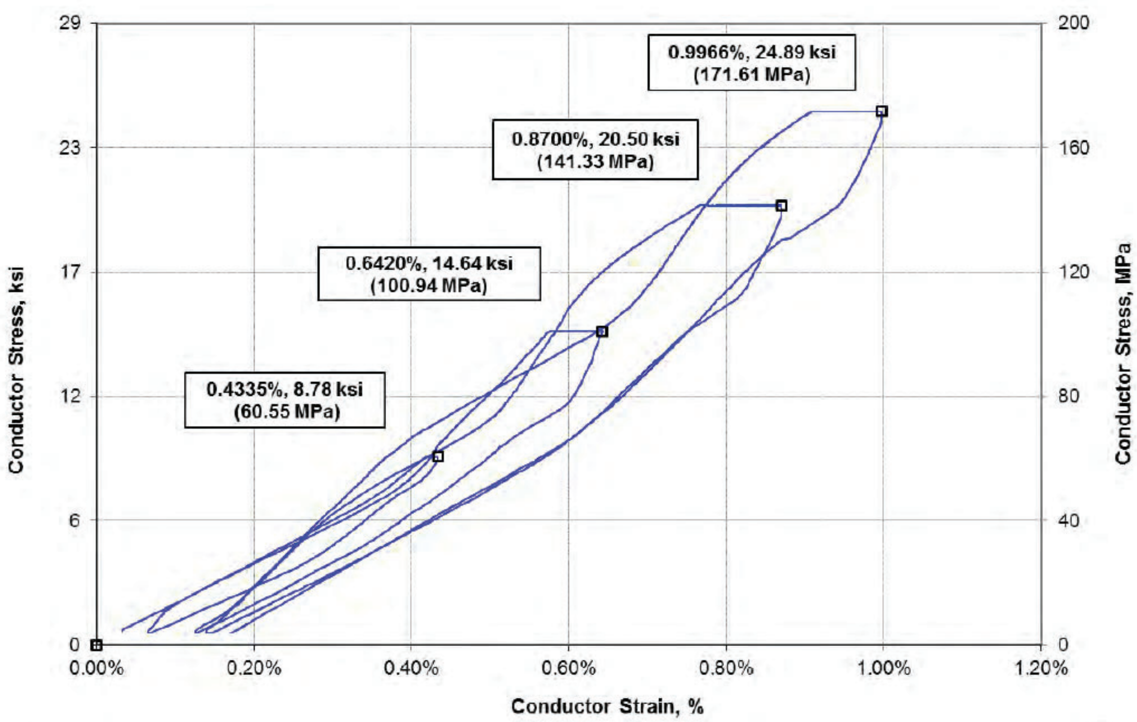

Figure 4-21. Stress vs. conductor strain during Southwire ACCS C^7 high temperature stress-strain test

The Southwire ACCS C^7 conductor core deformation is more elastic than the whole conductor, but it is more plastic than at room temperature. This suggests that the glass transition temperature T_g of the carbon-fiber composite (C^7) core is below the testing temperature of 180 °C. Raising the temperature of the core above its T_g allows its molecules to move more freely, resulting in a softer, more flexible material. It may have a lower strength, but it is also less brittle.

The Southwire ACCS C[7] core evaluated at high temperature experiences lower stress and strain values at every step compared to room temperature, except for in step 1. There, the stress and strain measured for the high temperature sample is higher than at room temperature.

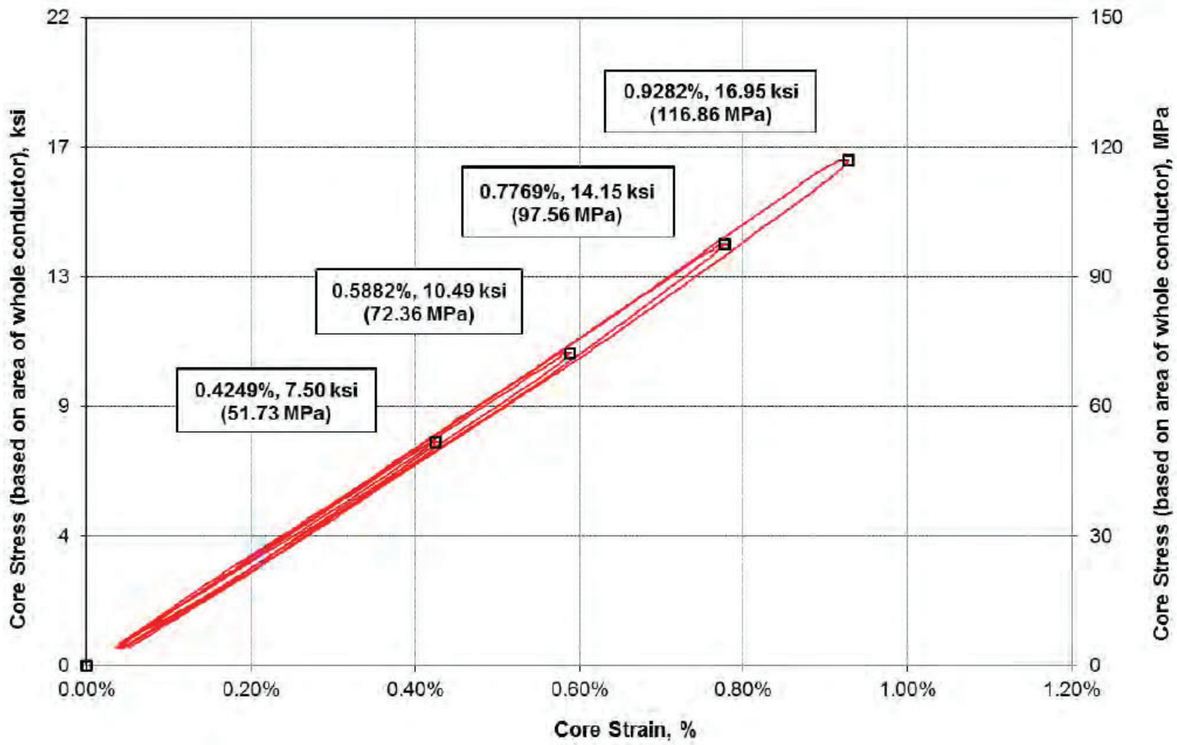

Figure 4-22. Stress vs. core strain during Southwire ACCS C[7] high temperature stress-strain test

The modulus of elasticity (MOE) can be obtained from the slope of the unloading segment from the last hold for the Southwire ACCS C[7] whole conductor and core, respectively. The MOE of the aluminum layers is calculated by subtracting corresponding data points of the Southwire ACCS C[7] whole conductor and core. The MOE of the Southwire ACCS C[7] whole conductor was found to be 7,720 ksi, whereas the MOE of the conductor core was found to be 1,868 ksi. The MOE of the whole Southwire ACCS C[7] conductor at high temperature is 1,518 ksi lower than at room temperature. The MOE of the cores is similar regardless of testing temperature. The strength of the Southwire ACCS C[7] conductor at high temperature is lower than that of the ACCR conductor, since the annealed aluminum used to strand ACCS is softer and less brittle than the aluminum-zirconium alloy in ACCR.

Equations for the stress-strain behavior of each sample were generated from a 3rd order least-squares curve-fit polynomial of the data points at the end of each hold period. The equation took the same general form as Equation 4-2.

The stress-strain curve calculated from the gathered data for T13 ACCS/TW/C[7] components is shown in Figure 4-23.

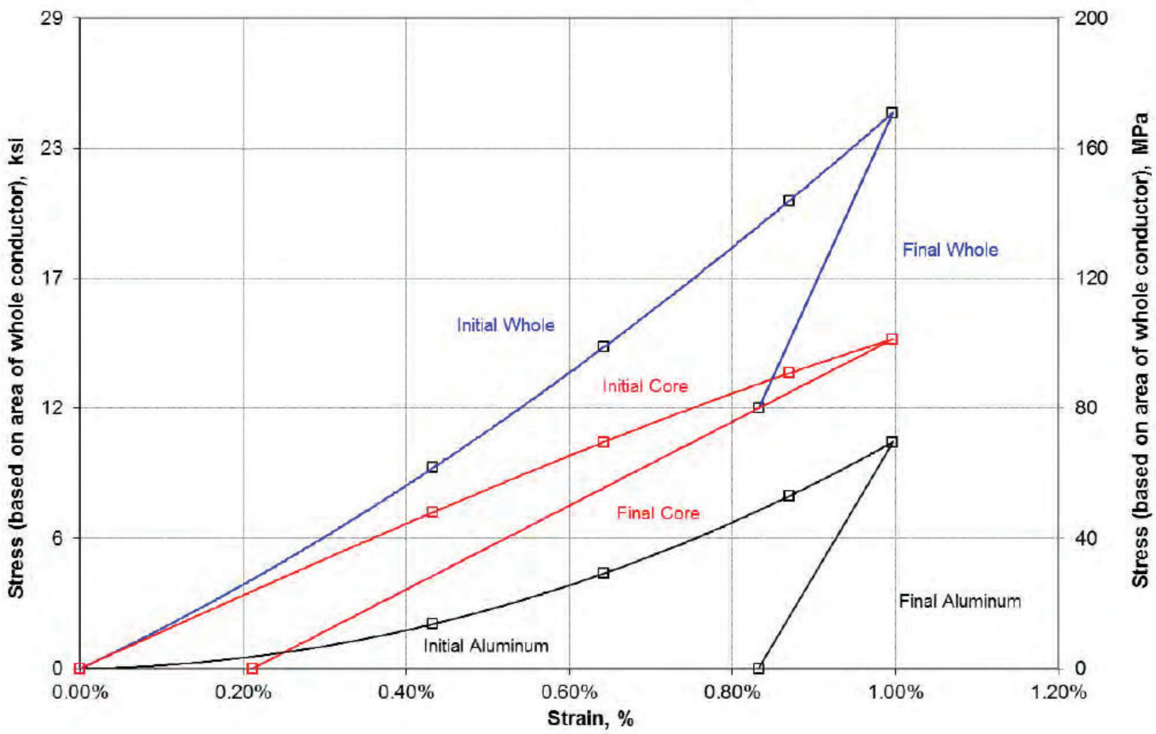

Figure 4-23. Stress-strain curve at 180 °C for T13 ACCS/TW/C^7 (Southwire ACCS C^7) conductor

The calculated MOE and coefficients of the stress-strain polynomial are shown Table 4-14. The values for the aluminum components of the Southwire ACCS C^7 conductor are found by subtracting the core from the whole conductor.

Table 4-14. Summary of Southwire ACCS C[7] high temperature stress-strain test results

Value	Whole Conductor		Core Only		Aluminum Only	
	ksi	MPa	ksi	MPa	ksi	MPa
a_4 (x^4)	0.00	0.00	0.00	0.00	0.00	0.00
a_3 (x^3)	-1.06	-7.31	-1.79	-12.34	0.73	5.03
a_2 (x^2)	8.92	61.52	0.16	1.13	8.76	60.39
a_1 (x)	17.01	117.25	16.33	112.56	0.68	4.68
a_0	-0.02	-0.11	0.00	0.01	-0.02	-0.12
MOE based on Area of Conductor	7,720	53,228	1,868	12,882	5,852	40,347
MOE based on Area of Component	N/A	N/A	14,144	97,521	6,742	46,487

Tension plotted against time for the Southwire ACCS C[7] whole conductor sample is shown in Figure 4-24. The Southwire ACCS C[7] conductor broke at 27,992 lb. (124.5 kN). The failure occurred near the center of the effective sample length as shown in Figure 4-25.

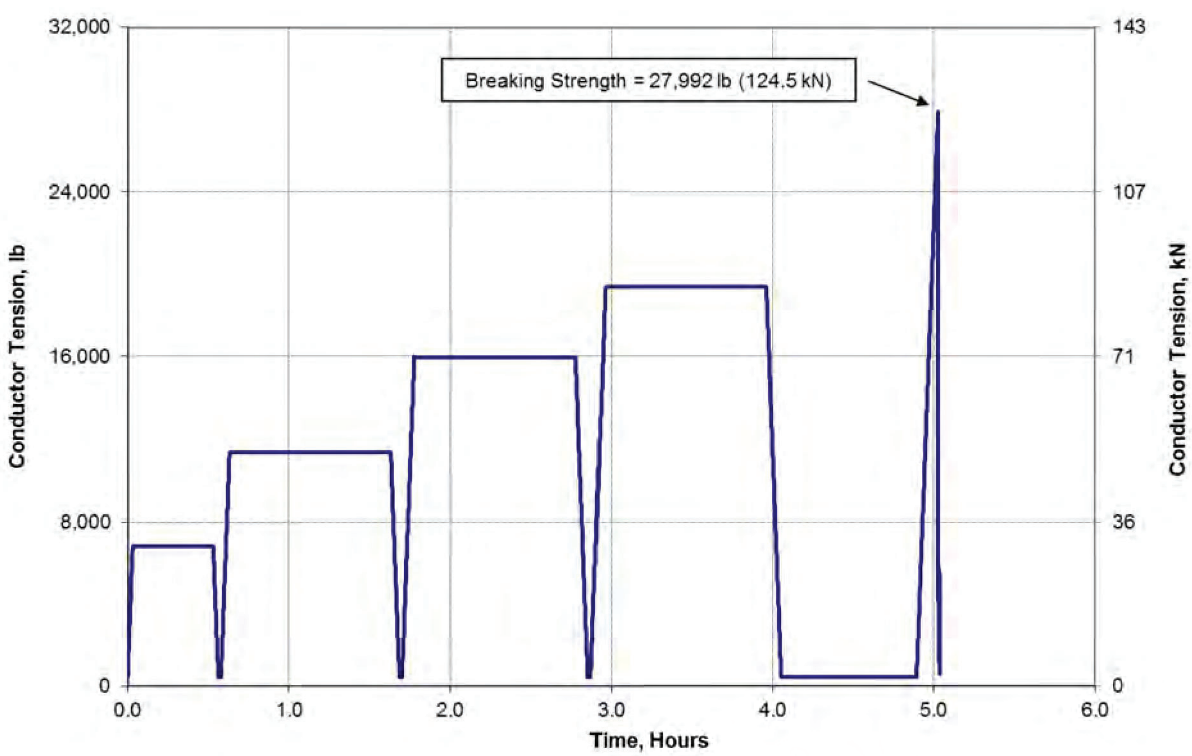

Figure 4-24. Loading history for the Southwire ACCS C[7] high temperature stress-strain test

Figure 4-25. T13 ACCS/TW/C^7 (Southwire ACCS C^7) conductor at failure location for high temperature test

Conclusion

The objective of the stress-strain tests is to determine the stress-strain characteristics of the Southwire T13 ZTACCR/TW/C^7 and T13 ACCS/TW/C^7 conductors at ambient temperature and at a maximum temperature of 180 °C. The data from these tests may be used to assist in the calculation of sags and tensions during the design of overhead transmission lines.

Stress-strain data from an 8-step loading schedule was used to develop best-fit equations for the behavior of each sample evaluated.

In Figure 4-26, the 4th order stress-strain equations for whole conductor ACCR and ACCS evaluated at room temperature were plotted. The ACCR modulus of elasticity (MOE) is higher than that of ACCS, measured at 10,082 ksi and 9,238 ksi, respectively. However, after a strain of 0.6% is reached, the slope of the curves is very similar between the two conductors. The strength of ACCR is higher than the strength of ACCS, with a measured strength at failure of 46.5 ksi and 34.9 ksi, respectively.

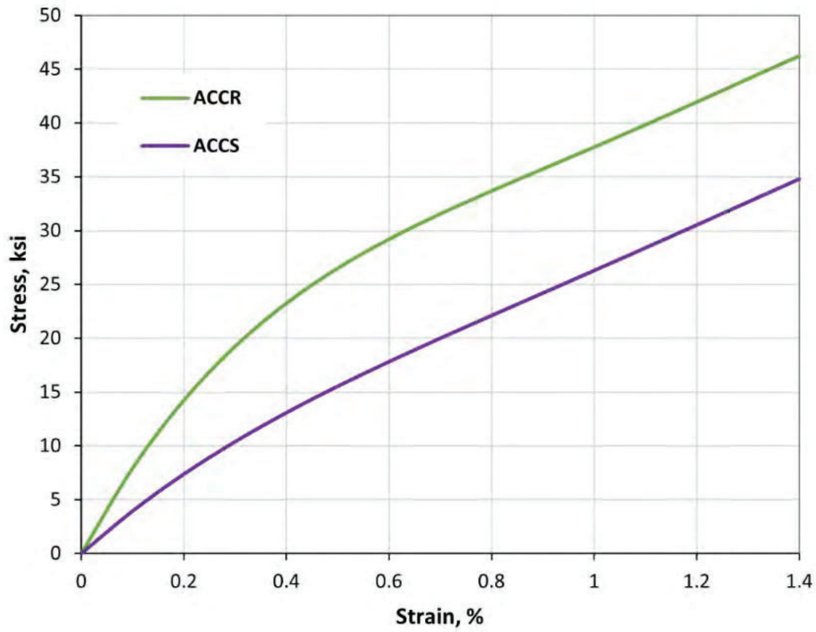

Figure 4-26. Stress-strain curves for whole conductor ACCR and ACCS samples

The stress-strain equations for whole conductor ACCR evaluated at room temperature and high temperature were plotted in Figure 4-27. The best-fit equation for the high temperature data was a 3rd order polynomial. The curves are quite different shapes and terminate at notably different strain values.

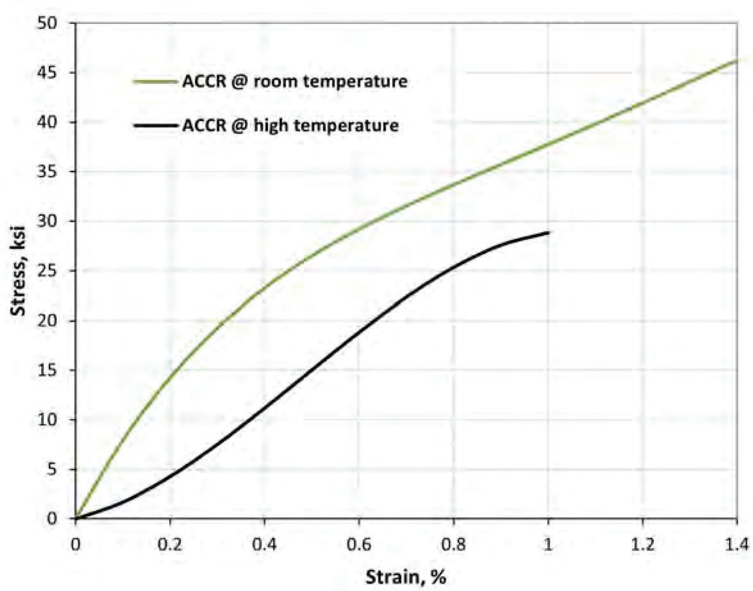

Figure 4-27. Stress-strain curves for whole conductor ACCR samples at room temperature and high temperature

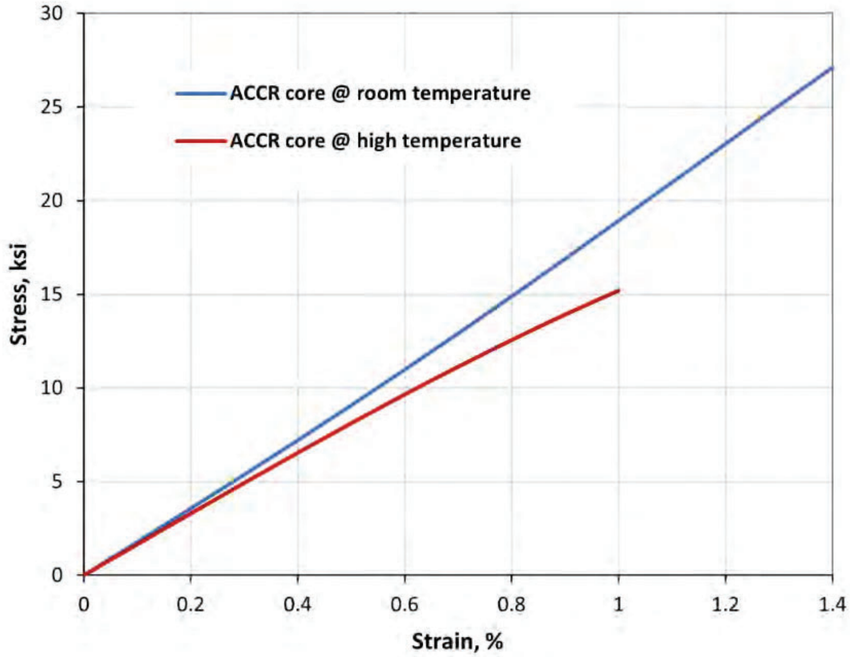

Figure 4-28. Stress-strain curves for ACCR core samples at room temperature and high temperature

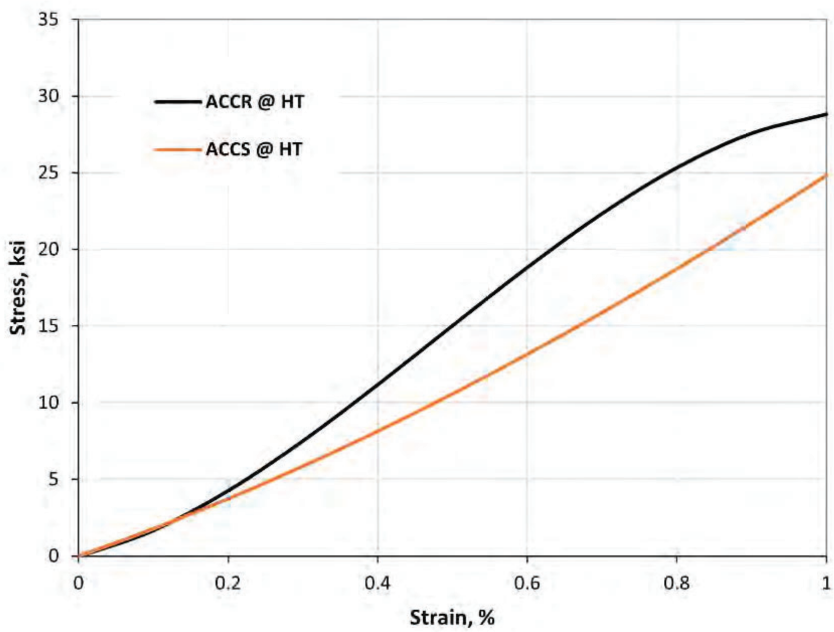

Figure 4-29. Stress-strain curves for ACCR and ACCS whole conductor samples at high temperature