675/TW 3M Brand Composite Conductor
Evaluation of Materials from ORNL Field Test

3M Company

NEETRAC Project Number: 04-121

November, 2004

A Research Center of the
Georgia Institute of Technology

Requested by: Mr. Colin McCullough
3M

Principal Investigator: Paul Springer, PE

Reviewed by: Dale Callaway

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SUMMARY

A 675/TW-kcmil 3M Brand Composite Conductor (also referred to as ACCR – Aluminum Conductor Composite Reinforced) was evaluated in an outdoor test line at the Oak Ridge National Laboratory. During five months of operation, the conductor experienced significant time at temperatures above 200°C, and also experienced temperature cycling from ambient temperature to temperatures above 200°C. At the conclusion of the outdoor testing, conductor and connectors from the Oak Ridge National Laboratory (ORNL) outdoor test line were sent to NEETRAC and evaluated to determine the effect of exposure to outdoor conditions and in-service temperature cycles. Data from tests on the same materials "as manufactured" were retrieved for baseline property values. Evaluation results show that expected creep has occurred, but mechanical and electrical properties of the conductor are unchanged. Dissection of the compression dead-ends and compression splice revealed two problems with connector installation.

KEY FINDINGS

1) Stress-strain results show the expected effect of creep from in-service tension.
2) Mechanical and electrical properties of the conductor and connector are unchanged from baseline (new) conditions, other than conductor creep.
3) Connector dissection showed failure to wire-brush the conductor, and failure to inject inhibitor into the fill port prior to compression. Neither problem affected in-service performance during the field trial, but long-term reliability could be negatively impacted by improper installation.

SAMPLES

1) Two (2) AFL (Alcoa-Fujikura Ltd.) compression dead ends (catalogue # B9085-C) with ~10 meters (33 ft) of conductor attached. One dead end was marked "tree-side". The other was not marked. Both conductor tails were clamped at the cut location to preserve the "in-service" position of all conductor components.
2) Two (2) AFL compression splices (catalogue # B9095-D) with ~5 meters (16 ft) of conductor attached to each end. Both free ends were clamped at the cut location to preserve the "in-service" position of all conductor components.
3) Free span conductor, approximately 40 meters (130 ft) with the free ends clamped at the cut point. The "in-service" position of the conductor components was preserved to measure the "in-service" stress-strain characteristics.

PROCEDURE

The scope of the evaluation included the following tests:

I) Conductor tensile tests (three samples plus stress-strain "bonus" samples): Samples from the "free-span" conductor were terminated using cast-resin terminations. Clamps were used to preserve the as-received position of the conductor layers until the resin cured. The sample preparation method ensures that the lab tensile test loads each conductor strand in the same manner as a field overload, and thereby measure the in-service conductor strength. Free conductor between the end fittings is 20 feet (6 meters).

II) Connector tensile tests (two dead-ends, two splices): Cast-resin fittings were applied to the sample's free end (one per dead-end, and two per splice sample). The procedure preserves the "as received" position of the conductor components, and thereby assures that the breaking strength is the same as existed when the samples were in service on the test span.

III) Conductor resistance (one sample): Welded equalizers were installed at each end of a 22-foot long sample from the free-span section. A second set of voltage equalizers in the form of tightly-wrapped solid copper strands are applied nominally 20 feet apart in the test section. The sample is placed on a flat surface, and pulled with sufficient tension to remove any residual curvature in the conductor. Tension was not measured, but is estimated at 200 – 300 lb. A digital low-resistance Ohmmeter was used to make a 4-wire resistance measurement for the conductor section between the two voltage equalizers. A digital multimeter was used to verify the sample was electrically isolated.

IV) Connector dissection (one dead end, one splice): A milling machine was used to split the aluminum sleeve and reveal the internal splice components. Correct installation is verified by observing proper placement of the core grip, proper conductor preparation, and proper injection of inhibitor compound prior to compression.

V) Stress-strain: A sample from the free-span section was terminated with cast-resin using a process that ensures that each conductor layer and strand is not displaced from its in-service position. The 1999 Aluminum Association guide for conductor stress-strain testing was followed with the exception of special values for the elastic properties of the metal matrix composite (MMC) core were used instead of values for steel core used in ACSR conductors. The core strand from another sample is used to measure core stress-strain, and determine the elastic properties of the composite conductor.

RESULTS

I) Conductor tensile tests (three samples as-received, plus the stress-strain sample after the stress-strain test):

Sample #	Breaking Load (lb)	% RBS	Failure Mode
04121T1	24,770	110	All strands fractured in the gage section
04121T2	25,430	113	All strands fractured at the resin fitting
04121T3	22,780	101	All strands fractured in the gage section next to a drilled thermocouple hole
Stress-strain conductor	25,250	112	Mid-span break, all strands
Stress-strain core	12,820	111	Mid-span break, all strands

See appendix I for chart showing test data

II) Connector tensile tests (two dead-ends, two splices):

Sample #	Breaking Load (lb)	% RBS	Failure Mode
04121SP1 (splice)	24,010	107	All strands fractured at the resin fitting
04121SP2 (splice)	24,530	109	All strands fractured ~ 5" inside splice
04121DE1 (dead end)	24,730	110	All strands fractured ~ 6" inside dead end
04121DE2 (dead end)	22,330	99	All strands fractured ~ 5" inside dead end

See appendix II for chart showing test data.

III) Conductor resistance (one sample):

Resistance of a 20 ft test section was read five (5) times over the course of a day. Values agreed within 0.13%. The average of all readings is 0.1332 Ω/mile at 20° C. The published value is 0.1317 Ω/mile at 20° C. See appendix III for photographs of the test sample, and a worksheet showing data and calculations.

IV) Connector dissection (one dead end, one splice): See appendix IV for photographs and discussion documenting the connector dissections. The dissections and inspections showed good workmanship for core and aluminum insertion depth, component placement, and the crimping operation. For the core grip, proper insertion and crimping were observed. Two problems were noted for both the dead end and the splice:

i. Installation instructions stipulate that the center cavity be filled with oxide inhibitor compound through an injection port. The center cavity contained no oxide inhibitor compound, showing that this step was omitted. Compound was applied liberally on the conductor OD (outside diameter), so this is not a serious issue for a short-term field test. Over a long period of time, water and contaminants could build up in the hollow spaces, and cause problems – particularly corrosion of the steel core grip.

ii. There is no evidence that the conductor was wire-brushed prior to splice installation. AFL requires wire-brushing of the conductor OD only in cases where the connector is installed on weathered conductor. However, most field and lab experience is that failure to wire-brush new conductor can cause premature connector failure.

V) Stress-strain: See appendix V for stress-strain equations and charts illustrating the stress-strain test. The term "initial modulus" is used with the field-aged test data for consistency with the test procedure. "Initial" is in quotes because the conductor is not at initial condition following the field test. Stress-strain results are similar to results from the same conductor prior to the field test. The principal difference is that creep during the 30% load hold phase is less on the field sample, apparently because the field loads caused the initial creep to be removed from the conductor.

CONCLUSION:

Test results show the conductor properties are not changed by the field trial. Mechanical strength of connectors is unchanged from values measured for the same fittings before the field trial. The only significant difference is the change in the initial modulus coefficients from the stress-strain test. That is expected because the conductor is no longer at "initial" conditions after creep in the field.

EQUIPMENT LISTING

1) MTS Servo-hydraulic tensile machine, Control # CQ 0195 (load and crosshead data)
2) Dynamics Research Corporation (DRC)/NEETRAC cable extensometer, Control # CQ 3002 (strain data).
3) Yokogawa DC100 data acquisition system, Control # CN 3022 (temperature data)
4) HBM linear position indicator for crosshead displacement (for reference only)
5) AVO/Biddle Digital Low Resistance Ohmmeter, Calibration Control #CQ 1097

REFERENCES AND STANDARDS LISTING

1) ASTM E4, (Calibration of Load Testing Machines)
2) ANSI C119.4, (Connector testing)

Acknowledgement:

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Disclaimer:

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

APPENDIX I, Conductor Tensile Data

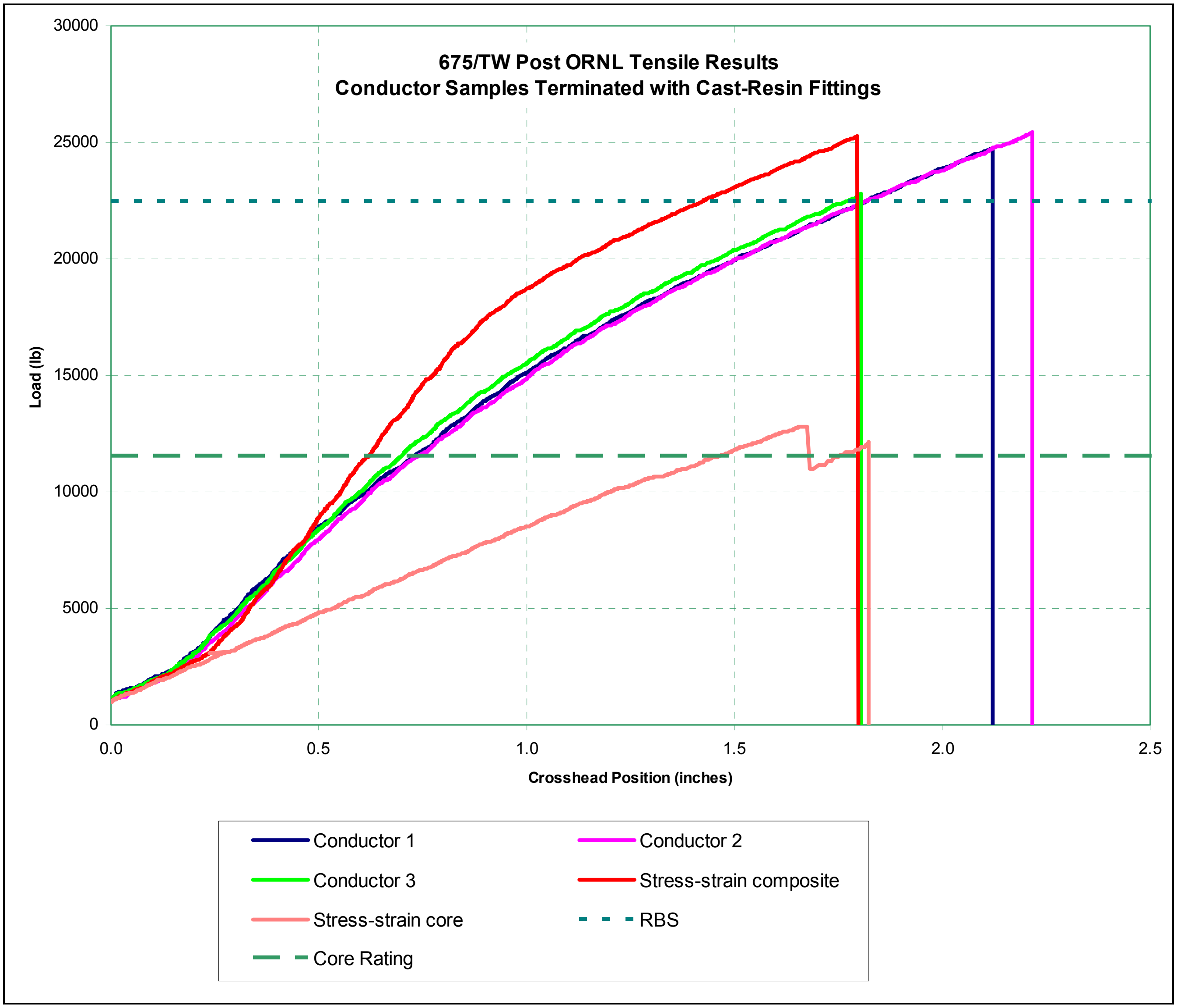


Figure 1, free-span conductor tensile test data

APPENDIX II, Data from Connector Tensile Tests

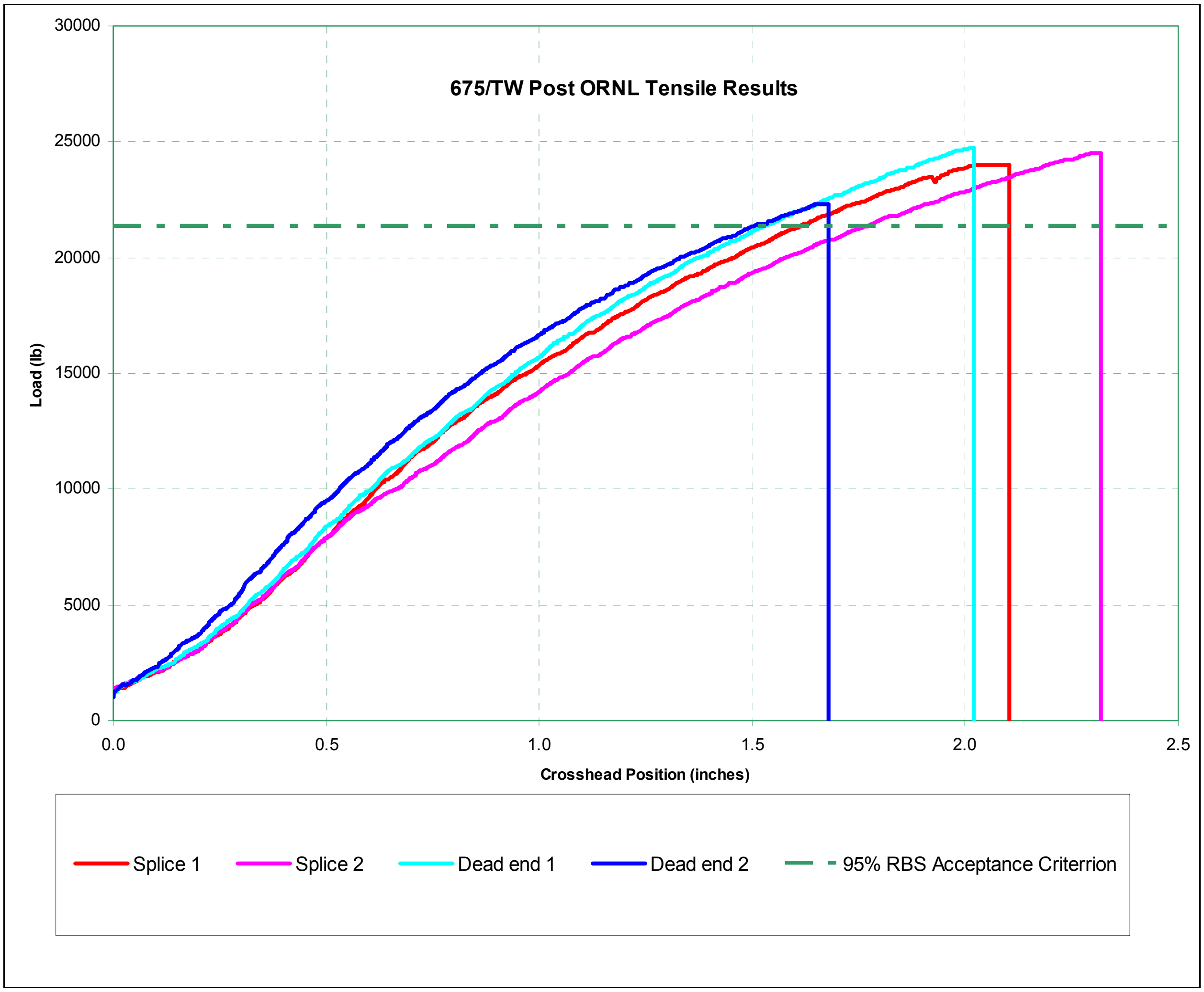
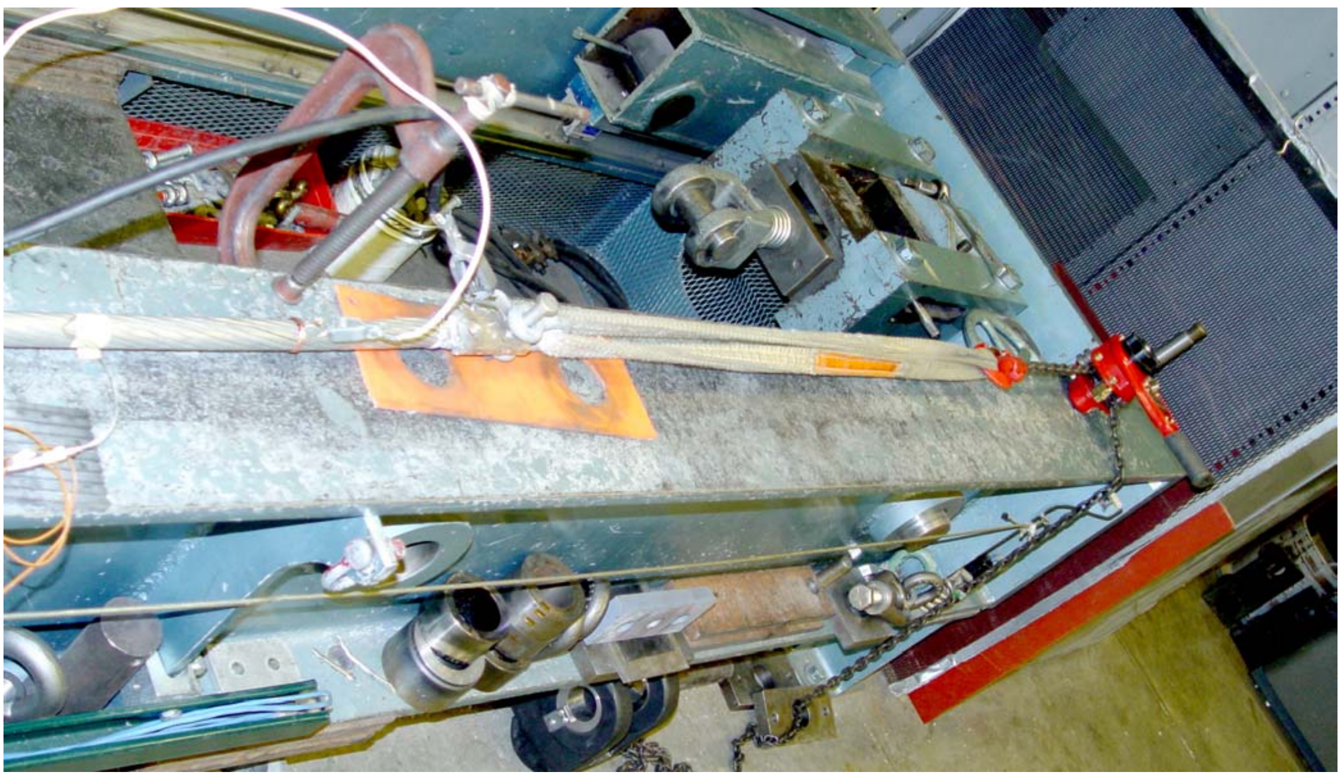


Figure 2, connector tensile test data

Photograph 1, splice sample after tensile test

APPENDIX III, Conductor Resistance

Photograph 2, current connection (left), and voltage connection (right), typical each end of sample



Photograph 3, resistance sample tensioning device, current, and voltage terminals
(air gap, fabric strap and rubber pads ensure the sample is isolated)

Resistance of a 20 ft test section was read several times in the course of a day as noted in the table below. The average of all readings 0.1332 Ω/mile at 20° C. The published value is 0.1317 Ω/mile.

NEETRAC Project No. 04-121					
AVO (Biddle) DLRO, Calibration Control # CQ1097					
Temperature coefficient for resistance:		0.0036			
Resistance measurement on a 20' gage section of 675 ACCR/TW setup in the tensile room on the MTS frame, welded equalizers, pulled to ~200 lbs tension w/a come-a-long					
These readings taken manually 10/14/04 @ 9:54 am					
Conductor Temperature:	21.5	deg C			
Test Section:	20.000	ft			
Resistance Readings	506.8	μΩ	At	21.5	deg C
	506.7	μΩ	At	21.5	deg C
	506.7	μΩ	At	21.5	deg C
	506.73	μΩ	At	21.5	deg C
Ω/ft:	2.5337E-05	Ohm/ft	At	21.5	deg C
Ω/ft:	2.5200E-05		At	20.0	deg C
Ω/mi	0.13378	Ohm/mi	At	21.5	deg C
Ω/mi @ 20C:	0.13306		At	20.0	deg C
These readings taken manually 10/14/04 @ 10:32 am					
Conductor Temperature:	21.8	deg C			
Test Section:	20.000	ft			
Resistance Readings	507.4	μΩ	At	21.8	deg C
	507.4	μΩ	At	21.8	deg C
	507.3	μΩ	At	21.8	deg C
	507.37	μΩ	At	21.8	deg C
Ω/ft:	2.5368E-05	Ohm/ft	At	21.8	deg C
Ω/ft:	2.5231E-05		At	20.0	deg C
Ω/mi	0.13394	Ohm/mi	At	21.8	deg C
Ω/mi @ 20C:	0.13322		At	20.0	deg C

(Continued on next page)

These readings taken manually 10/14/04 @ 10:53 am					
Conductor Temperature:	21.8	deg C			
Test Section:	20.000	ft			
Resistance Readings	507.4	μΩ	At	21.8	deg C
	507.4	μΩ	At	21.8	deg C
	507.3	μΩ	At	21.8	deg C
Average	507.37	μΩ	At	21.8	deg C
Ω/ft:	2.5368E-05	Ohm/ft	At	21.8	deg C
Ω/ft:	2.5231E-05		At	20.0	deg C
Ω/mi	0.13394	Ohm/mi	At	21.8	deg C
Ω/mi @ 20C:	0.13322		At	20.0	deg C
These readings taken manually 10/14/04 @ 2:34 pm					
Conductor Temperature:	21.9	deg C			
Test Section:	20.000	ft			
Resistance Readings	507.4	μΩ	At	21.8	deg C
	507.4	μΩ	At	21.8	deg C
	507.5	μΩ	At	21.8	deg C
Average	507.43	μΩ	At	21.8	deg C
Ω/ft:	2.5372E-05	Ohm/ft	At	21.9	deg C
Ω/ft:	2.5235E-05		At	20.0	deg C
Ω/mi	0.13396	Ohm/mi	At	21.9	deg C
Ω/mi @ 20C:	0.13324		At	20.0	deg C
These readings taken manually 10/14/04 @ 4:52 pm					
Conductor Temperature:	21.7	deg C			
Test Section:	20.000	ft			
Resistance Readings	506.9	μΩ	At	21.8	deg C
	507.0	μΩ	At	21.8	deg C
	506.9	μΩ	At	21.8	deg C
Average	506.93	μΩ	At	21.8	deg C
Ω/ft:	2.5347E-05	Ohm/ft	At	21.65	deg C
Ω/ft:	2.5210E-05		At	20.0	deg C
Ω/mi	0.13383	Ohm/mi	At	21.65	deg C
Ω/mi @ 20C:	0.13311		At	20.0	deg C
Errors:	Gage length	0.05%			
	Instrument	0.20%			
	Temperature	0.18%			
RMS Error:		0.27%			
Average, all readings:	**0.13317**	Ω/mi	At	20.0	deg C
3M nominal	0.13170	Ohm/mi	At	20.0	deg C

APPENDIX IV, Connector Dissection Details

Photograph 4, splice cavity showing injection port. The plug was present, but there is no evidence that inhibitor compound was injected to fill the cavity

Photograph 5, exit from splice showing inhibitor on conductor OD

Photograph 6, opposite end of splice, again showing inhibitor only on conductor OD

Photograph 7, close-up of conductor OD shows no evidence of wire-brush marks

APPENDIX V, Stress-strain Results

Detailed Procedure:

Composite conductor:

1) Apply load of 1,000 lbs. Remove sag with a mid-span support
2) Install extensometer, and set to zero.
3) Pull to 30% of RBS (6,750 lbs)
4) Hold for 30 minutes.
5) Relax load to 1,000 lbs.
6) Pull to 50% RBS (11,240 lbs)
7) Hold for one hour
8) Relax load to 1,000 lb
9) Pull to 70% RBS (15,740 lb)
10) Hold for one hour.
11) Relax load to 1,000 lbs.
12) Pull to 75% RBS (16,870 lbs).
13) Relax load to 1,000 lbs, and remove the extensometer (for its own protection).
14) Pull sample to destruction.

Core strands:

1) Pull to calculated initial tension (in this case, 399 lbs). Remove sag with a mid-span support
2) Install extensometer, and set to zero
3) Pull to same strain as conductor at start of 30% of RBS test (0.12324%)
4) Hold for 30 minutes.
5) Relax load to 399 lbs.
6) Pull to same strain as conductor at start of 50% of RBS test (0.21796%)
7) Hold for one hour.
8) Relax load to 399 lbs.
9) Pull to same strain as conductor at start of 70% of RBS test (0.33403%)
10) Hold for one hour
11) Relax load to 399 lbs.
12) Pull to 75% of the core RBS (8,670 lbs)
13) Relax load to 399 lbs, and remove the extensometer (for its own protection).
14) Pull sample to destruction.

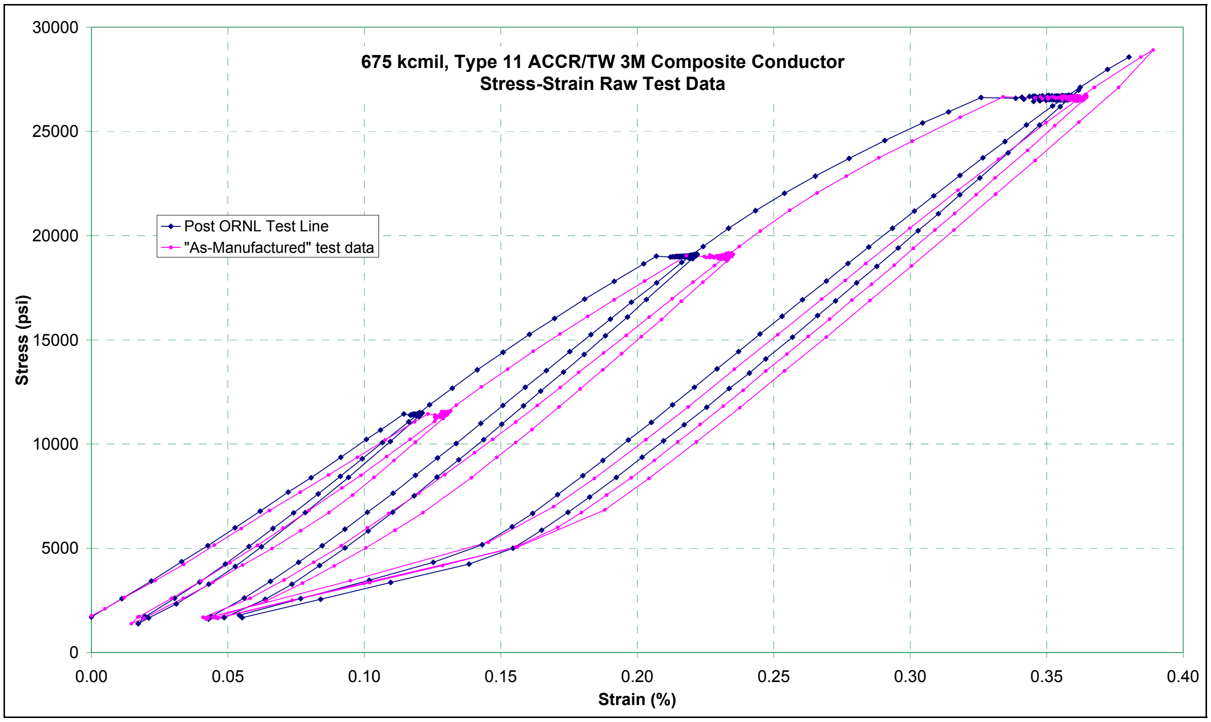


Figure 3, plot of raw data recorded during conductor stress-strain test (blue), and same data for conductor tested from same lot before the field test

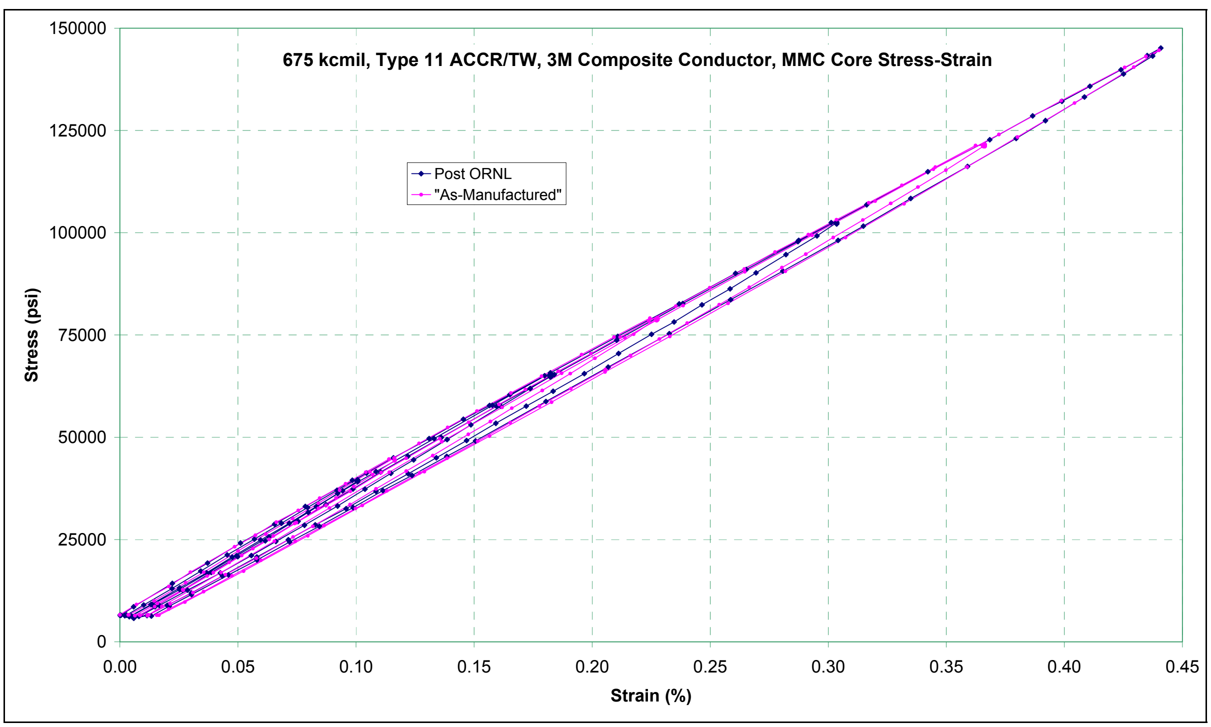


Figure 4, core stress-strain shows essentially no change due to field test

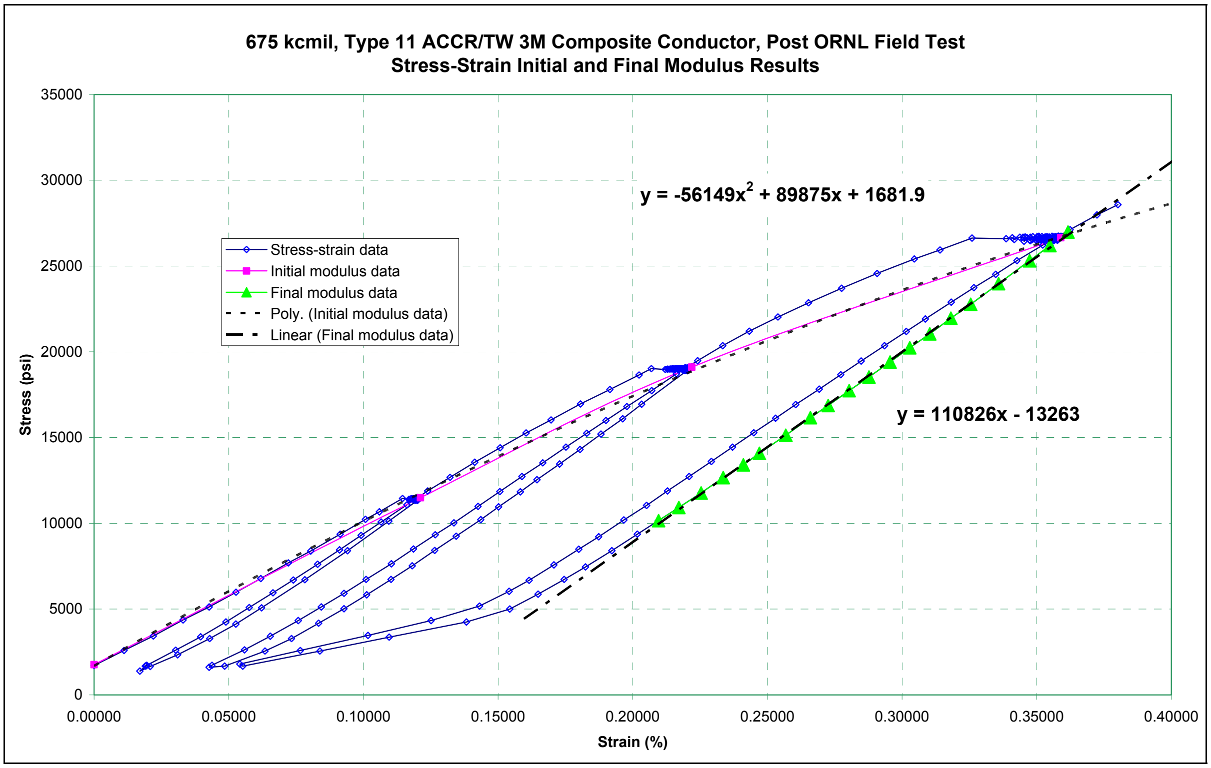


Figure 5, construction of conductor "initial" and final modulus on stress-strain data

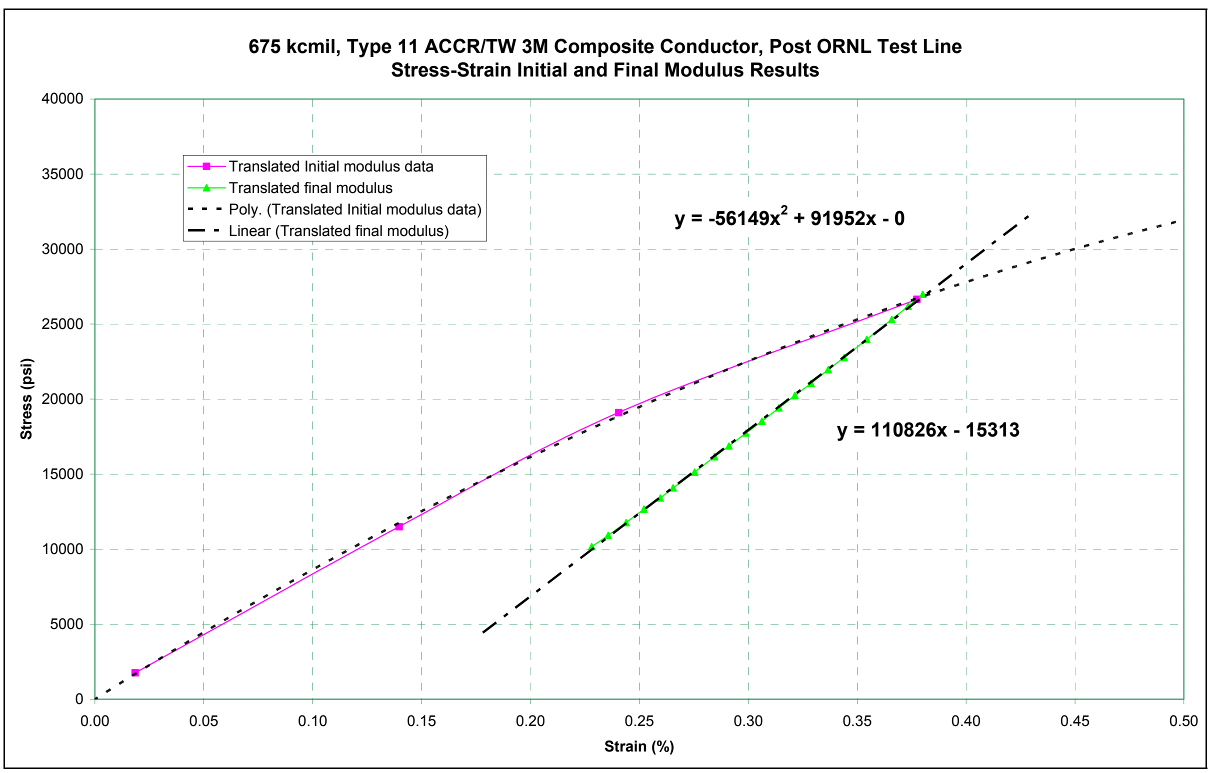


Figure 6, initial and final conductor modulus, translated to zero along strain axis

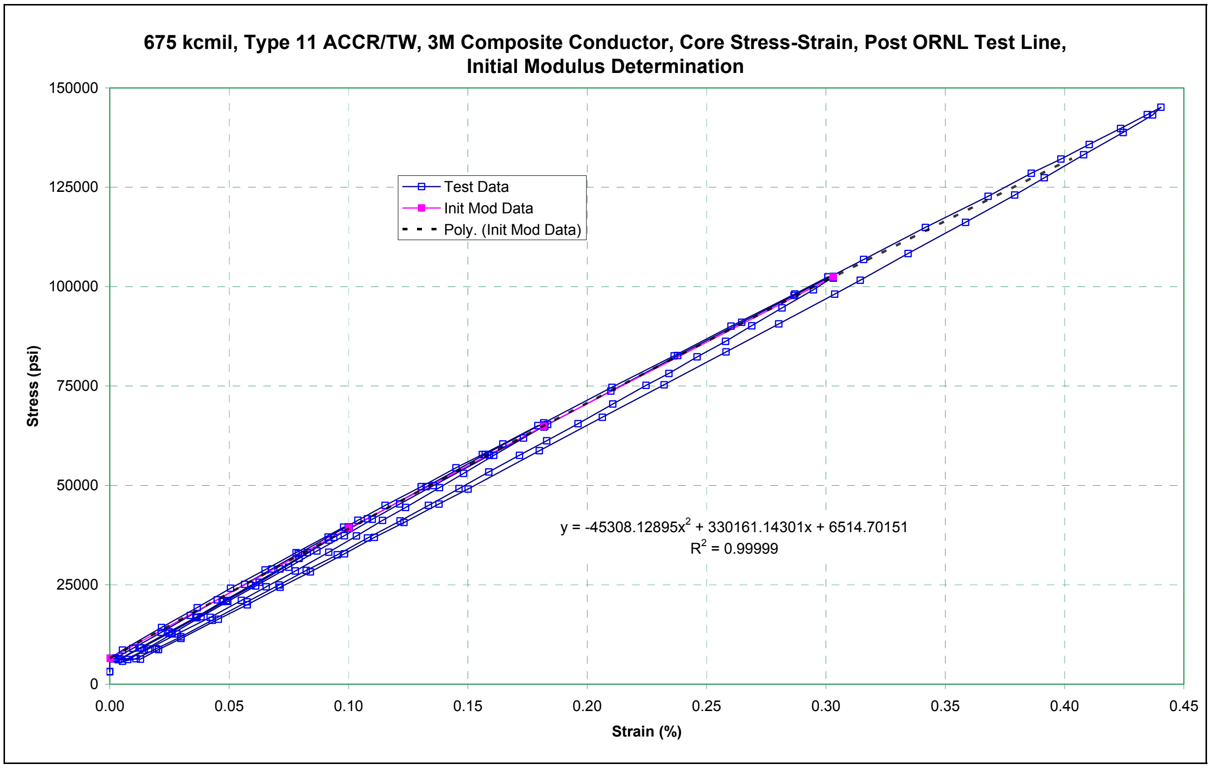


Figure 7, construction of core “initial” modulus on stress-strain data

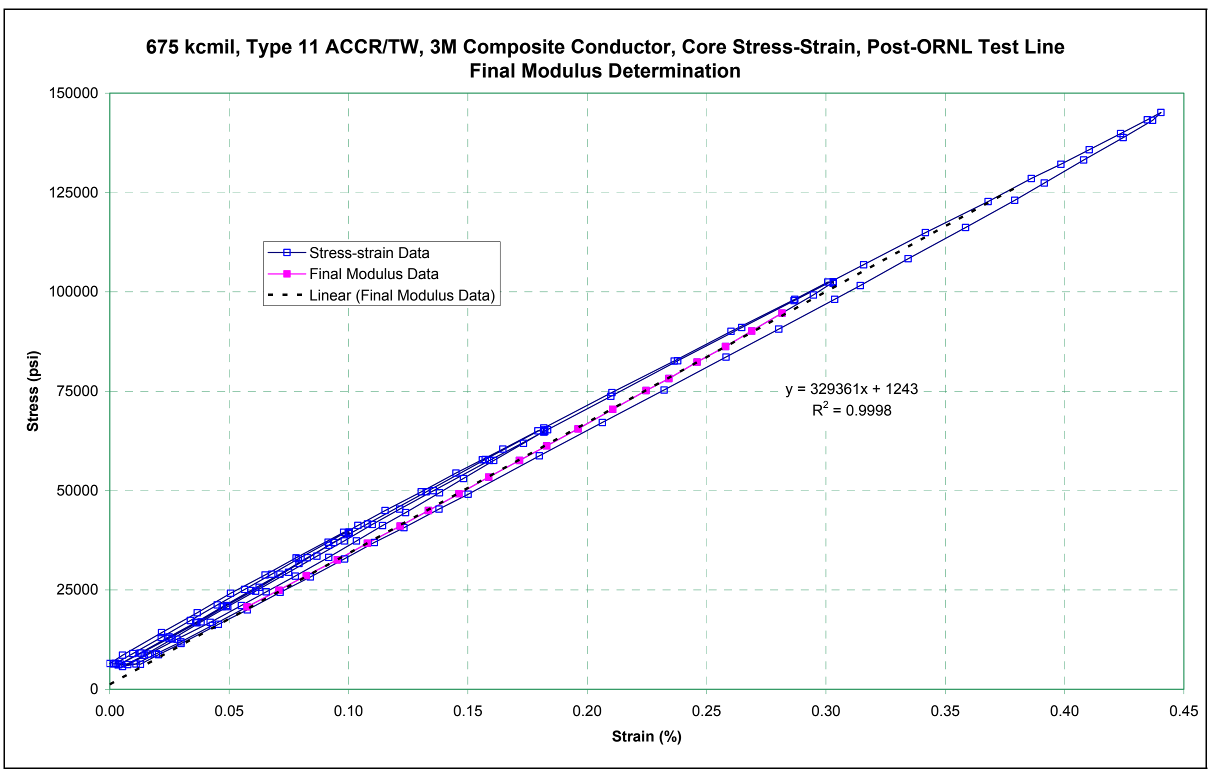


Figure 8, construction of core final modulus on stress-strain data

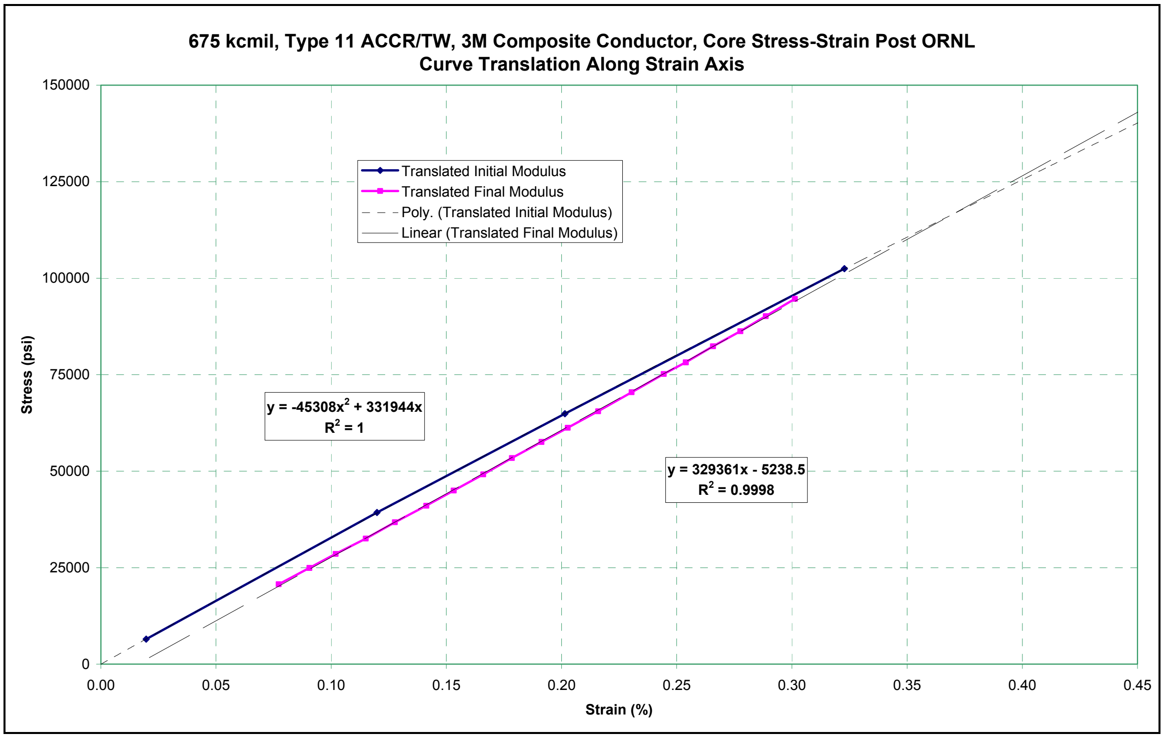


Figure 9, initial and final core modulus, translated to zero along strain axis

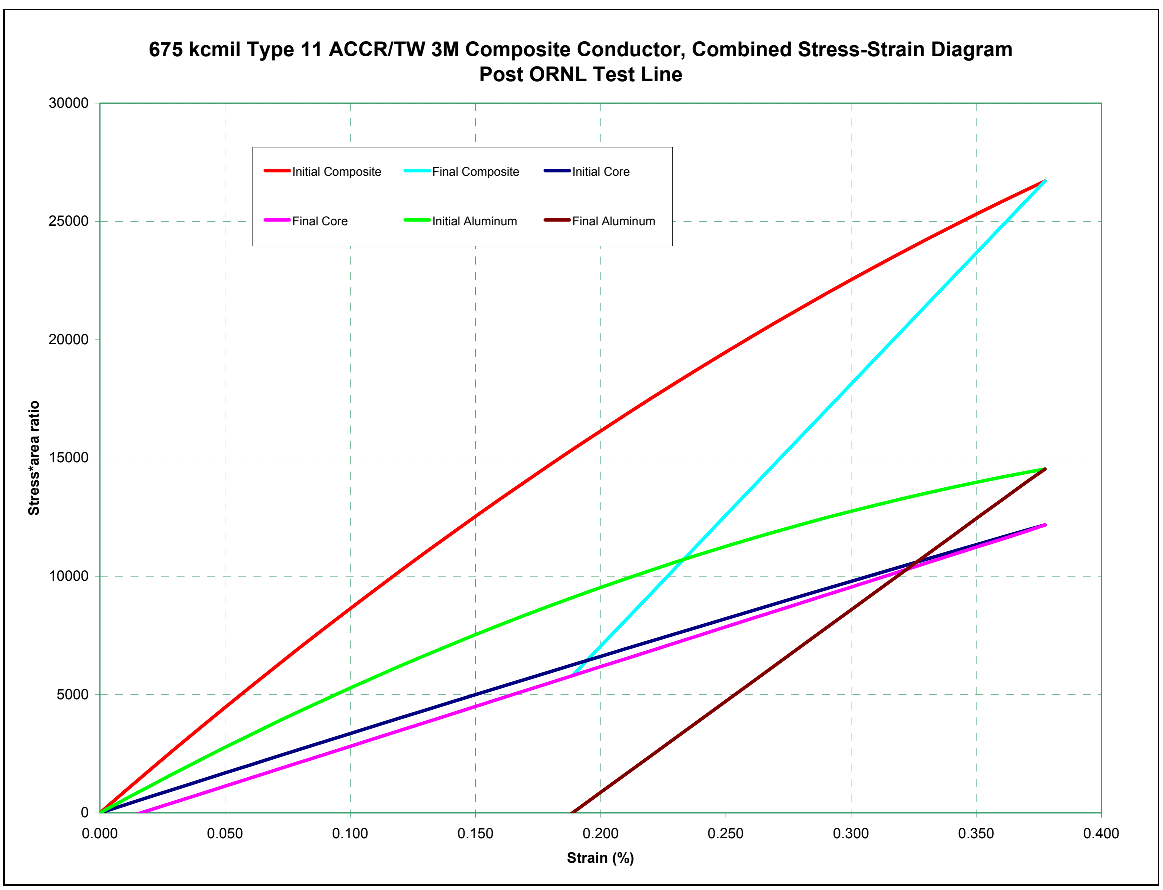


Figure 10, combined stress-strain graph (see following text for equations)

Equations for Stress-Strain Properties (Post ORNL results in report text, reference data from pre-ORNL test is shown in *blue italics text)*:

Composite Conductor Properties, direct test values:

"Initial" Modulus for Stress Strain Curve: Stress (psi) = -56149*(Strain%)^2+89875*(Strain%)+1682
Initial Modulus for Stress Strain Curve: Stress (psi) = -30776(Strain%)^2+79610*(Strain%)+1695*

Final Modulus for Stress Strain Curve: Stress (psi) = 110826*(Strain%) – 13263
Final Modulus for Stress Strain Curve: Stress (psi) = 108935(Strain%) – 13364*

Tensile Test, Stress Strain Sample: 25250 lb (112% RBS)
Tensile Test, Stress Strain Sample: 25470 lb (113% RBS)

Composite Conductor, data shifted along strain axis to provide correct zero strain reference:

"Initial" Modulus for Stress Strain Curve: Stress (psi) = -*56149**(Strain%)^2 + *91952**(Strain%)
Initial Modulus for Stress Strain Curve: Stress (psi) = -30776(Strain%)^2 + 80910*(Strain%)*

Final Modulus for Stress Strain Curve: Stress (psi) = *110826**(Strain%) – *15313*
Final Modulus for Stress Strain Curve: Stress (psi) = 108935(Strain%) – 15665*

Core Strand Properties, direct test values:

"Initial" Modulus for Stress Strain Curve: Stress (psi) = -45308*(Strain%)^2+330161*(Strain%)+6515
Initial Modulus for Stress Strain Curve: Stress (psi) = -39619(Strain%)^2+327809*(Strain%)+6611*

Final Modulus for Stress Strain Curve: Stress (psi) = *329361**(Strain%) + *1243*
Final Modulus for Stress Strain Curve: Stress (psi) = 327961(Strain%) – 364*

Tensile Test, Stress Strain Sample: 12820 lb (111% of nominal rating)
Tensile Test, Stress Strain Sample: 12860 lb (111% of nominal rating)

Core Properties, data shifted along strain axis to provide correct zero strain reference:

"Initial Modulus" for Stress Strain Curve: Stress (psi) = -45308*(Strain%)2 + 331944*(Strain%)
Initial Modulus for Stress Strain Curve: Stress (psi) = -39619(Strain%)2 + 329403*(Strain%)*

Final Modulus for Stress Strain Curve: Stress (psi) = 329361*(Strain%) - 5240
Final Modulus for Stress Strain Curve: Stress (psi) = 327961(Strain%) - 6962*

Aluminum Properties (computed, direct measurement is not possible):
"Initial" Modulus for Stress Strain Curve: Stress (psi) = -57386*(Strain%)^2+64558*Strain
Initial Modulus for Stress Strain Curve: Stress (psi) = -29767(Strain%)^2+52545*Strain*

Final Modulus for Stress Strain Curve: Stress (psi) = = 85881*Strain -16224
*Final Modulus for Stress Strain Curve: Stress (psi) = = 83934*Strain -16479*