NCSX Modular Coil Composite Conductor

Torsion Measurement of the Conductor Shear Modulus at Both Room and Liquid Nitrogen Temperatures

15 Dec 2004

Measurement Method

- The shear modulus measurement was based on the general principals contained in the Standard Test Method: ASTM E 143-02 “Shear Modulus at Room Temperature[1]”.
  - Because of the material shape, construction and the cryogenic temperature requirements, this standard could not be followed exactly.
  - [1]Standard does not provide any limits on “Room Temperature”
- The shear modulus was determined with a torsion test that applied an external torque to the sample and measured the corresponding angle of twist.

Shear Modulus Formula

For a long rectangular bar, the formula for the shear modulus, G, is determined by:[2,3]

$G=TL/\theta K$

Where:
T= Twisting moment (in-lbf)
L= length of sample (in)
θ= Angle of twist (radians)
K= Polar moment of inertia factor (in^4)

For a rectangular bar:
$K= ab^3[16/3-3.36(b/a)(1-b^4/12a^4)]$ for a>b

Where:
a= ½ the length of the wider section face (in)
b= ½ the length of the narrower section face (in)

[2] From "Roark's Formulas for Stress and Strain" 7^{th} ed
[3] For bars that are: (1) straight, uniform section and of homogeneous isotropic material, (2) loaded only by equal and opposite twisting couples, (3) not stressed beyond the elastic limit.

The composite conductor material is clearly neither homogeneous or isotropic and this is demonstrated by marked deviation from the formula $E/G=2(1-\mu)$. This indicates that the shear modulus is dependant on the direction of measurement. For this measurement the shear is in the plane of the material section perpendicular to longitudinal direction of the conductor. The material structure is relatively uniform across the sectional plane, and the measurement is only valid in that plane.

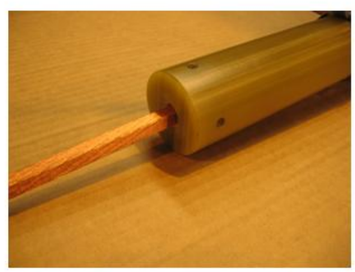
Test Samples

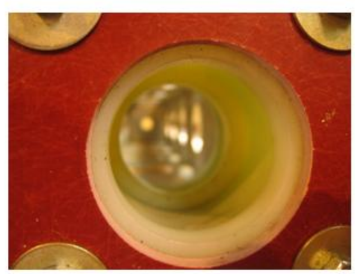
- The test samples were taken from the second and third sets of VPI molded bars.
- Four bars from each set were selected and cut to a length of 24"(resultant gauge length of 22.25"). The section dimensions of each bar were also measured.

Test Fixture

The test fixture consisted of a vertical ridged torque frame mounted below a horizontal surface plate. The vertical torque frame hung inside a 30" high LN2 vacuum flask. The sample was attached to a clamp on each end with four 10-32 cup-end set screws. One end clamp, made of steel, was inserted into the bottom of the torque frame with a key to lock it to the frame. The top clamp, made from G-10, extended through the surface plate through two nylon bearings and was free to rotate and move vertically. A rotary indicator and torque load cell were attached to the top G-10 clamp.

Fixture Details





Calibration

- The Torque Load Cell was calibrated with a certified weight acting on a measured radius arm attached to the cell.
- The entire apparatus and procedure were tested by measuring the shear modulus of a round steel rod and a square copper rod at room temperature.
  - The 0.250" diameter steel rod had a measured shear modulus of 11067 Ksi (STDEV 1752 Ksi) compared to the published value of 11500 Ksi
  - The 0.375" square copper rod had a measured shear modulus of 6255 Ksi (STDEV 616 Ksi) compared to the published value of 5800 Ksi

Test Procedure

For each sample, at room temperature, the torque was stepped from 10 in-lb to 50 in-lb in 10 in-lb steps in the positive (CW from end view) rotation direction. Then using the same increments the torque was stepped in the negative rotation direction. At each step the angular rotation was recorded along with the torque value. This cycle was repeated two more times for each direction of rotation. The sample was then submerged in liquid nitrogen and the entire measurement sequence was repeated.

Initial trial tests determined that the conductors remained well in the elastic region for torque values of up to 50 in-lb

Measurement Results

		Shear Modulus (Ksi)									
		Sample								Total	
Temp	Rotation	2-10-2	2-8-2	2-10-1	2-8-1	3-10-3	3-8-3	3-8-1	3-10-1	AVG	STD
Room	CW	1902	1550	1795	1734	1866	1785	2028	1814	**1809**	138
Room	CCW	1719	1671	1594	1783	1528	1415	1784	1503	**1625**	137
LN2	CW	2621	2531	2836	2631	2650	2459	2863	2695	**2661**	138
LN2	CCW	2608	2603	2673	2644	2366	2155	2952	2747	**2594**	241

Related Material Property Observations

- The properties between the two groups of samples had measurable differences, particularly in the clockwise to counterclockwise modulus ratio.
- It was observed that a moderate transverse compression greatly reduced the torsion shear strength of the composite conductor. A section of conductor that was compress transversely prior to testing, subsequently failed with an applied torque of less than 50 in-lb. Further testing would be required to quantify this failure process.

Related Material Property Observations

- During the cool down from room temperature to liquid nitrogen temperature, the conductor sample was observed to rotate along its length. This effect was measured with the following results.
  - If the conductor is free to rotate, the average measured amount of rotation is 0.0024 radians or 0.14 degrees per linear inch of conductor in the positive or clockwise direction.
  - If the conductor is held firm along its length, the developed internal rotational torque is about 0.7 in-lb per linear inch of conductor.