SUBMILLIMETER ARRAY PROJECT
TECHNICAL MEMO 158

TITLE: ANALYSIS OF TESTS CONDUCTED ON SMA BUS TUBES FROM ANTENNA 1

TEST DATE: MARCH 18-26, 2008

TEST LOCATION: SIMPSON GUMPERTZ AND HEGER, INC (SGH)
41 SEYON STREET
BUILDING 1, SUITE 500
WALTHAM, MA. 02453

TEST PROCEDURE: SMA PROCEDURE NUMBER: 41700490002, REV. OD

SGH TEST ENGINEER: ARTHUR DAVIES

SMA ENGINEER: GEORGE NYSTROM

INTRODUCTION:

The SMA-BUS structure was designed and analyzed by Phillip Raffin while employed at SAO. William Davis (SAO) performed subsequent analyzes to evaluate dynamic load inputs caused by Azimuth and Elevation accelerations. The Davis analysis was to ensure the dynamic loads were less than those specified by Raffin for each tube type. These analyses are available in SMA technical memos TM 137, TM 130, TM 119, TM 55 and TM 51.

Nytex Corporation manufactured the SMA-BUS tubes in Taiwan to SMA specification number: 41700490003. Nytex performed acceptance testing to the load values given in the specification, which are identical to those employed in our testing program. The SMA project initiated a test program in June 2003 in partnership with SGH to provide testing and technical consultation. Tubes from our spare tube inventory were selected to provide a reasonable sample. This testing was reported in Technical memo TM 145. Second and third tests were performed in August 2005 and March 2008. These tests are reported in TM 151 and TM157 respectively.

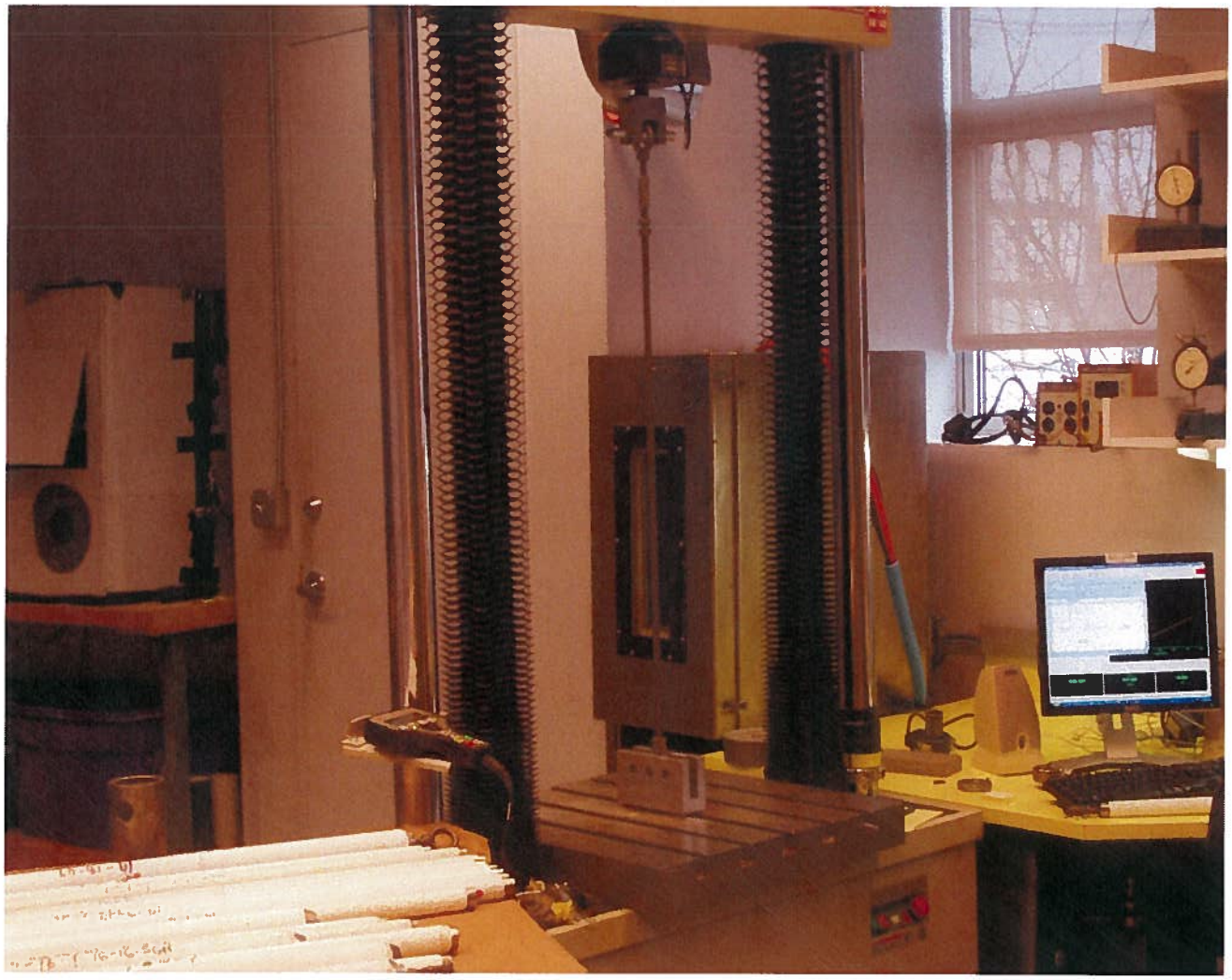
We had hoped to develop equipment that would apply loads being experienced in the deployed antennas to these spare tubes. This would make the spare tubes a better representation for determining tube health. Bond aging and environmental stressing (gravitational, wind, antenna motions, temperature and environmental exposure) would be accounted for. However, this was not done. Therefore, we have now instituted a program to swap out antenna tubes with these tested spare tubes. The removed antenna tubes will give us a true test article to better understand tube health and by implication BUS health. Although this is only a small statistical sample, it may provide a warning should tube failure happen within either the removed Antenna or spare tubes.

ANTENNA 1 TEST RESULTS:

Antenna 1 tubes passed the load testing as reported in Technical memo 145. The original test program was concerned only with pass/fail load testing at the tube assemblies acceptance loads. SMA wanted to evaluate the tube assemblies strain using the test data. SGH noted the MTS testing machine was not instrumented for making direct strain measurements. However, SMA believed that the data could be used to make a reasonable estimate and therefore a better understanding of the tube assembly's mechanical properties.

The SGH testing machine is a MTS model 30-G Electro-Mechanical Universal Tester. It measures the crosshead motion relative to its base for an applied load. The motion is measured in microns. When the crosshead moves away from the base it is called an extension as is the case in our testing. We need to define the following terms. Extension is applied to all elements in the load train, which are part of the cross head motion. Strain requires knowledge of the mechanical properties, load, cross-sectional area and length

under load. The tube assemblies and calibration rod are the only load train elements for which we can estimate a strain using the test data. These are not direct strain measurements but rather an estimated strain based on the measured extension (displacement) between the machines base and cross head. The MTS machine does apply a calibrated load to the tubes under test. The tube strain can then be estimated, if the extension of all other components is removed. The test setup for machine calibration is shown in figure 1 below. The Machine calibration was intended to check its operational parameters (software) and proof test the holding fixtures against possible breakage under load. A scan over the load range was conducted providing a data set of load versus extension. This data set is used to estimate the machines extension during tube assembly testing.



Machine calibration test setup
Figure 1

Analysis:
In order to arrive at an estimated antenna tube assembly strain, we needed to determine the extension associated for all the components in the load train. Using the machine calibration, those components are the MTS machine, test rod and the holding fixture components. The test rods' strain can be calculated as shown in Appendix A. We needed to calculate the test rods strain at the twelve Antenna 1 tube test loads. The rods calibration was a rapid load scan so therefore, we need to extrapolate to determine the total extension at these loads. These recorded and extrapolated values are shown in Appendix B. The MTS machine and holding fixture extension can then be estimated by subtracting the test rods' strain motion from the total measured extension at the various loads. This value is called the Machine extension. Figure 2 below shows these displacements as a function of applied load.

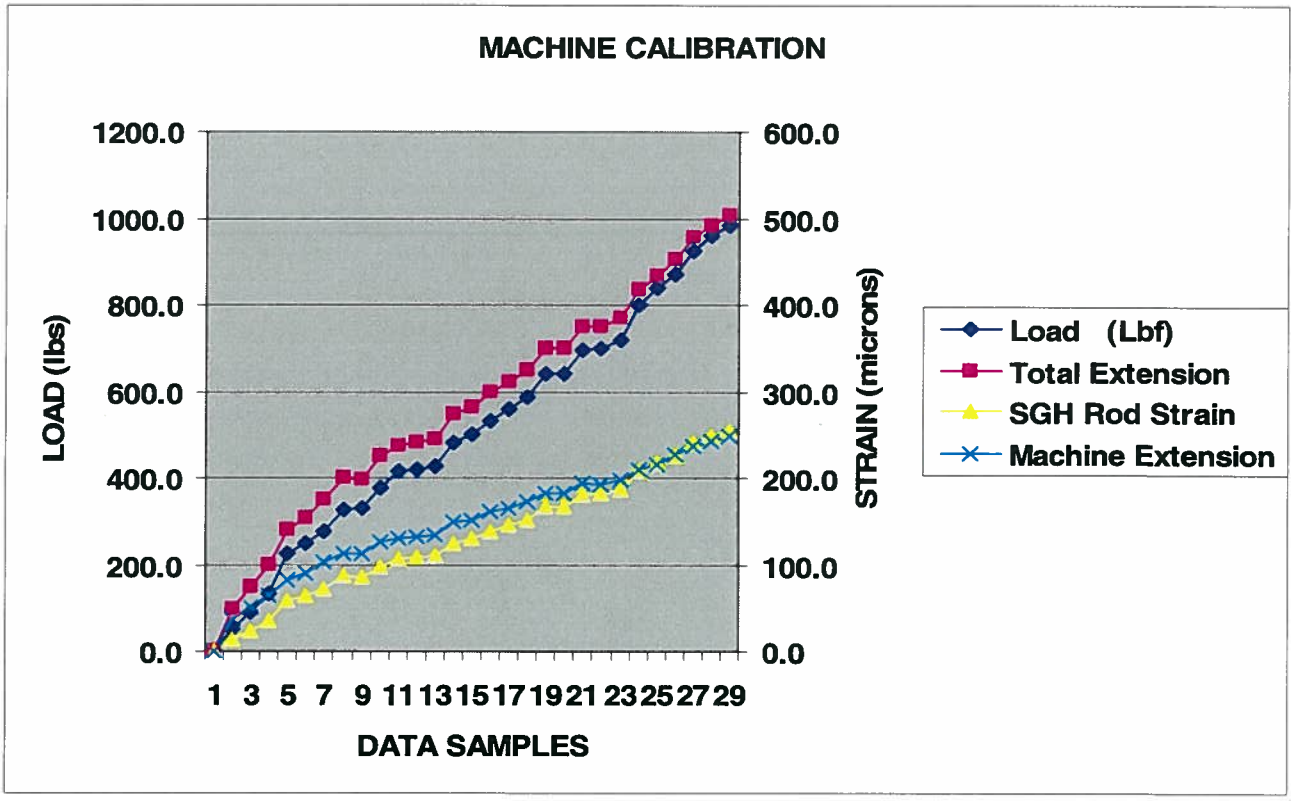


Figure 2
SGH machine calibration

The machine calibration data clearly shows that the machine and its holding fixtures are a large contributor to the measured extension. In fact, it is nearly equal to the Rod strain or 50% of the measured extension. Therefore, it is not ideal for making accurate antenna tube assemblies strain measurements as noted by SGH.

The tube assemblies have three components that come under load. These are the end fittings, end fitting to tube bonds and the carbon fiber tube. The tube assemblies strain was calculated using specified material properties, published material properties and modeled (W. Davis, CE) bonded joint stress calculations. These strain calculations for the Antenna 1 tube A1-5 are shown in Appendix A. The other tube assemblies were calculated in a similar manner. The estimated antenna tube assembly's strains are shown below in Figures 3-6.

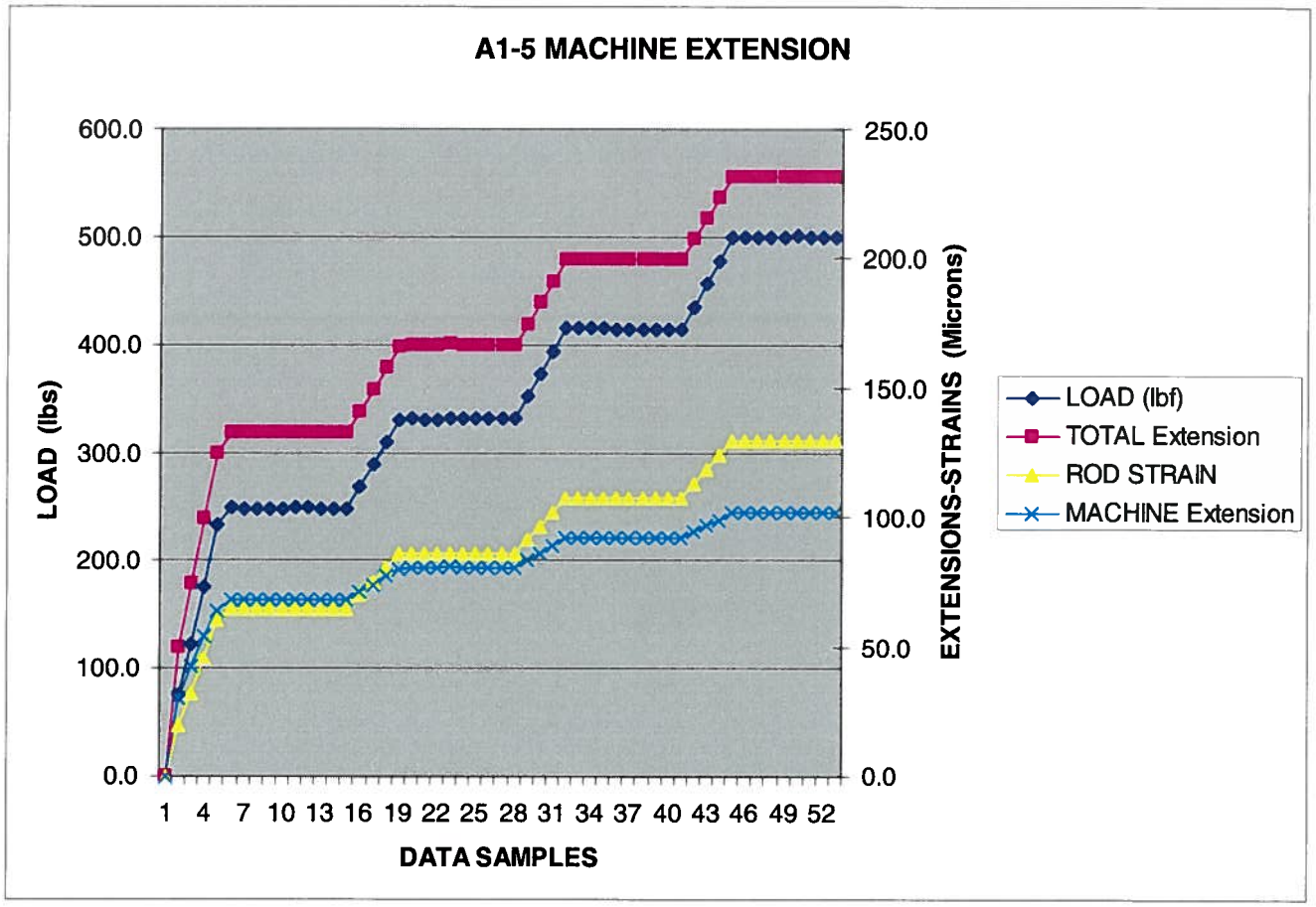


FIGURE 3

Figure 3 shows the calibration rod strain plotted at the tubes test loads. The MTS machine's total extension and computed machine extension are also shown. This clearly shows that the Machine and holding fixtures contribute significantly to the overall measurement.

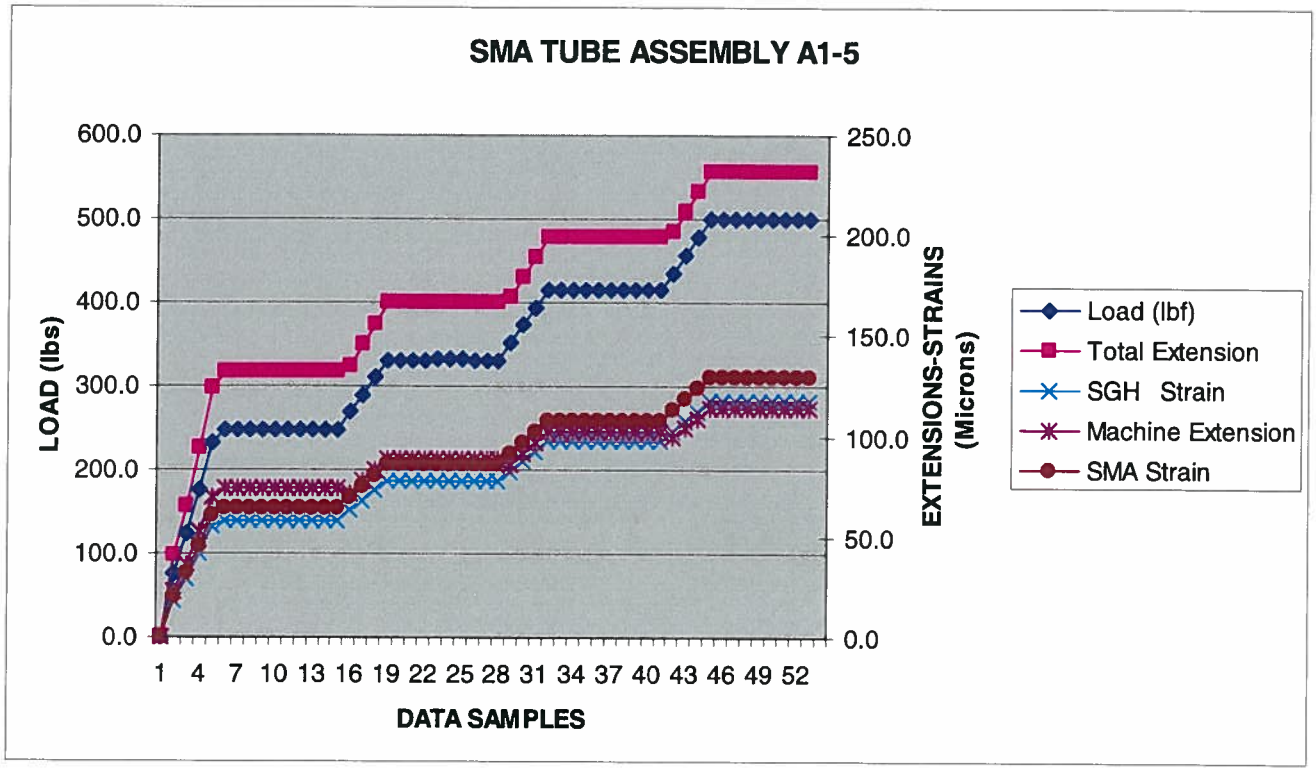


FIGURE 4

In Figure 4, the rod is replaced with a term called the SGH strain. The SGH strain is calculated as: SGH strain = Rod strain x (Rod stiffness/Tube stiffness). This in effect makes the rod equal in stiffness to the tube under test. By subtracting its calculated strain from the total extension gives an estimated value for the tube strain. Also plotted is the calculation for the A1-5 tube and it is called the SMA strain. We see excellent correlation between the estimated and calculated strains for the tube assemblies. Inspection of the data in Appendix B shows the effect of the tube stiffness on total extension. Comparing similar loads, we see smaller total extensions for increasing tube stiffness. The calculated tube and rod stiffness are given below showing the relative stiffness.

SGH ROD= 0.9876×10^5 lbs/in
A1-5= 1.089×10^5 lbs/in
A1-7= 1.635×10^5 lbs/in
A1-15= 3.163×10^5 lbs/in

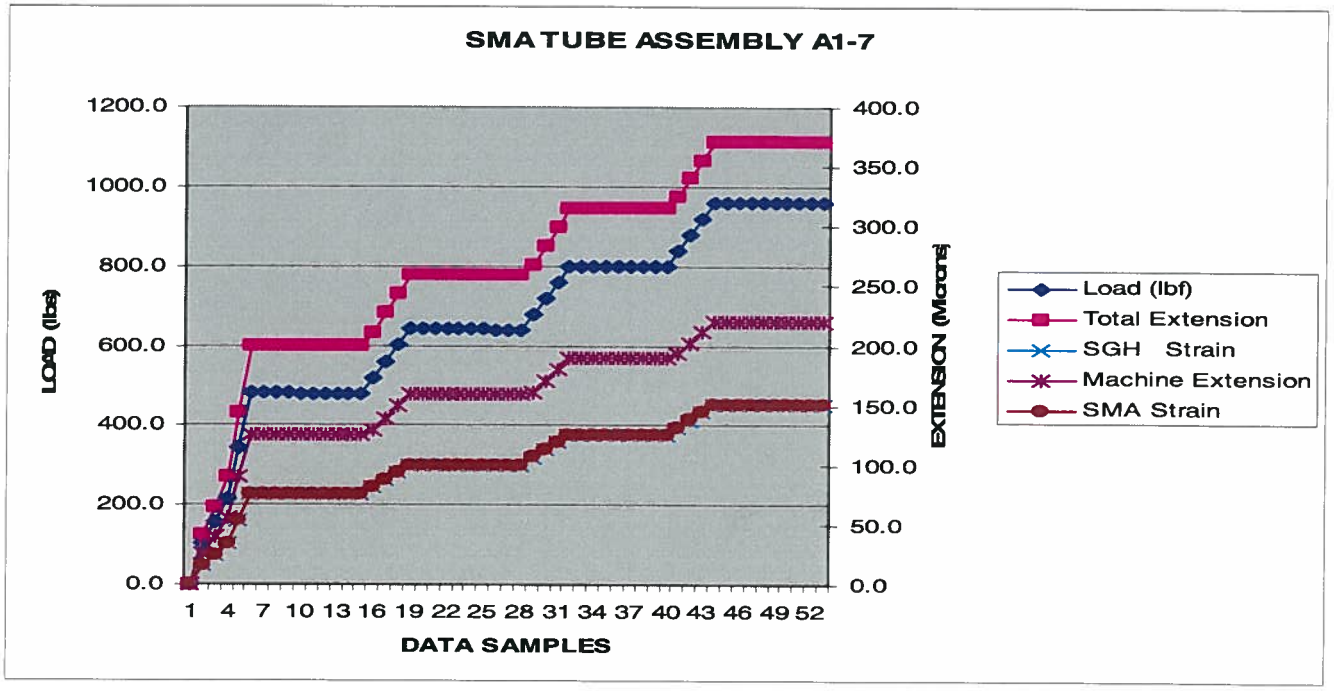


Figure 5

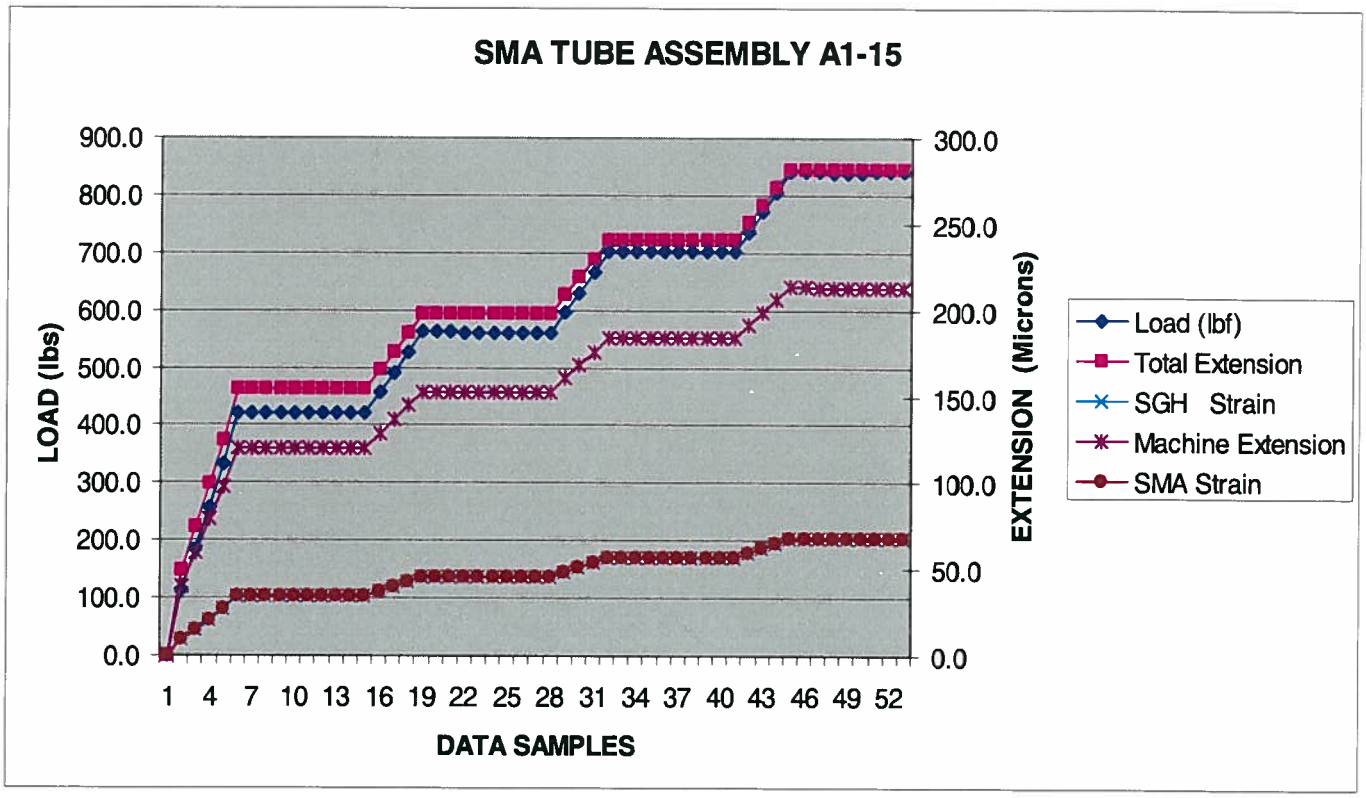


Figure 6

Antenna tubes A1-7 and A1-15 are shown in Figures 5 and 6 with their values derived in an identical manner as A1-5. We can clearly see that the derived test value (SGH Strain) agrees all most exactly with the SAO predicted strain for these two tubes.

CONCLUSIONS:

The data reveals that the MTS machine and its holding fixtures account for large extensions which are comparable to the test article. This makes a direct tube assembly strain measurement unattainable. However, we can see that the error margin between estimated and calculated tube assembly strains are relativity small, thereby giving confidence that the tube calculations are accurate. Those calculations also use the expected mean values for all properties. The carbon fiber tube specification (41700490000) gives the Young's modulus as 20,000,000-psi ±2.5% and a later document from Bill Bruckman changed the modulus to a nominal value of 17,000,000 psi and increases the tube's wall thickness to maintain its overall stiffness. Also, the tube assembly's creep measurements are affected by the stiffness of the test setup. They are expected to be approximately 50% smaller than previously reported.

All previous testing has been done to verify that the tubes strength has not degraded below the design factor of safety of 1.5 times the maximum expected load. These tests basically repeated the acceptance testing done by the tube manufacturer and are adequate for the intended purpose.

However, if the project wants to verify the design properties, we must employ a strain measurement system. This would allow direct strain measurements to be made, thereby removing any uncertainty. The present holding fixtures can be used except the threaded rod must be replaced. We need a solid rod. It will allow proper attachment of the strain measurement system and will improve system calibration. The testing specification must be changed to provide holding loads during the machine calibration. This will allow a direct comparison between the machines calibration and tube tests.

This analysis does imply that the nominal tube manufacturing specifications have been achieved. This may be sufficient for understanding the tube properties. However, a better holding fixture, strain measurement system and modification of the machine calibration would improve the data attained and is recommended for our next test.

SGH MACHINE CALIBRATION
SIMULATED TUBE CALCULATIONS

THE SGH COMPONENTS USED TO SIMULATE A TUBE ASSEMBLY ARE CALCULATED BELOW
THE ROD, COUPING AND THREAD STRAIN CAN BE COMPUTED USING KNOWN PROPERTIES

ROD CALCULATION:

$$A1 := 0.7854 \cdot \left[(.50in)^2 - (.265in)^2 \right]$$

CROSS SECTIONAL AREA: $A1 = 0.141\,in^2$

ROD LENGTH: $L1 := 36in$

TUBE MODULUS: $E1 := 29600000 \frac{lb}{in^2}$

SGH TEST LOADS:

$$P := \begin{pmatrix} 248 & 331 & 414 & 500 \\ 480 & 640 & 800 & 960 \\ 420 & 560 & 700 & 840 \end{pmatrix} lb$$

$$S1 := \frac{P \cdot L1}{A1 \cdot E1} \qquad microns := .000039 \cdot in$$

ROD STRAIN:

$$S1 = \begin{pmatrix} 54.8 & 73.1 & 91.4 & 110.4 \\ 106 & 141.4 & 176.7 & 212 \\ 92.8 & 123.7 & 154.6 & 185.5 \end{pmatrix} microns$$

COUPLING CALCULATION

CROSS SECTIONAL AREA: $A2 := 0.7854 \cdot \left[(1.00in)^2 - (.50in)^2 \right]$

$A2 = 0.589\,in^2$

COUPLING LENGTH: $L2 := 2.50in$

COUPLING MODULUS: $E2 := 29600000 \frac{lb}{in^2}$ cal15

$$S2 := \frac{P \cdot L2}{A2 \cdot E2}$$

COUPLING STRAIN:

$$S2 = \begin{pmatrix} 0.91 & 1.22 & 1.52 & 1.84 \\ 1.76 & 2.35 & 2.94 & 3.53 \\ 1.54 & 2.06 & 2.57 & 3.09 \end{pmatrix} microns$$

THREAD STRAIN

THE SGH COUPLING WAS TIGHTENED AND THE LOCKING NUTS TORQUED, THE THREAD STRAIN UNDER TEST LOADS ARE:

ROD AREA: $RA := 0.7854 \cdot \left(.50^2 in^2\right)$

$RA = 0.196 in^2$

$TA := RA - A1$

THREAD AREA = RA MINUS THE A1 $TA = 0.055 in^2$

THREAD MODULUS: $E3 := 29600000 \cdot \left(\frac{lb}{in^2}\right)$

$L3 := 1.0in$

$S3 := \frac{P \cdot L3}{TA \cdot E3}$

THREAD STRAIN: $S3 = \begin{pmatrix} 3.9 & 5.2 & 6.5 & 7.9 \\ 7.5 & 10.1 & 12.6 & 15.1 \\ 6.6 & 8.8 & 11 & 13.2 \end{pmatrix} \text{microns}$

PREDICTED STRAIN DUE TO TEST LOADS

$PS := S1 + 2 \cdot S2 + 2 \cdot S3$

TOTAL STRAIN: $PS = \begin{pmatrix} 64.4 & 85.9 & 107.5 & 129.8 \\ 124.6 & 166.2 & 207.7 & 249.2 \\ 109 & 145.4 & 181.7 & 218.1 \end{pmatrix} \text{microns}$

$STIFFNESS := \frac{P}{PS}$

$STIFFNESS = \begin{pmatrix} 9.876 \times 10^4 & 9.876 \times 10^4 & 9.876 \times 10^4 & 9.876 \times 10^4 \\ 9.876 \times 10^4 & 9.876 \times 10^4 & 9.876 \times 10^4 & 9.876 \times 10^4 \\ 9.876 \times 10^4 & 9.876 \times 10^4 & 9.876 \times 10^4 & 9.876 \times 10^4 \end{pmatrix} \frac{lb}{in}$

SMA TUBE A1-5 STRAIN CALCULATION

THE SMA BUS TUBES ARE WEAKEST FOR TENSION APPLIED LOADS; THEREFORE, SGH TESTING APPLIES ONLY TENSILE LOADS AND THE FOLLOWING STRAIN CALCULATIONS ARE APPLICABLE.

CARBON FIBER TUBE CALCULATION:

CROSS SECTIONAL AREA: $A1 := 0.7854 \cdot \left[(1.055in)^2 - (.9173in)^2 \right]$

$A1 = 0.213\,in^2$

TUBE LENGTH: $L1 := 23.243in$

TUBE MODULUS: $E1 := 17000000 \frac{lb}{in^2}$

SGH TEST LOADS: $P := (248 \;\; 331 \;\; 414 \;\; 500)lb$

$S1 := \frac{P \cdot L1}{A1 \cdot E1}$ $\qquad$ $microns := .000039 \cdot in$

TUBE STRAIN: $S1 = (40.76 \;\; 54.401 \;\; 68.043 \;\; 82.177)\,microns$

END FITTING CALCULATION

CROSS SECTIONAL AREA: $A2 := 0.7854 \cdot \left[(.8779in)^2 - (.314in)^2 \right]$

$A2 = 0.528\,in^2$

FITTING LENGTH: $L2 := 1.0in$

FITTING MODULUS: $E2 := 29600000 \frac{lb}{in^2}$

$S2 := \frac{P \cdot L2}{A2 \cdot E2}$ $\qquad$ cal15

FITTING STRAIN: $S2 = (0.407 \;\; 0.543 \;\; 0.679 \;\; 0.821)\,microns$

STRAIN IN BOND JOINT

THE SMA TUBE BONDS WERE EXTENSIVELY MODELED AND BOND LINE SHEAR STRESSES CALCULATED. THOSE CALCULATED STRESSES ARE USED TO COMPUTED THE CORRESPONDING DEFORMATON. THE EPOXY USED WAS 3M -DP-460. 3M INC. RECOMMENDS A YOUNGS MODULUS OF 300,000 PSI BE USED.

ADHESIVE MODULUS: $E3 := 300000 \cdot \left(\frac{lb}{in^2}\right)$

MODELED STRESS: $s3 := (98.5 \quad 131.5 \quad 164.4 \quad 198.6) \cdot \frac{lb}{in^2}$

$S3 := \frac{s3}{E3} \cdot in$

ADHESIVE DEFORMATION $S3 = (8.419 \quad 11.239 \quad 14.051 \quad 16.974)\,\text{microns}$

PREDICTED TOTAL STRAIN

TUBE, 2 FITTING & 2 BONDS $PS := S1 + 2 \cdot S2 + 2 \cdot S3$

TUBE TOTAL STRAIN: $PS = (58.411 \quad 77.966 \quad 97.504 \quad 117.767)\,\text{microns}$

$STIFFNESS := \frac{P}{PS}$

TUBE STIFFNESS: $STIFFNESS = \left(1.089 \times 10^5 \quad 1.089 \times 10^5 \quad 1.089 \times 10^5 \quad 1.089 \times 10^5\right) \frac{lb}{in}$

APPENDIX B

DATA SAMPLES FROM SGH TESTING MEASUREMENTS

LOADS ARE IN POUNDS AND TOTAL EXTENSION ARE MICRONS

A1-5 tube		A1-7 tube		A1-15 tube		SGH Calibration			
Load (lbf)	Total Extension	Load (Lbf)	Total Extension	Load (Lbf)	Total Extension	Load (Lbf)	Total Extension	SGH Rod Strain	Machine Extension
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
75.8	49.5	100.3	49.5	113.5	49.5	50.9	49.5	13.2	36.3
122.9	74.5	156.4	74.5	182.7	74.5	90.5	74.5	23.5	51.0
175.8	99.5	216.5	99.5	256.0	99.5	133.6	99.5	34.7	64.8
233.3	124.5	344.2	149.5	332.6	124.5	225.6	149.0	58.6	90.4
248.6	132.6	480.2	200.0	421.4	154.0	248.0	157.7	64.4	93.3
247.6	132.5	481.5	200.5	421.5	154.0	274.4	174.5	71.2	103.3
247.6	132.5	480.3	200.5	420.9	154.0	324.7	199.5	84.3	115.2
247.7	132.5	479.8	200.5	420.7	154.0	331.0	203.0	85.9	117.1
247.6	132.5	479.1	200.5	420.6	154.0	375.8	224.5	97.6	126.9
248.6	132.5	476.1	199.5	420.6	154.0	414.0	236.8	107.5	129.3
248.5	132.5	475.9	199.5	420.5	154.0	420.0	240.2	109.0	131.2
248.1	132.5	475.9	199.5	420.4	154.0	427.2	244.3	110.9	133.4
247.9	132.5	475.8	199.5	420.3	154.0	480.0	274.5	124.6	149.9
248.0	132.5	475.6	199.5	420.2	154.0	500.0	277.2	129.8	147.4
330.9	166.0	640.5	259.5	562.1	198.0	533.3	295.7	138.5	157.2
331.0	166.5	640.5	259.5	562.0	198.0	560.0	310.5	145.4	165.1
330.9	166.5	640.5	259.5	562.0	198.0	587.1	324.5	152.4	172.1
330.8	166.5	640.4	259.5	561.3	198.0	640.0	349.0	166.2	182.8
332.3	167.0	640.4	259.5	561.3	198.0	641.4	300.7	166.5	134.2
332.1	166.5	640.5	259.5	561.2	198.0	696.5	326.5	180.8	145.7
331.7	166.5	640.4	259.5	561.2	198.0	700.0	328.2	181.7	146.5
331.4	166.5	637.4	258.5	561.2	198.0	719.7	337.4	186.9	150.5
331.3	166.5	637.4	258.5	561.1	198.0	800.0	375.1	207.7	167.4
331.2	166.5	637.4	258.5	561.1	198.0	840.0	437.8	218.1	219.7
415.0	199.5	800.2	315.0	701.0	240.5	868.2	452.5	225.4	227.1
415.1	199.5	800.2	315.5	703.0	240.5	924.3	467.8	240	227.8
415.0	199.5	800.2	315.5	703.0	240.5	960.0	491.0	249.2	241.8
415.0	199.5	800.2	315.5	702.6	240.5	980.8	502.5	254.6	247.9
414.6	199.5	800.0	315.0	702.0	240.5				
414.5	199.5	800.1	315.0	701.8	240.5				
414.5	199.5	800.1	315.5	701.7	240.5				
414.4	199.5	800.1	315.5	701.8	240.5				
414.4	199.5	800.1	315.5	701.4	240.5				
414.4	199.5	960.2	371.0	701.4	240.5				
499.3	231.5	960.2	371.0	840.6	281.5				
499.2	231.5	960.1	371.0	840.6	281.5				
499.1	231.5	960.1	371.0	840.3	281.0				
499.1	231.5	960.0	371.0	839.4	281.0				
500.1	231.5	960.0	371.0	838.9	281.0				
500.5	231.5	960.0	371.0	838.9	281.0	Rod Test didn't have any "Hold at Load" values			
500.4	231.5	960.0	371.0	840.1	281.0	However did cover the full range of testing loads			
499.6	231.5	960.0	371.0	840.3	281.0	by scanning at a constant rate. Extrapolation is			
499.4	231.5	959.4	370.5	840.4	281.0	used to attend strains at loads not recorded.			