Preparation Torque Limit for Composites Joined with Mechanical Fasteners

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Current design guidelines for determining torque ranges for composites are based on tests and analysis from isotropic materials. Properties of composites are not taken into account. No design criteria based upon a systematic analytical and test analyses is available. This paper is to study the maximum torque load a composite component could carry prior to any failure. Specifically, the torque-tension tests are conducted. NDT techniques including acoustic emission, thermography and photomicroscopy are also utilized to characterize the damage modes.

I. Introduction

Aerospace structures utilize innovative, lightweight composite materials for exploration activities in low earth orbit, for the space shuttle and space station and will be used for future space exploration beyond low earth orbit to the moon, Mars and other destination as well as in future crew exploration vehicles. Due to size limitations, manufacturing facilities, contractual obligations or particular design requirements, the joining of composite components will be required. The common methodologies for joining composite components that have analytical precedence and practical applications are the adhesively bonded and mechanically fastened joints. In some applications both methods are simultaneously incorporated into the design. Guidelines and recommendations for establishing design criteria, analyzing and testing composites are readily available for engineers to adapt for their particular applications. However, guidelines and recommendations based on analysis and testing are not available for specifying a fastener torque range used in joining composite components. The purpose of this investigation is to develop an initial process for recommending a torque range to apply to metallic mechanical fasteners used to join composite components and select an acceptable non-destructive failure detection methodology to determine composite specimen failure.

Recommended torque values to apply to fasteners vary from industrial specifications, fastener type or specific applications. At NASA's Marshall Space Flight Center (MSFC) an in-house standard, MSFC-STD-486, "Standard Threaded Fasteners, Torque Limits for," is the guideline used to specify torque values and ranges. The torque values specified in MSFC-STD-486 are based on fastener tests and are dependant upon the fastener material and strength. The torque value is directly related to the tension in the fastener. When the fastener is used to join components and is tightened, the bolt elongates producing a tension or pre-load in the fastener which then results in a compressive load on the components being mated. Isotropic materials used to join components have documented material properties for design and analysis purposes. An-isotropic materials, such as laminated composites, require material properties in the through-the-thickness direction that may not be available and have, generally, much lower strength than that in the plane of isotropic materials.

One method for developing recommendations for torquing mechanical fasteners to join composite components involves testing composite specimens with bolts. To establish a testing methodology and acceptance/failure criteria the Torque versus Tension machine located at NASA's Marshall Space Flight Center is used to perform these tests. In addition, an Acoustic Emissions transducer is placed on each specimen, to capture the transient elastic waves generated during the tightening sequence for later analytical evaluation, to "listen" for any cracking of the matrix

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material or fiber breakage resulting from the compressive force during the tightening process. After test completion the specimen is subjected to thermography, a non-destructive evaluation technique that detects subsurface anomalies/defects by measuring thermal contrasts.

II. Experimental Study

A. Initial Torque vs. Tension Test

Two sets of torsion vs. tension tests were conducted – initial tests and follow on tests.

The material selected for initial tests was 3" wide IM7/8552 pre-preg tape, a typical aerospace composite material. Seventy-two (72) 5" x 5" test specimens were built and tested. Table 1 identifies the test matrix for the 72 test specimens with three different balanced and symmetrical configurations and three different fastener hole diameters: [0°, ±45°, 90°]3s, [0°, ±45°, 90°]4s, [0°, ±45°, 90°]5s, and ¼", ½" and ¾" diameter, respectively. The [0°, ±45°, 90°] configuration was selected base on MIL-HDBK-17, Polymer Matrix Composites, guidelines and the size based on suggested edge distance and width to diameter ratios of 3 and 6, respectively. The following 180 ksi ultimate tensile strength fasteners were utilized in performing the tests: ¼"-28 NAS1954C32, ½"-20 NAS1958C32 and ¾"-16 NAS1962C32.

Table 1. Specimens for Initial Tests

Configuration	Thickness (in.)	Hole Diameter (in.)	Qty
[0°, ±45°, 90°]3s	.132	.261 – .272	8
[0°, ±45°, 90°]3s	.132	.531 – .562	8
[0°, ±45°, 90°]3s	.132	.781 – .812	8
[0°, ±45°, 90°]4s	.176	.261 – .272	8
[0°, ±45°, 90°]4s	.176	.531 – .562	8
[0°, ±45°, 90°]4s	.176	.781 – .812	8
[0°, ±45°, 90°]5s	.220	.261 – .272	8
[0°, ±45°, 90°]5s	.220	.531 – .562	8
[0°, ±45°, 90°]5s	.220	.781 – .812	8

The primary objectives of this initial series of tests are to determine a valid test methodology and acceptance/failure criteria. The test methodology selected is the same technique used by MSFC to establish torque limits on mechanical fasteners and is deemed acceptable for performing similar tests - not on the bolts - but on the composite material being reacted against. The only modification to this methodology for determining torque limits of a composite specimen is that the composite specimen is placed between the reaction plate and the nut/washer. Also it is noted that the reaction plate is specific to the Torque versus Tension machine and the composite specimen rests on the reaction plate. The reaction plate has a 2.0" diameter hole in the center that is used to provide collars for various sized fasteners during faster torque tests. Collars are not used during the composite material testing. The 2.0" diameter hole in the center of the reaction plates results in a bending of the composite specimen around the hole. However, the goal of this initial testing is to be able to detect failure; therefore the intent of these tests is to actually fail the composite to assess the acoustic emissions data and evaluate the effectiveness of the thermography results.

B. Follow on Torque vs. Tension Test

Realizing that the large hole in the reaction plate causes bending of the composite plate, eight new reaction plates were fabricated that match the Torque versus Tension machine requirements but have holes for each of the following fasteners: 1/4", 5/16", 3/8", 7/16", ½", 5/8", 9/16", and ¾" diameter. Utilizing these reaction plates, additional

Torque versus Tension testing was performed with additional test specimens. The new test specimens were fabricated from four different pre-impregnated materials to determine, if any, interaction between the various fiber and matrix combinations that are identified as follows:

1) high modulus graphite fiber and high strength structural epoxy matrix - IM7/8552
2) low modulus glass fiber and high strength structural epoxy matrix - S2GL/8552
3) intermediate modulus carbon fiber and high strength structural epoxy matrix - AS4/977-3
4) low modulus glass fiber and fire retardant structural epoxy matrix - HYE E773FR/S-2

Each of the four materials were fabricated in each of the following configurations: [0°, ±45°, 90°]3s, [0°, ±45°, 90°]4s, and [0°, ±45°, 90°]5s. The thickness of each material configuration varies because the pre-preg thicknesses varies. Specifically, for IM7/8552, t = 0.007"; for S2/8552, t = 0.006"; for AS4/977-3, t = 0.0085", and for E773FR/S-2, t = 0.0085'.

Table 2 identifies the test matrix and shows that each material type and material configuration was tested three times for each of the eight different bolt sizes resulting in 288 Torque versus Tension tests. The variation in thickness between the AS4/977-3 and E773FR/S-2 is presumed to be due to the different cure cycles. The bolts used are 180 KSI ultimate tensile strength fasteners as described in the NAS1953 thru NAS1970 fastener specification.

Table 2. Specimens for Follow on Tests

Thickness / Hole size	IM&/8552			S2/8552			AS4/997-3			S2/E773FR		
	.185	.245	.308	.145	.202	.250	.180	.243	.310	.203	.276	.340
.272 – .261	3	3	3	3	3	3	3	3	3	3	3	3
.332 – .323	3	3	3	3	3	3	3	3	3	3	3	3
.397 – .386	3	3	3	3	3	3	3	3	3	3	3	3
.468 – .452	3	3	3	3	3	3	3	3	3	3	3	3
.562 – .561	3	3	3	3	3	3	3	3	3	3	3	3
.600 – .570	3	3	3	3	3	3	3	3	3	3	3	3
.659 – .630	3	3	3	3	3	3	3	3	3	3	3	3
.812 – .781	3	3	3	3	3	3	3	3	3	3	3	3

C. Torque vs. Tension Tests

Testing consisted of installing a fastener in a specimen, placing the acoustic emission transducer on the test specimen and tightening the fastener until either the fastener reached its maximum tension allowable or the composite specimen failed. Figure 1 shows a test specimen in the Torque versus Tension Tester at MSFC. The bolt head is retained in a specialized fixture attached to the load cell of the Torque versus Tension Tester and the test specimen is positioned on a stationary reaction plate with the shank of the bolt protruding through the stationary reaction plate and the test specimen. A nut retains the test specimen to the stationary reaction plate. For this initial testing, the Torque versus Tension machine's standard reaction plate was used. The reaction plate provides a mounting area for the test specimen and provides the reaction to the torque induced compressive bolt load. The reaction plate has an approximately 2.0" diameter hole in the center. An adjustable torque sensor provides the tightening operation by turning the nut. The Torque versus Tension Tester records the bolt tension and corresponding torque produced during the tightening sequence.

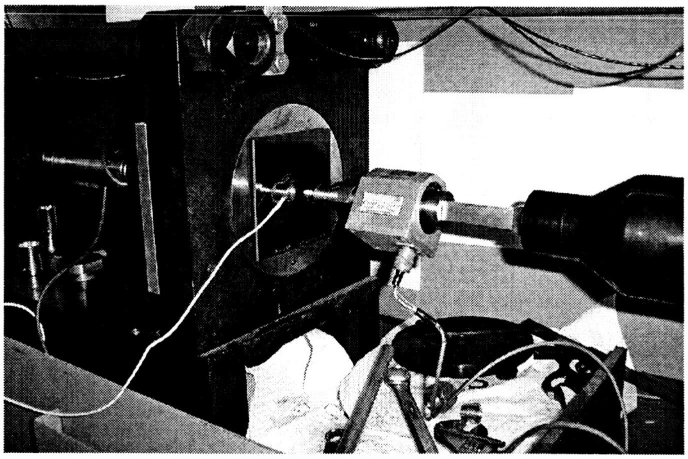

Figure 1. Torque versus Tension Tester

D. Acoustic Emission

Acoustic emission, according to ASTM, refers to the generation of transient elastic waves during the rapid release of energy from localized sources within a material. The source of these emissions is associated with the dislocation movement accompanying plastic deformation and the initiation and extension of cracks in a structure under stress. The Acoustic Emission NDT technique is based on the detection and conversion of these high frequency elastic waves to electrical signals. This is accomplished by directly coupling piezoelectric transducers on the surface of the structure under test and loading the structure. Sensors are coupled to the structure by means of a fluid couplant and secured. The output of the piezoelectric sensor during loading is amplified through a low-noise preamplifier, filtered to remove any extraneous noise and processed by electronic equipment. Acoustic data was recorded for all tests as well as torque versus tension data from the MSFC Torque-Tension machine. Figure 2 shows a graph of the AE energy and Tension versus Torque data from test specimen 17 - .132" thick, IM7/8552 using a 1/4" diameter fastener. AE energy is defined as the integral of the AE signal amplitude following the onset time. Failure, in these tests, occurs when the composite test specimen bends about the 2.0" diameter hole, a loud audible noise is heard by the test operator and the tension instantly decreases; although there is no visible damage to the test specimen. As shown in the graph the maximum energy occurs at the maximum tension. Also, as shown in Figure 2, AE activity does not occur until over halfway to "failure" indicating that there is no internal stress re-distribution in the initial tightening process. Note also that the torque values at "failure" are significantly higher than the recommended MSFC-STD-486 (Table VI) torque range of 5.8 to 7.0 ft*lb for a ¼" 180 KSI fastener.

It is necessary to indicate that the AE sensor detects stress waves only when stress waves are present i.e. the AE sensor detects and records when internal structural changes occur. If there are no internal structural changes then the AE sensor does not record data. The data generated in Figure 2 is based on test observations that the maximum AE energy occurs near the maximum tension. These results indicate that Acoustic Emissions is an applicable method for non-destructively determining internal structural changes during active testing.

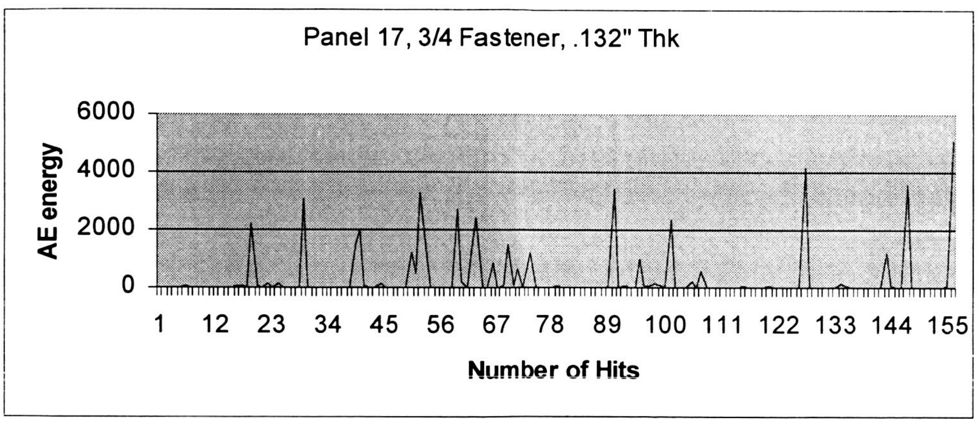

Figure 2. AE Energy vs. Number of Counts

E. Thermography and Photomicroscopy

After the specimens were tested, thermographic pictures were taken of the failed samples. Figure 3 shows the results of a typical sample of both front, early and late, and back, early and late, response to thermal imaging. The white areas indicate subsurface delaminations around the bolt holes and the early images show defects closer to the surface than that of the late images. In addition, photomicroscopy was utilized on one sample to investigate whether the damage was due to fiber breakage or matrix delamination. Here, the samples were sectioned through the damage zones detected with thermography, polished and viewed under a 50x digital photomicroscope. Figure 4 shows the photomicroscopy results and a delamination at the mid-plane where the maximum interlaminar shear stress occurs. Although not all specimens had photomicroscopy performed on them, from the testing methodology and the thermography results, it is observed that all specimens failed due to delaminations around the bolt hole, but not fiber breakage, resulting from excessive bending of the composite specimen around the large hole in the stationary reaction plate.

III. Results and Discussion

A. Initial Torque vs. Tension Test

A summary of the torque values at "failure" for the three thicknesses with three different fastener sizes are shown in Table 3. The results are from the average of eight (8) tests per thickness and fastener size. The torque data listed in the "Torque" column are the torque values at failure of the composites. For reference the MSFC-STD-486 values are also listed. For the ¼" diameter fasteners the torque values from testing far exceeds the recommended torque range but are not appropriate for practical applications due to the fact that the bolt is now overloaded. For the ½" diameter fasteners the torque values from testing are about on-half the recommended values and the ¾" diameters fastener the torque values from testing are approximately equal to the recommended values. However, the Torque versus Tension data along with the Acoustic Emissions data provides an indication of the compressive load required to cause internal structural stresses that might cause failure to the matrix or fiber.

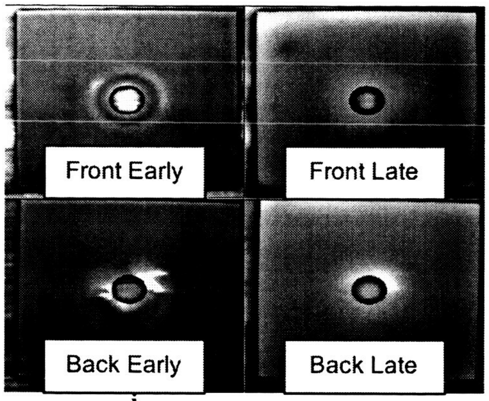

Figure. 3 Thermographic Images

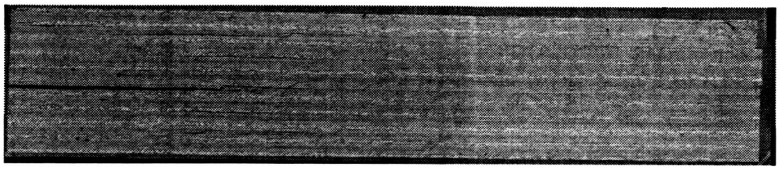

Figure 4. Photomicroscopy

Table 3. Comparison of Torque/Tension Limit for IM7/8552 [0/±45/90]

Fastener Size	Specimen Thickness (in)	Torque in.lb(ft.ib)	MSFC-STD-486 in.lb(ft.lb)
NAS1954C ¼"	.132	254 (21.1)	70 – 85 (5.8 – 7.0)
	.176	225 (18.7)	
	.220	234 (19.5)	
NAS1958C ½"	.132	294 (24.5)	620 – 730 (51.6 – 60.8)
	.176	433 (36.0)	
	.220	448 (37.3)	
NAS1962C ¾"	.132	1160 (96.6)	1930 – 2270 (160.8 – 189.1)
	.176	2228 (185.6)	
	.220	2307 (192.2)	

B. Follow on Test

The follow on tests were performed exactly as described for the initial testing except that the torque vs. tension machine was constrained to torque to the maximum value specified in MSFC-STD-486 (Table VI) and the reaction plate has a hole in the center that corresponds to the fastener size. Table 4 is a summary of the follow on test results including the Torque and corresponding Tension. Each value represents the average of three tests as described in Table 2.

Table 4 - Torque and Tension Results from Follow on Tests

Fastener		1/4"		5/16"		3/8"		7/16"	
Material	Thickness (in.)	Torque (ft.lb)	Tension (lb)	Torque (ft.lb)	Tension (lb)	Torque (ft.lb)	Tension (lb)	Torque (ft.lb)	Tension (lb)
IM7/8552	0.185	7.0	1550	13.3	2282	25.2	2691	41.4	4591
	0.245	7.0	1350	13.1	2155	25.3	2507	41.9	4760
	0.308	7.0	1444	13.1	2161	25.3	2662	42.4	4781
AS4/977-3	0.180	7.0	1552	13.2	2019	25.4	2975	40.4	4519
	0.243	7.0	1394	13.1	2026	25.2	2834	40.4	4614
	0.310	7.0	1388	13.1	2124	25.1	2835	40.5	4562
S2/8552	0.145	6.9	1539	13.2	2697	25.4	3289	40.4	4839
	0.202	7.0	1566	13.0	2366	25.2	2612	40.5	4697
	0.250	6.9	1522	13.2	2404	25.5	3155	42.9	4967
S2/E773FR	0.203	7.0	1335	13.1	2135	25.1	2998	40.7	4353
	0.276	7.0	1495	13.0	2070	25.1	3082	42.2	4918
	0.340	7.0	1429	13.0	1908	25.2	2537	40.3	4588
Fastener		1/2"		9/16"		5/8"		3/4"	
Material	Thickness (in.)	Torque (ft.lb)	Tension (lb)	Torque (ft.lb)	Tension (lb)	Torque (ft.lb)	Tension (lb)	Torque (ft.lb)	Tension (lb)
IM7/8552	0.185	61.4	7256	82.6	7774	115.6	8235	186.6	17644
	0.245	61.0	7073	84.7	7647	115.7	7967	193.4	13274
	0.308	61.1	7059	84.6	7839	117.7	7733	189.1	11964
AS4/977-3	0.180	61.1	7381	84.5	7204	115.2	9402	188.5	26570
	0.243	61.6	7261	85.3	7610	116.2	8562	189.0	26258
	0.310	64.0	7399	85.1	7181	127.2	8816	188.0	20681
S2/8552	0.145	62.8	6879	85.2	7647	115.2	8901	190.5	27121
	0.202	67.2	7727	84.8	7762	116.1	8436	192.0	22462
	0.250	61.5	7295	84.6	7693	117.1	8555	191.3	16504
S2/E773FR	0.203	61.1	6043	84.7	6918	116.9	8283	189.0	26563
	0.276	61.4	6844	84.4	7547	116.9	8104	191.0	26733
	0.340	61.3	6320	85.0	7207	115.0	7946	186.6	30382

Referring to Figure 5, Acoustic Emissions Energy and Tension versus Torque At Maximum Torque and Tension, (typical of the results from initial testing) most of the internal structural deformation, due to bending, occurs as the tension approaches its maximum and the resulting acoustic energy levels are larger than during any other portion of the test. Table 5 summarizes the maximum acoustic energy levels recorded for the 72 initial tests and is the acoustic energy level at maximum torque and tension. Although the deformation is caused by bending, the key observations are that the deformation is captured by the acoustic sensor and essentially no acoustic waves are detected at the MSFC-STD-486 safe torque levels.

Table 6 summarizes the maximum acoustic energy levels recorded for the 288 follow on tests and indicates that the acoustic energy levels, for specimens torqued to the maximum specified in MSFC-STD-486, is not sufficient to cause damage to the composite component. In addition, each of the follow on tested specimens were subjected to themography analysis and revealed no indications of permanent internal damage. Therefore, the acoustic energy levels observed for these tests indicate that torquing to the values specified in MSFC-STD-486 are acceptable for the materials and thicknesses tested.

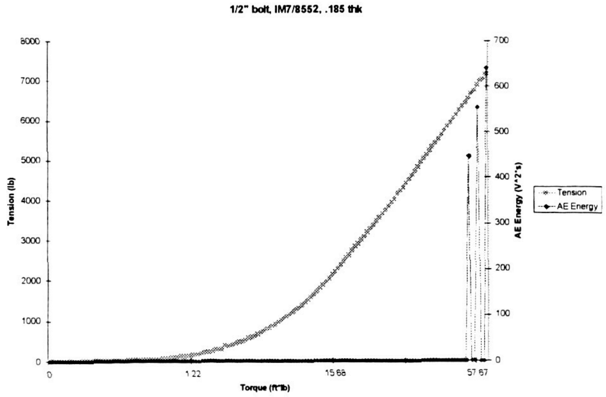

Figure 5. AE Energy and Tension vs. Torque At MSFC-STD-486 Torque Value

Table 5 - Acoustic Energy (V^2*s) Level for Initial Tests

Fastener Size			1/4"		1/2"		3/4"
Material	Thickness (in)	Specimen Panel Number	Acoustic Energy (V^2*s)	Specimen Panel Number	Acoustic Energy (V^2*s)	Specimen Panel Number	Acoustic Energy (V^2*s)
IM7/8552							
	0.132	Panel 41	14446	Panel 65	8398	Panel 17	5068
		Panel 42	428	Panel 66	6204	Panel 18	4237
		Panel 43	9891	Panel 67	5841	Panel 19	2662
		Panel 44	*	Panel 68	7676	Panel 20	5051
		Panel 45	9240	Panel 69	6600	Panel 21	5863
		Panel 46	21152	Panel 70	4344	Panel 22	6794
		Panel 47	8243	Panel 71	3507	Panel 23	4357
		Panel 48	20139	Panel 72	12850	Panel 24	5315
	0.180	Panel 33	6416	Panel 57	5689	Panel 9	2486
		Panel 34	3370	Panel 58	6204	Panel 10	3537
		Panel 35	2	Panel 59	7029	Panel 11	3375
		Panel 36	9825	Panel 60	5349	Panel 12	4128
		Panel 37	3429	Panel 61	7479	Panel 13	4863
		Panel 38	1607	Panel 62	6944	Panel 14	4332
		Panel 39	126	Panel 63	8453	Panel 15	2472
		Panel 40	2962	Panel 64	7287	Panel 16	2133
	0.220	Panel 25	5099	Panel 49	9811	Panel 1	#
		Panel 26	5210	Panel 50	9804	Panel 2	3453
		Panel 27	7697	Panel 51	11743	Panel 3	**
		Panel 28	7697	Panel 52	5485	Panel 4	3887
		Panel 29	45	Panel 53	4814	Panel 5	4582
		Panel 30	-	Panel 54	8810	Panel 6	4504
		Panel 31	-	Panel 55	6092	Panel 7	*
		Panel 32	-	Panel 56	6204	Panel 8	*

Table 6. Acoustic Energy (V^2 *s) Levels for Follow on Tests

Fastener Size	Thickness (in.)	Specimen	1/4"	5/16"	3/8"	7/16"	1/2"	9/16"	5/8"	3/4"
IM7/8552	0.185	A	4	*	*	28	642	*	*	*
		B	32	16	*	78	129	*	*	74
		C	81	*	351	33	*	*	*	25
	0.245	A	*	*	*	1	414	*	*	9
		B	16	34	17	*	358	*	*	2
		C	13	*	*	51	3	*	*	18
	0.308	A	8	126	*	*	*	6	26	6
		B	8	*	*	7	89	*	*	33
		C	-	143	*	127	7	*	26	32
AS4/977-3	0.180	A	28	*	20	*	17	4	*	37
		B	31	*	1	3	24	*	*	*
		C	81	152	6	6	*	*	15	6
	0.243	A	16	*	16	89	218	*	*	104
		B	128	*	93	*	1	16	*	12
		C	15	8	13	35	445	21	2	64
	0.310	A	25	*	11	21	243	7	2	*
		B	*	*	24	91	352	*	90	16
		C	3	*	58	3	314	*	2	*
S2/8552	0.145	A	9	*	*	*	52	*	1	27
		B	96	*	*	1	180	*	24	*
		C	*	*	12	*	485	*	20	*
	0.202	A	9	*	2	2	63	*	62	*
		B	4	*	22	*	57	*	28	14
		C	*	*	*	6	*	120	2	*
	0.250	A	18	38	67	9	*	*	42	24
		B	*	*	81	131	15	*	22	*
		C	*	*	70	16	-	*	24	37
S2/E773FR	0.203	A	16	*	49	*	*	*	25	*
		B	2	*	137	5	2	21	32	325
		C	6	16	*	9	*	*	96	2
	0.276	A	30	2	115	*	24	*	33	632
		B	5	*	61	*	76	*	*	517
		C	2	16	171	28	*	*	*	8
	0.340	A	*	*	65	*	*	4	249	35
		B	1	*	19	3	247	*	29	472
		C	*	*	32	55	69	*	30	9

IV. Conclusion

Two series of tests, one including 72 test specimens and the other 288 test specimens, were performed to determine the validity of utilizing MSFC-STD-486, "Standard Threaded Fasteners, Torque Limits for," for applying torque values to metallic fasteners used to join composite components. A non-destructive evaluation technique, acoustic emissions, was used to access damage to the test specimen during the torquing sequence. The initial 72 composite components were tested to failure to ascertain failure limits which were determined, through testing, to be the maximum tension (and torque) at the maximum recorded acoustic energy level. The follow on set of 288 test specimens were subjected to the same conditions as the initial set of test specimens except that the torque was constrained to the maximum allowed per MSFC-STD-486. The results from these tests indicated that there was none to very minor internal stress distributions and no permanent internal damage to any of the composite test specimens torqued to the maximum values for the thicknesses and materials tested.

The utilization of MSFC-STD-486 for torquing composite components using the materials, material thicknesses, fasteners sizes and fastener type identified in this report is recommended. However, for other thickness, materials, fastener sizes, hole tolerances, fastener types, etc. it is recommended that torque vs. tension tests be preformed using acoustic emissions to monitor the acoustic energy levels. Also, these tests were limited to a single fastener. It is recommended that similar tests be performed that include multiple fasteners.

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