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Experimental Observations for Determining the Maximum Torque Values to Apply to Composite Components Mechanically Joined With Fasteners

(MSFC Center Director's Discretionary Fund Final Report, Project No. 03–13)

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ACRONYMS

AE	acoustic emissions
MSFC	Marshall Space Flight Center
NDT	nondestructive technique

TECHNICAL MEMORANDUM

EXPERIMENTAL OBSERVATIONS FOR DETERMINING THE MAXIMUM TORQUE VALUES TO APPLY TO COMPOSITE COMPONENTS MECHANICALLY JOINED WITH FASTENERS
(MSFC Center Director's Discretionary Fund Final Report, Project No. 03–13)

1. INTRODUCTION

Aerospace structures utilize innovative, lightweight composite materials for exploration activities in low-Earth orbit for the Space Shuttle and the *International Space Station*. Composite structures will be used for future space exploration beyond low-Earth orbit to the moon, Mars, and other destinations in crew exploration vehicles and habitats. These structural components will take advantage of the high strength-to-weight ratio, good thermal characteristics, and tailorability offered by composite structures. For a variety of reasons, including size limitations, manufacturing facilities, contractual obligations, or particular design requirements, the joining of composite components will be required. Adhesively bonded and mechanically fastened joints are common methodologies for joining composite components that have analytical precedence and practical applications. 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 intent of this investigation is to develop an initial process for determining the maximum torque values to apply to mechanical fasteners used to join composite components and hence, the initiation of a recommended torque limit that designers utilize when specifying torque values to join composite components with mechanical fasteners.

2. PURPOSE

The objective of this investigation is to develop an initial process for determining the maximum torque values to apply to mechanical fasteners used to join composite components, and select an acceptable nondestructive failure detection methodology to determine composite specimen failure. The intent is to generate a recommended torque limit to apply to composite components joined with mechanical fasteners that designers specify on manufacturing drawings.

3. BACKGROUND

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, "Torque Limits for Standard Threaded Fasteners"[1] 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 preload 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. Anisotropic materials, such as laminated composites, require material properties in the through-the-thickness direction that may not be available and generally have much lower strength than that in the plane of isotropic materials.

4. TASK DESCRIPTION

An obvious method for developing a testing process for torquing mechanical fasteners to join composite components is to test composite specimens with bolts. The torque versus tension machine, located at MSFC, is used to establish a testing methodology and acceptance/failure criteria. In addition, an acoustic emissions (AE) transducer is placed on each specimen to capture the transient elastic waves generated during the tightening sequence. The AE transducer listens for any cracking of the matrix material or fiber breakage resulting from the compressive force during the tightening process. After test completion the specimen is subjected to thermography, a nondestructive evaluation technique that detects surface and subsurface anomalies and defects by measuring thermal contrasts through the thickness of the test specimen.

The primary objective of this initial series of tests is 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. It is also 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-in diameter hole in the center that is used to provide collars for various sized fasteners during faster torque tests. One of these collars is replaced with the composite specimen during testing. The 2-in diameter hole in the center of the reaction plate 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 AE data and evaluate the effectiveness of the thermography results.

5. MATERIAL SELECTION/TEST SPECIMEN CONFIGURATION

The material selected to initiate this task was 3-in wide IM7/8552 prepreg tape, a typical aerospace composite material. This particular material was left over from a previous composite intertank development task. Since the material was out of date, tensile tests were performed to verify the original properties of the material.[2] Seventy-two 5×5-in test specimens were built and tested. Table 1 identifies the test matrix for the 72 test specimens with three different balanced and symmetrical material lay-up configurations and three different fastener hole diameters: $[0°,\pm45°,90°]3_s$, $[0°,\pm45°,90°]4_s$, $[0°,\pm45°,90°]5_s$, and ∅ ¼ in, ∅ ½ in, and ∅ ¾ in, respectively. The $[0°,\pm45°,90°]3_s$, $[0°,\pm45°,90°]4_s$, $[0°,\pm45°,90°]5_s$ corresponds to specimen thickness of 0.132 in (24 layers), 0.176 in (32 layers), and 0.220 in (40 layers). The [0°,±45°,90°] balanced and symmetrical material layup configuration was selected based on guidelines from MIL–HDBK–17, "Polymer Matrix Composites,"[3] and the size was based on MIL–HDBK–17 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: 1/4 in-28 NAS1954C32, 1/2 in-20 NAS1958C32, and 3/4 in-16 NAS1962C32.

Table 1. Test matrix for initial 72 test specimens.

Configuration	Thickness (in)	Hole Diameter (in)	Quantity
$[0°,\pm45°,90°]3_s$	0.132	0.261–0.272	8
$[0°,\pm45°,90°]3_s$	0.132	0.531–0.562	8
$[0°,\pm45°,90°]3_s$	0.132	0.781–0.812	8
$[0°,\pm45°,90°]4_s$	0.176	0.261–0.272	8
$[0°,\pm45°,90°]4_s$	0.176	0.531–0.562	8
$[0°,\pm45°,90°]4_s$	0.176	0.781–0.812	8
$[0°,\pm45°,90°]5_s$	0.220	0.261–0.272	8
$[0°,\pm45°,90°]5_s$	0.220	0.531–0.562	8
$[0°,\pm45°,90°]5_s$	0.220	0.781–0.812	8

6. TESTING

Testing consisted of installing a fastener in a specimen (table 1), placing the AE 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. Figure 2 is a graphic model of the torque versus tension test machine and identifies its major components. Figures 3 and 4 are a top view and a cross-sectional view of the torque versus tension machine, respectively. Figure 5 is a detailed view of the typical test setup. Figure 6 identifies the specific components of the test setup. The bolt head is retained in a specialized fixture attached to the load cell of the torque versus tension tester. 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-in diameter hole in the center. An adjustable torque transducer provides the tightening operation by turning the nut. The torque versus tension tester records the bolt tension and the corresponding torque produced during the tightening sequence.

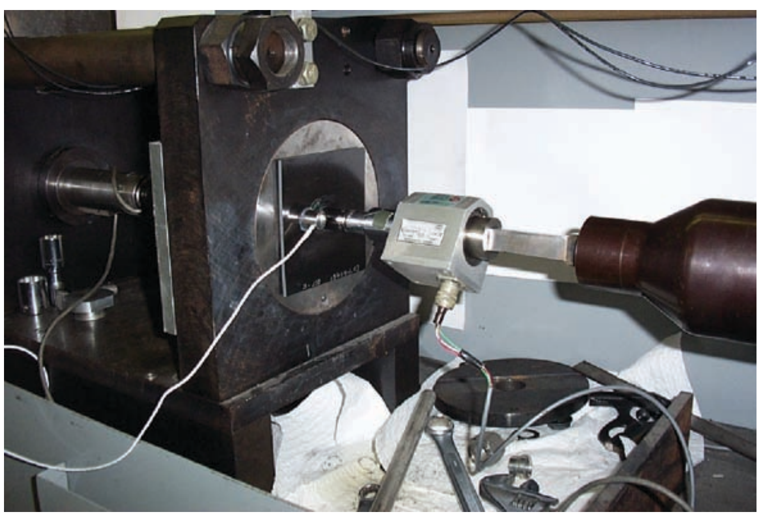

Figure 1. Torque versus tension test.

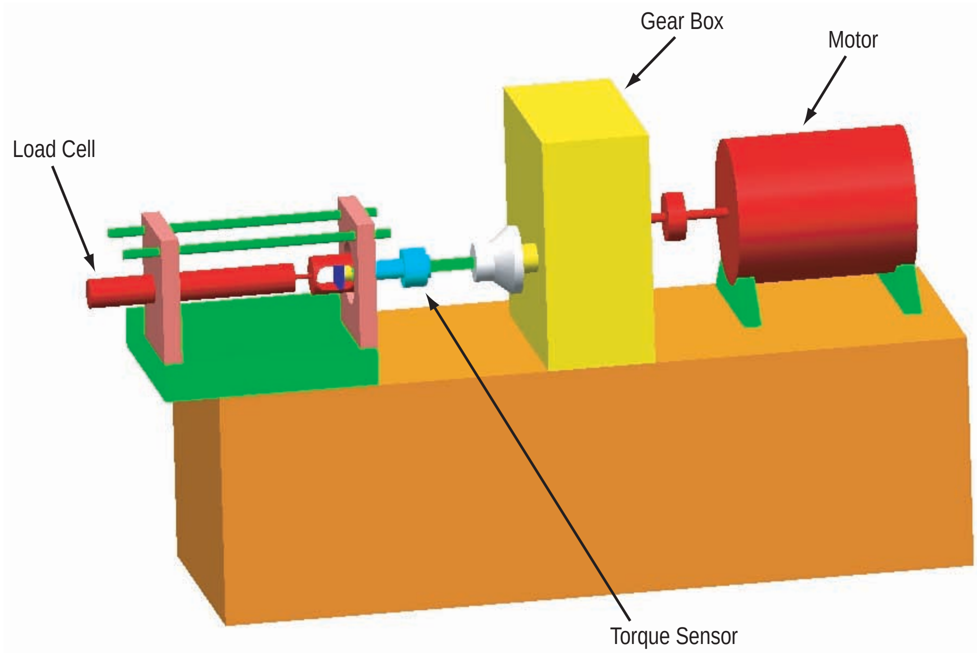

Figure 2. Torque versus tension machine configuration.

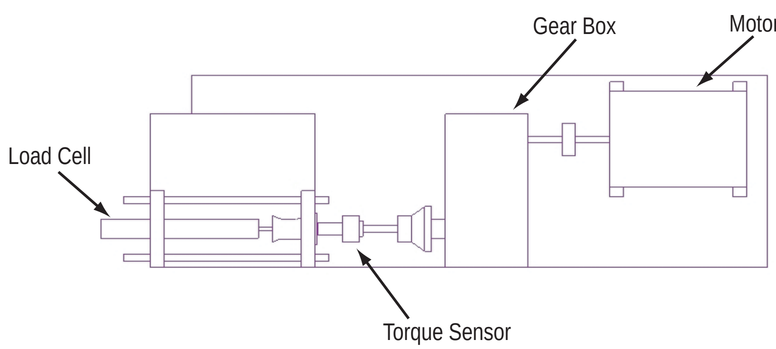

Figure 3. Top view of torque versus tension machine.

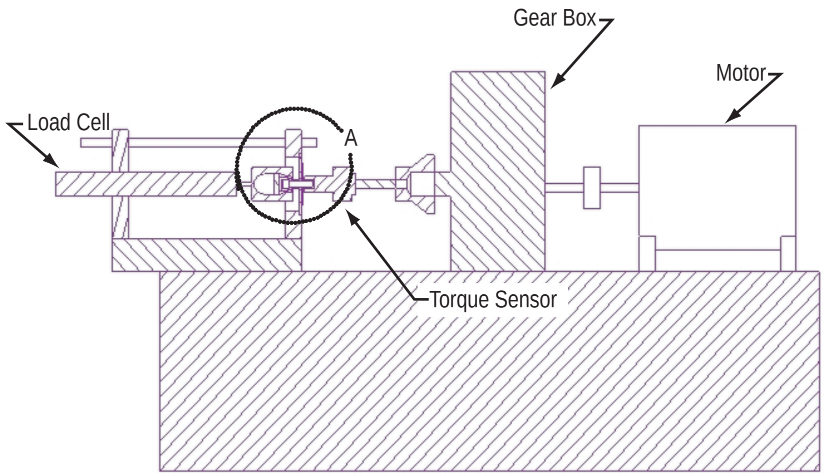

Figure 4. Torque versus tension cross section.

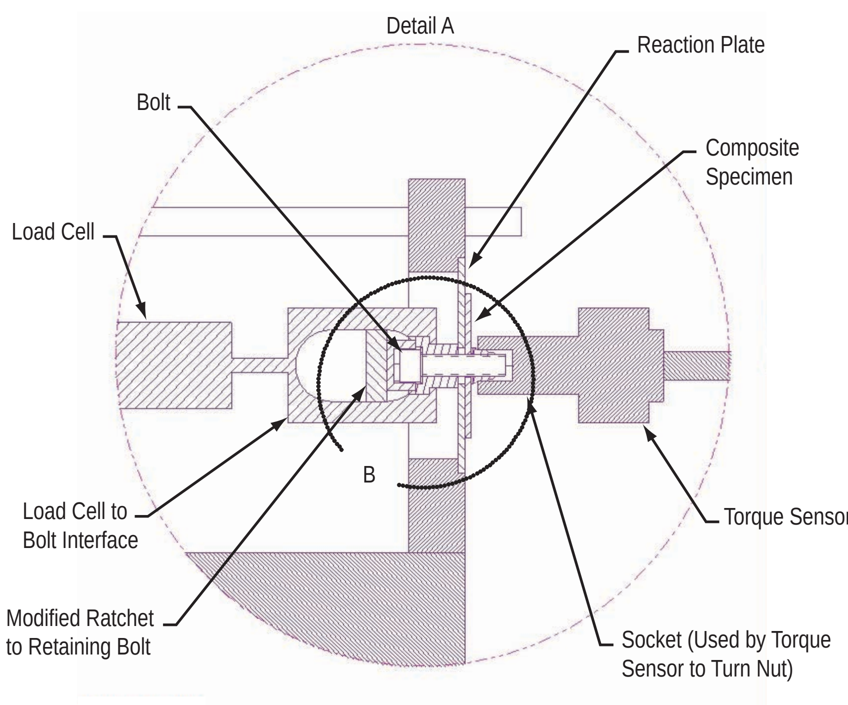

Figure 5. Detailed view of test setup.

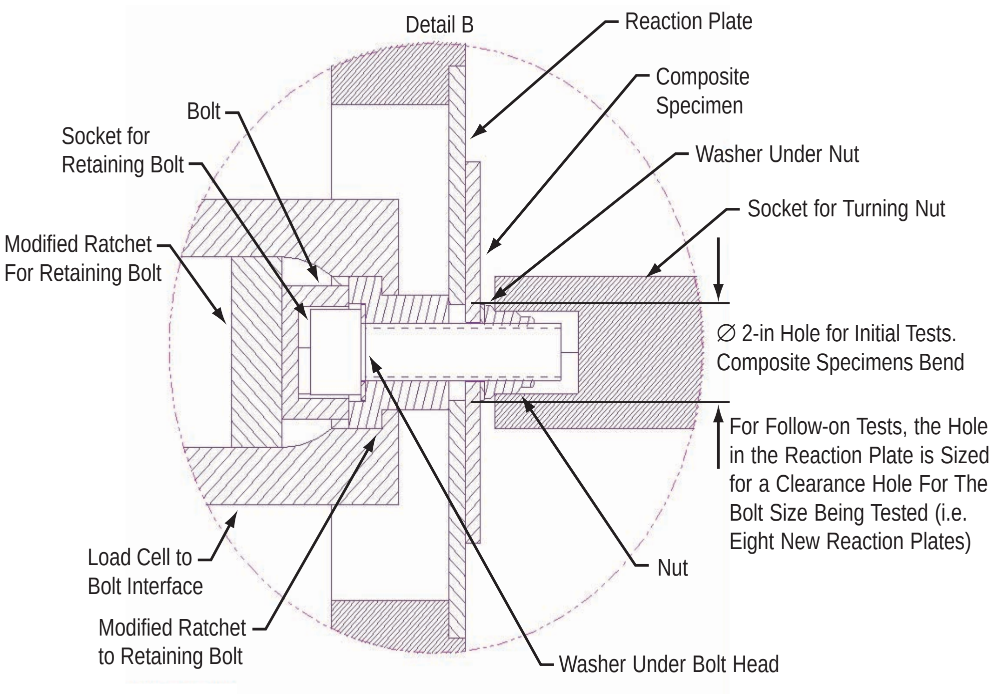

Figure 6. Details of specific test components.

7. TEST PROCEDURE

The detailed procedure used for performing the tests is as follows:

(1) Install bolt into load cell adapter with a washer under the bolt head.

(2) Adjust load cell position depending upon thickness of specimen.

(3) Mount test specimen onto fastener.

(4) Lubricate panel around hole, to prevent noise during the initial tightening, and lubricate the washer and nut with Conoco grease.

(5) Install lubricated washer and nut.

(6) Provide an initial preload on the nut with a hand-held, spring-type torque wrench so that the specimen and the stationary reaction plate are adjacent to one another.

(7) Retain the fastener head with a standard socket and modified ratchet.

(8) Attach the torque transducer to the nut. Tightening is performed from the nut.

(9) Attach the AE sensor to the panel. Initially the sensor was hot glued, which was also used as the coupling fluid to the specimen, but after a few tests the sensor would either come off due to the released energy of the failed specimen, especially for the 3/4-in fasteners, and be destroyed or the sensor would be destroyed due to operator difficulties in removing the sensor from the hot glue. The preferred method was to use vacuum grease as the coupling fluid and tape the sensor to the specimen.

(10) Turn on the AE data acquisition system.

(11) Begin the test by turning on the torque versus tension tester data acquisition system and motor to drive the torque transducer.

As the nut is tightened the tension load on the bolt, and hence the compressive load on the composite test specimen, increases and bending occurs around the 2-in diameter hole. Failure of the composite occurs when the tension and torque suddenly decreases and a distinct audible noise can be heard. During the tightening operation an audible noise is heard, but the tension and torque continues to increase; therefore, for this initial testing, the test is continued until the tension and torque instantly decreases. The values obtained at failure are observed to be the maximum compressive load and maximum torque the composite specimen may withstand. The 2-in diameter hole in the center of the reaction plate results in bending of the flat composite specimen around the large hole. Therefore, the failure is caused by bending of the composite plate around the hole and not a true through-the-thickness tension failure. However, the intent of this task is to develop a testing procedure for torquing composite specimens and to develop a failure detection methodology. The testing procedure and utilization of the MSFC torque versus tension machine is appropriate for determining the torque to apply to composite components joined with metallic mechanical fasteners.

8. ACOUSTIC EMISSIONS

AE, according to the American Society for Testing Materials,[4] 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 AE nondestructive technique (NDT) 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 coupling 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 and torque versus tension data was recorded for all tests (appendix A). Figure 7 shows a graph of the AE energy and tension versus torque data, from test specimen 33, 0.176-in thick material IM7/8552 using a 1/4-in diameter fastener. AE energy is defined as the integral of the AE signal amplitude following the onset time. Failure in these tests occurred when the tension instantaneously decreased due to excessive bending of the composite test specimen about the 2-in diameter hole. As shown in the graph, the maximum energy occurs at the maximum tension. Also, as shown in figure 7, AE activity does not occur until over halfway to failure, indicating that there is no internal stress redistribution in the initial tightening process. Note also that the torque values at failure are significantly higher than those recommended in Table VI of MSFC–STD–486 with a torque range of 5.8–7 ft•lb for a 1/4-in 180 ksi fastener.

It is necessary to note 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 7 is based on test observations that the maximum AE energy occurs near the maximum tension. These results indicate that AE is an applicable method for nondestructively determining internal structural changes during active testing.

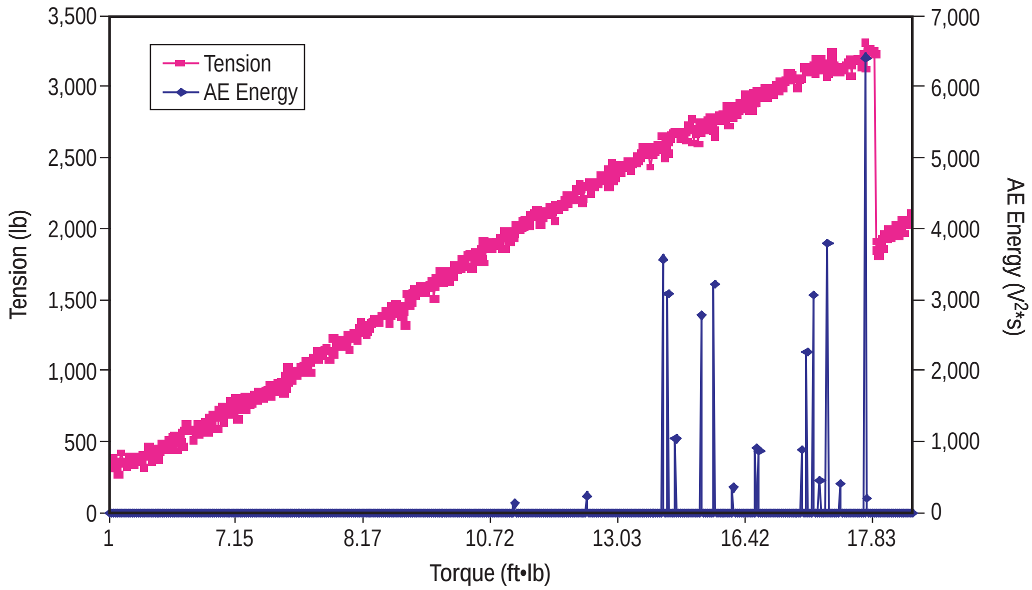

Figure 7. Torque versus tension and torque versus acoustic emissions energy—specimen 33.

9. TORQUE VERSUS TENSION DATA ANALYSIS RESULTS

A summary of the torque values at failure for the three thicknesses with three different fastener sizes is shown in table 2. The results are from the average of eight tests per thickness and fastener size. The torque data listed in table 2 are the torque values at failure of the composites.[1] For reference, the values identified in the MSFC–STD–486, Table V are the recommended torque values to apply to the respective fasteners. For the 1/4-in 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 1/2-in diameter fasteners, the torque values from testing are about one-half the recommended values, and for the 3/4-in diameter fasteners the torque values from testing are approximately equal to the recommended values. Because of the 2-in diameter hole in the reaction plate these results are not indicative of preferred design practices, but they do indicate that the process of utilizing the torque versus tension machine for determining torque values for fastening composite components is suitable and that using AE transducers is an acceptable failure detection methodology.

Table 2. Torque values from initial tests.

Fastener Size	Specimen Thickness (in)	Torque (in•lb)	Torque (ft•lb)	MSFC–STD–486 Table VI[1] (in•lb)	MSFC–STD–486 Table VI[1] (ft•lb)
NAS1954C 1/4 in	0.132	254	21.1	70–85	5.8–7.0
	0.176	225	18.7		
	0.220	234	19.5		
NAS1958C 1/2 in	0.132	294	24.5	620–730	51.6–60.8
	0.176	433	36.0		
	0.220	448	37.3		
NAS1962C 3/4 in	0.132	1,160	96.6	1,930–2,270	160.8–189.1
	0.176	2,228	185.6		
	0.220	2,307	192.2		

Comparison of torque/tension limit for IM7/8552 [0,±45,90]

10. THERMOGRAPHY

After the specimens were tested, thermographic pictures were taken of the failed samples. Figure 8 shows the front, early and late, and back, early and late, results of a typical sample response to thermal imaging. Early pictures show shallow defects while late images show deeper defects in the laminate. Because the thicknesses of the specimens were pushing the limits of the equipment, thermographs were taken from both front and back sides. 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 two samples to investigate whether the damage was due to fiber breakage or matrix delamination. A sample was sectioned through the damage zones detected with thermography, polished, and viewed under a $\times$ 50 digital photomicroscope. Figure 9 shows the photomicroscopy results and a delamination at the midplane where the maximum interlaminar shear stress occurs. Although not all specimens had photomicroscopy performed on them, it is observed that all specimens failed due to delaminations around the bolt hole. The thermography results indicate that on some specimens there is damage and on other specimens there are no detectable defects. However, it cannot be conclusively determined from the thermography results if the defect is from delamination or fiber breakage. The samples that had photomicroscopy performed were 0.132-in and 0.220-in thick composite specimens, with 3/4-in diameter fastener holes, and neither indicated fiber breakage. All specimens were tested in the same manner. From test observations and the photomicroscopy performed, it is highly unlikely that there were any fiber breakage defects in the specimens tested.

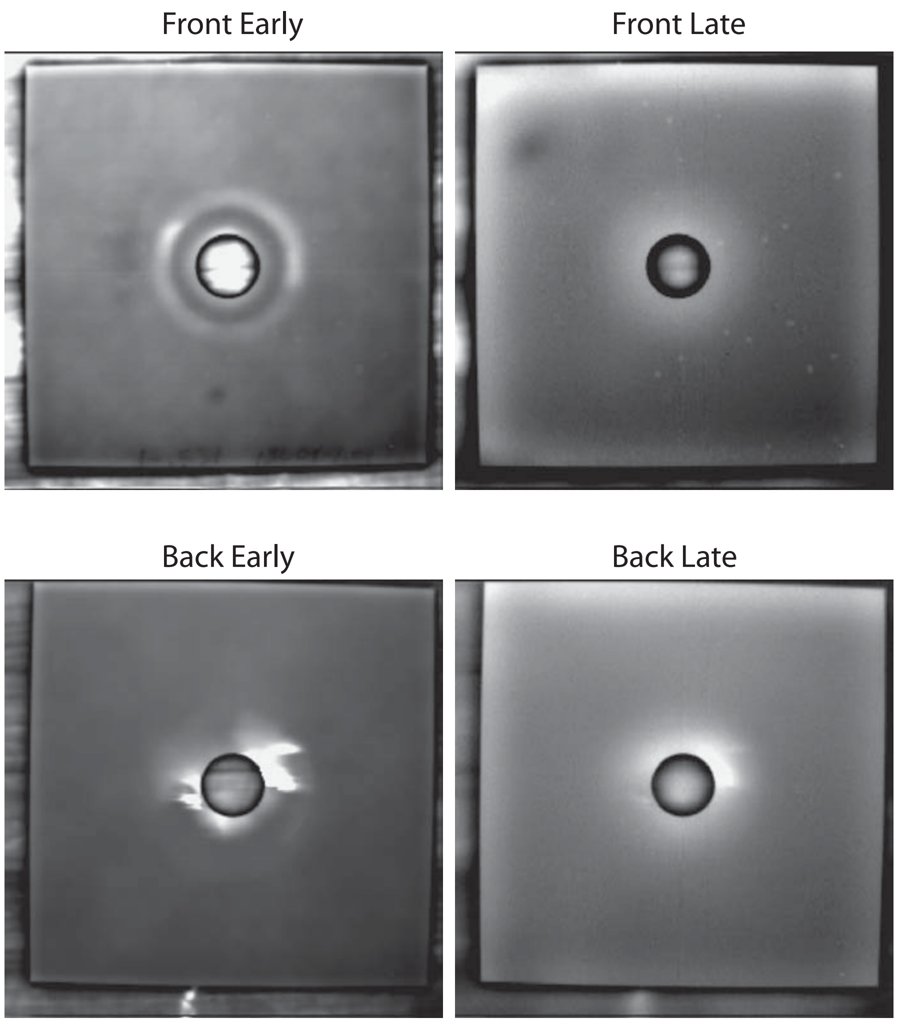

Figure 8. Thermal images of test specimen.

Figure 9. Photomicroscopy.

11. FOLLOW-ON TESTING TASK DESCRIPTION

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 in, ∅ 5/16 in, ∅ 3/8 in, ∅ 7/16 in, ∅ 1/2 in, ∅ 5/8 in, ∅ 9/16 in, and ∅ 3/4 in. The intent of the follow-on testing is to evaluate the composite specimen when subjected to the maximum torque recommended in MSFC–STD–486, Table VI.

12. FOLLOW-ON TESTING MATERIALS AND CONFIGURATION

Utilizing the new reaction plates, another set of torque versus tension testing was performed with additional test specimens. The additional test specimens were fabricated from four different preimpregnated materials to determine the interaction between the various fiber types and matrix combinations, if any, and are identified as follows:

- High-modulus graphite fiber and high-strength structural epoxy matrix—IM7/8552.
- Low-modulus glass fiber and high-strength structural epoxy matrix—S2/8552.
- Intermediate modulus carbon fiber and high-strength structural epoxy matrix—AS4/977–3.
- Low-modulus glass fiber and fire-retardant structural epoxy matrix—S2/E773FR.

Each of the four materials were fabricated in each of the following balanced and symmetrical material layup configurations: $[0°,\pm45°,90°]3_s$, $[0°,\pm45°,90°]4_s$, and $[0°,\pm45°,90°]5_s$. The thickness of each material configuration varies, as shown in table 3.

Table 3. Follow-on testing materials and configuration.

Material	Ply Thickness	$[0°,\pm45°,90°]3_s$ t (in)	$[0°,\pm45°,90°]4_s$ t (in)	$[0°,\pm45°,90°]5_s$ t (in)
IM7/8552	0.0070	0.185	0.245	0.308
S2/8552	0.0060	0.145	0.202	0.250
AS4/977–3	0.0085	0.180	0.243	0.310
S2/E773FR	0.0085	0.203	0.276	0.340

Table 4 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 through NAS1970 fastener specification.

Follow-on tests were performed exactly as described for the initial tests, except that the torque versus tension machine was constrained to torque to the maximum value as specified in MSFC–STD–486, Table VI, (table 5), and the hole in the center of the reaction plate corresponds to the fastener size. Tables 6(a) and 6(b) are 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 4.

Table 4. Test matrix for follow-on test specimens.

	IM7/8552			S2/8552			AS4/977–3			S2/E773FR		
	Thickness (in)											
Hole ∅	0.185	0.245	0.308	0.145	0.202	0.250	0.180	0.243	0.310	0.203	0.276	0.340
0.272–0.261	3	3	3	3	3	3	3	3	3	3	3	3
0.332–0.323	3	3	3	3	3	3	3	3	3	3	3	3
0.397–0.386	3	3	3	3	3	3	3	3	3	3	3	3
0.468–0.452	3	3	3	3	3	3	3	3	3	3	3	3
0.562–0.561	3	3	3	3	3	3	3	3	3	3	3	3
0.600–0.570	3	3	3	3	3	3	3	3	3	3	3	3
0.659–0.630	3	3	3	3	3	3	3	3	3	3	3	3
0.812–0.781	3	3	3	3	3	3	3	3	3	3	3	3

Table 5. MSFC–STD–486 standard torque values.

Fastener Size	MSFC–STD–486 (Table VI) Torque (ft•lb)
∅1/4	5.8–7.0
∅5/16	11.2–13.3
∅3/8	21.2–25.0
∅7/16	33.7–40.0
∅1/2	51.6–60.8
∅9/16	71.6–84.1
∅5/8	97.0–114.1
∅3/4	160.8–189.1

Table 6. (a) Torque and tension results from follow-on tests for fastener sizes 1/4 in, 5/16 in, 3/8 in, and 7/16 in. (b) Torque and tension results from follow-on tests for fastener sizes 1/2 in, 9/16 in, 5/8 in, and 3/4 in.

Material	Thickness (in)	Fastener Size							
		1/4 (in)		5/16 (in)		3/8 (in)		7/16 (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	1,550.0	13.3	2,282.1	25.2	2,691.3	41.1	4,590.7
	0.245	7.0	1,349.7	13.1	2,154.8	25.3	2,506.5	41.9	4,759.9
	0.308	7.0	1,443.8	13.1	2,160.7	25.3	2,662.4	42.4	4,780.7
AS4/977–3	0.180	7.0	1,551.6	13.2	2,019.0	25.4	2,974.7	40.4	4,518.5
	0.243	7.0	1,394.4	13.1	2,026.4	25.2	2,834.2	40.4	4,614.0
	0.310	7.0	1,387.8	13.1	2,124.4	25.1	2,834.5	40.5	4,561.5
S2/8552	0.145	6.9	1,539.3	13.2	2,697.2	25.4	3,288.7	40.4	4,838.5
	0.202	7.0	1,565.5	13.0	2,366.1	25.2	2,612.2	40.5	4,696.8
	0.250	6.9	1,521.7	13.2	2,403.7	25.5	3,155.4	42.9	4,967.2
S2/E773FR	0.203	7.0	1,335.4	13.1	2,134.8	25.1	2,998.4	40.7	4,352.7
	0.276	7.0	1,474.9	13.0	2,069.8	25.1	3,082.4	42.2	4,918.1
	0.340	7.0	1,429.0	13.0	1,908.1	25.2	2,537.3	40.3	4,587.6
MSFC–STD–486	–	7.0	–	13.3	–	25.0	–	40.0	–

(a)

Material	Thickness (in)	Fastener Size							
		1/4 (in)		5/16 (in)		3/8 (in)		7/16 (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	7,255.5	82.6	7,774.0	115.6	8,235.3	186.6	17,644.2
	0.245	61.0	7,073.3	84.7	7,646.6	115.7	7,966.6	193.4	13,273.5
	0.308	61.1	7,058.7	84.6	7,838.8	117.7	7,732.7	189.1	11,964.1
AS4/977–3	0.180	61.1	7,380.8	84.5	7,203.9	115.2	9,401.8	188.5	26,570.4
	0.243	61.6	7,260.7	85.3	7,610.3	116.2	8,562.0	189.0	26,257.8
	0.310	64.0	7,399.1	85.1	7,180.9	127.2	8,815.8	188.0	20,680.8
S2/8552	0.145	62.8	6,878.5	85.2	7,647.0	115.2	8,900.8	190.5	27,121.0
	0.202	67.2	7,727.4	84.8	7,762.0	116.1	8,435.7	192.0	22,461.8
	0.250	61.5	7,295.3	84.6	7,693.2	117.1	8,555.3	191.3	16,503.8
S2/E773FR	0.203	61.1	6,042.9	84.7	6,917.8	116.9	8,283.3	189.0	26,563.3
	0.276	61.4	6,844.4	84.4	7,547.3	116.9	8,103.9	191.0	26,732.9
	0.340	61.3	6,319.5	85.0	7,207.4	115.0	7,946.3	186.6	30,382.0
MSFC–STD–486	–	60.8	–	84.1	–	114.1	–	189.1	–

(b)

Referring to figure 7, torque versus tension and torque versus AE energy—specimen 33, 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 7 summarizes the maximum acoustic energy levels recorded for the 72 initial tests. The maximum acoustic energy level occurs at the maximum 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, Table VI safe torque levels. This indicates that there is no evidence of damage to the specimen at the MSFC–STD–486, Table VI torque levels.

Table 7. Acoustic energy (V^2*s) levels for initial tests.

Material	Thickness (in)	Fastener Size					
		1/4 (in)		1/2 (in)		3/4 (in)	
		Specimen Panel No.	Acoustic Energy (V^2*s)	Specimen Panel No.	Acoustic Energy (V^2*s)	Specimen Panel No.	Acoustic Energy (V^2*s)
IM7/8552	0.132	41	14,446	65	8,398	17	5,068
		42	428	66	6,204	18	4,237
		43	9,891	67	5,841	19	2,662
		44	*	68	7,676	20	5,051
		45	9,240	69	6,600	21	5,863
		46	21,152	70	4,344	22	6,794
		47	8,243	71	3,507	23	4,357
		48	20,139	72	12,850	24	5,315
	0.180	33	6,416	57	5,689	9	2,486
		34	3,370	58	6,204	10	3,537
		35	2	59	7,029	11	3,375
		36	9,825	60	5,349	12	4,128
		37	3,429	61	7,479	13	4,863
		38	1,607	62	6,944	14	4,332
		39	126	63	8,453	15	2,472
		40	2,962	64	7,287	16	2,133
	0.220	25	5,099	49	9,811	1	#
		26	5,210	50	9,804	2	3,453
		27	7,697	51	11,743	3	**
		28	7,697	52	5,485	4	3,887
		29	45	53	4,814	5	4,582
		30	–	54	8,810	6	4,504
		31	–	55	6,092	7	*
		32	–	56	6,204	8	*

– Indicates AE sensor fell off during test.
Initial test specimen, AE sensor intentionally not attached to specimen.
** AE sensor not calibrated.
* Indicates AE sensor attached to specimen, however no AE data was generated.

Figure 10 shows the results from a follow-on test using a 1/2-in bolt, IM7/8552 material, 0.185-in thick specimen that was torqued to a maximum of 61 ft•lb. This test specimen had the highest acoustic energy level, 642 V^2*s, of all the follow-on tests performed. The acoustic energy level recorded is significantly less than as observed in the initial tests, but suggests that there may be minor movement of the internal structure. This is most likely due to redistribution of the matrix material during the torquing sequence. Also, detectable acoustic energy waves could be generated by the rubbing of the washer against the composite component or the metallic socket. Table 8 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, Table VI, is not sufficient to cause damage to the composite component. In addition, each of the follow-on tested specimens were subjected to thermography analysis and revealed no indications of permanent internal damage (appendix B). Therefore, the acoustic energy levels observed for these tests indicate that torquing to the values specified in MSFC–STD–486, Table VI are acceptable for the materials and thicknesses tested.

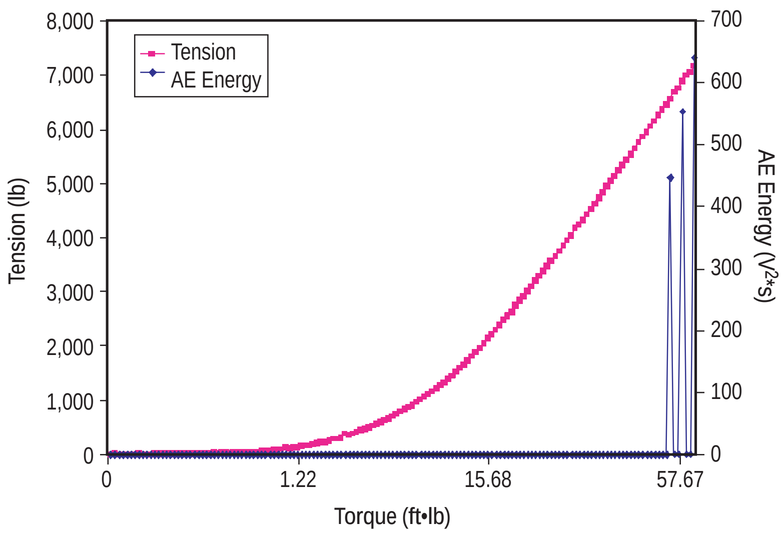

Figure 10. Torque versus tension and torque versus acoustic emissions energy follow-on test with 1/2-in bolt, IM7/8552 material, 0.185-in thick.

Table 8. Acoustic energy (V^2*s) levels for follow-on tests.

Material	Thickness (in)	Specimen	Fastener Size							
			1/4 (in)	5/16 (in)	3/8 (in)	7/16 (in)	1/2 (in)	9/16 (in)	5/8 (in)	3/4 (in)
			Acoustic Energy (V^2*s)							
IM7/8552	0.185	A	4	*	*	28	642	*	*	*
		B	32	16	*	78	129	*	*	74
		C	#	*	351	33	*	*	*	29
	0.245	A	*	*	*	1	414	*	*	9
		B	13	34	17	*	358	*	*	2
		C	16	*	*	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	*	2	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	3	*	11	21	527	7	2	*
		B	25	*	24	91	352	*	90	16
		C	*	*	58	3	314	*	2	*
S2/8552	0.145	A	9*	*	*	*	52	*	1	27
		B	9	*	*	1	180	*	24	*
		C	96	*	12	*	485	*	20	*
	0.202	A	*	*	2	2	63	*	62	*
		B	9	*	22	*	57	*	28	14
		C	4	*	*	6	*	120	2	*
	0.250	A	*	38	67	9	*	*	42	24
		B	18	*	81	131	15	*	22	*
		C	*	*	70	16	–	*	24	37
S2/E773FR	0.203	A	16	*	49	*	*	*	25	*
		B	6	*	137	5	2	21	32	325
		C	167	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

– Indicates AE sensor fell off during test.
* Indicates AE sensor was on specimen, however no AE data was generated.
# Data lost.

13. CONCLUSIONS

A process has been developed for recommending a torque range to apply to metallic mechanical fasteners used to join composite components. This process consists of a torque versus tension test, AE evaluation during torque versus tension testing, and nondestructive thermal images, thermographs, taken after the tests.

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, "Torque Limits for Standard Threaded Fasteners" for applying torque values to metallic fasteners used to join composite components. AE, a nondestructive evaluation technique, was used to assess damage to the test specimen during the torquing sequence. The initial 72 composite components were tested to failure to ascertain failure limits that were determined, through testing, to be the maximum tension and torque at the maximum acoustic energy level recorded. 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 288 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.

14. RECOMMENDATIONS

Utilization of MSFC–STD–486, “Torque Limits for Standard Threaded Fasteners” for torquing composite components using the materials, material thicknesses, fastener sizes, and fastener types identified in this report is recommended. However, for other thicknesses, materials, fastener sizes, hole tolerances, fastener types, etc. it is recommended that torque versus tension tests be performed using AE to monitor the acoustic energy levels. Because these tests were limited to a single fastener it is also recommended that similar tests be performed that include multiple fasteners.

APPENDIX A—TEST RESULTS FROM INITIAL 72 TEST SPECIMENS

Contact Frank Thomas at 256–544–4936 or frank.p.thomas@nasa.gov for either a paper copy or electronic copy.

APPENDIX B—TEST RESULTS FROM 288 FOLLOW-ON TEST SPECIMENS

Contact Frank Thomas at 256–544–4936 or frank.p.thomas@nasa.gov for either a paper copy or electronic copy.

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13. ABSTRACT *(Maximum 200 words)* Aerospace structures utilize innovative, lightweight composite materials for exploration activities. These structural components, due to various reasons including size limitations, manufacturing facilities, contractual obligations, or particular design requirements, will have to be joined. The common methodologies for joining composite components are the adhesively bonded and mechanically fastened joints and, in certain instances, both methods are simultaneously incorporated into the design. Guidelines and recommendations exist for engineers to develop design criteria and analyze and test composites. However, there are no guidelines or recommendations based on analysis or test data to specify a torque or torque range to apply to metallic mechanical fasteners used to join composite components. Utilizing the torque tension machine at NASA's Marshall Space Flight Center, an initial series of tests were conducted to determine the maximum torque that could be applied to a composite specimen. Acoustic emissions were used to nondestructively assess the specimens during the tests and thermographic imaging after the tests.			
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