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Influence of Clamp-Up Force on the Strength of Bolted Composite Joints

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Introduction

COMPOSITE materials offer the potential for a reduction in the number of individual parts and joints in a structure because large one-piece components can replace multipart assemblies. Nevertheless, there are many situations where composite parts must be joined and often mechanical fasteners provide the only practical method of joining those parts. The long-term strength of mechanically fastened joints of composite members can be directly affected by the clamp-up force of the fastener and thus perhaps by the relaxation of this force due to the viscoelastic character of the composite materials of the joint.

Collings[1] provided a comparison of the behavior of composite joints with pins with no lateral constraint, finger-tight lateral constraint, and high lateral constraint. Stacking sequence and fiber orientation were shown to affect the bearing strength for the three constraint conditions considered. Experimental results by Crews[2] for graphite/epoxy laminates indicated that increasing fastener clamp-up force in a joint improved both the static strength and fatigue limit. A further study by Crews and Naik[3] concluded that the lateral support provided by the bolt clamp-up force influenced both the amount of hole elongation and the failure mode.

Shivakumar and Crews[4] used a two-dimensional finite element analysis to investigate the viscoelastic response of a simple bolted joint of graphite/epoxy laminates. An empirical equation was developed to calculate the clamp-up force as a function of time, material properties, and initial clamp-up force. The analysis predicted a clamp-up force relaxation of up to 31% after 20 years at room temperature/dry conditions. Slepetz et al.[5] investigated bolt clamp-up relaxation for highly clamped tension connectors for composite sandwich panels. Results indicated that the clamp-up force relaxation was not excessive at room temperature and below, but it was significant for higher temperatures near the service limit.

Methods for predicting the effect of bolt clamp-up force relaxation on the strength of mechanically fastened joints of thermoplastic composite materials were investigated during the present study. A test program, using two thermoplastic composite materials, was conducted to determine the influence of clamp-up force on joint strength, to measure the relaxation of the joint clamp-up force with time, and to measure the change of joint strength as a function of time.

Received Sept. 18, 1992; revision received July 25, 1993; accepted for publication Aug. 3, 1993.

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Test Description and Procedures

A two-phase test program was developed. The objective of the phase 1 testing was to establish a correlation between joint strength and fastener clamp-up force while the phase 2 tests were to quantify the short-time relaxation in the clamp-up force and to then measure the influence of relaxation on the joint strength.

Sixteen specimens of each of two composite materials, Dupont's IM6/KIII and ICI-Fiberite's IM8/APC(HTA), were tested during the phase 1 tests. A specimen of each material was tested for each of the possible combinations of two temperatures, two fastener types, and four torque levels. The two temperature conditions considered were room temperature (25.6°C)/dry and hot (121.1°C)/dry. Fastener types included both protruding head and countersink head titanium fasteners with nominal shank diameters of 0.635 cm. Torque levels of 0 (finger-tight), 3.39, 7.34, and 11.3 m-N were utilized to produce the desired range of clamp-up force.

Twelve specimens of each material were tested during the phase 2 tests. Both materials, the two fastener types, and the two temperature conditions were retained in the test array, but the number of torque levels was reduced to two (7.34 and 11.3 m-N) since the relaxation of the fastener clamp-up force would be more pronounced for the higher torque values. In addition, the time of duration of clamp-up force and in-plane tensile load were added as two new parameters. The 24 specimens of phase 2 were tested approximately 30 days after the application of the clamp-up force. Some of the specimens were also subjected to an in-plane axial tensile load to determine what effect in-service joint loading might have on the measured relaxation.

Each test coupon was a 32-ply quasi-isotropic laminate with a stacking sequence of $(45/90/\text{-}45/0)_{4s}$ and dimensions of 3.81×15.24 cm. A 0.635-cm-diam fastener hole was located 1.905 cm from each end of the coupon on the lengthwise centerline. Coupons prepared for the countersink fasteners had one of the two holes countersunk to a depth of 0.274 cm.

A single-shear joint was chosen for the test configuration since it permitted the use of both countersink and protruding head fas-

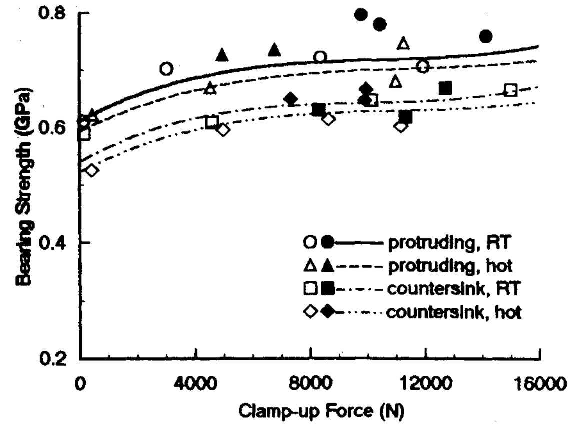

Fig. 1 Bearing strength vs clamp-up force for IM8/APC(HTA).

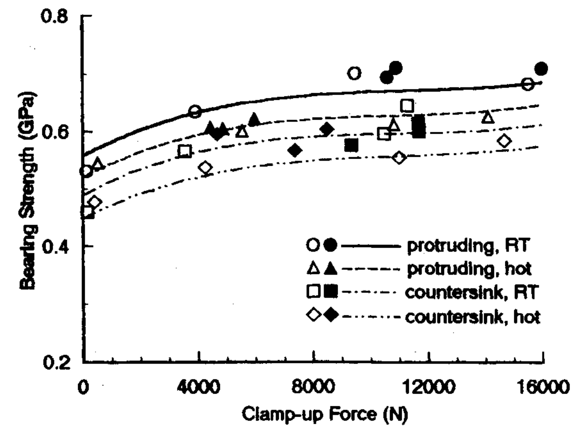

Fig. 2 Bearing strength vs clamp-up force for IM6/KIII.

Table 1 Summary of test results for IM8/APC(HTA)

Torque, m-N	Axial load	Time, h	F_t/F_o	Clamp-up force, N	Bearing stress, GPa
Protruding fastener, 25.6°C					
0	no	0	1	151	0.610
3.39	no	0	1	3,029	0.701
7.34	no	0	1	8,376	0.721
11.30	no	0	1	11,957	0.705
11.30	no	744	0.942	14,145	0.759
7.34	yes	696	0.954	9,794	0.796
11.30	yes	696	0.969	10,449	0.779
Protruding fastener, 121.1°C					
0	no	0	1	449	0.620
3.39	no	0	1	4,542	0.668
7.34	no	0	1	10,996	0.680
11.30	no	0	1	11,263	0.746
11.30	no	768	bad	sensor	0.705
7.34	yes	792	0.876	4,951	0.726
11.30	yes	792	0.910	6,775	0.734
Countersink fastener, 25.6°C					
0	no	0	1	151	0.588
3.39	no	0	1	4,599	0.608
7.34	no	0	1	10,160	0.647
11.30	no	0	1	15,017	0.666
11.30	no	744	0.966	17,188	0.669
7.34	yes	696	0.956	8,323	0.630
11.30	yes	696	0.955	11,343	0.618
Countersink fastener, 121.1°C					
0	no	0	1	418	0.525
3.39	no	0	1	4,991	0.594
7.34	no	0	1	8,652	0.613
11.30	no	0	1	11,183	0.602
11.30	no	768	0.936	9,973	0.666
7.34	yes	792	0.902	7,348	0.649
11.30	yes	792	0.913	9,933	0.647

Table 2 Summary of test results for IM6/KIII

Torque, m-N	Axial load	Time, h	F_t/F_o	Clamp-up force, N	Bearing stress, GPa
Protruding fastener, 25.6°C					
0	no	0	1	129	0.530
3.39	no	0	1	3,906	0.632
7.34	no	0	1	9,466	0.698
11.30	no	0	1	15,502	0.681
11.30	no	744	0.913	10,898	0.707
7.34	yes	744	0.926	10,582	0.691
11.30	yes	744	0.933	15,978	0.707
Protruding fastener, 121.1°C					
0	no	0	1	520	0.543
3.39	no	0	1	5,529	0.597
7.34	no	0	1	10,809	0.609
11.30	no	0	1	14,092	0.623
11.30	no	792	0.900	5,961	0.620
7.34	yes	840	0.883	4,866	0.602
11.30	yes	840	0.857	4,435	0.605
Countersink fastener, 25.6°C					
0	no	0	1	151	0.458
3.39	no	0	1	3,554	0.563
7.34	no	0	1	10,471	0.593
11.30	no	0	1	11,285	0.632
11.30	no	744	0.922	11,677	0.611
7.34	yes	696	0.915	9,337	0.573
11.30	yes	696	0.951	11,681	0.597
Countersink fastener, 121.1°C					
0	no	0	1	409	0.475
3.39	no	0	1	4,252	0.535
7.34	no	0	1	11,000	0.552
11.30	no	0	1	14,661	0.582
11.30	no	768	0.901	8,483	0.601
7.34	yes	840	0.807	7,371	0.564
11.30	yes	840	0.850	4,675	0.593

teners in the composite specimen. The joint test assembly consisted of a composite test coupon, steel pull strap, and a 0.635-cm titanium fastener with collar. The steel pull strap was designed to counteract the eccentricity of the single-shear joint and thus minimize the effects of bending loads.

Titanium protruding head and 100-deg countersink head fasteners were used as joint fasteners. A steel 0.081-cm-thick flat washer was placed underneath the head of all of the protruding head fasteners and a steel self-locking collar was used for both fastener types. Three air wrenches, each preset to one of the three torque levels of 3.38, 7.34 and 11.3 m-N, were used to apply the required torque to the fasteners.

Initial fastener clamp-up force and subsequent relaxation was measured using bolt force sensors which function as thin compression load cells. They employ a four-arm strain-gauge bridge to average the load distribution around the circumference of the fastener head.

Two back-to-back strain gauges were mounted to each test coupon to align the joint assembly within the test machine prior to loading and to monitor bending strain during the tests. A displacement extensometer was used during all failure tests to obtain a direct measurement of the elongation of the fastener hole within the composite specimen. A 245-kN (55 kip) universal testing machine was used for the 32 phase 1 tests, and a 98-kN (22 kip) universal testing machine was used for the remainder of the tests. An environmental chamber was mounted on the column standards of the 98-kN test machine to provide the elevated temperature environment. The temperature of the test specimen was monitored with a thermocouple taped directly to the specimen surface.

The phase 2 tests to monitor the relaxation of clamp-up force were conducted in two sets with a total of 12 specimens being monitored simultaneously in each set. The first set was tested at room temperature/dry conditions while the second set was placed in an oven at 121°C. The joint assemblies were either sealed in a plastic bag or placed in an airtight container with packages of desiccant to absorb the moisture in the air.

Results

The joint failure strength for each test specimen was determined from the uniaxial tensile load and displacement data. Several failure criteria were considered to determine the joint failure strength. The failure criteria chosen involved constructing an offset line parallel to the initial linear portion of the load-displacement curve. An offset of 4% of the nominal fastener diameter was used and the load at the intersection of the offset line and the load-displacement curve was defined to be the load for joint failure. This approach provided consistent results and in most cases the failure load determined from the stroke-load curves was nearly identical to that obtained from the extensometer-load curves using this same offset method.

A summary of the joint failure results and corresponding test parameters for the phase 1 and phase 2 tests of the IM8/APT(HTA) specimens is given in Table 1. The clamp-up force values are those obtained immediately prior to the start of the failure test. The phase 2 results include the added test parameters of specimen inplane uniaxial tensile load, the elapsed time over which relaxation of the clamp-up force was monitored, and the ratio of the measured clamp-up force F_t at the end of the relaxation time period to the initial clamp-up force F_o. Table 2 contains a similar summary of the test results for the IM6/KIII material.

A graphical presentation of these test results for the IM8/APC(HTA) material are presented in Fig. 1 while Fig. 2 contains a similar presentation for the IM6/KIII material. These two figures also contain curves generated by the application of a multiple correlation statistical analysis code[6] to the phase 1 test results. Even though these curves are based on a limited amount of test data, they were used as an attempt to represent the trends found between the variables of the tests. They indicate that for both materials increasing clamp-up force increased the joint bearing strength and increasing the temperature decreased the joint strength. In addition, the strength of the joint with protruding head fasteners was greater than that of the joint with countersink fasteners. The general shape of these curves is similar to the results presented by Crews[3] for graphite/epoxy joints.

The normalized relaxation ratio F_t/F_o in Table 1 shows the fastener clamp-up force relaxation ranging from a minimum of approximately 3% to a maximum of 19% over the 30-day period. An average of 4% more relaxation was measured for the IM6/KIII material than for the IM8/APC(HTA) material. The clamp-up force relaxation for the hot/dry condition was approximately 5% greater than for the room-temperature condition. The magnitude of clamp-up force had a minimal effect upon the amount of relaxation observed. The fastener head type was found to have no effect on the amount of relaxation.

Conclusions

The clamp-up force was determined to have a significant effect on the strength of a mechanically fastened composite material joint. The maximum measured increase in joint strength was 28% over that of a finger-tight joint. Other variables determined to affect the joint strength were fastener head type, material, and temperature.

The clamp-up force relaxation of the short-term tests did not significantly lower the joint strength of either material. Long-term relaxation tests or prediction analyses based upon the short-term test results would be necessary to predict the influence of long-term joint relaxation on joint strength.

Acknowledgments

This research program was jointly sponsored by The Boeing Company, Wichita and the Kansas Technology Enterprise Corporation. The authors wish to thank Gary Cassatt, Jim Westermann, and William J. Renton for their support of this effort.

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