



Effects of Specimen Geometry on Flatwise Tensile Strength

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Summary

The through-thickness or flatwise strength of a uniaxial polymer matrix composite was investigated with several test specimen geometries and starting plate thicknesses. The use of thinner plates is desirable to save material and lower costs during materials development programs. The various configurations gave similar results with the exception of thin, straight-sided specimens. Thin specimens tended to provide invalid results per ASTM International D7291; however, the addition of a large, shallow radius improved the results. The Weibull distribution provided a good fit to the combined data.

Introduction

Enabling efficiency, reliability, low noise, and low emissions from the next generation of fixed-wing aircraft will require the use of lightweight, multifunctional materials with improved structural and thermal capabilities. State-of-the-art carbon fiber/resin composites address a number of these requirements. A well-known drawback of laminated composites, however, is the low through-thickness (out-of-plane) strength.

The through-thickness or flatwise tensile (FWT) strength of composite materials is needed for the simulation of complex structures, analysis of thick sections such as fan and motor containment systems, and analysis of support structures in vertical takeoff and landing (VTOL) vehicles because large through-thickness stresses can develop. Further, an adequate materials database is needed for correlation to larger scale impact test (Ref. 1), to verify simulation models (Ref. 2), and as input to system reliability models being developed for electric propulsion components in urban air mobility (UAM) vehicles (Ref. 3).

The FWT strength and elastic modulus are limiters of composite performance because they are dominated by the resin properties, which are much lower than those of the reinforcing fibers that dominate the in-plane behavior.

This study measures the FWT strength and modulus of elasticity for a common epoxy/carbon fiber system manufactured as thick and thin plates. During composite development studies, it is more cost effective to manufacture thin plates than thick plates. However, machining the usual spool-type specimen from relatively thin (0.125 to 0.25 in.) plates is not practical or representative of the unit cell for many composite systems. To compare the effect of thin versus thick plates and test section geometry on FWT results, four specimen designs were compared.

Material

Test specimens were fabricated from unidirectional tape prepreg carbon fiber-reinforced polymer. The fibers in the material were IM7-G 12K carbon fibers from Hexcel Corporation. The bulk plies in each specimen consisted of conventional 8552 resin from Hexcel® (HexPly® 8552 prepreg).

Flatwise Tensile (FWT) Strength

The standard testing method specified in ASTM International D7291 (Ref. 4) allows a variety of geometries and, as part of the baseline material study for a bonding project, a comparison was made to determine if significant differences exist and if material could be conserved by reducing the thickness of the starting plate and thus the test specimen.

Five FWT strength tests were performed per ASTM D7291 with the geometries shown in Figure 1. The FWT test involves coring disks from a plate of the material, machining the surfaces parallel if necessary, bonding the cored disk to pull-tabs, machining the tabs and disk concentric, strain gaging the disks, and aligning and loading the resultant specimens to failure. Figure 2 shows the various stages of specimen production and testing.

Because a standard 1-in.-diameter coupon was used for FWT strength testing, coupon stress analysis was not performed beyond the experimental comparisons described in the following sections. Some analysis of the FWT test configuration can be found in NASA/TM—2019-220055 (Ref. 5).

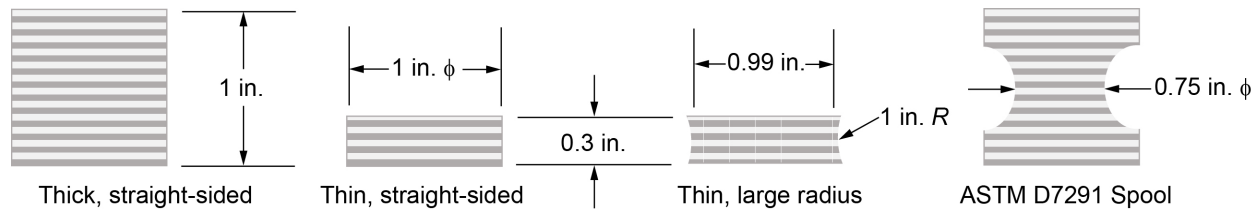


Figure 1.—Geometry and dimensions of 1-in.-diameter FWT test specimens.



Figure 2.—Stages of specimen production and testing. (a) Starting plate with cutting layout. (b) Cored specimens with faces ground parallel. (c) Specimens bonded to tabs and turned concentric. (d) Spool gage section cut into straight-sided specimens. (e) and (f) Strain gaged specimens mounted in the test rig. Pull-tab diameter is nominally 1 in.

Figure 3 shows an example stress–train curve for a baseline spool test; Table I shows the bending strains for this test. Figure 4 shows the average strength with a 90-percent confidence interval. Summary statistics are given in Table II. Stress–strain behavior is nearly linear, with abrupt failure exhibited. Analysis of variance (ANOVA) indicated that the strength differences between thick and thin plates machined in the different configurations are not significantly different at 95 percent or better, with the exception of the thin, straight-sided specimens. These were made from the thick plate by thinning cored plugs. Four of five specimens failed through a mix of the surface ply and the adhesive and thus were invalid (SA type failure per D7291). The one valid test exhibited a strength of 7,996 psi, similar to that of the other geometries. That result is not significantly different from the tall specimen results but differs from the thin-radius results and the spools. The thinning process may have damaged the materials and influenced the results. Therefore, all data except for that from the thin, straight-sided specimens were combined to provide an engineering value.

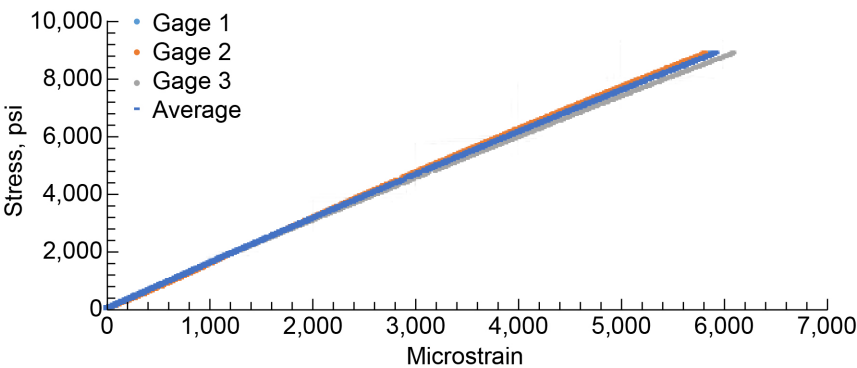


Figure 3.—Example stress–strain curve for baseline spool test.

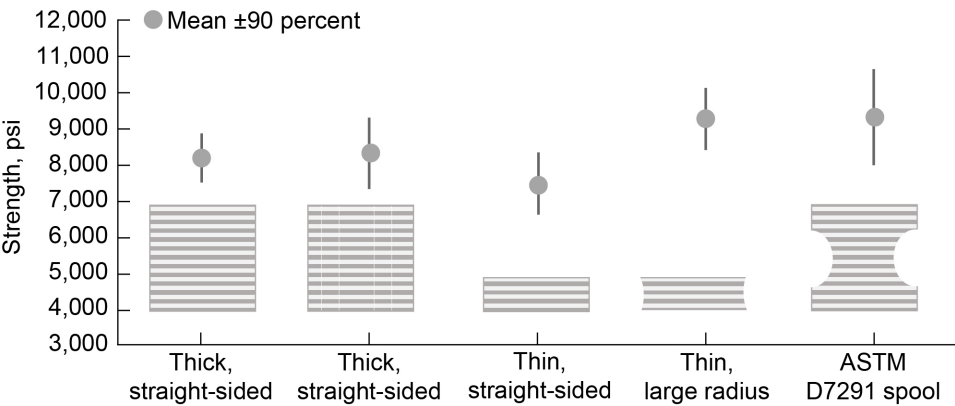


Figure 4.—Average strength with 90 percent confidence intervals. Five tests were run per group.

TABLE I.—BENDING STRAINS FOR BASELINE SPOOL TEST	
Load = 760 lb	b ₁ = 10
Strain 1 = 1,018	b ₂ = 5
Strain 2 = 1,043	b ₃ = -15
Strain 3 = 1,038	θ = 0.87
Average = 1,033	Max. bending = 15
-----	Percent bending = 1

TABLE II.—SUMMARY STATISTICS

Specimen type	Fracture strength, ^a psi	Elastic modulus, ×10 ⁶ psi	Failure strain, %	Percent bending, (at 1,000 μe)	Break distance, %	Comments
Thick, straight-sided	8,208±711	1.72	0.50	4.2	25	Thick plate, set 1
Thick, straight-sided	8,120±990	1.65	0.51	10.8	23	Thick plate, set 2
Thin, straight-sided	7,497±845 ^b	1.87	0.41	5.1	SA	Thick plate
Large, shallow radius	9,304±925	1.63	0.60	7.4	22	Thin plate
Standard spool	9,341±1,414	1.57	0.62	2.9	31	Thick plate
Pooled data	8,743±1,126	1.64±0.06	0.56±0.09	6.5 ±2.3	-----	-----

^aOne standard deviation.

^bSA—All but one of five specimens failed through a mix of the surface ply and the adhesive. The one valid test exhibited a strength of 7,996 psi.

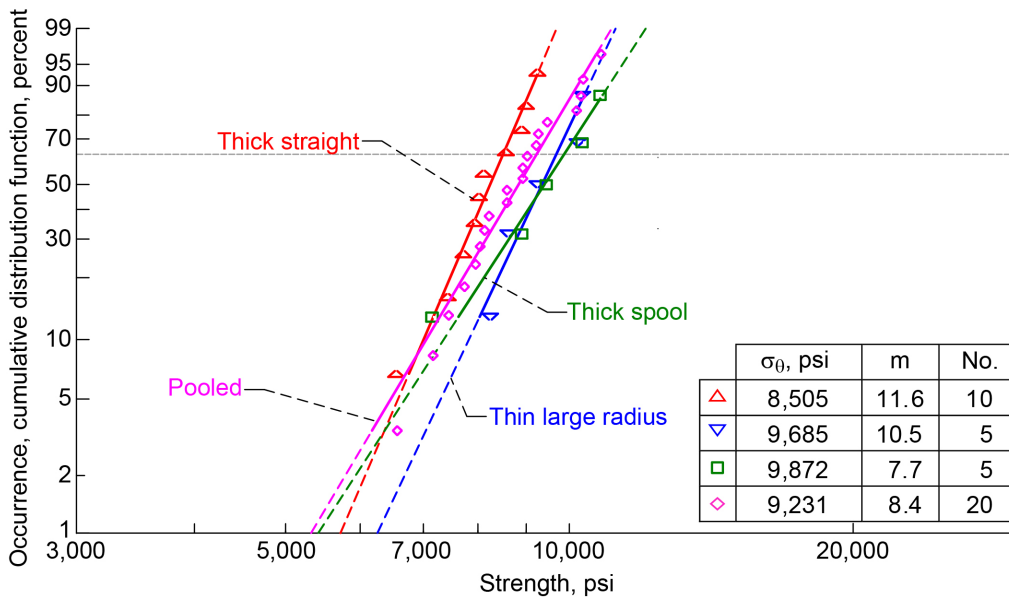


Figure 5.—Weibull distributions for the groups.

Although the differences are not statistically significant for valid tests, a systematic trend can be seen, with large, straight-sided specimens being ~11 percent weaker than shallow-radiused and spool specimens.

More data might allow a difference to be distinguished. The difference could also be a scale effect, with large samples sampling more flaws than thin samples.

Because the material exhibits little deformation during failure (0.5 percent), it might be viewed as brittle and the strength described with the Weibull distribution, as shown in Figure 5 for the geometries. The Weibull distribution is often used to describe the strength of brittle materials like ceramics and glasses because failure occurs from the weakest link or largest flaw and the Weibull distribution represents such extreme values.

Fit quality is very good, but relatively little data was generated for use of the Weibull distribution.

The pooled data exhibits a characteristic strength of 9,231 psi and Weibull modulus of 8.4. The Weibull modulus is in the typical range for brittle materials and implies neither very consistent nor highly variable material. If the Weibull distribution is used to scale the thin specimen characteristic strength to that of the thick specimens by using the common formula

$$\frac{\sigma_{f1}}{\sigma_{f2}} = \left(\frac{V_{e2}}{V_{e1}} \right)^{\frac{1}{m}} \quad (1)$$

an expected strength of 8,545 psi for thick specimen results versus a measurement of 8,505 psi for the two thick sets, where σ_{fi} is the measured characteristic strength, m is the average of the unbiased Weibull moduli via the maximum likelihood estimator for the sets (see Figure 5 inset), and V_{ei} is the effective volume. A similar result occurs (8,693 vs. 8,505 psi) if the area of the specimens is considered in Equation (1). Because the specimens are uniform, the effective volume or area is simply the volume or $(\pi r^2 h)$ surface area $(2\pi rh)$ of a cylinder.

Figure 6 shows examples of fracture surfaces. The fracture surfaces exhibit a fracture pattern representative of the underlying layup, regardless of the specimen geometry.



Figure 6.—Example fracture surfaces of baseline test specimens. Nominal specimen diameter is 1 in. (a) Thick. (b) Thin, radiused. (c) Spool. (d) Thin, straight-sided.

Conclusions

The FWT strength of a composite laminate was measured using four specimen geometries and the procedures of ASTM International D7291. The specimens were both thick and thin with straight and radiused sides. The differences in measured tensile strengths were not statistically significant at 95 percent confidence with five samples each, with the exception being the thin, straight-sided specimens. This implies that a variety of the geometries can be used to determine FWT strength for engineering purposes, including thick straight-sided, thin large-radiused, and spool configurations. This work verifies the use of thinner plates during the material development programs to reduce material used and lower costs. A more systematic study to obtain valid thin, straight-sided results would be beneficial.

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