Optimal Fiber Orientation for Fiber Reinforced Pressure Vessels

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ABSTRACT
The optimum fiber orientation for pressure vessels (pipes in particular) is often taken as 55 degrees. This orientation is found from a netting analysis in which the contribution of the matrix is neglected. This study examines optimum fiber orientations from analysis that include the contribution of the matrix using the Maximum Strain, Maximum Stress, and Tsai-Hill failure criteria. The accuracy of these predictions are compared with the burst pressure of cylindrical specimens as a function of their fiber angle. The tubes were fabricated from carbon/epoxy prepreg with a symmetric bias ply orientation. The cylindrical specimens were loaded at a 2:1 stress ratio in a newly developed biaxial test fixture. The results of this work point to an optimum fiber orientation of 50 degrees for a carbon/epoxy pressure vessel. The results provide further evidence that the Maximum Strain and the Maximum Stress failure criteria more accurately describe fiber dominated strength of fiber reinforced composites than interaction criteria.

1. Introduction

An advantage of fabricating parts with fiber reinforced composites is the ability to tailor the stiffness and strength of the structure to specific design loads. A common example involves long cylindrical pressure vessels, in which hoop stresses are double the axial stress. First introduced over 40 years ago, netting analysis is still used to determine the optimum fiber orientation for many pressure vessels. As the name implies, netting analysis assumes that load is carried only by the fibers. The optimum fiber angle is found from a stress transformation in which the axial and hoop stresses produce only fiber direction stress in the material coordinate system as

$$\theta = \tan^{-1}\sqrt{2} \cong 54.7^\circ \,.$$

Verifying the accuracy of an optimum fiber angle requires the application of a biaxial stress state. This may be accomplished in a number of ways. An approach that minimizes grip induced stress concentrations uses a cylindrical specimen, akin to a pressure vessel. The biaxial stress state is achieved by applying internal or external pressure to induce hoop stress while applying an axial load to achieve axial stress. Numerous examples can be found in the literature describing various fixture designs and coupon configurations [2,4-5,7,10-11].

Much of the work regarding biaxial testing has been devoted to the study of failure criteria [1-4,8]. A significant portion of the work, however, has considered pressure vessels [5-10]. Surprisingly, only a few studies have investigated the accuracy of the netting analysis optimum fiber angle [11-13]. The work was largely conducted before modern autoclave processing was developed, and considered relatively coarse differences in fiber orientation. This has made the experimental verification of an optimum fiber angle difficult.

This study introduces a test fixture and coupon that may be used to study tri-axial stress states. The fixture is used to compare the burst pressures of carbon/epoxy specimens with +/-45, +/-50, and +/-55 orientations. The experimental results are compared to failure criteria predictions to assess the suitability of netting analysis in pressure vessel design as well as evaluate the failure criteria.

2. Test Coupon

The test coupon was designed to be compatible with existing load frames and of sufficient size to allow multi-ply wall thicknesses to be investigated. To this end, the effect of fiberglass end tabs on the coupon stress state was analyzed using finite elements for a two inch diameter coupon. The model consisted of eight-node axi-symmetric elements. Analogous to a dog bone specimen, the tab thickness and taper angle were adjusted to minimize stress concentrations in the coupon. A tab thickness of 0.150 inches and a taper of eight degrees was observed to introduce a stress concentration of 1.06.

Test coupons were fabricated from a carbon/epoxy pre-preg (T600:125/33) using hand lay-up and an autoclave cure. The ply geometry was selected to provide continuous fiber reinforcement over the length of the part. To minimize fiber undulation, the part was debulked after each ply was applied. The specimen consisted of eight plies with the following lay-up $[\pm\theta]_{2S}$, representing a 0.060 inch cured wall thickness. Following the initial cure, e-glass/epoxy cloth pre-preg was applied to the ends of the specimen. The tabs were cured and machined to mate with the test fixture as shown in Figure 1. The coupon had an inside diameter of 2 inches and a length of 10 inches.

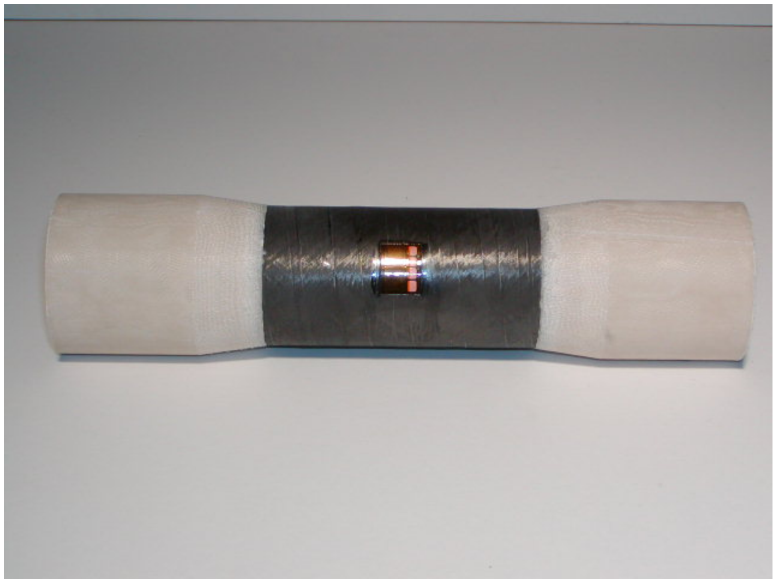

Fig. 1: Picture of 2 inch diameter specimen.

3. Multiaxial Test Fixture

A multiaxial test fixture was designed to introduce axial, hoop and torsional stress in the cylindrical test coupon as shown in Fig. 2. A photograph of individual components and the assembled fixture with test coupon are shown in Figs 3 and 4, respectively. Trunions extend from each end of the fixture to apply axial and torsional loads via a standard axial/torsion load frame using hydraulic grips. The fixture is designed to apply compression as well as axial loads using an external pressure sleeve (not shown). Axial load is introduced into the specimen via a tapered expandable mandrel, analogous to uniaxial wedge type loading grips. Bolting the grip to the fixture base forces the mandrel against the coupon. The mandrel tightens as axial load is applied. The core of the fixture base prevents the coupon from collapsing from the extreme grip forces.

A robust seal must exist through the test to maintain hoop stress in the test coupon. Many composite materials accumulate damage before failure. A synthetic sleeve was placed between the coupon and the fixture to maintain hydraulic pressure in the presence of damage and avoid chemical interaction between the hydraulic fluid and the coupon.

The fixture core has three possible configurations depending on the type of test to be carried out. For axial tension and internal pressure testing, slip-fit alignment pins connect the two halves of the core. For internal pressure testing, where pure hoop stress is required, the two halves of the core can be connected with a threaded stud to eliminate the axial effect from the applied pressure. The configuration for torsional testing uses no connection between the two halves of the core.

Strain was recorded using a 0/90 rosette strain gage (CEA-13-250UT-350, Micro Measurements). A small diameter hydraulic cylinder was mounted in a load frame, and served as a hydraulic intensifier. The load frame was operated in stroke control, and hydraulic pressure was recorded through the test.

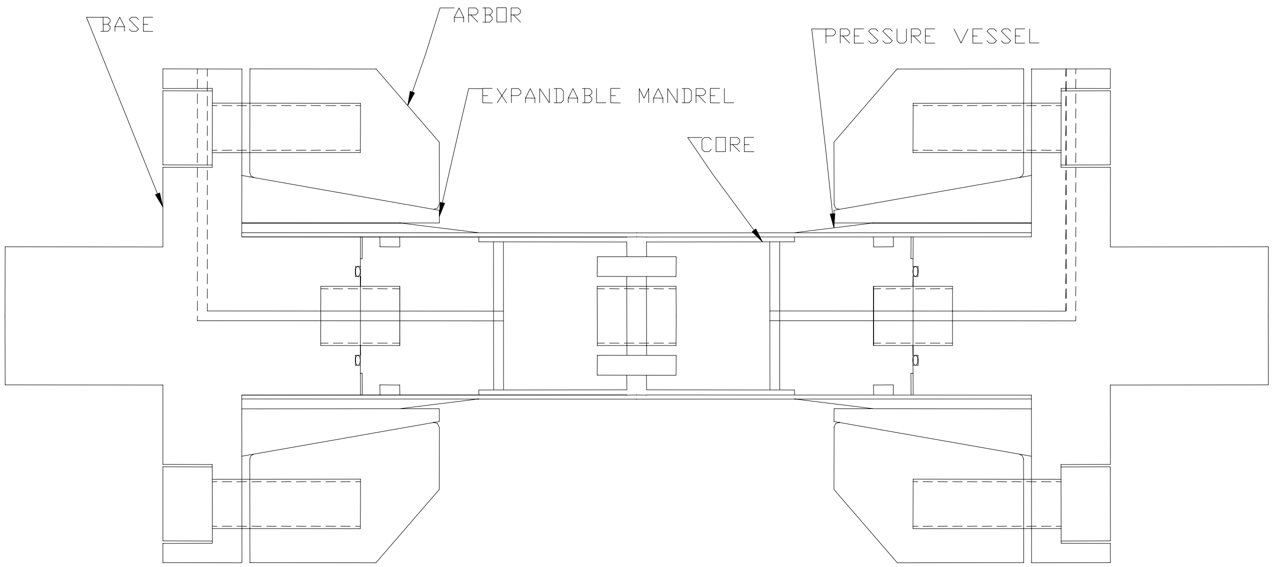

Fig. 2: Diagram of multiaxial load fixture.

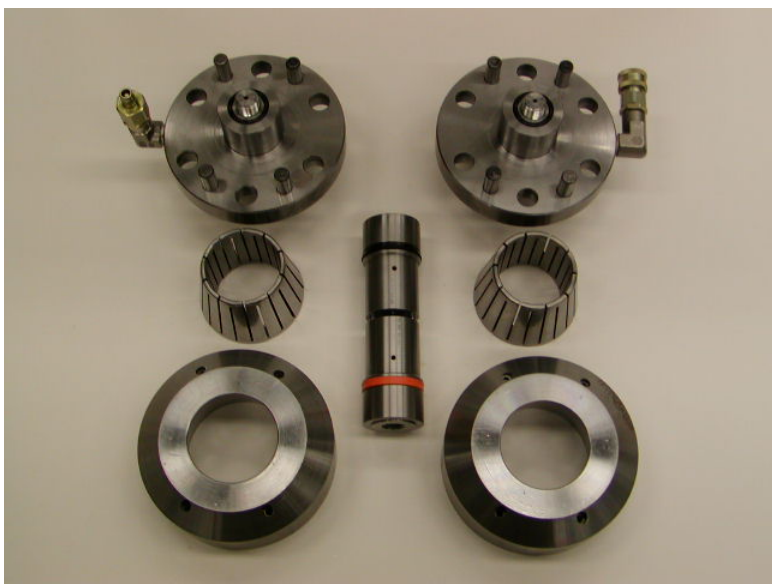

Fig. 3: Photograph of the components of the multiaxial test fixture

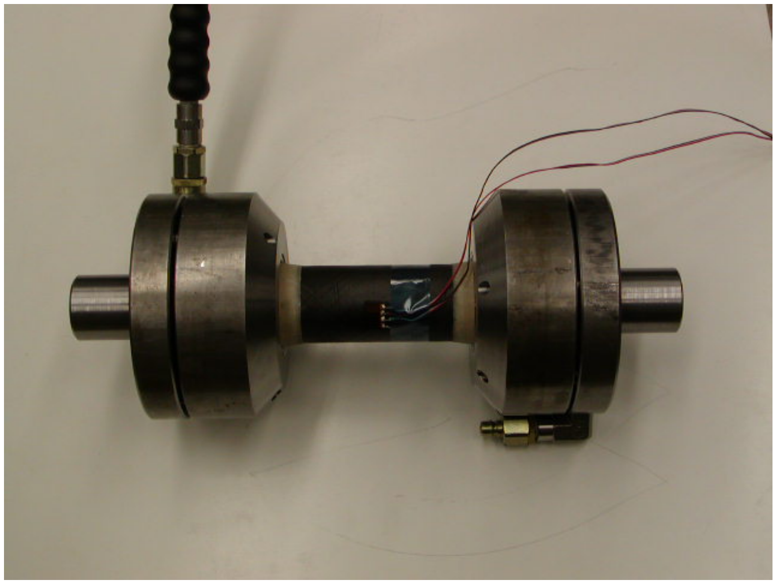

Fig 4: Photograph of the assembled fixture with a cylindrical test coupon.

3. Experimental Results

Failure criteria rely on the strength and elastic response of uniaxal coupons. Accordingly, uniaxial coupons were constructed and tested to failure. A summary of the uniaxial properties of the material under consideration are presented in Table 1. The coupons were 1 inch wide and 8.0 inches long. They were loaded at 0.2 inches/minute. Axial and transverse strain were recorded using a biaxial extensometer.

Cylindrical coupons were fabricated with 45, 50, and 55 degree orientations with respect to the long axis of the specimen. The burst pressure of each coupon is reported in Table 2. The 50 degree orientation appears to consistently provide higher burst pressures than either the 45 or the 55 degree orientations.

A photograph of a representative failure surface for each ply orientation is presented in Fig. 5. The 45 and 50 degree coupons tended to fail in the circumferential direction, while the 55 degree coupons tended to fail in the axial direction. A change in failure mode is expected near the optimum angle as the directional strength of the specimen changes with fiber orientation.

Table 1. Elastic and strength properties of uniaxial carbon/epoxy test coupons.

$[0]_6$		$[90]_{16}$		$[+/-45]_{2S}$	
E_1 (Msi)	$S_L^{(+)}$ (Ksi)	E_2 (Msi)	$S_T^{(+)}$ (Ksi)	G_{12} (Msi)	S_{LT} (Ksi)
19.94	333	1.35	6.28	0.66	13.13

Table 2. Burst pressures of cylindrical specimens

Specimen number	Lay-up	Pressure (Psi)
45-1a	$[+/-45]_{2S}$	3447
45-2a	$[+/-45]_{2S}$	4282
45-3a	$[+/-45]_{2S}$	4729
45-4a	$[+/-45]_{2S}$	4273
Average		**4183**
50-1a	$[+/-50]_{2S}$	4939
50-2a	$[+/-50]_{2S}$	4740
50-3a	$[+/-50]_{2S}$	4323
50-4a	$[+/-50]_{2S}$	5284
Average		**4821**
55-1a	$[+/-55]_{2S}$	4569
55-3a	$[+/-55]_{2S}$	3637
55-5a	$[+/-55]_{2S}$	3359
55-6a	$[+/-55]_{2S}$	3819
Average		**3846**

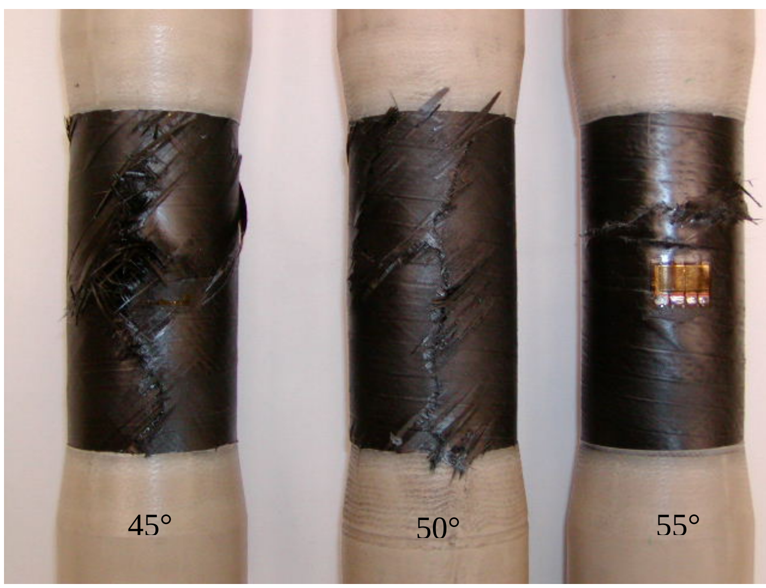

Figure 5. Failure surfaces of test coupons.

4. Discussion

Failure criteria, accounting for the contribution of the matrix, may be manipulated to predict an optimum fiber orientation. Unlike a netting analysis, however, the optimum angle would depend on the properties of the composite under consideration. Using the uniaxial elastic and strength properties, an optimum fiber orientation was obtained using the Maximum Stress, Maximum Strain, and the Tsai-Hill failure criteria, as shown in Fig. 6.

The optimum angle according to the Tsai-Hill criterion was found to be 52.5 degrees. The optimum angle according to the Maximum Stress and Maximum Strain failure criteria was 50.5 degrees. While the experimental and theoretical measures of optimum fiber orientation do not differ significantly from the accepted orientation of 55 degrees, they suggest that increased material performance could be realized by considering the contribution of the matrix in optimum fiber orientations of pressure vessels.

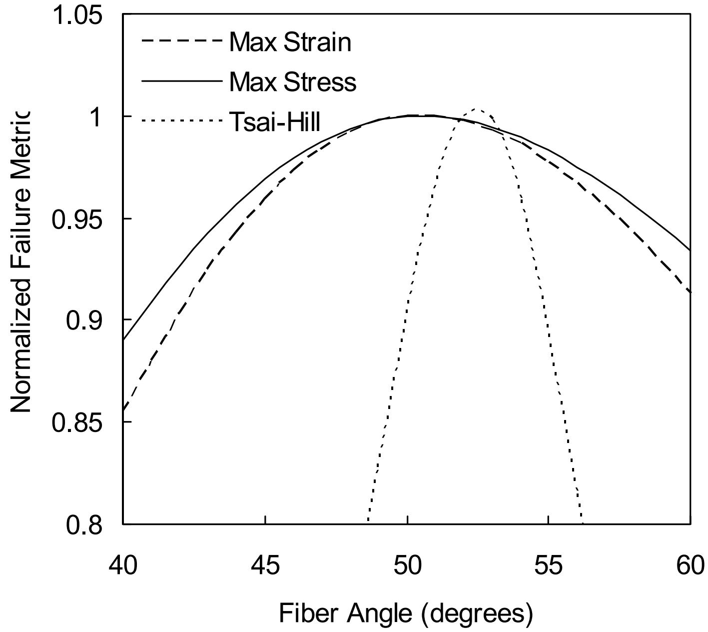

Fig. 6. Optimum fiber angle for the Maximum Stress, Maximum Strain, and the Tsai-Hill failure criteria.

5. Conclusions

In the foregoing, the optimum fiber orientation of an idealized pressure vessel was considered experimentally using a newly developed multiaxial test fixture. The results were then compared with accepted orthotropic failure criteria and the commonly used netting analysis orientation of 55 degrees.

The load fixture provided an efficient means of introducing multiaxial stress while minimizing stress concentrations inherent with flat multaxial coupons. A maximum burst pressure was observed for fiber angles of 50 degrees, which corresponded to that predicted by the Maximum Strain and Maximum Stress failure criteria.

Inspection of the failure surfaces supported the predictions of the Maximum Strain and the Maximum Stress failure criteria. Specimens with fiber orientations below the optimum exhibited a circumferential failure mode, while specimens with an orientation greater than the optimum exhibited an axial failure mode. The results indicate that the strength of composite pressure vessels is dependent on the matrix. Thus, to maximize the performance of composite pressure vessels the matrix contributions should be considered in the design process.

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