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Influence of filament winding parameters on composite vessel quality and strength

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An experimental design investigation of manufacturing and design variables that affect composite vessel quality, strength, and stiffness was conducted. Eight 20-in. cylinders (with one additional cylinder as a replicate) were manufactured and tested for hoop strength, hoop stiffness, fiber and void volume fraction distribution through thickness, residual stress, and interlaminar shear strength. Material and processing variables were divided into five categories: (a) resin, (b) fiber, (c) fabrication process, (d) design, and (e) equipment. Five variables were selected (from a list of 12) for study using a 1/4 fractional factorial design of experiment setup. The five variables were: (a) winding tension, (b) stacking sequence, (c) winding-tension gradient, (d) winding time, and (e) cut-versus-uncut helicals.

Statistical analysis of the data shows that the composite vessel strength was affected by the manufacturing and design variables. In general, it was found that composite strength was significantly affected by the laminate stacking sequence, winding tension, winding-tension gradient, winding time, and the interaction between winding-tension gradient and winding time. The mechanism that increased composite strength was related to the strong correlation between fiber volume in the composite and vessel strength. Cylinders with high fiber volume in the hoop layers tended to deliver high fiber strength. © 1997 Elsevier Science Limited.

(Keywords: filament winding; carbon fiber; mechanical properties; strength)

INTRODUCTION

The filament winding fabrication process is an effective method for manufacturing composite vessels. This method has been used extensively for both military and civilian applications. With a thermoset epoxy matrix, two of the most common ways of applying the material to the part are through wet and/or towpreg winding. In the wet winding method, the dry fiber is passed through a resin bath, causing resin impregnation. This is followed by application of the wet fiber to the mandrel. In the towpreg winding method, a pre-impregnated fiber is directly applied to the mandrel.

This paper discusses an experimental investigation into the influence of wet winding parameters on composite vessel quality and strength/stiffness response. There are numerous composite vessel applications in which composite quality parameters—as measured by void level and fiber/resin volume distributions through the thickness and ply thicknesses—are critical to adequate vessel performance. Composite void level can influence the degree of the ultrasonic inspectability of the vessel and influence resin-dominated strength properties in critical regions (e.g. dome and joint regions). Fiber volume distribution through the thickness could control vessel stiffness and strength performance. In instances where these parameters are critical, it is imperative that tight controls be exercised over both the void level and the fiber volume distribution through the thickness of the vessel. Given the complexity of the interaction between the various winding parameters (in particular when the wet winding method is used), it is important that these interactions be well understood and controlled to achieve the desired vessel quality.

Several analytical models[1–6] have recently been developed to model the interaction between various winding and curing parameters. These models have provided good results for the towpreg winding manufacturing method and should promote a better understanding of the interactions. However, less satisfactory predictions were obtained in the case of wet winding. In the current investigation a design of experiment (DOE) method to investigate the complex interaction between filament winding manufacturing and design variables affecting vessel strength and composite quality was selected.

APPROACH

Design of experiment (DOE)

DOE is an experimental design technique in which the main effects of a variable (i.e. factor) and the interaction effects of those variables can be measured[7–9]. In a DOE approach, more than one factor is changed at the same time (as opposed to investigating factors individually).

Considerable changes in each variable setting must be made so the effect of the change on the response can be measured. For example, to understand the effect of winding tension and resin content on fiber volume fraction in the composite, two extreme settings for tension and resin content would be used. For instance, tow tension settings of 3 lb./tow and 9 lb./tow could be used; resin content settings of 29% and 39% by weight could be used. With these setting extremes, active interference with the process is being made—not just passive observation. From this type of experimental approach, the main effect of each factor can be estimated, as well as the interaction effect of these factors.

A plant-wide survey was conducted to identify major variables with respect to the performance and quality of composite pressure vessels burst strength. The survey addressed five categories: (a) resin, (b) fiber, (c) fabrication process, (d) design, and (e) equipment. A total of 50 variables were ranked—the top 12 were considered. These top 12 variables are listed below along with the percent ranking:

Ranked list of top 12 variables

Ranking	Variable	Percent
1	Winding tension	71
2	Fiber strength variability	62
3	Stacking sequence	62
4	Resin B stage time (winding time)	57
5	Fiber damage during winding	57
6	Fiber wet-out	57
7	Winding tension gradient	48
8	Resin content	43
9	Total winding time	43
10	Winding time between layers	43
11	Hoop layer thickness	43
12	Cut-versus-uncut helicals	38

The variables for the study were selected from this list. From a budget standpoint, nine cylinders can be built and tested. This implies enough budget to study three, four, five, or six variables. Five variables were selected for study using a 1/4 fractional factorial design. The five variables selected for study were:

- winding tension
- laminate stacking sequence
- winding-tension gradient
- winding time between layers
- cut-versus-uncut helicals

To conduct a systematic DOE, variables need to be controllable. Therefore, because fiber strength variability cannot be controlled (at least not by the filament winder), fiber strength variability cannot be an experimental variable. Similarly, fiber damage during winding cannot be varied systematically, and so can also not be one of the experimental variables. Other reasons for selecting the above variables over other were: (a) some variables were redundant with those selected (e.g. B stage time, total winding time, winding time delay between layers, all which were collapsed into one variable designated as winding time), and (b) the effect of a variable on the outcome was known or could be inferred by other means (e.g. fiber strength variability—it was assumed that fiber strength in the composite was proportional to the strength of the fiber). Using this reasoning, variables 1, 3, 7, 9, and 12 were selected. It should be noted that, if the variables were selected systematically according to the ranked list, variable 8, resin content, would have been selected before variable 12, cut-versus-uncut helicals. This variable would have been good choice based on our current knowledge (attesting to the power of the ranked list). However, because of programmatic reasons, the last variable, No. 12, was selected. The cut-versus-uncut helical variable relates to the way we manufacture composite rocket and booster cases (which requires cutting some helical layers during manufacturing before the resin has fully gelled). This manufacturing process caused concern that helical layers may move, cause wrinkles in the composite, and degrade vessel burst strength.

The five-variable 1/4 fractional factorial test matrix and the settings for each variable are given in *Table 1*. Keys to the table are listed below.

- Lumped hoops layers lay-up: $(\pm 16.4/90_4)/(\pm 16.4)_3/(90/\pm 10_2)/(90/\pm 10)$.
- Dispersed hoop layers lay-up: $(\pm 16.4/90)_4/(\pm 10/90)_2/(\pm 10)$.
- Cut-versus-uncut helicals: all helicals are cut on the cut option, none on the uncut option.
- Low band tension: 32 lb. for 16.4 helicals and hoops.
- Low band tension: 21.3 lb. for 10 helicals.
- High band tension: 72 lb. for 16.4 helicals and hoops.
- High band tension: 48 lb. for 10 helicals.
- High band tension gradient: 72.0 lb., 57.6 lb., and 43.2 lb. (applied to the first three hoops).
- Low band tension gradient: 32.0 lb., 25.6 lb., and 19.2 lb. (applied to the first three hoops).
- Short winding time: 2 h for hoops and 3 h for helicals.
- Long winding time: 9 h for both hoops and helicals.

A total of nine cylinders were built. The ninth cylinder (designated 2B) was a duplication of the second cylinder and was needed to establish cylinder-to-cylinder variability. This information is required to make a statistical statement regarding the significance of the main and interaction effects. The 1/4 fractional factorial design assumes the interactions of some variables to be insignificant. The DOE was set up so as to minimize the confounding of second-order interactions (Appendix A), which were believed to be significant.

Cylinder fabrication

Eight 20-in.-diameter composite cylinders were filament wound over a 20-in. nominal-diameter steel mandrel (*Figure 1*). The mandrel has a 30-in.-long cylindrical section that flared into semi-elliptical domes on each end. Each cylinder winding parameter is unique and defined according to *Table 1*. All other winding parameters (e.g. winding speed, resin content, resin mixing time, etc.) are maintained at constant levels during the fabrication period

Table 1 Design and manufacturing variables test matrix

Cylinder no.	Stacking sequence	Cut-versus-uncut helicals	Winding band tensions	Winding tension gradient	Winding time between layers
1	Lumped	Cut	Low	No	Long
2	Lumped	Uncut	High	Yes	Short
3	Dispersed	Uncut	Low	No	Short
4	Dispersed	Cut	High	Yes	Long
5	Lumped	Cut	High	No	Short
6	Dispersed	Cut	Low	Yes	Short
7	Lumped	Uncut	Low	Yes	Long
8	Dispersed	Uncut	High	No	Long

Figure 1 Filament winding of 20-in.-diameter composite pressure vessel

Figure 2 Matching of 20 in. cylinder into 1 in. rings

of the eight cylinders. One cylinder (No. 2) was replicated to assess the natural variation in vessel strength and composite quality resulting from process time effect. The winding time variable was set to simulate full-scale composite vessel (which can vary in diameter between 40 and 120 in.) winding time variations. Because it is not known if the degree of resin advancement plays a role in the composite vessel quality and strength, winding time was selected as one of the variables to be studied. The low and high winding time setups were selected based on full-scale winding time extremes. A consistent winding time variation (*Table 1*) was accomplished by incorporating forced holds for each helical and hoop layer during the subscale, 20-in. cylinder winding.

After curing, the end domes were cut off and the 30-in.-long composite cylinder was extracted from the mandrel. The composite cylinder was then cut into twenty 1-in.-wide rings using a diamond cutting wheel (*Figure 2*). To assess material quality and strength, the rings were characterized using test methods discussed in the next section.

Material evaluation

Material from each cylinder was characterized for strength, stiffness, and quality using the following tests:

(1) Strength and stiffness measurements

- pressurized ring test to evaluate hoop strength and stiffness
- short-beam shear (SBS) test to evaluate interlaminar shear strength

(2) Quality measurements

- dimension measurements to determine the vessel outside diameter (OD) and wall thickness
- image analysis (IA) to determine fiber volume, resin content, and void levels
- split ring test to determine residual stresses

The cut rings were numbered consecutively (*Figure 2*) so that their axial location relative to the cylinder ends was known. Three of 20 rings were used in a split ring spring back test to determine the residual stress. Material from each of the three rings was also used for the IA and SBS tests. From the remaining 17 rings, at least 10 were chosen at random and tested in the pressurized ring test fixture.

RESULTS

The results section is divided into three subsections: Composite Strength and Stiffness Assessment, Composite Quality Assessment, and Statistical Analysis. In the first two, results from the measurements of composite strength, stiffness, and quality are presented. In the last section the statistical analysis results for the effect of the DOE factors on the measured composite strength, stiffness, and quality response variables are reported.

Composite strength and stiffness assessment

Hoop strength and stiffness. A minimum of ten rings from each cylinder were tested to failure using the 20-in. pressurized ring test method[10]. The pressurized ring test is used to measure the composite vessel hoop strength and stiffness. Recorded data included digital pressure versus strain, burst pressures, and failure hoop strains.

Table 2 summarizes the pressurized ring test results for cylinders one through nine. The table lists the cylinder numbers, number of rings tested, average ring burst pressures, average outside diameter (OD) hoop strain at failure, and calculated hoop stiffness. The data show that, with the exception of cylinder 3, the coefficient of variance (C.v.) on burst pressure tracks the C.v. on measured failure hoop strain very well. The reason for the differences in the C.v. for cylinder 3 is not known. The C.v. for modulus is relatively low, as expected. There is also a significant difference between the hoop modulus calculated for cylinder Nos. 2 and 2B, the replicate of cylinder No. 2. The reason for this difference is not known. Given the average burst pressure and average failure hoop strain, it is evident that the performance of these two cylinders was almost identical. It is believed that the calculated hoop modulus for cylinder No. 2B is too high. The modulus is calculated from the slope of the pressure-versus-hoop strain curve[10]. The difference in the average slopes between cylinder No. 2 and 2B was only 0.7%.

Maximum fiber strains and stresses were calculated using an anisotropic composite cylinder elasticity solution program together with the fiber volumes, ply thicknesses, and adjusted ply thicknesses as determined by the IA and outlined in the technical paper entitled 'Pressurized Ring Test for Composite Pressure Vessel Hoop Strength and Stiffness Evaluation'[10]. The failure strains of the rings are calculated based on the first-ply failure criterion. In this process, it is assumed that the ring will fail when the first hoop (inner-most hoop) ply fails. To determine the strain distribution through the ring thickness, a generalized plane-deformation elasticity solution for multilayer anisotropic cylinders subjected to internal pressure is used. The elasticity solution uses the lamina E_{11}, E_{22}, and G_{12} material nonlinearities in the solution. A detailed discussion of the nature of material nonlinearity and modeling are given in Refs. [10,11]. In general, the fiber, IM7, shows strain hardening while the resin-dominated E_{22} and G_{12} show strain softening with increasing strain. *Table 3* summarizes a comparison of the measured and the calculated OD hoop strain. The measured hoop strain at the ring OD is used to compare the accuracy of calculated hoop-strain distribution by the elasticity solution. The analyses of the rings use the IA data to provide: (a) the individual ply thickness, (b) the individual ply fiber volume, and (c) the individual ply void volume from which the adjusted ply thicknesses are

Table 2 Pressurized ring test results

		Measured burst pressure		Measured hoop strain		Calculated hoop modulus	
Cylinder no.	No. of ring	Average (psi)	C.v. (%)	Average (%)	C.v. (%)	Average (Msi)	C.v. (%)
1	16	3016	2.0	1.461	2.7	7.857	1.8
2	17	3076	2.8	1.483	2.5	8.393	2.3
2B	10	3069	1.7	1.484	1.9	9.464	1.0
3	16	2977	2.8	1.441	4.2	8.290	2.8
4	13	3004	3.4	1.457	3.5	8.313	0.9
5	13	3037	3.4	1.494	3.2	8.823	1.0
6	15	2900	1.2	1.415	1.7	8.331	1.0
7	10	2916	1.8	1.425	1.8	7.930	0.7
8	10	3003	1.2	1.459	1.1	8.439	0.8

Table 3 Summary of cylinders' hoop fiber strength

	Measured average		Calculated				Adjusted values	
Cylinder no.	Pressure (psi)	OD hoop strain (%)	OD hoop strain (%)	Percent difference	Max. fiber strain (%)	Max. fiber stress (ksi)	Max. fiber strain (%)	Max. fiber stress (ksi)
1	3016	1.461	1.458	0.2	1.509	606	1.512	607
2	3076	1.483	1.535	− 3.5	1.584	637	1.530	616
2B	3069	1.484	1.565	− 5.5	1.612	649	1.528	615
3	2977	1.441	1.540	− 6.7	1.592	641	1.490	599
4	3004	1.457	1.429	1.9	1.481	594	1.510	606
5	3037	1.494	1.505	− 0.7	1.553	624	1.542	620
6	2900	1.415	1.513	− 6.9	1.566	630	1.465	589
7	2916	1.425	1.405	1.4	1.457	584	1.477	592
8	3003	1.459	1.410	3.4	1.461	585	1.511	606

calculated. The analysis shows favorable agreement with the measured OD hoop strain, with the largest percent difference being 7%. The difference between the cylinders that showed the highest strain to failure (cylinder No. 5) and the lowest strain to failure (cylinder No. 6) is only 5.6%. The error in the calculated strains to failure was unacceptable for the statistical analysis of the results. Therefore, the calculated fiber hoop strain to failure (at the innermost hoop ply) is adjusted (*Table 3*) proportionally to the percent error between the calculated and the measured OD hoop strains.

Table 4 Summary of the short-beam shear test results

Cylinder no.	Failure load Average (lb.)	Failure load C.v. (%)	Failure stress Average (psi)	Failure stress C.v. (%)
1	1215	7	3543	7
2	1254	11	4043	11
2B	1142	11	3454	11
3	1671	5	5174	5
4	1571	8	4702	8
5	1235	7	4042	7
6	1577	14	3938	14
7	1191	16	3053	16
8	1592	11	4033	11

Table 5 Summary of the cylinders' dimensions

Cylinder no.	Cylinder outside diameter (in.) Average	Cylinder outside diameter (in.) SD	Cylinder wall thickness (in.) Average	Cylinder wall thickness (in.) SD
1	20.877	0.010	0.258	0.002
2	20.809	0.012	0.232	0.001
2B	20.777	0.014	0.219	0.001
3	20.838	0.014	0.246	0.001
4	20.800	0.017	0.252	0.000
5	20.801	0.015	0.230	0.015
6	20.859	0.017	0.251	0.010
7	20.839	0.008	0.260	0.004
8	20.840	0.020	0.245	0.006

Short-beam shear (SBS) results

Table 4 summarizes the results of the SBS tests. These tests were conducted using the standard ASTM test method for apparent interlaminar shear strength of parallel fiber composites by short-beam method (D2344-88). The results listed in the table are based on tests of six specimens that were removed from each of the three rings used in the split ring test (two specimens per ring). The span length of the specimen is oriented in the ring circumferential direction (test method A).

Composite quality assessment

Dimensional assessment. The average OD and wall thickness of the cylinders are summarized in *Table 5*. The ODs recorded in the table are average values calculated from the measured dimensions of 20 rings cut out of each cylinder. The average wall thickness is determined from IA measurements of three rings from each cylinder.

Image analysis results

Composite quality assessment is accomplished using the IA method. This method is discussed in detail in Ref. [10] and is not included. In general, both fiber volume and void volume fractions show variations from the inside diameter (ID) of the cylinder to its OD. In some cylinders, this variation (gradient) is more severe than others, depending on the manufacturing/design parameters. A comparison of cylinder No. 3, which shows strong fiber volume fraction gradient, and cylinder No. 1, which shows weak fiber volume gradient through the thickness, is shown in *Figure 3*. Similarly, a comparison of cylinder No. 5, which shows strong void volume fraction gradient, and cylinder No. 7, which shows weak fiber volume gradient through the thickness, is shown in *Figure 4*. The symbols in the figures identify the fiber and void volume fractions in each hoop/ helical layer through the cylinder thickness.

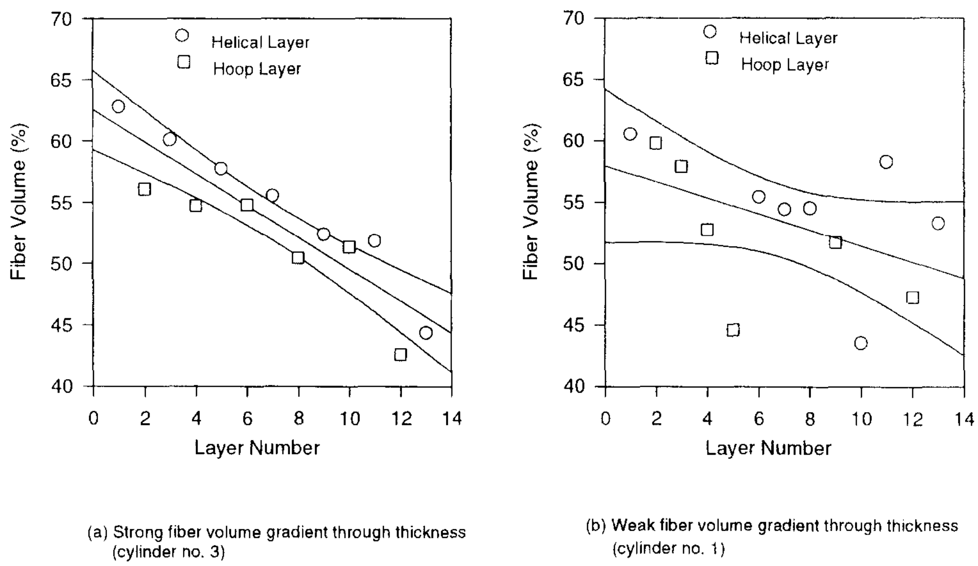

Figure 3 Typical layer-by-layer fiber volume distribution through 20 in. cylinder thickness: (a) strong fiber volume gradient through thickness (cylinder no. 3); (b) weak fiber volume gradient through thickness (cylinder no. 1)

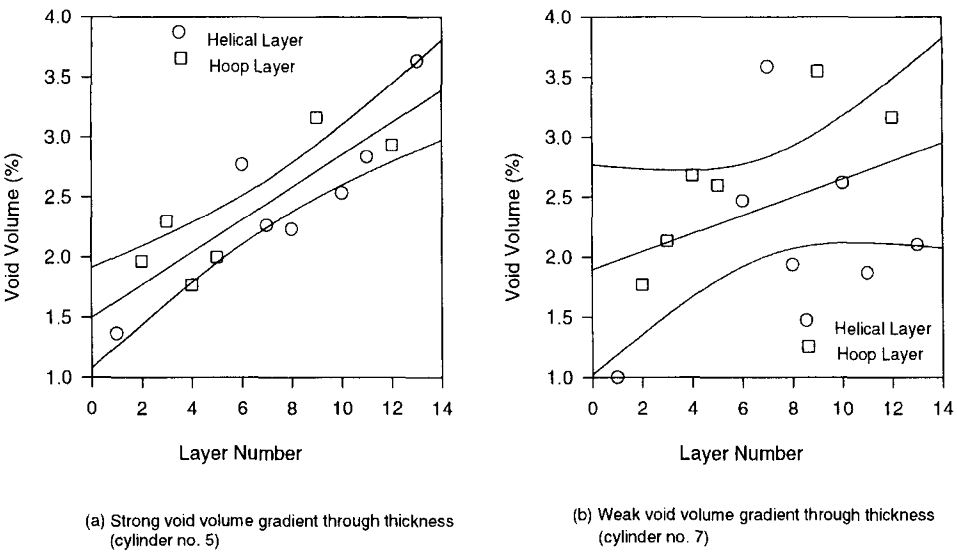

Figure 4 Typical layer-by-layer void volume distribution through 20 in. cylinder thickness: (a) strong void volume gradient through thickness (cylinder no. 5); (b) weak void volume gradient through thickness (cylinder no. 7)

Table 6 Summary of fiber volume distribution through the cylinder thickness

Cylinder no.	Average fiber volume (%)	Estimated intercept (%)	Estimated slope (%)	Significance level, α	R^2 (%)
1	53.40	58.00	− 0.654	0.019	22
2	58.20	67.10	− 1.274	0.000	81
2B	60.20	69.30	− 1.288	0.000	90
3	53.60	62.60	− 1.288	0.000	85
4	53.20	58.30	− 0.733	0.038	34
5	59.20	68.90	− 1.397	0.000	80
6	52.40	58.90	− 0.937	0.046	31
7	53.40	56.00	− 0.372	0.445	5
8	55.70	61.30	− 0.802	0.035	34

Table 7 Summary of void volume distribution through the cylinder thickness

Cylinder no.	Average void volume (%)	Estimated intercept (%)	Estimated slope (%)	Significance level, α	R^2 (%)
1	3.93	2.292	0.144	0.369	7
2	2.29	1.439	0.106	0.031	46
2B	2.34	1.924	0.060	0.113	21
3	2.94	1.113	0.262	0.010	47
4	2.26	1.594	0.095	0.060	29
5	2.44	1.495	0.136	0.000	73
6	2.82	2.333	0.069	0.243	12
7	2.42	1.894	0.075	0.178	16
8	1.97	1.232	0.105	0.019	41

To include the fiber and void volume fraction data in the statistical analysis in a meaningful way, the IA data for each cylinder were statistically analysed using linear regression analysis. The results of this analysis are summarized in *Tables 6* and *7* for the fiber and void volume fractions, respectively. Resin content and fiber volume are directly related (or at least strongly correlated). Therefore, no analysis of the resin content was performed. *Tables 6* and *7* list three physical parameters—the average, the intercept, and the slope for each of the fiber and void volume distributions through the composite. The intercepts closely relate to the maximum fiber volume and/or minimum void volume in each composite. It also closely relates to these properties in the first hoop layer in the laminate. The slope is related to the gradient of these properties through the composite thickness. Hence, the IA data are reduced into three meaningful parameters. These parameters can then be used to characterize fiber and void volume distributions using statistical analysis of the DOE data.

Tables 6 and *7* also list the significance levels for the slope and R^2 (i.e. the percent of variance in the data explained by the linear regression model) for the model as a whole. A significance level of $\alpha < 0.04$ indicates that including the slope in the linear regression model is important (i.e. the gradient through the thickness is significant). This is combined with a large value for R^2, indicating a low variability of the data around the regression line (model line).

A cursory examination of *Table 6* indicates a strong relationship between the significance level and R^2 values. That is, cylinders that exhibit a significant gradient in the fiber volume through the thickness also exhibit a distribution that tended to closely follow the linear model. In addition, it is apparent from the data that these cylinders also tended to exhibit a larger fiber volume gradient through the thickness (larger absolute values of the slope). On the other hand, examination of *Table 7* indicates that most cylinders did not exhibit a large void volume gradient through the thickness. This is apparent from the significance level of including the slope in the model (which, in most cases, was not significant in addition to the relatively low values for R^2). That is, in general, the voids tended to be distributed uniformly throughout the laminate thickness.

Table 8 Summary of the cylinders' residual stress data

	Springback (in.)		Residual moment (lb.-in.)	
Cylinder No.	Average	C.v. (%)	Average	C.v. (%)
1	0.308	2	− 1.342	2
2	0.070	57	− 0.215	57
2B	− 0.063	104	0.173	104
3	0.038	76	− 0.144	76
4	0.005	0	0.021	0
5	0.232	21	− 0.666	21
6	− 0.107	94	0.430	94
7	0.230	6	− 1.046	6
8	0.100	16	− 0.381	16

Residual stress results

The method for calculating the residual moments and stresses based on the springback data of the measured rings is outlined in Appendix B. A summary of the data is given in *Table 8*. Because the residual stresses are related to the residual moments, the table only summarizes the springback and residual moment data.

Statistical analysis

A multiple stepwise forward regression analysis of the data was conducted to ascertain the important variables (i.e. those that had an effect) on the given response variables. Secondly, an analysis of variance (ANOVA) was performed using the variables that had a significant effect on the output. This approach ensured that only variables that have a significant effect are included in the statistical model.

In most instances, when the main effects are confounded with the second-order effects they dominate (larger than) the second-order interaction contribution. Therefore, it is generally (not always) safe to assume that the contribution from the second-order effect is negligible when confounded with the first-order effect. On the other hand, when two second-order effects are confounded, such an assumption may lead to erroneous results.

As previously discussed in the Approach section, before the actual testing started, it was assumed that all second-order interactions effects were negligible except for the interaction between cut-versus-uncut helicals with winding-tension gradient (BC) and winding time (BE). In reality,

Table 9 Analysis of variance summary of the effect of processing and design variables on vessel strength, stiffness, and quality

Measured response	A: Stacking sequence	B: Cut versus uncut helicals	C: Winding tension	D: Tension gradient	E: Winding time	DE Interaction	BE + CD interaction[a]	R^2 for model
Composite strength and stiffness response variables								
Burst pressure	High	No	Yes	High	Marginal	Yes	High	99
Measured OD hoop strain	High	High	High	High	High	No	High	100
Maximum fiber strain to failure	High	Yes	High	High	Yes	No	High	100
SBS failure load	High	No	No	No	No	No	No	96
Pressure versus strain slope	Yes	Yes	No	No	High	No	High	93
Hoop modulus	No	No	Yes	No	Marginal	No	No	57
Composite quality response variables								
Cylinder outside diameter	No	No	Yes	No	No	No	No	57
Cylinder wall thickness	No	No	High	No	High	No	No	81
Average fiber volume	High	No	High	No	Yes	No	No	87
Maximum (intercept) fiber volume	Yes	No	High	No	High	No	No	95
Fiber volume gradient	No	No	High	High	High	Yes	High	100
Average void volume	No	No	Yes	No	No	No	No	42
Maximum (intercept) void volume	No	No	No	No	No	No	No	-
Void volume gradient	No	No	No	Yes	No	No	No	42
Residual moment	Yes	No	No	Yes	High	No	No	78

[a]In the case of burst pressure and fiber volume responses, only the CD interaction is believed to be significant. In the case of hoop fiber strain, the contribution of each interaction cannot be separated; however, it is believed that only CD interaction is significant in this case too

Table 10 Summary of the main effects of processing and design variables effects on vessel strength, stiffness, and quality

Measured response	A: Stacking sequence		B: Cut vs. Uncut		C: Winding tension		D: Tension gradient		E: Winding time	
	Lumped (−)	Dispersed (+)	Uncut (−)	Cut (+)	Low (−)	High (+)	No (−)	Yes (+)	Short (−)	Long (+)
Composite strength and stiffness response variables										
Burst pressure (psi)	3010	2971	No significant effect		2952	3029	3008	2973	No significant effect	
Measured OD hoop strain (%)	1.466	1.443	1.457	1.452	1.436	1.473	1.464	1.445	1.458	1.451
Maximum fiber strain to failure (%)	1.516	1.494	1.503	1.507	1.486	1.524	1.514	1.496	1.507	1.502
SBS failure load (lb.)	1209	1603	No significant effect		No significant effect		No significant effect		No significant effect	
Pressure versus strain slope	1.996	2.009	1.994	2.011	No significant effect		No significant effect		1.989	2.017
Hoop modulus (Msi)	No significant effect		No significant effect		8.102	8.626	No significant effect		8.593	8.135
Composite quality response variables										
Cylinder outside diameter (in.)	No significant effect		No significant effect		20.853	20.809	No significant effect		No significant effect	
Cylinder wall thickness (in.)	No significant effect		No significant effect		0.253	0.238	No significant effect		0.238	0.254
Average fiber volume	56.3	53.7	No significant effect		53.2	56.8	No significant effect		56.1	53.9
Maximum (intercept) fiber volume	62.8	60.3	No significant effect		58.9	64.2	No significant effect		64.7	58.4
Fiber volume gradient	No significant effect		No significant effect		− 0.813	− 1.053	− 1.035	− 0.831	− 1.226	− 0.640
Average void volume	No significant effect		No significant effect		2.983	2.303	No significant effect		No significant effect	
Void volume gradient	No significant effect		No significant effect		No significant effect		0.162	0.026	No significant effect	
Residual moment (lb.-in)	− 0.533	− 0.029	No significant effect		No significant effect		− 0.633	0.071	− 0.100	− 0.462

when the BC interaction is estimated, the actual estimate is for the BC and DE interactions; when the BE interaction is estimated, BE and CD interactions are estimated together[9]. Hence, BC is confounded with DE, and BE is confounded with CD. Confounding means that the effects of each cannot be separated. Based on the analysis of the data, the author currently believes that it is the interactions between winding-tension gradient, winding time (DE), and the interaction between winding tension and winding-tension gradient (CD) that are the important second-order interactions in the confounding patterns.

The results of the analysis of variance are summarized in *Table 9*. The statistical effect of each variable on the outcome is identified by a comment regarding the qualitative significance level of including the variable in the model. That is, $\alpha \leq 0.01$ indicates that the effect of the independent variable is highly significant (designated in the table as 'Highly'), $0.01 < \alpha \leq 0.05$ indicates that the effect of the independent variable is significant (designated in the table as 'Yes'), and $\alpha > 0.05$ indicates that the effect of the independent variable is not significant (designated in the table as 'No'). Independent variables with α close to 0.05 but larger than 0.05 were designated in the table as marginally significant.

The analysis results showed that the following manufacturing and/or design variables had a strong effect on the burst capability of the cylinders: (a) laminate stacking sequence, (b) winding-tension gradient, and (c) the interaction between winding-tension gradient and winding tension. Winding tension and winding-tension gradient interaction with winding time were found to have a significant effect on burst pressure. On the other hand, fiber strain at failure was strongly affected by: (a) laminate stacking sequence, (b) cut-versus-uncut helicals, (c) winding tension, (d) winding-tension gradient, (e) winding time, and (f) the combined interactions BE (cut-versus-uncut helicals with winding time) plus CD (interaction between winding-tension gradient and winding tension). In most cases, these effects were highly significant.

Table 10 summarizes the magnitude of the main manufacturing and design variables effects on the measured composite vessel response and quality. The tables allow assessment of the changes in vessel response and quality because of changes to the manufacturing and design variables between the low ($-$) and high ($+$) settings. The data in the table only include information for main effects of manufacturing and design variables that significantly influenced the measured responses. *Table 10* shows that the main effects of the variables on strength are relatively small, with the effect of winding tension being the largest (2.5%). The mechanism by which composite strength increases with winding tension and short winding time is related to the increase in fiber volume as discussed next.

The relationships between the different response variables are investigated by the linear regression analysis. The results of the analysis are summarized in *Table 11*. The table shows a strong (as expected) relationship between the measured failure OD hoop strain and the cylinder burst pressure, and maximum fiber strain. The table also shows a strong relationship between measured failure hoop strain and the average and maximum fiber volume in the composite. No relationship between composite strength, fiber volume gradient through the thickness, or any of the void parameters was found. However, the average fiber volume in the composite was found to be related to the fiber gradient through the thickness. Whereas, the maximum fiber volume through the composite thickness was found to be significantly related to the fiber gradient through the thickness. The void level in the composite did not show any relationships with the other response variables.

Figure 5 shows that the burst pressure and maximum fiber strain of the composite vessels at failure increase with increased fiber volume fraction in the hoop layers. *Table 9* shows that fiber volume distribution parameters were strongly affected by winding tension and winding time, with high winding tension producing higher fiber volume. Similarly, shorter winding time produced composite with higher fiber volume compared with longer winding times. The mechanism by which these variables produce higher fiber volume is related to the fiber motion through the resin. First by tension and second by lower resin viscosity. Both

Table 11 Correlation analysis results for the relationship between cylinder response variables

Independent variable	Dependent variable	Model R^2	Model significance level, α	Comments
Burst pressure	Failure hoop strain	91	0.001	Highly significant
Average fiber volume	Failure hoop strain	75	0.003	Highly significant
Maximum fiber volume	Failure hoop strain	65	0.008	Highly significant
Fiber volume gradient	Failure hoop strain	36	0.089	Not significant
Average void volume	Failure hoop strain	2	0.690	Not significant
Maximum void volume	Failure hoop strain	26	0.160	Not significant
Void volume gradient	Failure hoop strain	17	0.260	Not significant
Maximum fiber strain	Failure hoop strain	99	0.000	Highly significant
Average fiber volume	Fiber volume gradient	47	0.041	Significant
Maximum fiber volume	Fiber volume gradient	81	0.001	Highly significant
Average void volume	Void volume gradient	17	0.263	Not significant
Maximum void volume	Void volume gradient	28	0.143	Not significant
Spring back	Residual moment	75	0.003	Highly significant

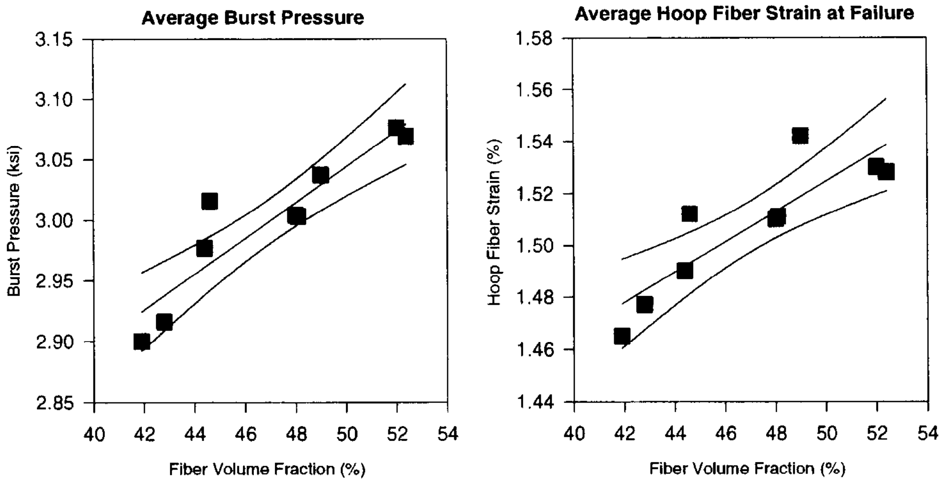

Figure 5 Composite vessel strength versus minimum loop layers fiber volume fraction

Table 12 Qualitative summary of the manufacturing and design variables main and interaction effect on vessel strength

DOE variable	Burst pressure	Measured OD hoop strain	Max. fiber strain at failure
A: Stacking sequence	Lumped hoop plies	Lumped hoop plies	Lumped hoop plies
B: Cut-versus-uncut helicals	No effect	Uncut Cut	
C: Winding tension	High	High	High
D: Winding tension gradient	No gradient	No gradient	No gradient
E: Winding time	Short	Short	Short
BE: Cut vs. uncut × Winding time	No effect	Uncut and short time	Uncut and short time
DE: Tension gradient × winding time	With gradient and short time	No effect	No effect
CD: Winding tension × tension gradient	With gradient and high tension	Without gradient and high tension	Without gradient and high tension

parameters (high tension and lower viscosity) produce higher fiber motion and, therefore, larger fiber compaction, which leads to higher fiber volume.

As expected, the laminate stacking sequence had a significant effect on SBS strength. Cylinders that had lumped hoop plies gave 25% lower strength compared with cylinders with dispersed hoop plies.

DISCUSSION OF RESULTS

Composite strength and stiffness measures

The statistical analysis showed that the following manufacturing and design variables had a significant effect on cylinder burst pressure: (a) laminate stacking sequence, (b) winding tension gradient, and (c) an interaction between winding tension and winding tension gradient. Winding tension and winding tension gradient interaction, with winding time were found to have a significant effect on burst pressure. On the other hand, fiber strain at failure was strongly affected by: (a) laminate stacking sequence, (b) cut-versus-uncut helicals, (c) winding tension, (d) winding tension gradient, (e) winding time, and (f) the combined interactions of cut-versus-uncut helicals with winding time plus interaction effect between winding tension gradient and winding tension. In most cases, these effects were highly significant. A qualitative summary of the main and interaction effects of the manufacturing and/or design variables on strength is given in *Table 12*. The variable setting that maximized composite vessel strength is listed in each cell. The table shows that, for the most part, the settings that maximized burst pressure also maximized the hoop fiber failure strain.

The composite cylinder stiffnesses were evaluated using two response parameters—the slope of the pressure-versus-OD hoop strain curve and laminate hoop modulus. The laminate hoop modulus is calculated from the slope using the measured cylinder wall thicknesses and diameters. *Table 9* shows that the manufacturing and/or design variables that significantly affect the slope do not track the variables that affect the modulus. The reason for this discrepancy is that the calculated modulus for cylinder No. 2B (replicate of cylinder No. 2) was 13% higher than the modulus for cylinder No. 2. On the other hand, the difference in slope was only 0.7%. These differences affect the results of the ANOVA that is based on variance between replicates.

In general, the data show that the composite hoop modulus was affected by the winding tension and winding time. As with the strength, these effects are related to the fiber volume. The hoop modulus increased with fiber tension and was higher for the short winding time compared with the long winding time. These trends correspond to an increase in fiber volume with a change in those parameters. On the average, the hoop modulus for the high winding tension was 6.5% higher than that of the low winding tension. Similarly, the average hoop modulus for the short winding time was 5.6% higher than that of the long winding time.

Cut-versus-uncut helicals generally did not affect any of the composite strength measures. It did seem to have some effect on the measured failure OD hoop strain and maximum fiber strain. However, the effects tended to be almost negligible. An average difference of −0.34% in the measured failure OD hoop strain between the uncut and cut helicals cylinders, and a difference of 0.27% in the maximum fiber strain between the uncut and cut helicals cylinders was seen. In general, the author believe that in the current investigation the cut-versus-uncut helicals did not have an important influence on composite response.

Composite quality measures

Cylinder wall thickness was found to be greatly affected by winding tension and time. The wall thicknesses of the cylinders decreased with an increase in winding tension and a decrease in winding time. On the average, cylinders that were would with high winding tension had 5.9% thinner wall thickness relative to cylinders wound with low winding tension. On the other hand, cylinders wound in a short time had on the average 6.3% thinner wall thickness relative to cylinders wound over a long winding time. The mechanism by which these differences occur is related to squeezing the resin out during the winding, as discussed previously.

Table 9 shows that stacking sequence, winding-tension gradient, and winding time had significant effects on the residual moment. Winding tension was also found to have no significant effect on residual moment. This is surprising because, in general, cylinders that were would with higher fiber tension were more difficult to extract from the mandrel. In most instances, the mandrel with the composite had to be placed in the freezer overnight, after which the composite was extracted from the cylinder without difficulties. Nevertheless, the residual moment did not seem to be affected by winding tension.

The data showed that the cylinders with dispersed hoop lay-up had, on the average, less spring back than the cylinders with the lumped hoop plies lay-up. Similarly, cylinders that were wound with a tension gradient and short winding time exhibited less springback than the cylinders wound without tension gradient and long winding time.

Table 9 shows that the laminate lay-up sequence had a highly significant effect on the average fiber volume and a significant effect on the maximum fiber volume in the composite. Quantitative analysis of the data shows that, on average, the lumped hoop plies had 4.8% higher average fiber volume and 4.1% higher maximum fiber volume than the dispersed hoop plies laminate. Stacking sequence had no effect on the fiber volume gradient through the composite thickness.

Cut-versus-uncut helicals did not affect any of the fiber volume distribution parameters. On the other hand, winding tension had a highly significant effect on all of the fiber volume distribution parameters. In all cases, an increase in winding tension resulted in an increase in those parameters. On the average, an increase in winding tension from the low to the high setting caused a 6.8% increase in the average fiber volume, 9.0% increase in the maximum fiber volume, and 22.8% increase in the fiber volume gradient through the thickness.

The winding-tension gradient had a highly significant effect on the fiber gradient through the composite thickness. Cylinders that were wound without winding-tension gradient had higher (by 24.5%) fiber volume gradient through the thickness as compared to cylinders wound with fiber tension gradient through the thickness. There was also a strong interaction between winding-tension gradient and winding tension and winding time. On the average, cylinders that were wound without tension gradient and high winding tension and/or short winding time had higher fiber volume gradient through the thickness.

For the most part, the void in the composite was not affected to a great degree by any of the manufacturing and design variables. The average void content in the composite was only significantly affected by winding tension, with the higher winding tension setting yielding on the average composite with 23% lower void by volume. The minimum (distribution intercept) void level in the composite was not affected by any of the manufacturing and design variables. On the other hand, the void distribution gradient through the thickness was significantly affected by winding-tension gradient. On the average, cylinders that were would with tension gradient had an 84% smaller void volume gradient through the thickness. That is, cylinders that were wound with tension gradient tended to have more uniformly distributed voids through the thickness than cylinders that were wound without a tension gradient.

CONCLUSIONS

An experimental design investigation of the effect of manufacturing and design variables on composite vessel response was conducted. In the process of the investigation, eight 20-in. cylinders, with one additional cylinder as a replicate, were manufactured and tested for hoop strength, hoop stiffness, fiber and void volume distribution through the thickness, residual stress, and interlaminar shear strength.

Statistical analysis of the data showed some very significant results, which should be very helpful in improving composite pressure vessel performance and quality. Some of the more significant findings relate to how composite pressure vessel strength was affected by the manufacturing and design variables. In general it was found that composite strength was significantly affected by the laminate stacking sequence, winding tension, winding-tension gradient, winding time, and the interaction between winding-tension gradient and winding time. The mechanism by which composite strength increases was related to the strong correlation between fiber volume in the composite and strength. The data showed that composite case strength increased with an increase in the maximum fiber volume in the hoop layers. Cylinders with high fiber volume (around 68%) in the first hoop ply tended to deliver higher fiber strength. It was found that fiber volume parameters (i.e. average, maximum, and gradient) were strongly affected by winding tension and winding time. High winding tension produced higher fiber volume. Similarly, shorter winding time produced higher fiber volume than long winding time. The mechanism by which these variables produce higher fiber volume is related to the fiber motion through the resin. First by tension, and second by the resin having lower viscosity. Both parameters (high tension and lower viscosity) produce higher fiber motion and therefore larger fiber compaction which leads to higher fiber volume.

In general, analysis of the data showed that composite strength increased for cylinders wound without winding gradient, wound in short time, with high winding tension, and with multiple (lumping) hoop plies in each layer. However, in the main effects of these variables on strength were relatively small, with the effect of winding tension being the largest (2.5%).

APPENDIX A

DOE confounding pattern

The confounding pattern for a 1/4 fractional factorial test setup is represented by the following pattern (a detailed discussion of the confounding effect in DOE can be found in Ref. [9]):

Confounding pattern for current DOE

Measured effect	Where:
Average	A = stacking sequence
A + BD + CE	B = Cut versus uncut
B + AD + ho	C = Winding tension
C + AE + ho	D = Winding-tension gradient
D + AB + ho	E = Winding time between layers
E + AC + ho	AB = stacking sequence interaction
BC + DE + ho	with cut versus uncut, etc.
BE + CD + ho	ho = higher order interactions

For an eight run experiment eight measured effects can be estimated. From the confounding pattern, all of the main factors (i.e. A, B, C, etc.) are obscured with second (i.e. AB, AD, AE, etc.)—and higher-order interactions. However, some of these second-order interactions may be considered insignificant or zero, relative to the effect they may have on composite vessel strength and quality. All higher-order interactions are assume to be zero. By assuming some of the interactions to be zero, the main effects (of these factors) can be estimated. Table A1 lists the interactions and predicted significance of these interactions. Using these assumptions, the main effects and important two-factor interactions are free to be estimated.

Table A1 Interaction and their predicted significance

Interaction	Description of interaction	Predicted significance effect
AB	Stacking sequence × cut versus uncut	No
AC	Stacking sequence × winding tension	No
AD	Stacking sequence × winding-tension gradient	No
AE	Stacking sequence × winding time	No
BC	Cut versus uncut × winding tension	Yes
BD	Cut versus uncut × winding-tension gradient	No
BE	Cut versus uncut × winding time between layers	Yes
CD	Winding tension × winding tension gradient	No
CE	Winding tension × winding time	No
DE	Winding-tension gradient × winding time	No

APPENDIX B

Split ring springback residual stress analysis

The stresses for the split ring test are determined by measuring the ring springback δ and relating this value to the residual moment distribution. A complete description for these analysis calculations can be found in Refs. [12,13]. A brief summary of relevant equations follows.

The moment M distribution through the ring thickness may be written in terms of the split ring spring back, circumferential stiffness, E_T, and the composite ring inner a and outer b radii[12]

$$M=\int_a^b \frac{\delta E_\theta}{8\pi r}\left[\frac{(b^2-a^2)^2-4a^2b^2\left(\ln\frac{b}{a}\right)^2}{2(b^2-a^2)}\right] \tag{B1}$$

In term of the total residual moment (or effective moment) the above relationship reduces to[12]:

$$M=\frac{\delta E_\theta \ln\left(\frac{b}{a}\right)\left[(b^2-a^2)^2-4a^2b^2\left(\ln\frac{b}{a}\right)^2\right]}{16\pi(b^2-a^2)} \tag{B2}$$

For pure bending of a curved beam with cylindrical anisotropy the corresponding radial σ_r and hoop σ_θ stress components are given by[13]:

$$\sigma_r=-\frac{M}{b^2hg}\left[1-\frac{1-c^{k+1}}{1-c^{2k}}\left(\frac{r}{b}\right)^{k-1} - \frac{1-c^{k-1}}{1-c^{2k}}c^{k+1}\left(\frac{b}{r}\right)^{k+1}\right] \tag{B3}$$

$$\sigma_\theta=--\frac{M}{b^2hg}\left[1-\frac{1-c^{k+1}}{1-c^{2k}}\left(\frac{r}{b}\right)^{k-1} - \frac{1-c^{k-1}}{1-c^{2k}}kc^{k+1}\left(\frac{b}{r}\right)^{k+1}\right] \tag{B4}$$

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