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Research Article

Optimization of viscoelastic behaviors of bioinspired asymmetric helicoidal CFRP composites using Taguchi Method

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Keywords: Helicoidal composites; DMTA; Fiber orientation; Bouligand structure; CFRP; Taguchi method

Abstract

The dynamic mechanical properties play an important role in the selection of suitable materials in the manufacturing wing of aircraft and wind turbine blades. In this paper, the standard Taguchi method was used to examine the effect of inter-ply stacking angles of 0° (UD), 0/90° (cross-ply), 5°, 15°, 10°, 20°, 25° 30° and aging temperature (ambient temperature, 40°, 60°) on the dynamic mechanical properties of bioinspired asymmetric helicoidal Carbon Fiber Reinforced Plastic (CFRP) composites. The standard Taguchi's L_{18} was used. The signal-to-noise ratio and analysis of variance were introduced to analyze and estimate the optimal combination parameters. The results show the dynamic mechanical properties are linearly correlated to the fiber architecture and aging temperature. Analysis of variance (ANOVA) indicates that inter-ply stacking angles (15°, and 20°) and aging temperature (40°, 60°) are the main significant factors affecting the dynamic mechanical values at a 95% confidence level. Inter-ply stacking angles are finally noted as critical factors affecting the extent of macromolecular mobility within helicoidally stacked continuous fiber CFRP composites. A confirmation test validated the optimized results and it was found that there were improvements in S/N ratios from initial to optimal setting. The experimental and expected results are very close, with an error ratio not exceeding 5%.

Abbreviations

Coeff: Coefficient; SE Coeff: Standard error Coefficient; T: T-Statistics; P: Probability value; Seq.: Sequential term; Adj. SS: Adjusted Sum of Square; Adj. Ms: Adjusted mean of Square; DF: Degree of Freedom; F: F-Statistics; UD: Unidirectional; H5: 5°; H10: 10°; H15: 15°; H20: 20°; H25: 25°; H30: 30°

Introduction

Composites are materials consisting of at least two materials combined to obtain a material with characteristics different from its constituents, whereas the constituents remain separate and distinct within a composite structure [1]. Helicoidal composite structures in nature are fundamentally asymmetrical and are known to have exceptional tolerance to impact damage [2,3] This architecture consists of stacked laminates of aligned fibers that are rotated by an angle relative to their neighboring laminates to form twisted (Bouligand) architectures with a variety of functions, such as thermal regulation and physical protection [1,4]. In order to reduce fracture, researchers have begun to focus more on the development of helical CFRP as an alternative to typical laminated composite structures [5,6]. The dynamic mechanical performance of helical CFRP, however, has received less attention, even though high-performance composites are commonly used in aerospace and automotive technologies where their viscoelastic and dynamic thermo-mechanical properties are of importance [7,8]. The dynamic mechanical analyzer is an experimental method by which independent anisotropic variables can be examined [9]. While it is known that storage modulus, loss modulus, and glass

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transition temperature (Tg) vary with inter-ply pitch angle [10-12] there is no report clearly correlating the characteristics these properties as a function of orientation architecture.

For the composite, most of the research focused on experimental tests of the mechanical properties of the composites Muralidhara, et al. [13]; Nwambu, et al. [14] Ekwedigwe, et al. [15]. The correlation between the mechanical properties and the characteristic parameter, e.g., the composition of the composite and the operating conditions is of prime importance for designing proper composites in order to satisfy various functional requirements. Optimization of characteristic parameters on mechanical properties of carbon fiber reinforced composites and finding out the optimal combination of parameters [16]. For the optimization process, among the various techniques such as genetic algorithm, artificial neural network, Taguchi method, and several studies have reported that the Taguchi method has shown a 95% confidence level compared to others [17]. In the Taguchi method, a smaller number of tests is required and it can extract information more precisely and efficiently compared to another approach. Furthermore. it will produce better consistency and reproducibility of results since it uses both a set of standard orthogonal arrays which can be used for many other experimental situations and a standard method for the analysis of results [16]. In this paper, the standard Taguchi method was used to examine the effect of inter-ply stacking angles of 0° (UD), 0/90° (cross-ply), 5°, 15°, 10°, 20°, 25° 30° and aging temperature (ambient temperature, 40°, 60°) on the dynamic mechanical properties of bioinspired asymmetric helicoidal Carbon Fiber Reinforced Plastic (CFRP) composites

Materials and experimental details

Materials and composite fabrication

MR70 12P carbon fiber prepreg with Toray E750 toughened epoxy resin (Mitsubishi Chemical Carbon Fibre Composites) was vacuum bag manufactured into composite laminates comprising the following different inter-ply orientation angles: 0° (UD), 0/90° (cross-ply), 5°, 15°, 10°, 20°, 25° and 30°. While UD and cross-ply composites are symmetric composites, helicoidal composites (5° - 30°) displayed an asymmetrical Bouligand structure. All CFRP composite laminates were manufactured using 20 plies and were 1.9mm thick after curing, which was conducted in a convection oven (Sciquip HT 230), raising the temperature from ambient temperature to 135°C over one hour, holding this temperature for another hour, and then cooling the composite over an hour back to ambient (room) temperature. Table 1 provides information on the stacking sequences used, and the relative fractions of plies oriented between 0° - 45° of the loading axis, and the fraction of those oriented at 46° - 90° of the loading axis [3].

Samples for DMTA testing (3-point bending mode) were prepared and thermal sweep testing was conducted in accordance with ISO 6721-11 [18] using a Triton 2000 Series DMTA. The specimens (*n* = 3 for each series) were cut to 42 mm (long) and 8.2 mm (wide), a heating rate of 4 °C/min ramped between 50 °C -230 °C at 1Hz at an amplitude of 50 µm. The 3-point bending test span was 15 mm [3].

Experimental design based on the Taguchi method

The experimental procedure is designed with Taguchi's L_{18} orthogonal array to reduce the experiment numbers. Taguchi's L_{18} orthogonal array contained two columns and eighteen rows, with seventeen degrees of freedom to treat one parameter with three levels and another parameter with six levels. Each machining parameter level is set according to Taguchi's L_{18} orthogonal array, based on the Taguchi experimental design method. The experimental observation is further transformed into a signal-to-noise (S/N) ratio using the MINITAB 14 software (Minitab user manual (2003)]. The different levels of variables used in the experiment are given in Table 1.

The S/N ratio for maximum load and stress values can be expressed as the "Higher is better" characteristic, which is calculated as a logarithmic transformation of the loss function. The S/N ratios determined from experimentally observed values are statistically studied by analysis of variance (ANOVA)

Results and discussion

Loss modulus of the CFRP composite

The response surface regression of loss modulus (GPa) versus inter-ply pitch angles and three different aging temperatures (C). The analysis was done using coded units (Table 2).

Table 1: Laminate stacking sequences for composite sample sets (*n* = 3) arranged at specific pitch angles. The fraction of plies with fibers oriented between 0° - 45° and between 46° - 90° are shown for each sample set.

Pitch angle	ID	Stacking sequence	No. plies between (0° - 45°)	No. plies between (46° - 90°)	Fraction (0° - 45°)	Fraction (46° - 90°)
0°	UD	[0°/0°/0°/...../0°]	20	0	1	0
5°	ID5	[0°/5°/10°/15° /20°/.....//95°]	10	10	0.5	0.5
10°	ID10	[0°/10°/20°/30°/40°/.....//190°]	11	9	0.55	0.45
15°	ID15	[0°/15°/30°/45°/60°/.....//285°]	13	7	0.65	0.35
20°	ID20	[0°/20°/40°/60°/80°/.....//380°]	14	6	0.7	0.3
25°	ID25	[0°/25°/50°/75°/100°/.....//475°]	14	6	0.7	0.3
30°	ID30	[0°/30°/60°/90°/120°/.....//570°]	13	7	0.65	0.35
0/90°	ID90	[0°/90°/0°/90°/.....................]	10	10	0.5	0.5

Table 2: Estimated Regression Coefficients for LOSS MODULUS (GPa).

Term	Coef.	SE Coef.	T	P
Constant	5.59298	0.6084	9.193	0.0000
Stacking Angles	-0.07519	0.3975	9.193	0.003
Aging Temp (C)	-0.57000	0.3217	-1.772	0.097
Stacking Angles	-1.03929	0.6825	-1.523	0.149
Stacking Angles*Aging Temp (C)	-0.66042	0.4739	-1.394	0.184

S = 1.20376 PRESS = 63.8687
R-Sq = 66.67% R-Sq(pred) = 73.70% R-Sq(adj) = 65.56%.

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The investigation looks at the predicted regression coefficients for the loss modulus (GPa) in composites made from carbon fiber-reinforced plastic (CFRP) that are inspired by biological structures. The interactions between the two important variables stacking angles and aging temperature were taken into account. The regression model shows that stacking angles have a substantial negative coefficient of -0.07519 (p = 0.003) influence on the loss modulus of CFRP composites. This shows that changes in stacking orientations can affect how these composites' dynamic mechanical characteristics behave. This is consistent with earlier research by Muralidhara, et al. [13] that emphasized how important fiber design is in shaping how composite materials behave.

Likewise, the regression model of aging temperature was negative (-0.57000), indicating the impact of aging temperature was statistically significant at the standard significance levels (p = 0.097). The analysis also evaluated interaction effects, revealing that squared stacking angles and aging temperature terms negatively influence the loss modulus. However, like the main effects, these interactions were statistically significant ($p > 0.05$).

Overall, the model accounts for approximately 66.67% of the variability in the loss modulus, indicating moderate explanatory power [16]. As shown in Table 1, the predicted R-squared value (73.70%) suggests that the model effectively predicts the loss modulus based on the chosen variables.

According to the ANOVA Table 3, the aging temperature and stacking angles have a big impact on the dynamic Loss modulus characteristics of bio-inspired asymmetric helicoidal CFRP composites. The considerable linear effects of both variables (p = 0.003) indicate that variations in stacking angles and aging temperature have a significant effect on the loss modulus [17]. Squared stacking angles, squared aging temperatures, and their interaction, however, show appreciable impact. The low residual error indicates that the model explains a significant percentage of the variability in the loss modulus, despite the fact that the overall model's significance is only moderately strong (p = 0.187).

Table 4 presents the forecasted outcomes derived from the regression model, demonstrating that these projections have a 95% likelihood of falling within the lower and upper boundaries, as indicated by the 95% Confidence Interval in Table 3. The model's predictions resulted in a correlation factor (R) of 0.735 and a coefficient of determination (R^2 = 0.54) for the loss modulus (GPa). This suggests that the model's predictions exhibit an accuracy of approximately 73.5%.

Figure 1, presented that there was a perfect correlation between the actual values and the predicted values, which signifies that there is a very good agreement with the model predictions and experimental results.

Young modulus of CFRP composite

The response surface regression of Young Modulus (GPa) versus Inter-ply pitch angles and aging temp (C).

Table 3: Analysis of Variance for Loss Modulus (GPa).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	12.5854	12.5854	2.51709	1.74	0.187
Linear	2	3.6326	4.6004	2.30022	1.59	0.002
Angles	1	0.2060	0.0518	0.05184	0.04	0.003
Angle Temp (C)	1	3.4266	4.5486	4.54860	3.14	0.003
Square	2	6.1384	6.1384	3.06921	2.12	0.155
Stacking Angles	1	3.3604	3.3604	3.36036	2.32	0.149
Aging Temp (C)	1	2.7781	2.7781	2.77806	1.92	0.186
Interaction	1	2.8144	2.8144	2.81437	1.94	0.184
Stacking Angles*Aging Temp (C)	1	2.8144	2.8144	2.81437	1.94	0.184
Residual Error	15	21.7355	21.7355	1.44903		
Total	20	34.3209				

Table 4: Predicted Response for New Design Points Using Model for Loss Modulus (GPa).

Samples	Aging temp (C)	Loss modulus (GPa)		95 Confidence interval (95% CI)	
		Actual value	Predicted value	Lowest value	Highest value
UD	Unaged	1..15	2.3	1.76817	5.54089
UD	40	7	5.09	3.02809	6.09353
UD	60	7.5	5.25	2.07329	5.59746
H5	Unaged	5.6	5.42	3.08025	5.77373
H5	40	4.2	5.03	3.91001	6.16948
H5	60	3.4	4.16	2.89783	5.43727
H10	Unaged	5.8	4.96	3.78788	6.14911
H10	40	4.5	5.28	4.16545	6.41001
H10	60	3.6	4.26	3.10969	5.42786
H15	Unaged	6.05	5.27	4.11354	6.44456
H15	40	5.1	5.3	4.13925	6.47027
H15	60	4.15	4.14	2.97354	5.30456
H20	Unaged	5.78	5.36	4.17803	6.53927)
H20	40	4.8	5.09	3.96856	6.21312
H20	60	4.02	3.78	2.61928	4.93745
H25	Unaged	5.04	5.21	3.86056	6.55403
H25	40	4.1	3.99	3.51623	5.77571
H25	60	3.7	3.78	1.91702	4.45645
H30	Unaged	4.3	4.312	2.93863	6.71135
H30	40	3.7	3.97	2.43743	5.50286
H30	60	3.07	2.36	0.60207	4.12623

R = 0.735103617

As presented in Table 5, the estimated regression coefficients for Young Modulus (GPa) in bioinspired asymmetric helicoidal Carbon Fiber-Reinforced Plastic (CFRP) composites show that stacking angles have a minimal influence with a small negative coefficient, but that aging temperature has a significant influence on a significant negative coefficient (p = 0.001). Young Modulus is not considerably impacted by interaction effects, such as squared stacking angles and stacking angles with aging temperature. The model's high R-squared value (90.3%) and

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good prediction rate (73.09%) show significant explanatory power. The corrected R-squared value (83.80%) highlights the robustness of the model. According to this, stacking angles are not as important as aging temperature in influencing the stiffness of CFRP composites, which is consistent with Banerjee, et al. [19] and Nwambu et al., [3] studies emphasizing the impact of temperature on CFRP composites.

As presented in Table 6, the analysis of variance (ANOVA) was used to examine the effect of inter-ply stacking angles (0°, 0/90°, 5°, 15°, 10°, 20°, 25°, and 30°) and aging temperature on material properties of bioinspired asymmetric helicoidal Carbon Fiber-Reinforced Plastic (CFRP) composites. With an F-statistic of 3.44 and a p-value of 0.029, the total model was statistically significant, indicating that the combined effects of stacking angles and aging temperature affect the Young Modulus. In particular, the substantial linear effects of stacking angles (p = 0.004) and aging temperature (p = 0.003) showed their influence. Squared terms and interaction effects, however, did not reach statistical significance (p = 0.498). Because the residual error was so small, the model likely accounts for a sizable proportion of the variation in the Young Modulus.

The predicted results from the regression model are shown in Table 7, which also shows that they are 95% likely to fall between the lower and higher boundaries indicated by the 95% Confidence Interval in Table 7. The Young modulus (GPa) was predicted by the model to have a correlation factor (R) of 0.730 and a coefficient of determination (R2 = 0.534). This suggests that the predictions made by the model have an accuracy rate of about 73.0%.

Figure 2 presented that there was a perfect correlation (R) between the actual values and the predicted values, which signifies that there is a very good agreement between the model predictions and experimental results [20,21].

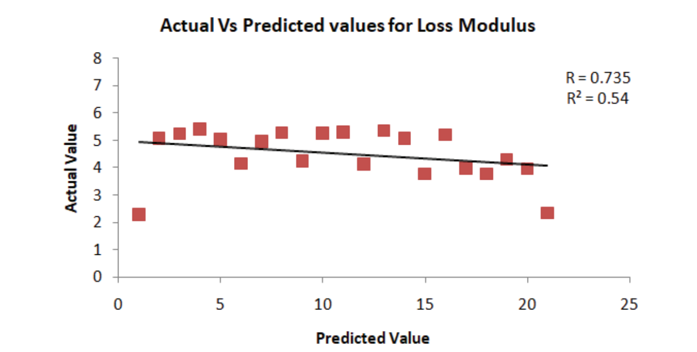

Figure 1: Relationship between Actual versus Predicted value for Loss modulus.

Table 5: Estimated Regression Coefficients for young modulus (GPa).

Term	Coef.	SE Coef.	T	P
Constant	50.4083	2.189	23.031	0.000
Stacking Angles	-0.0440	1.430	-0.031	0.001
Agingh Temp (C)	-4.7429	1.157	-4.098	0.001
Stacking Angles*Aging Temp (C)	0.6210	1.705	0.364	0.721

S = 0.4102 R-Sq = 90.3% R-Sq(pred) = 73.09% R-Sq(adj) = 83.80%.

Table 6: Analysis of Variance for young modulus (GPa).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	322.658	322.658	64.532	3.44	0.029
Linear	2	292.807	314.943	157.472	8.40	0.004
Stacking Angles	1	0.006	0.018	0.018	0.00	0.003
Aging Temp (C)	1	292.801	314.926	314.926	16.79	0.001
Square	2	27.362	27.362	13.681	0.73	0.498
Stacking Angles*Stacking Angles	1	2.460	2.460	2.460	0.13	0.722
Aging Temp (C)*Aging Temp (C)	1	24.902	24.902	24.902	1.33	0.267
Interaction	1	2.489	2.489	2.489	0.13	0.721
Stacking Angles*Aging Temp (C)	1	2.489	2.289	2.489	0.13	0.721
Residual Error	15	281.288	281.288	18.753		
Total	20	603.946				

Table 7: Predicted Response for New Design Points using Model for Young Modulus (GPa).

Samples	Aging temp (C)	Young modulus (GPa)		95 Confidence interval (95% CI)	
		Actual value	Predicted value	Lowest value	Highest value
UD	Unaged	57	54.0591	47.2731	60.8451
UD	40	54	49.2596	43.7458	54.7734
UD	60	48	43.3313	36.9923	49.6702
H5	Unaged	50	53.3434	48.4986	58.1881
H5	40	45	48.8199	44.7558	52.884
H5	60	35	43.0296	38.4619	47.5973
H10	Unaged	47	52.8253	48.5781	57.0724
H10	40	44.5	48.5778	44.5405	52.6151
H10	60	43	42.9255	38.7558	47.0952
H15	Unaged	55.5	52.5048	48.3119	56.6976
H15	40	50	48.5333	44.3405	52.7262
H15	60	43.5	43.019	38.8262	47.2119
H20	Unaged	57.8	52.3819	48.1347	56.6291
H20	40	52	48.6865	44.6492	52.7238
H20	60	45.4	43.3102	39.1405	47.4799
H25	Unaged	53	52.4566	47.6119	57.3014
H25	40	51	49.0372	44.9731	53.1014
H25	60	46	43.799	39.2313	48.3667
H30	Unaged	50	52.729	45.943	59.515
H30	40	46	49.5856	44.0718	55.0995
H30	60	43	44.4854	38.1464	50.8243

R = 0.730923298.

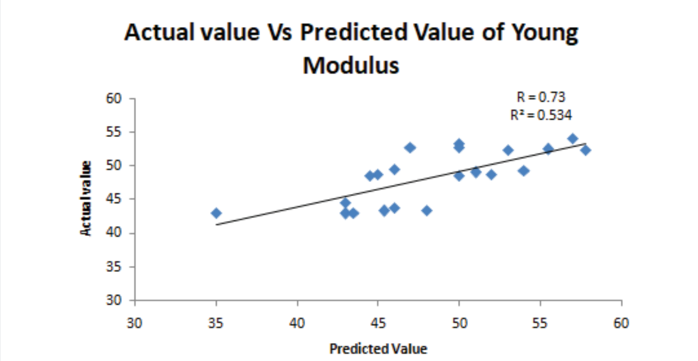

Figure 2: Relationship between Actual versus Predicted value for %Yield.

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Conclusion

The following conclusions were obtained: the dynamic mechanical properties are linearly correlated to the fiber architecture and aging temperature. Analysis of variance (ANOVA) indicates that inter-ply stacking angles (15°, and 20°) and aging temperature (40°, 60°) are the main significant factors affecting the dynamic mechanical values at a 95% confidence level. Inter-ply stacking angles are finally noted as critical factors affecting the extent of macromolecular mobility within helicoidally stacked continuous fiber CFRP composites which correspond with the experimental result [3]. A confirmation test validated the optimized results and it was found that there were improvements in S/N ratios from initial to optimal setting. The experimental and expected results are very close, with an error ratio not exceeding 5%.

With the use of the Taguchi optimization method, it was established that fiber architecture and aging temperature are determinant factors in the fabrication of helicoidally stacked continuous fibre CFRP composites though the method could not identify specifically the processing parameters (inter-ply stacking angles) with the highest effect.

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