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Research Article

Taguchi analysis of the tensile behaviour of unaged and hygrothermally aged asymmetric helicoidally stacked CFRP composites

Nwambu CN*, Chibueze GI, Nwankwo EN and Ekwedigwe CM

Composite Laboratory, Department of Metallurgical and Materials Engineering, Faculty of Engineering, Nnamdi Azikiwe University, Awka, Nigeria

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***Corresponding authors:** Nwambu CN, Composite Laboratory, Department of Metallurgical and Materials Engineering, Faculty of Engineering, Nnamdi Azikiwe University, Awka, Nigeria, Tel: +2348036764210; E-mail: cn.nwambu@unizik.edu.ng ; cn.nwambu@gmail.com

ORCiD: https://orcid.org/0000-0001-5892-7202

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Abstract

Taguchi method was used to predict and optimize the effects of hygrothermal aging on the tensile behavior of asymmetric helicoidally stacked Carbon Fiber Reinforced Plastic (CFRP) composites. This research is in furtherance to the previous work, which dealt purely with experiments. MR70 12P carbon fiber epoxy prepreg sheets were manufactured into laminated composites comprising constant inter-ply pitch angles ranging from 0° to 30°. The composites were tested in tension as either dry unaged specimens or following hygrothermal aging in seawater at the constant temperatures of 40 °C and 60 °C for 2000 hrs. Optimizations were conducted based on Taguchi L_{18} orthogonal array considering two design parameters viz. inter-ply stacking angles and hygrothermal aging temperature. The result depicted that the combination of aging temperature (C) and stacking angles are major factors in determining the tensile behavior of composite materials ($p = 0.011$). The model explains 86.6% of tensile strength variability, with a predicted R-squared value of 93.04%. The model's robustness is supported by the adjusted R-squared value of 77.6%. Analysis of variance shows that inter-ply stacking angles are the main significant factor affecting the tensile behaviors at a 95% confidence level. A confirmation test was carried out to validate the optimized results and it was found that there were improvements in S/N ratios from initial to optimal setting.

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

Helicoidal composite structures are found in mantis shrimps (*Odontodactylus scyllarus*) (Suksangpanya, et al. 2017) and crab carapaces [1], have an excellent combination of mechanical properties, including but not limited to toughness and impact resistance (Pinto, et al. 2016). Mantis shrimps are able to use their dactyl clubs to smash through the tough exoskeletal components of prey whilst retaining the integrity of their limbs (Wang, et al. 2014) [2], whereas crab carapace impact resistance is a result of combined structural hierarchy where helicoidal microstructures work alongside the macro-scale geometries of the carapace itself [3]. This architecture consists of stacked laminates of aligned fibres 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 [1,4,5]. 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 [6,7]. Nwambu, et al. [8] previously investigated experimentally the tensile behavior of unaged and hygrothermally aged asymmetric helicoidally stacked CFRP composites. The result of the investigation revealed that both tensile modulus and tensile strength are

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found to be detrimentally affected by hygrothermal aging, and the extent to which aging affects these properties is a function of the inter-ply pitch angle. Based on the foregoing, there is a need to identify specifically the processing parameters with the highest effect. This will ensure better consistency and reproducibility of the inter-ply pitch angle and hygrothermally aged composite. Several previous studies have focused on experimental tests of mechanical properties of the composites especially tensile properties [9-11]. 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 optimal combination of parameters are of utmost importance [12]. For the optimization process, several studies have reported that the Taguchi method has shown a 95% confidence level compared to others such as the genetic algorithm, artificial neural network, and Taguchi method [13]. In the Taguchi method, a smaller number of tests is required and it can extract information more precisely and efficiently compared to other approaches. 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 [12]. To date, there are no reports on the Taguchi analysis of the effects of hygrothermal aging on the tensile properties of asymmetric helicoidally stacked CFRP composites and this paper aims to fill this gap in knowledge.

Materials and experimental details

Materials and composite fabrication

The materials and experimental techniques used are as stated in the previous work [14]. Unidirectional MR70 12P carbon fiber epoxy prepreg supplied from Mitsubishi Chemical Carbon Fiber and Composites and Toray E750 toughened epoxy resin was used to manufacture helicoidal CFRP composites. The Unidirectional (UD) plies were stacked using a constant increase in inter-ply pitch angle to form a laminated structure. Six different sample configurations were manufactured for conditioning and testing using the following inter-ply pitch angles in each configuration: 0° (unidirectional, UD), 5° (ID5), 10° (ID10), 15° (ID15), 20° (ID20), 25° (ID25), and 30° (ID30).

Experimental design based on the Taguchi method

The experimental procedure is designed with Taguchi's L_{18} orthogonal array to reduce the experiment numbers. 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 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

Response surface regression of tensile strength (Mpa) versus ageing temp (C) and inter-ply angles.

The previous work [8] investigated the hygrothermally aged asymmetric helicoidal composite experimentally while this work statistically analyzed the experimental results to determine the best combination of processing parameters that can provide the optimal physical and mechanical conditions [12].

Based on this, Table 1 presents the estimated regression coefficients that provide insights into the complex relationship between fiber architecture, aging temperature, and material strength. The significantly negative coefficient for stacking angles (-111.7, $p = 0.041$) highlights the critical role of stacking angles in determining tensile strength. Selecting appropriate stacking angles is crucial for achieving desired tensile strength levels in CFRP composites according to previous literature [8] (Suksangpanya, et al. 2017). Considering the aging temperature effect, although the coefficient for aging temperature (-151.5) is negative, it's not statistically significant ($p = 0.128$) at conventional significance levels. However, this suggests that aging temperature may still play a role in tensile strength, warranting further investigation. The significant interaction term "Stacking Angles * Stacking Angles" ($p = 0.026$) underscores the importance of considering squared stacking angles when optimizing tensile strength. In contrast, "Ageing temperature (C) * Stacking Angles" are major factors in determining the tensile behavior of composite materials ($p = 0.011$). Model Fit: The model explains 86.6% of tensile strength variability, with a predicted R-squared value of 93.04%. The model's robustness is supported by the adjusted R-squared value of 77.6% [12].

In addition, Analysis of variance (ANOVA), as presented in Table 2, analyzed the tensile strength (MPa) in bioinspired asymmetric helicoidal Carbon Fiber-Reinforced Plastic (CFRP) composites which evaluates the influence of inter-ply stacking angles (0°, 0/90°, 5°, 15°, 10°, 20°, 25°, and 30°) and aging temperature on material strength. The "Regression" row in the ANOVA table indicates that the overall model shows statistical significance, with an F-statistic of 0.05 and a p - value of 0.115. This implies that the combined effects of stacking angles and aging temperature significantly affect tensile strength. The

Table 1: Estimated Regression Coefficients for STRENGTH (Mpa).

Term	Coef	SE Coef	T	P
Constant	747.6	177.61	4.209	0.001
Ageing Temp (C)	-151.5	93.92	-1.613	0.128
Stacking Angles	-111.7	116.05	-0.963	0.041
Ageing Temp (C)*Ageing Temp (C)	-138.5	186.36	-0.743	0.469
Stacking Angles*Stacking Angles	491.2	199.23	2.465	0.026
Ageing Temp (C)*Stacking Angles	-117.0	138.33	-0.846	0.011

S = 188.7, R-Sq = 86.6%, R-Sq(pred) = 93.04%, R-Sq(adj) = 77.6%.

Abbreviations: Coeff: Coefficient; SE Coeff: Standard error Coefficient; T: T-Statistics; P: Probability value

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analysis categorizes effects into linear, square, and interaction terms. Among these, only the "Square" term is statistically significant ($p = 0.044$), indicating that squared stacking angles have an impact on tensile strength. Other terms, including "aging temp (C)," "Stacking Angles," and interactions, are also statistically significant ($p > 0.05$).

Table 3 presents the predicted values resulting from the regression model, and it can be observed that these values are 95% certain to fall inside the lowest and highest conceivable values (i.e., the 95% Confidence Interval). The correlation factor (R) for the model predictions was 0.9304, indicating that regression model predictions are 93.04% correct which agrees with the work of Anmar, et al. [13].

As earlier predicted in Table 1 of response surface regression of tensile strength, the Figure 1 shows a perfect correlation between the actual values and the predicted values, which signifies that there is a very good agreement between the model predictions and experimental results [8].

Response surface regression of stiffness (GPa) versus ageing temp (C) and stacking angles

According to the Estimated Regression Coefficients for Stiffness (GPa) analysis as shown in Table 4, stacking angles significantly ($p = 0.022$), affected stiffness (26.270), indicating that the stiffness of the material changes as the stacking angle changes. In addition, the aging temperature coefficient (15.928), is statistically significant at standard levels. Stiffness is greatly impacted by interaction factors, such as squared stacking angles and interactions between stacking angles and aging temperature. The model's predictive R-squared value is 94.8% (R-Sq(pred)), while its adjusted R-squared value is 83.2% (R-Sq(adj)), demonstrating robustness. The model explains 89.9% of stiffness variability (R-Sq).

As shown in Table 5, an F-statistic of 4.96 ($p = 0.007$) from the ANOVA indicates that the combined effects of stacking angles and aging temperature have a substantial impact on stiffness. The effects are broken down into linear, square, and interaction terms in the study of the main and interaction effects. Significant values are found for aging temp (C) and stacking angles (p 0.05), and squared stacking angles are also significant ($p = 0.007$). Stiffness is strongly influenced by interaction factors, such as the combination of aging temp (C) and stacking angles (p 0.01). Also, the comparatively small residual error implies that the model adequately accounts for the variations in stiffness.

Table 2: Analysis of Variance for Tensile Strength (MPa).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	1329971	1329971	265994	0.05	0.015
Linear	2	422877	435749	217875	1.76	0.205
Ageing Temp (C)	1	277708	321311	321311	2.60	0.128
Stacking Angles	1	145169	114439	114439	0.93	0.351
Square	2	818763	818763	409382	3.32	0.044
Ageing Temp (C)*Ageing Temp (C)	1	68216	68216	68216	0.55	0.041
Stacking Angles*Stacking Angles	1	750547	750547	750547	6.08	0.026
Interaction	1	88331	88331	88331	0.72	0.041
Ageing Temp (C)* Stacking Angles	1	88331	88331	88331	0.72	0.041
Residual Error	15	1852231	1852231	123482		
Total	20	3182202				

Abbreviations: Seq.: Sequential term; Adj. SS: Adjusted Sum of Square; Adj. Ms: Adjusted mean of Square; DF: Degree of Freedom; F: F-Statistics

Table 3: Predicted Response for New Design Points using Model for Tensile Strength (MPa).

Samples	Ageing temp (C)	Tensile strength (MPa)		95 Confidence interval (95% CI)	
		ACTUAL VALUE	PREDICTED VALUE	Lowest value	Highest value
UD	Unaged	1731.198	1703.29	695.8	1797.14
UD	40	1636.7375	1624.42	898.04	3369.46
UD	60	1360.06675	1400.3	1351.72	9042.21
H5	Unaged	512.194	572.57	777.04	1789.05
H5	40	467.299	493.7	923.83	3312.83
H5	60	356.365	269.58	1347.6	8963.48
H10	Unaged	675.327	804.89	826.15	1797.69
H10	40	638.7936667	726.01	927.99	3262.43
H10	60	718.675	501.9	1327.43	8885.4
H15	Unaged	673.7854	826.68	852.78	1813.44
H15	40	675.5553333	747.81	914.88	3213.9
H15	60	748.8345	523.69	1292.68	8806.53
H20	Unaged	883.917	878.66	866.09	1827.1
H20	40	1012.9386	799.79	888.19	3163.57
H20	60	357.2548	575.67	1244.47	8725.72
H25	Unaged	1248.3486	1181.07	872.81	1831.97
H25	40	1002.9384	1102.2	850.58	3108.77
H25	60	910.0616667	878.08	1183.58	8642.18
H30	Unaged	1127.413	885.03	876.65	1824.33
H30	40	865.822875	806.16	803.56	3047.98
H30	60	279.9942	582.04	1110.47	8555.5

R = 0.930458081
Abbreviations: UD: Unidirectional; H5: 5˚; H10: 10˚; H15: 15˚; H20: 20˚; H25: 25˚; H30: 30˚

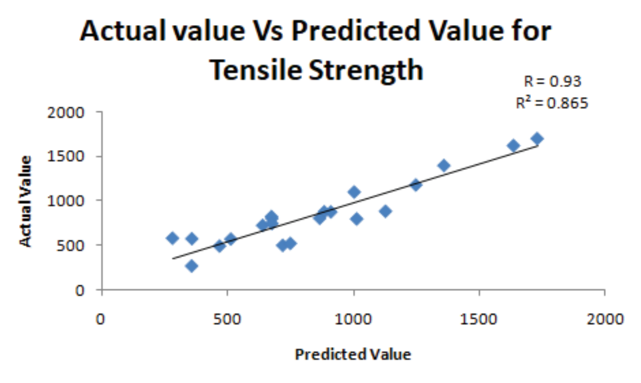

Figure 1: Relationship between Actual versus Predicted value for %Yield.

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In a nutshell, the analysis of variance (ANOVA) agreed with previous studies that stiffness in bioinspired asymmetric helicoidal CFRP composites is considerably influenced by stacking angles and aging temperature [6,8] (Pinto, et al. 2016). Interactions and squared stacking angles also affect stiffness variation. selecting the right stacking angle, and consideration of interactions are vital for achieving desired stiffness in composites.

Table 6 shows the predicted values obtained from the regression model for stiffness, and it was seen that the predicted values are 95 % certain to be within the lowest and highest possible values (i.e. 95% Confidence interval) which correspond to the report of Anmar, et al. [13] that the experimental and expected results are very close, with an error ratio not exceeding 5%. The model predictions gave a correlation factor (R) of 0.948 which implies that the model predictions are 94.8 % accurate.

Furthermore, Figure 2 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 of Nwambu, et al. [14-16].

Table 4: Estimated Regression Coefficients for Stiffness (GPa).

Term	Coef	SE Coef	T	P
Constant	66.385	15.781	4.207	0.001
Ageing Temp (C)	-15.928	8.344	-1.909	0.076
Stacking Angles	-26.270	10.311	-2.548	0.022
Ageing Temp (C)* Ageing Temp (C)	-11.302	16.558	-0.683	0.505
Stacking Angles*Stacking Angles	65.609	17.701	3.706	0.002
Ageing Temp (C)*Stacking Angles	-6.971	12.291	-0.567	0.579

S = 18.06, R-Sq = 89.9%, R-Sq(pred) = 94.8%, R-Sq(adj) = 83.2%.
Abbreviations: Coeff: Coefficient; SE Coeff: Standard error Coefficient; T: T-Statistics; P: Probability value

Table 5: Analysis of Variance for Stiffness (GPa).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	24188.2	24188.2	4837.6	4.96	0.007
Linear	2	10028.4	9879.5	4939.7	5.07	0.021
Ageing Temp (C)	1	3202.2	3551.6	3551.6	3.64	0.076
Stacking Angles	1	6826.2	6327.8	6327.8	6.49	0.022
Square	2	13846.2	13846.2	6928.1	7.10	0.007
Ageing Temp (C)*Ageing Temp (C)	1	454.2	454.2	454.2	0.47	0.505
Stacking Angles*Stacking Angles	1	13392.0	13392.0	13392.0	13.74	0.002
Interaction	1	313.5	313.5	313.5	0.32	0.579
Ageing Temp (C)*Stacking Angles	1	313.5	313.5	313.5	0.32	0.579
Residual Error	15	14622.3	14622.3	974.8		
Total	20	38810.5				

Abbreviations: Seq.: Sequential term; Adj. SS: Adjusted Sum of Square; Adj. Ms: Adjusted mean of Square; DF: Degree of Freedom; F: F-Statistics

Table 6: Predicted Response for New Design Points using Model for Stiffness (GPa).

Samples	Ageing temp (C)	Stiffness (GPa)		95 Confidence interval (95% CI)	
		Actual value	Predicted value	Lowest value	Highest value
UD	Unaged	188.14712	191.706	106.991	204.845
UD	40	190.9516	180.516	111.3	330.667
UD	60	152.9739825	159.851	261.945	945.25
H5	Unaged	78.60524	75.435	112.92	202.837
H5	40	71.195455	64.245	113.824	326.088
H5	60	33.46003	43.58	262.572	939.249
H10	Unaged	72.346684	83.007	116.051	202.372
H10	40	66.79124667	71.817	114.482	321.899
H10	60	66.83841667	51.152	261.831	933.361
H15	Unaged	65.651906	79.677	117.239	202.594
H15	40	62.14972333	68.487	113.663	317.932
H15	60	68.184095	47.822	259.849	927.459
H20	Unaged	79.251516	76.122	117.239	202.686
H20	40	72.731582	64.931	111.691	313.861
H20	60	33.336308	44.266	256.726	921.441
H25	Unaged	103.909928	105.256	116.831	202.054
H25	40	73.730762	94.066	108.806	309.448
H25	60	95.08274667	73.401	252.535	915.236
H30	Unaged	113.27536	89.984	116.163	200.364
H30	40	85.304395	78.793	105.141	304.559
H30	60	28.32545	58.128	247.311	908.807

R = 0.94822638
Abbreviations: UD: Unidirectional; H5: 5˚; H10: 10˚; H15: 15˚; H20: 20˚; H25: 25˚; H30: 30˚

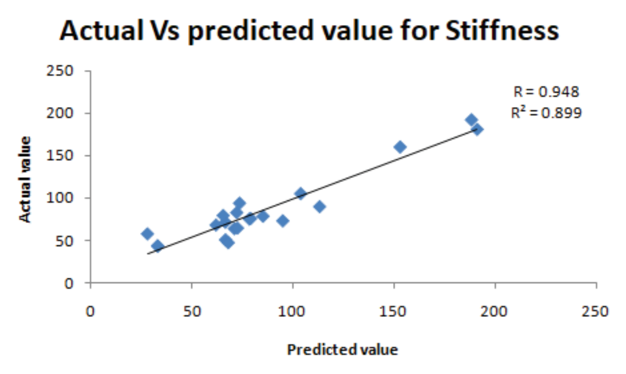

Figure 2: Relationship between Actual versus Predicted value for stiffness.

Conclusion

Asymmetric helicoidally stacked Toray E750 carbon fiber reinforced toughened epoxy resin composites were optimized with the Taguchi method with an aim to determine the significant levels of stacking angles and ageing temperature on their properties under tensile loading in unaged and hygrothermally aged conditions. The following conclusions were drawn from the analysis. The stacking angles and ageing temperature show a linear correlation to the tensile strength of asymmetric helicoidally stacked carbon fiber reinforced

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toughened epoxy resin composites. It was established that Inter-ply stacking angles are critical factors affecting the extent of macromolecular mobility within helicoidally stacked continuous fiber CFRP composites. It was confirmed that ageing temperature has an 86% effect on the stiffness of asymmetric helicoidally stacked carbon fiber-reinforced toughened epoxy resin composites. Analysis of variance indicates that both inter-ply stacking angle and ageing temperature affect the tensile strength values at a 95% confidence level. The Taguchi optimization and experimental results are very close, with an error ratio not exceeding 5%. The result shows the Taguchi approach could be a very helpful tool for the design of experiments based on the processing parameters and control levels.

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