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Mathematical Modeling of the In-Plane Shear Behavior of Dry Thick Non-Crimp Stitched Textile Reinforcements

Hafeth Bu Jldain [1*], Adel Agila [2] and Abdussalam Bojeldain[3]

[2] Department of Mechanical Engineering, Omar Al-Mukhtar University, Libya.

[3] Department of Mathematics, Omar Al-Mukhtar University, Libya.

***Corresponding author:** hafeth.bujldain@omu.edu.ly Department of Mechanical Engineering, Omar Al-Mukhtar University, Libya

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Abstract

A novel dry, thick, non-crimp stitched textile reinforcement was developed at the University of Ottawa's Preforming Technology Laboratory to satisfy the growing demand for thick textile reinforcements in aerospace manufacturing applications. Previous experimental investigations examined the influence of stitch orientations (R-45, R+45, R0, and R90) on the in-plane shear behavior of the reinforcement. Among these orientations, the R-45 and R+45 configurations demonstrated superior shearability. The present study develops a mathematical model to simulate the in-plane shear response of the reinforcement using MATLAB. The proposed model provides an efficient alternative to extensive experimental testing, which is both time-consuming and costly. Experimental data obtained from articulated-frame shear tests were fitted using polynomial regression techniques. Different polynomial orders were evaluated using numerical and graphical fitting criteria to determine the optimal model complexity. The results showed excellent agreement between the simulated and experimental responses for both R-45 and R+45 stitch orientations, thereby validating the effectiveness of the proposed modeling approach. The developed generalized mathematical model provides a reliable and computationally efficient tool for predicting the in-plane shear behavior of thick stitched textile reinforcements.

Keywords: In-Plane Shear; Textile Reinforcement; Dry Thick Non-Crimp Fabrics; MATLAB Modeling; Carbon Fiber.

INTRODUCTION

The increasing demand for advanced textile reinforcements in aerospace applications has motivated the development of thick non-crimp fabrics capable of sustaining complex forming operations. A novel stitched carbon-fiber reinforcement was recently developed at the University of Ottawa Preforming Technology Laboratory (uOttawa fabric) (Bu Jldain, 2021), Figure 1.

The in-plane shear behavior of textile reinforcements is a critical parameter in predicting formability and wrinkling during composite manufacturing processes. Previous experimental investigations examined the in-plane shear behavior of the uOttawa fabric using different stitch orientations. The results demonstrated that specimens stitched in the R-45 and R+45 orientations exhibited superior shearability, requiring relatively low shear forces to achieve shear angles ranging from 50° to 55° before the onset of wrinkling (Bu Jldain, 2021), Figure 2.

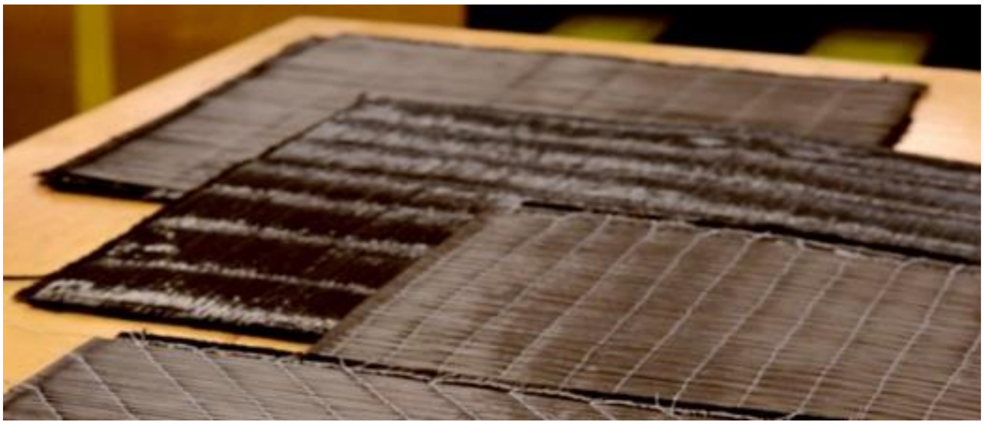


Figure: (1). Fabrics made at the University of Ottawa Preforming Technology Laboratory (Bu Jldain 2021).

The shear response was experimentally evaluated using the articulated-frame method integrated with a universal testing machine (McGuinness et al., 1997; Long, 2005; Canavan et al., 1995; Zu et al., 2009).

Although experimental investigations provide valuable insight into the deformation behavior of textile reinforcements, such testing procedures remain time-consuming and resource-intensive. Consequently, the development of predictive mathematical models represents an attractive alternative for evaluating the shear behavior of textile reinforcements while reducing experimental effort and cost.

The objective of the present study is therefore to develop a mathematical model capable of accurately representing the in-plane shear behavior of the uOttawa stitched textile reinforcement using MATLAB-based polynomial fitting techniques.

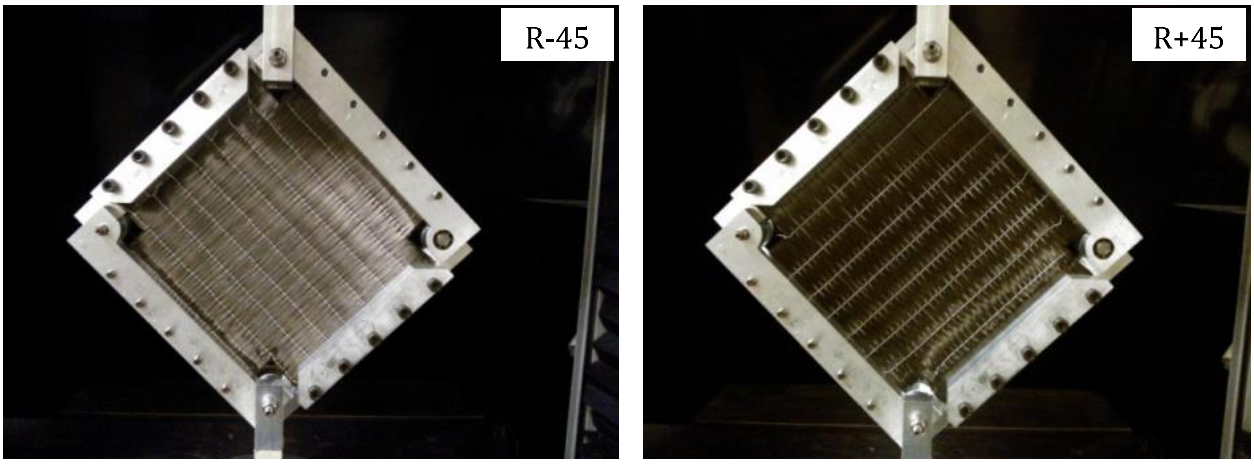


Figure: (2). Stitching orientations for testing samples made from uOttawa fabrics (Bu Jldain 2021**).**

EXPERIMENTAL DATA

Samples manufactured at the University of Ottawa Preforming Technology Laboratory were tested under two stitch orientations, namely R-45 and R+45. Each configuration was evaluated using two physical specimens subjected to four consecutive shear cycles (Bu Jldain, 2021).

For simplicity, the tested samples are identified using the following abbreviations:

- S1NC1: Sample 1, negative stitching orientation (R-45), Cycle 1
- S1PC2: Sample 1, positive stitching orientation (R+45), Cycle 2
- S2NC3: Sample 2, negative stitching orientation (R-45), Cycle 3
- S2PC4: Sample 2, positive stitching orientation (R+45), Cycle 4

The experimental shear-force data are presented graphically in Figure 3. A total of sixteen shear tests were conducted to characterize the in-plane shear behavior of the uOttawa fabric.

Samples S1N and S2N were tested using a stitching orientation of −45°, whereas samples S1P and S2P were tested using a stitching orientation of +45°. The resulting experimental curves provide the basis for developing the mathematical model presented in this study.

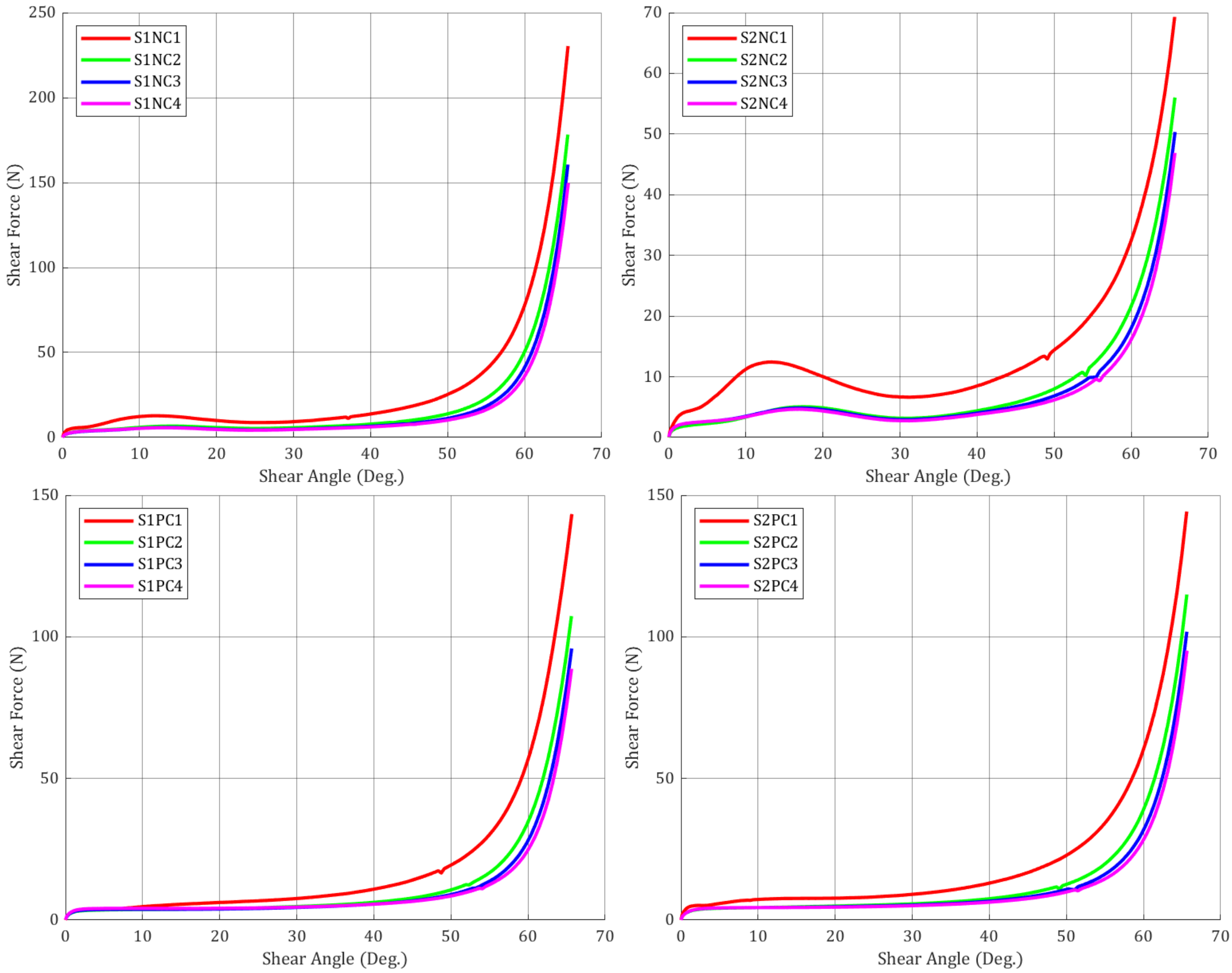


Figure: (3). Graphical representations of experimental data of each sample at four different cycles.

MATHEMATICAL MODEL

MATLAB was employed to model the shear-force response of each tested sample (Houcque, 2005; Hahn and Valentine, 2022; Chapman, 2024). In the developed model, the shear force represents the dependent variable y (N), whereas the shear angle represents the independent variable x (degrees).

The experimental data were fitted using polynomial regression through MATLAB's *polyfit* function (MathWorks, 2024). The polynomial model can be expressed as:

$$y = a_0 + a_1 x + a_2 x^2 + \ldots\ldots.. + a_m x^m$$

where a_m represent the polynomial coefficients and m denotes the polynomial order.
The optimal polynomial order was determined through both numerical and graphical fitting criteria (Kutner et al., 2005; Montgomery and Runger, 2018).

Numerical Evaluation Criteria

The following statistical indicators were used to evaluate the fitting accuracy:

- Sum of Squared Errors (SSE)
- Root Mean Squared Error (RMSE)
- Coefficient of Determination (R^2)
- Adjusted R^2
- Standard Error (SE)

Graphical Evaluation Criteria

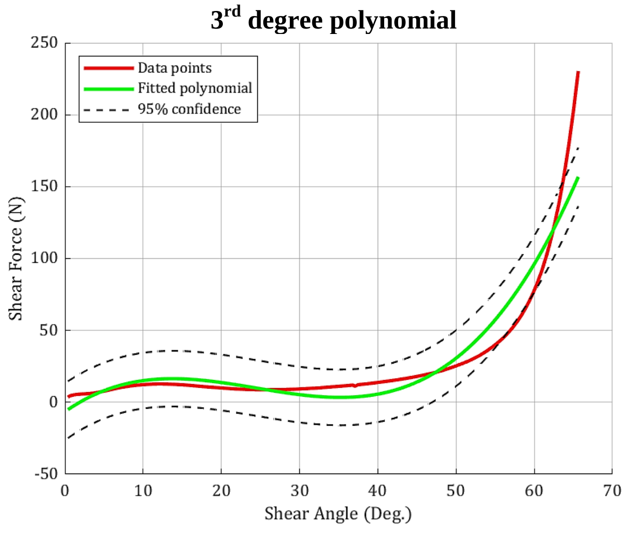
1. The graphical evaluation included:

- Plotting the experimental data
- Plotting the predicted polynomial response
- Plotting the 95% confidence intervals

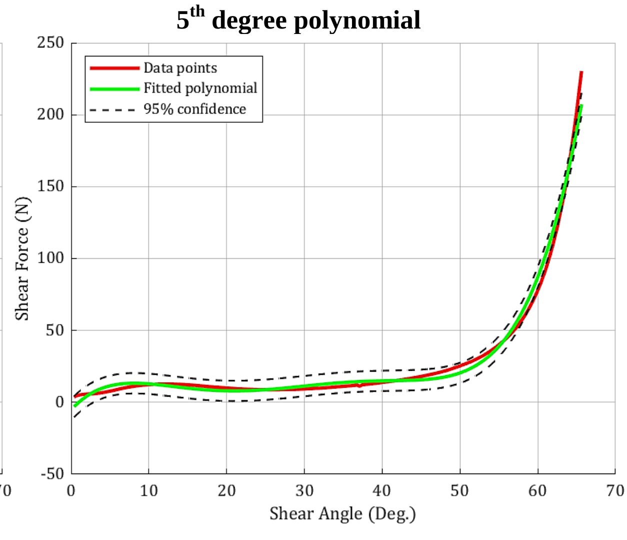
A MATLAB script was developed and executed for polynomial orders ranging from the 3rd to the 12th degree for all samples and loading cycles.

The same evaluation procedure was applied to all samples and loading cycles, and similar results were consistently obtained. Consequently, the 9th-degree polynomial was selected as the most suitable mathematical representation of the in-plane shear response.

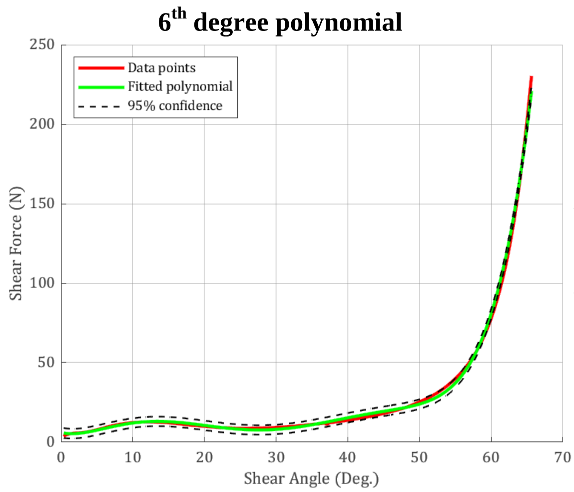
As an example the following information for sample S1NC1 are presented in the following charts and tables of Figure 4 and Figure 5.

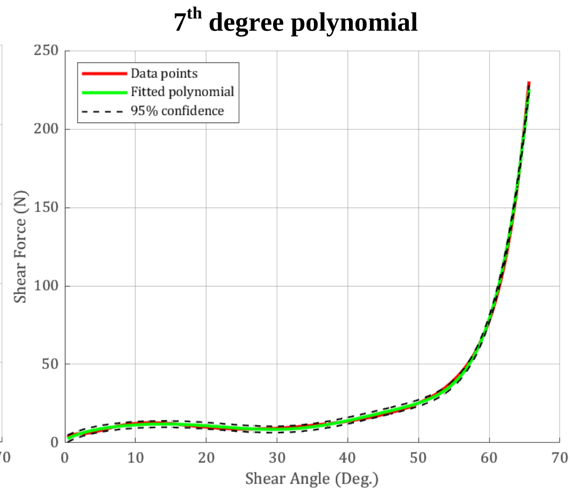


SSE	R^2	Adjusted R^2	RMSE	SE
20610	0.8983	0.8969	9.5496	9.6352



SSE	R^2	Adjusted R^2	RMSE	SE
2706.7	0.9866	0.9863	3.4607	3.5076

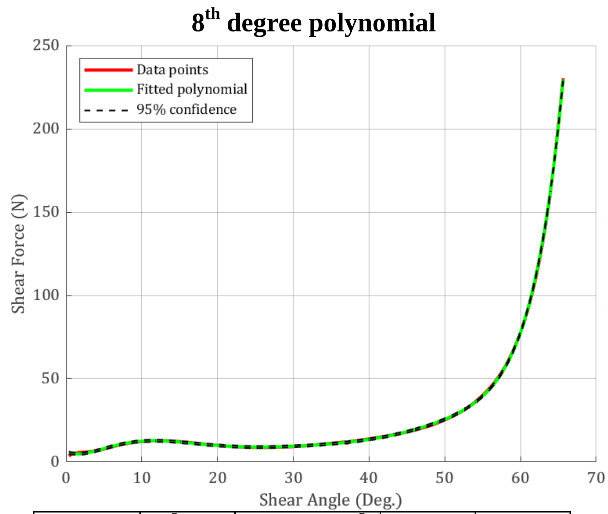


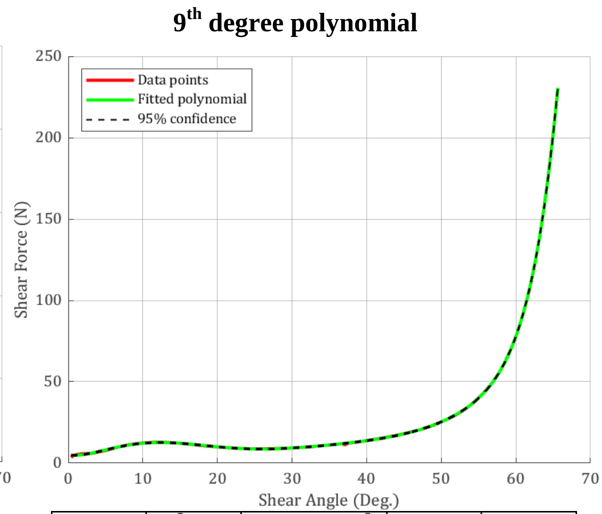


SSE	R^2	Adjusted R^2	RMSE	SE
474.968	0.9977	0.9976	1.4497	1.4727

SSE	R^2	Adjusted R^2	RMSE	SE
223.594	0.9989	0.9989	0.9947	1.0127

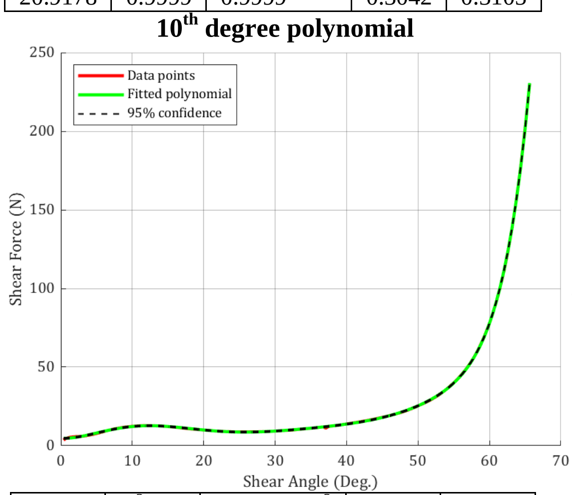
Figure: (4). Graphical and numerical representations for different values of order m ranging from 3rd to 7th degree.

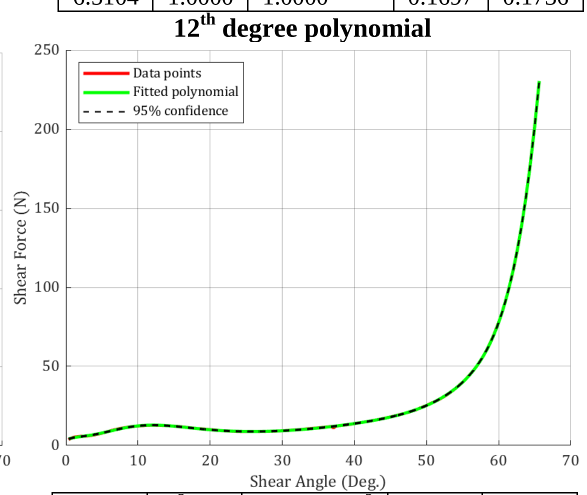




SSE	R^2	Adjusted R^2	RMSE	SE
20.9178	0.9999	0.9999	0.3042	0.3105

SSE	R^2	Adjusted R^2	RMSE	SE
6.5104	1.0000	1.0000	0.1697	0.1736





SSE	R^2	Adjusted R^2	RMSE	SE
6.2951	1.0000	1.0000	0.1669	0.1711

SSE	R^2	Adjusted R^2	RMSE	SE
2.7011	1.0000	1.0000	0.1093	0.1126

Figure: (5). Graphical and numerical representations for different values of order m ranging from 8th to 12th degree.

The numerical and graphical evaluations demonstrated that increasing the polynomial order significantly improved the fitting accuracy. However, the 9th-degree polynomial provided the optimal balance between fitting accuracy and model complexity.

The numerical fitting statistics for all samples are summarized in Table 1. The obtained values indicate near-perfect agreement between the experimental and modeled responses, with R^2 values approaching unity and RMSE values below 0.3 for all tested cases (Hastie et al., 2009; James et al., 2021).

Table (1). Values of the numerical statistics for each sample at four different cycles using **9th degree** polynomial.

Sample	Cycle	SSE	R^2	Adjusted R^2	RMSE	SE
	C1	6.5104	1.0000	1.0000	0.1697	0.1736
	C2	3.3410	1.0000	1.0000	0.1211	0.1238
S1N	C3	2.9823	1.0000	1.0000	0.1144	0.1170
	C4	3.6801	0.9999	0.9999	0.1270	0.1299
	C1	6.5104	1.0000	1.0000	0.1697	0.1736
Sample	Cycle	SSE	R^2	Adjusted R^2	RMSE	SE
	C1	20.6674	0.9990	0.9990	0.3011	0.3079
	C2	1.4737	0.9999	0.9999	0.0804	0.0822
S2N	C3	1.0556	0.9999	0.9999	0.0680	0.0696
	C4	0.9850	0.9999	0.9999	0.0657	0.0672
	C1	20.6674	0.9990	0.9990	0.3011	0.3079
Sample	Cycle	SSE	R^2	Adjusted R^2	RMSE	SE
	C1	14.5347	0.9998	0.9998	0.2525	0.2582
	C2	3.4626	0.9999	0.9999	0.1232	0.1260
S1P	C3	3.0795	0.9999	0.9999	0.1162	0.1189
	C4	3.4626	0.9999	0.9999	0.1232	0.1260
	C1	14.5347	0.9998	0.9998	0.2525	0.2582
Sample	Cycle	SSE	R^2	Adjusted R^2	RMSE	SE
	C1	12.6764	0.9999	0.9999	0.2358	0.2411
	C2	3.3274	0.9999	0.9999	0.1208	0.1235
S2P	C3	3.5150	0.9999	0.9999	0.1242	0.1270
	C4	3.5105	0.9999	0.9999	0.1241	0.1269
	C1	12.6764	0.9999	0.9999	0.2358	0.2411

RESULTS

Based on the fitting evaluation, the 9th-degree polynomial was selected to model the in-plane shear behavior of the tested specimens. The resulting polynomial function can be expressed as:

$$y = a_0 + a_1 x + a_2 x^2 + \ldots\ldots + a_9 x^9$$

where a_0, a_1, a_2,…, a_9 are the polynomial coefficients defining the mathematical model.
The coefficients obtained using MATLAB are presented in Table 2 for all samples and loading cycles.

Table (2). Coefficients of the polynomial represent the mathematical model of each sample at four different cycles.

Sample	a_0	a_2	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
MS1NC1	16529.3	-66803.0	105946.2	-78129.3	19293.3	8198.8	-6104.0	1138.3	-22.19	4.87
MS1NC2	29574.0	-138122.5	270889.7	-288291.5	179752.1	-66234.2	13970.3	-1616.5	109.12	1.08
MS1NC3	30555.6	-141837.6	275885.6	-290621.2	179045.8	-65112.0	13558.1	-1552.4	102.33	1.02
MS1NC4	31785.0	-147609.9	287059.4	-302333.4	186416.4	-68051.9	14316.5	-1671.1	110.33	1.00
MS1N	27110.9	-123593.3	234945.2	-239843.8	141127.0	-47799.8	8935.3	-925.4	74.90	1.99
Sample	a_0	a_2	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
MS2NC1	12786.8	-61996.9	123645.6	-128885.7	73001.3	-20408.5	1720.0	125.0	35.57	1.89
MS2NC2	12848.1	-66260.3	144273.7	-171160.5	119089.9	-48647.4	11067.8	-1269.7	73.20	0.49
MS2NC3	14419.6	-73674.2	158808.4	-186599.5	128861.5	-52518.5	12058.6	-1428.0	84.27	0.61
MS2NC4	15210.5	-77354.0	165842.8	-193755.8	133076.1	-54008.5	12385.7	-1472.8	86.74	0.60
MS2N	13816.2	-69821.3	148142.6	-170100.4	113507.2	-43895.7	9308.0	-1011.4	69.95	0.90
Sample	a_0	a_2	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
MS1PC1	3294.1	-16036.1	35529.4	-45430.4	35585.7	-17016.4	4785.3	-737.5	63.53	1.68
MS1PC2	8491.7	-39278.4	78156.2	-87119.2	59428.3	-25426.8	6716.8	-1027.7	80.31	1.29
MS1PC3	12517.8	-58583.9	116702.4	-128741.4	85806.9	-35387.2	8891.1	-1282.2	93.43	1.23
MS1PC4	16553.8	-78307.3	156913.7	-173177.6	114727.4	-46662.1	11453.7	-1597.7	111.14	1.30
MS1P	10214.3	-48051.4	96825.4	-108617.1	73887.1	-31123.1	7961.7	-1161.3	87.10	1.37
Sample	a_0	a_2	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
MS2PC1	10732.9	-50774.8	102093.8	-112934.6	74602.1	-30022.3	7315.2	-1068.1	96.76	2.37
MS2PC2	13001.3	-62014.4	126213.0	-142404.8	97023.9	-40777.1	10372.8	-1500.5	110.85	1.09
MS2PC3	15122.4	-71803.0	144902.1	-161598.3	108563.7	-44942.1	11271.9	-1614.2	117.47	1.07
MS2PC4	16814.1	-79887.0	160902.0	-178624.6	119132.0	-48830.3	12099.4	-1710.2	122.42	1.03
MS2P	13917.7	-66119.8	133527.7	-148890.6	99830.4	-41142.9	10264.8	-1473.3	111.88	1.39

Four mathematical models, namely MS1N, MS2N, MS1P, and MS2P, were obtained by averaging the polynomial coefficients corresponding to the four loading cycles of each specimen.

Figure 6 presents the experimental data together with the corresponding mathematical models for all tested samples.

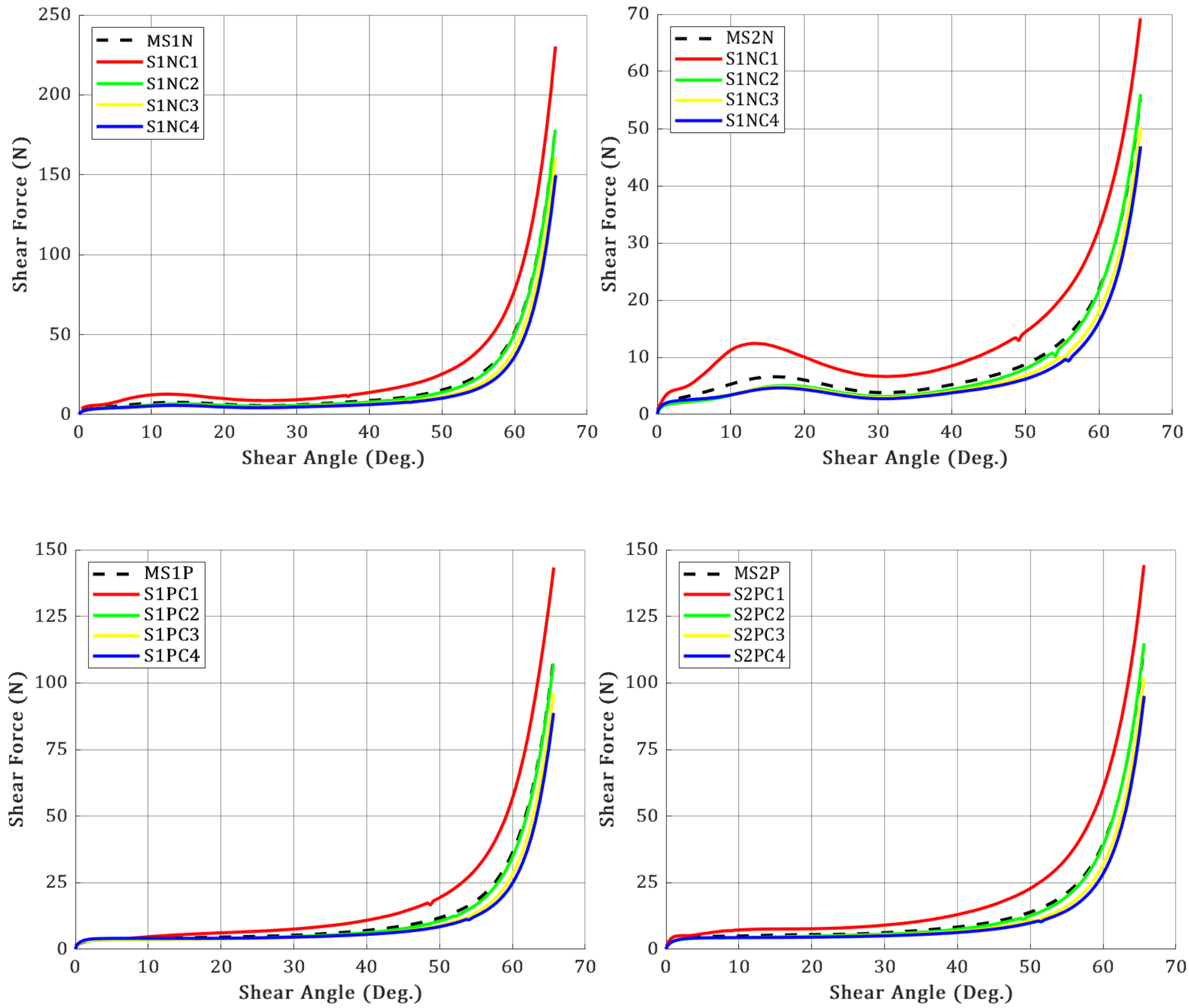


Figure: (6). Graphical representation of the resulted mathematical models, MS1N, MS2N, MS1P and MS2P, along with the experimental data of each sample tested at four different cycles.

DISCUSSION

As shown in Figure 6, the developed mathematical models demonstrate near-perfect agreement with the experimental measurements and successfully represent the overall in-plane shear behavior of the thick stitched textile reinforcement, despite the observed variations in shear-force magnitudes among the tested specimens.

Figure 7 illustrates the graphical representation of the four developed models: MS1N, MS2N, MS1P, and MS2P. It can be observed that the MS1N and MS2N models exhibit noticeable deviations compared with the MS1P and MS2P models.

This deviation is attributed to the misalignment of the stitching lines relative to the edges of the shear frame during testing. The effect is evident in the appearance of a localized disturbance in the experimental curves at shear angles ranging approximately from 10° to 20°, as shown previously in Figure 3.

In contrast, samples S1P and S2P did not exhibit such disturbances, indicating more stable and representative shear behavior.

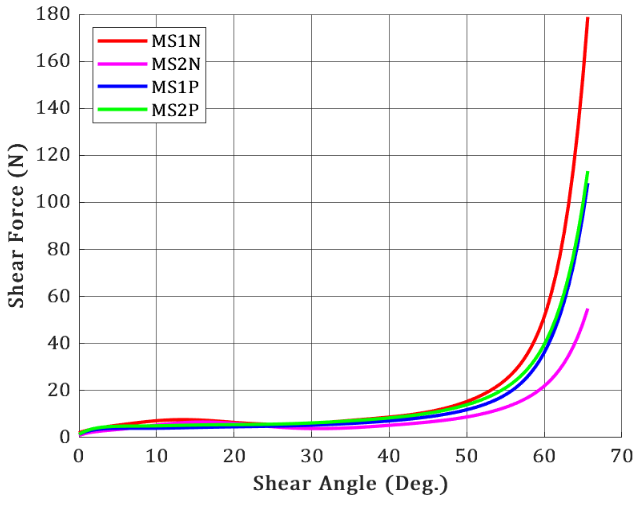


Figure: (7). Graphical representation of the resulted mathematical models, MS1N, MS2N, MS1P and MS2P.

Consequently, the MS1P and MS2P models were selected to establish a generalized mathematical model (GMM) capable of representing the overall in-plane shear behavior of the thick non-crimp stitched fabric independently of loading cycle or stitch orientation and can be expressed in the form of a polynomial of 9th degree order as:

$$GMM = a_0 + a_1 x + a_2 x^2 + \dots\dots + a_9 x^9$$

The generalized mathematical model was obtained by averaging the coefficients of MS1P and MS2P which are listed below,

Coefficients	a_0	a_2	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
GMM	12066.0	-57085.6	115176.6	-128753.9	86858.7	-36133.0	9113.3	-1317.3	99.49	1.38

The resulting GMM, together with the experimental data, is presented in Figure 8. The comparison demonstrates excellent agreement between the generalized model and the experimental responses of samples S1P and S2P. Conversely, larger deviations are observed for samples S1N and S2N due to the previously discussed stitch-line misalignment effects.

The results therefore confirm that proper alignment during shear testing is essential for obtaining representative in-plane shear measurements for thick stitched textile reinforcements.

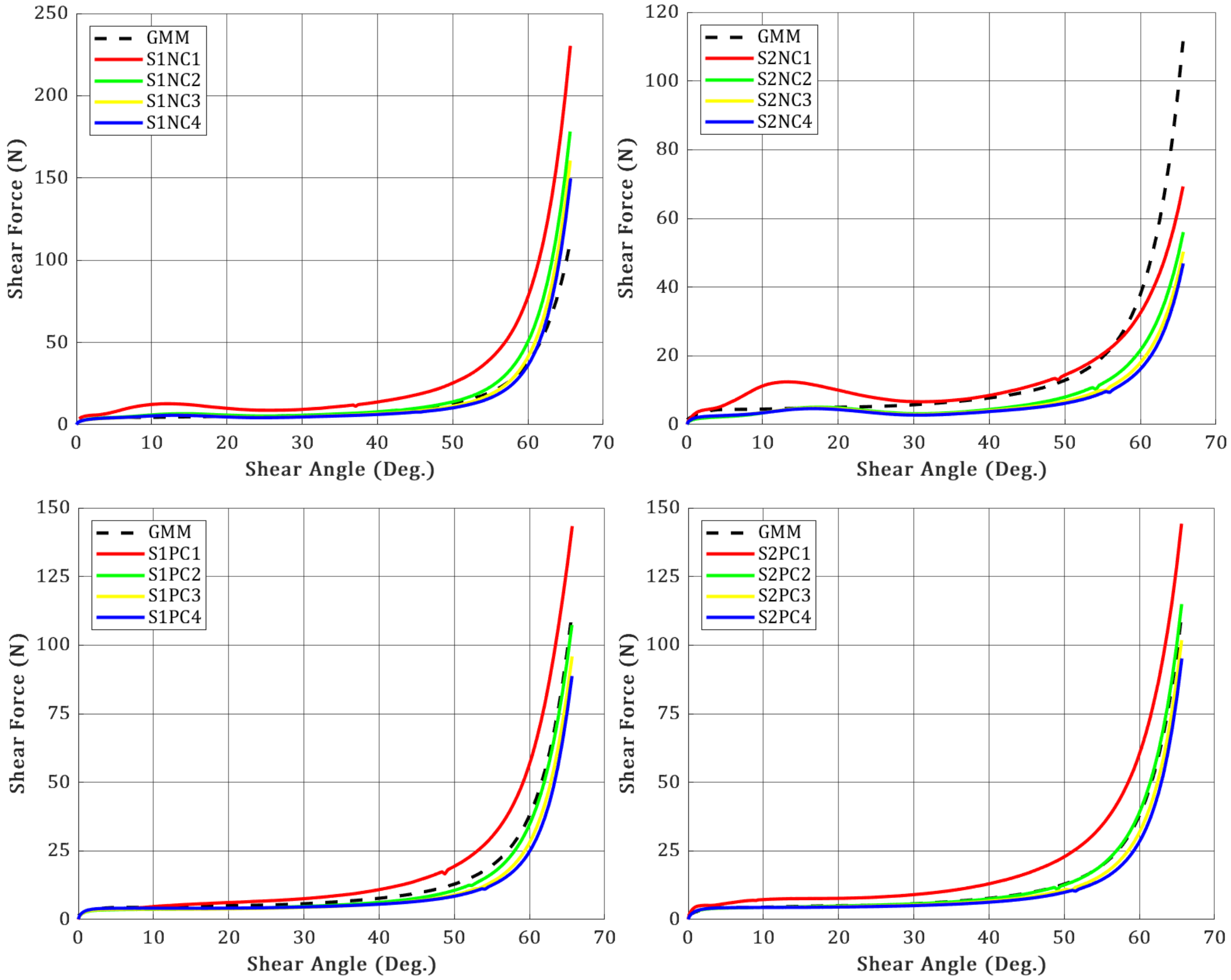


Figure :(8). Graphical representation of the general mathematical model (GMM) along with the experimental data of each sample tested at four different cycles.

CONCLUSION

This study developed a mathematical model capable of predicting the in-plane shear behavior of a novel dry non-crimp thick stitched carbon-fiber reinforcement.

Experimental investigations demonstrated that the R-45 and R+45 stitch orientations provide excellent shearability, thereby supporting the suitability of the developed reinforcement for aerospace forming applications.

MATLAB-based polynomial fitting techniques were employed to model the experimental response. Among the polynomial orders investigated, the 9th-degree polynomial provided the best balance between fitting accuracy and model simplicity.

A generalized mathematical model was subsequently developed by averaging the representative polynomial coefficients obtained from the experimental data. The resulting model demonstrated near-perfect agreement with the measured shear response.

The proposed mathematical model significantly reduces the need for extensive physical testing and provides an efficient and cost-effective tool for predicting the formability behavior of thick stitched textile reinforcements.

Future work will focus on extending the proposed model to reinforcements with different thicknesses and integrating the developed model into finite-element forming simulations.

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Author contributions: Contribution is equal between authors.

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