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In-plane Shear Behaviour of Novel Thick Stitched Textile Reinforcements Part II: Quantitative Analysis of Shear Locking Angle

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Abstract— **A quantitative analysis of the in-plane shear test results reported in PhD thesis of Hafeth Bu Jldain was preformed in this paper. Analysis of the results was conducted from experimental and analytical bases. It was conducted experimentally through comparing the results obtained for uO-APT samples with the results obtained for samples made from an industrial fabric manufactured by GmbH Saertex. The analytical validation was conducted through systematic Taguchi plans. These plans investigate, the effect of the type of reinforcement (A and B), the effect of the number of layers, and the effect of stitching setup (R-45, R+45, R0 and R90) on the behavior of the reinforcements. The plans primarily analyzed the extent to which the reinforcement may shear and the force required to do so.**

Shear test results for stitching orientation R-45 and R+45 show the ability of the new fabric to shear under lower shear forces, which ranged between 0 N and 25 N needed to shear uO-APT reinforcements to shear angles ranging from 50° to 55° before wrinkling was observed.

Index Terms: **In-plane shear test, dry fabrics, thick carbon fibres reinforcement, non-crimp fabrics, Taguchi.**

I. INTRODUCTION

A number of shear tests were conducted to define the behaviour of the new uO-APT reinforcements upon shearing [1]. The limit to in-plane shear for any fabric may be evaluated using the in-plane shear locking angle (γ_L). Shear locking angle is a common criteria used when investigating shear behaviour of textiles before wrinkles appear. The locking angle is defined as the angle at which the onset of wrinkling may be observed. This value along with the shear force (F_S) determines the ability of a fabric to undergo in-plane shear. The limit to in-plane shear may be evaluated using established practice reported in the literature [2-7], through quantification of the in-plane shear locking angle (γ_L). The shear locking data obtained for uO-APT fabrics were compared with those obtained for Saertex industrial fabrics are shown in Table. Both results were analyzed and compared using three Taguchi [8] plans that are presented here.

II. TAGUCHI PLANS

The quantitative analysis of in-plane shear test results was performed as follows. Data generated in the shear tests is investigated, namely the effect of the type of reinforcement (A and B), the effect of the number of layers, and the effect of stitching setup (R-45, R+45, R0 and R90) on the behaviour of the reinforcements, primarily analyzed as the extent to which the reinforcement may shear and the force required to do so. The locking angle is determined as the intercept of a tangent to the shear force to shear angle curve with the horizontal, abscissa axis taken where the slope approaches maximum value, at which the onset of wrinkling can be observed visually. Table I, II, III and IV show shear locking angle (γ_L) values determined for samples made from uO-APT and Saertex fabrics at different setups.

Table 1. Values of the shear locking angle obtained for A4 samples made from uO-APT fabric.

Type	Group	Setup	Sample	*Shear locking angle γ_L (°)*			
				C1	C2	C3	C4
uO-APT	A4	R-45	S1	60.0	60.5	61.0	61.5
			S2	58.5	59.5	60.0	60.5
		R+45	S1	58.5	60.0	60.5	61.0
			S2	58.5	60.0	60.5	61.0

Table 2. Values of the shear locking angle obtained for A5 samples made from uO-APT fabric.

Type	Group	Setup	Sample	*Shear locking angle γ_L (°)*			
				C1	C2	C3	C4
uO-APT	A5	R-45	S1	56.0	58.0	59.0	60.0

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	S2	58.5	60.0	60.5	61.0
R+45	S1	58.0	60.0	61.0	61.5
	S2	58.0	59.0	60.0	60.5

Table 3. Values of the shear locking angle obtained for A6 samples made from uottawafabrics tested at r0 and r90.

Type	Group	Setup	Sample	Shear locking angle γ_L (°)			
				C1	C2	C3	C4
uO-APT	A6	R0	S1	59.5	61.5	62.0	62.5
			S2	58.0	60.0	61.0	61.5
		R90	S1	55.0	57.5	58.5	59.5
			S2	56.5	59.0	60.0	60.5

Table 4. Values of the shear locking angle obtained for B6 samples made from Saertex fabrics tested at r0 and r90.

Type	Group	Setup	Sample	Shear locking angle γ_L (°)			
				C1	C2	C3	C4
Saertex	B6	R0	S1	58.5	60.5	61.0	61.5
			S2	58.5	60.5	61.0	61.5
		R90	S1	36.0	41.0	43.5	46.0
			S2	34.0	40.0	43.5	45.5

It should be noted that test groups equivalent to groups A4 and A5 were not conducted simply as a result of the construction of the SAERTEX fabric used in performing this work.

At cycle C1 the average value of the shear locking angle γ_L is approximately 60.0° and it increases to 60.5°, 61.0° and 61.5° as the sample is cycled (C2, C3 and C4). Shear test results from R+45 stitching configuration gave approximately the same average shear locking angle values as the R-45 stitching configuration, although the standard deviation was marginally larger. Table I and II show the shear locking angle γ_L at each cycle for both sub-groups samples.

Each quantitative response was analyzed using three 2-level Taguchi [8] plans labeled as the first, second and third plans, featured 3, 2 and 3 parameters respectively. In-plane shear data was analyzed as a longer series of smaller plans for lack of symmetry in the data: Although there is an equivalent group B6 featuring tests performed on industrial reinforcements to group A6 featuring tests performed on uO-APT reinforcements, there are no such equivalents to groups A4 and A5. This results from the fact that whilst stitch orientation could be modified in uO-APT reinforcements, the same could not be done with the Saertex industrial reinforcements used in the context of this work. As such more comparisons may be made, with each one pertaining to a smaller set of data as explained below.

The FIRST PLAN compared the effect of the 3 following parameters and their interactions using data from groups A4 and A5, for two modalities represented as (-) and (+) in the plan on the in-plane shear locking angle γ_L, quantitative response:

- Parameter *A*: smaller number of layers (-) vs. larger number of layers (+);
- Parameter *B*: setup in rig at R-45 (-) vs. setup in rig at R+45 (+);
- Parameter *C*: shear cycle 1 (-) vs. shear cycle 4 (+).

The SECOND PLAN compared the effect of the 2 following parameters and their interactions using data from groups A4 and A6, for two modalities represented as (-) and (+) in the plan on the in-plane shear locking angle γ_L, quantitative response:

- Parameter *A*: setup in rig at R+45 (-) vs. setup in rig at R90 (+);
- Parameter *B*: shear cycle 1 (-) vs. shear cycle 4 (+).

Finally, the THIRD PLAN compared the effect of the 3 following parameters and their interactions using data from groups A6 and B6, for two modalities represented as (-) and (+) in the plan on the same three quantitative responses:

- Parameter *A*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *B*: setup in rig at R0 (-) vs. setup in rig at R90 (+);
- Parameter *C*: shear cycle 1 (-) vs. shear cycle 4 (+).

It can be noticed that whilst the first plan compares setup in apparatus at R-45 with setup in apparatus at R+45 through parameter *B*, the second plan compares setup in apparatus at R+45 with setup in apparatus at R90 through parameter *A*. The comparison defined by parameter *B* in the first plan is not expected to identify a significant effect; however, it is useful in quantifying its amplitude with those of comparisons made through parameters *A* and *C* in the same plan. On the other hand, and again because of data structure resulting from the physical reality of the reinforcements tested, comparing the effect of having stitch that is either parallel with yarns or with stitch at 45° from them through parameter *A* in the second plan is expected to be of much greater significance. Parameter *B* in the third plan, which pertains to setup and orientation of stitch lines in the apparatus, differs from both parameter *A* in the second plan and parameter *B* in the first plan. Whilst its effect is not expected to be as strong as that of parameter *A* in the second plan, it is expected to be stronger than that of parameter *B* in the first as the difference in physical configurations is more significant with stitch lines being either subject to tension, or collapsed.

The first plan focuses on the effect of the number of layers along with other parameters on the response in shear. Data analyzed in this plan was generated from tests listed in Tables 1and 2. The second plan focuses on the effect of the orientation of stitch lines, either parallel to yarn orientations or along a bisector between these orientations, along with the cycle number on the response in shear. Data analyzed in this plan was generated from tests listed in Tables 1 and 3. The third plan focuses on differences in behavior observed with uO-APT and industrial reinforcements, along with other parameters on the response in shear. Data analyzed in this plan was generated from tests listed in Tables 3 and 4.

The plans are fully factorial. The first and third plans quantify independently the main effects of parameters *A*, *B*, and *C* as well as all the effects of all 3 interactions of two parameters *AB*, *AC* and *BC* and the interaction of 3 parameters *ABC*. The second plan quantifies independently the main effects of parameters *A* and *B* as well as the effect of the single interaction *AB*. All tests were replicated on 2 samples which enables the quantitative evaluation of inner-group variability and comparison with between-group variability; the statistical significance of the effects of parameters could, here again, be assessed through multi-factorial analyses of variances and calculation of F-ratios [8].

The modalities taken by each parameter for each test in all plans are listed in Table 5 for the first and third plan and in Table 6 for the second plan. Actual parameters corresponding to labels *A* to *C* along with the modalities corresponding to labels + and – in each case appear in the previous pages for all plans; one should note that parameters corresponding to the various labels change from plan to plan.

Table 5. Modalities taken by all parameters and interactions for first and third plans.

Run	A	B	C	AB	BC	ABC
1	+	+	+	+	+	+
2	+	+	-	+	-	-
3	+	-	+	-	-	-
4	+	-	-	-	+	+
5	-	+	+	-	+	-
6	-	+	-	-	-	+
7	-	-	+	+	-	+
8	-	-	-	+	+	-

Table 6. Modalities taken by all parameters and interactions for second plan.

Run	A	B	AB
1	+	+	+
2	+	-	-
3	-	+	-
4	-	-	+

III. ANALYSIS OF SHEAR LOCKING ANGLE RESULTS

Values of the locking angle γ_L appear in Table VII for the first plan evaluating the effect of the number of layers along with other parameters, in Table 8 for the second plan evaluating the effect of the orientation of stitch lines along with other parameters, and in Table 9 for the third plan evaluating the effect of reinforcement type along with other parameters. In these tables, labels S1 and S2 identify the sample number as mentioned previously. Therefore, one value of the locking angle γ_L is reported for each specific shear test, cycle number and sample number. Tables 7, 8 and 9 also state explicitly the correspondence between the run numbers as introduced in Tables 5 and 6 along with the systematic variation of parameters *A* to *C* and their interactions. Here again as for the plan discussed in [1]. It should be noted that modalities taken by each interaction at each run, as presented by + and – labels in Tables 5 and 6, are the product of modalities taken by the corresponding individual parameter on the same line and therefore, all evaluations of the effects of main parameters and interactions are independent [8].

Table 7. Responses for the first plan (°).

Run	Sub-group	S1	S2	$LAVG(\gamma_L)$	$LSTD^2(\gamma_L)$
1	A5/R+45/C4	61.5	60.5	61.00	0.500
2	A5/R+45/C1	58.0	58.0	58.00	0.000
3	A5/R-45/C4	60.0	61.0	60.50	0.500
4	A5/R-45/C1	56.0	58.5	57.25	3.125
5	A4/R+45/C4	61.0	61.0	61.00	0.000
6	A4/R+45/C1	58.5	58.5	58.50	0.000
7	A4/R-45/C4	61.5	60.5	61.00	0.500
8	A4/R-45/C1	60.0	58.5	59.25	1.125
	Average				0.719
	Variance	4.598			
	F-Ratio			6.395	

Table 8. Responses for the second plan (°).

Run	Sub-group	S1	S2	$LAVG(\gamma_L)$	$LSTD^2(\gamma_L)$
1	A6/R90/C4	59.5	60.5	60.00	0.500
2	A6/R90/C1	55.0	56.5	55.75	1.125
3	A4/R+45/C4	61.0	61.0	61.00	0.000
4	A4/R+45/C1	58.5	58.5	58.50	0.000
	Average				0.406
	Variance	10.448			
	F-Ratio			25.734	

Table 9. Responses for the third plan (°).

Run	Sub-group	S1	S2	$LAVG(\gamma_L)$	$LSTD^2(\gamma_L)$
1	B6/R90/C4	46.0	45.5	45.75	0.125
2	B6/R90/C2	36	34	35.00	2.000
3	B6/R0/C4	61.5	61.5	61.50	0.000
4	B6/R0/C2	58.5	58.5	58.50	0.000
5	A6/R90/C4	59.5	60.5	60.00	0.500
6	A6/R90/C2	55	56.5	55.75	1.125
7	A6/R0/C4	62.5	61.5	62.00	0.500

8	A6/R0/C2	59	58	58.75	1.125
	Average				0.672
	Variance	179.355			
	F-Ratio			266.95	

The first step in the quantitative analysis of the data presented in Tables 7, 8 and 9 is the one-way analysis of variance (ANOVA) over the data collected as a whole, for each plan, culminating in the calculation of an F-ratio in each case. The F-ratios are compared with tabulated values, indicating an F-ratio that is significant or not. A significant F-ratio obtained from a one-way ANOVA performed on the data as a whole provides an indication that some parameters or their interactions may have a quantifiable effect of the response, above and beyond fluctuations in the data due to experimental variability [8].

Quantities pertaining to the three one-way ANOVAs performed as part of the analysis of the shear data appear in Tables VII to IX. $LAVG(\gamma_L)$ and $LSTD^2(\gamma_L)$ represent the line average and the line standard deviation of γ_L for each run, for the 2 samples associated to the given run. Equations for these quantities are presented in [1] and [8].

Values of the F-Ratio associated with one-way ANOVAs performed for each plan are obtained by dividing the overall variance between subgroups by the overall variance within subgroups, where a subgroup refers to a set of 2 values of locking angle γ_L associated with a given run, in a procedure similar to that described in [1] and [8]. Values of the overall variances between and within subgroups appear in Tables 7, 8 and 9. It is interesting to note that the three plans return values of the F-ratio that differ very significantly. The values indicate that the effect of the thickness of reinforcements that are otherwise constructed in the same way, including similar orientations of stitch lines extending parallel to the yarns, is less pronounced along with the effect of cycling.

Considering the first plan, the F-ratio was calculated at 6.395 from experimental data. Considering total, between and within numbers of degrees of freedom of 15, 7 and 8 respectively, arrived at by subtracting 1 from the product of the number of sub-groups and sub-group size, 8 and 2 respectively in the first case, by subtracting 1 from number of subgroups 8 in the second case, and by subtracting the between value from the total value in the third case, and using a stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 6.18 [8]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for the first plan, 6.395 and 6.18, indicate that there is marginal scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the shear locking angle.

Considering the second plan, the F-ratio was calculated at 25.734 from experimental data. Considering total, between and within numbers of degrees of freedom of 7, 3 and 4 respectively, and using the same false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 16.7 [8]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted from the second plan, 25.734 and 16.7, indicate that there is stronger scope in calculating contrast F-ratios for this plan.

Finally, considering the third and F-ratio was calculated at 266.95 from experimental data, using the same false alarm theoretical risk α of 0.01 will lead to the same value critical value of 6.18 [8]. The calculated and tabulated values of the F-ratio indicate very strong scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the shear locking angle in this case.

Given the above conclusions, the next step in analyzing the effects of the parameters on shear consists in calculating contrasts associated with each parameter and interaction of parameters, for each plan. Contrasts are defined in [1] and [8]. Adjustment terms were equal to 8/2 for the first and third plans, and to 4/2 for the second plan. Values of the mean square within for all the data *MSW*, for each plan, appear in Tables 10 to 12.

Table 10. Contrasts for first plan (°).

Parameter	$\hat{C}$	*SS*($\hat{C}$)	*Contrast F-ratio*
A	-3.0	2.25	3.13
B	0.5	0.06	0.09
C	10.5	27.56	**38.35**
AB	2.0	1.0	1.39
AC	2.0	1.0	1.39
BC	0.5	0.06	0.09
ABC	-1.0	0.25	0.35
MSW		0.719	

Table 11. Contrasts for second plan (°).

Parameter	$\hat{C}$	*SS*($\hat{C}$)	*Contrast F-ratio*
A	-3.75	7.03	**17.31**
B	6.75	22.78	**56.08**
AB	1.75	1.53	3.77
MSW		0.406	

Table 12. Contrasts for third plan (°).

Parameter	$\hat{C}$	*SS*($\hat{C}$)	*Contrast F-ratio*
A	-35.75	319.52	**475.56**
B	-44.25	489.52	**728.58**
C	21.25	112.89	**168.02**
AB	-34.25	293.27	**436.49**
AC	6.25	9.77	**14.53**
BC	8.75	19.14	**28.49**
ABC	6.75	11.39	**16.95**
MSW		0.672	

Values of the mean square within for all the data *MSW*, for each plan, appear in Tables 10 to 12 Tthey are used towards calculating the F-ratios for individual contrasts, which appear in these tables. Here again it is verified that the average of contrast F-ratios presented in Tables 10 to

12 are equal to the one-way ANOVA F-ratios presented in Tables 7 to 9, as expected.

Calculated contrast F-ratios must be compared with tabulated values. In this case, a single degree of freedom is associated with each contrast and $SS(C)$ whilst the number of within degrees of freedom associated with MSW remains unchanged at 8 for the first and third plans and 4 for the second plan. Using the same stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 11.3 for first and third plans and 21.2 for the second plan [8]. Values of contrast F-ratios superior to 11.3 and 21.2, deemed significant, are highlighted in Tables 9, 10 and 12. Results from Table 9 reveal that one main parameter has a significant effect on response γ_L for the first plan. Results from Table 11 reveal that two main parameters have significant effect on response γ_L for the second plan. Finally, results from Table 12 reveal that all 3 main parameters and 4 interactions have significant effect on response γ_L for the third plan. Significant main effects and interactions of parameters are summarized in Table 13, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figures 1 to 3.

Table 13. Summary of significant main effects and interactions of parameters.

First plan, response γ_L	Second plan, response γ_L	Third plan, response γ_L
		A (-)
	B (+)	B (-)
C(+)		
		AB(-)
		AC(+)
		BC(+)
		ABC(+)

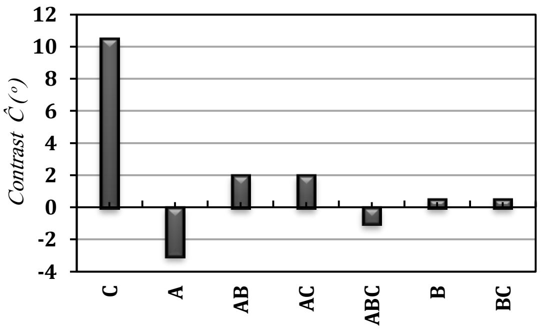

Figure 1. Main effects and interactions of parameters in decreasing order, response γ_L, first plan.

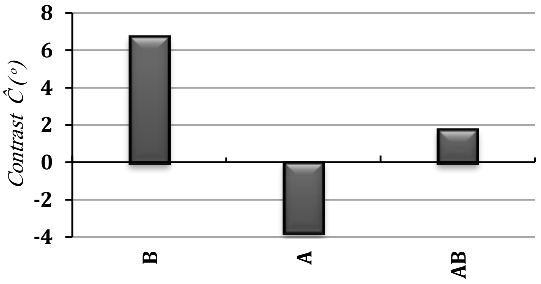

Figure 2. Main effects and interactions of parameters in decreasing order, response γ_L, second plan.

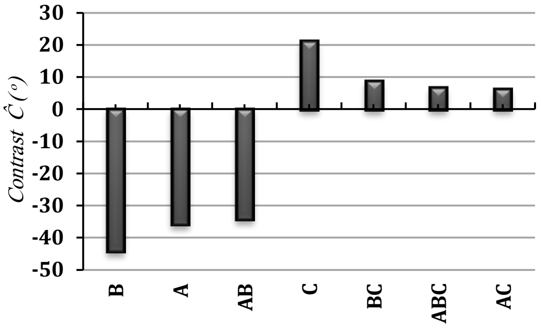

Figure 3. Main effects and interactions of parameters in decreasing order, response γ_L, third plan.

IV. CONCLUSIONS

The behavior of dry thick reinforcements such as uO-APT subjected to in-plane shear plays an important role in the onset of wrinkles during shearing. The in-plane shear behavior of uO-APT thick reinforcements and Saertex industrial reinforcements were investigated in this work.

The tables and figures show that in the first plan parameter *C*, C1 (-) vs. C4 (+), which compared shear locking angle values in cycle 1 with cycle 4, has a leading effect on the shearing locking angle response. In contrast to parameter *C*, parameter *A*, smaller number of layers (-) vs. larger number of layers (+), and parameter *B*, setup in rig at R-45 (-) vs. setup in rig at R+45 (+), have no significant effect on the shearing locking angle response.

In the second plan, parameter *B* representing cycle C1 (-) vs. C4 (+) has again a leading effect on the shearing locking angle response. Unexpectedly, parameter *A*, setup in rig at R+45 (-) vs. setup in rig at R90 (+) has a minor effect on the locking angle response.

In the third plan parameter *B*, setup in rig at R0 (-) vs. setup in rig at R90 (+), has the leading effect. Parameter *A*, uO-APT reinforcement (-) vs. industrial reinforcement (+), has the second leading effect, followed by the interaction between them *AB*, comes has the third leading effect on the shearing locking angle response. Cycle C1 (-) vs. C4 (+) has again a significant effect but it is a distant fourth, followed by other interactions.

The above systematic plans identify very clearly that the most important differences in shear behavior arise when comparing shear test results obtained at the first shearing cycle C1 with those obtained at fourth cycle C4.

This is related mainly to failure of stitches that most likely to happen at the first shearing cycle.

Both systematic plans show that fabric type, stitching orientations and thickness have also some important effects on the shear behavior of a fabric. uO-APT and industrial reinforcements have different constructions and different stitching assembly methods which explain the different behavior in shear as observed from curves recorded and presented in in part I of this paper [1]. It should be mentionned that setup in apparatus at R-45 (-) vs. setup in apparatus at R+45 (+) induced little significant differences to be reported on the response to shear; both setups led to the same behavior.

As a general conclusion, a number of shear tests were conducted to define the behaviour of the new uO-APT reinforcements upon shearing. The limit to in-plane shear for any fabric may be evaluated using the in-plane shear locking angle γ_L . The locking angle is defined as the angle at which the onset of wrinkling may be observed. This value along with the shear force determines the ability of a fabric to undergo in-plane shear. Shear test results for stitching orientation R-45 and R+45 show the ability of the new fabric to shear under lower shear forces, which ranged between 0 N and 25 N needed to shear uO-APT reinforcements to shear angles ranging from 50° to 55° before wrinkling was observed [1], leading to differences when compared with shear results obtained for stitching orientation R0 and R90.

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