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Single Curvature Bending Results of Structural Stitched Textile Reinforcements Part II: Quantitative Analysis Using Taguchi Method

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Abstract— **A Novel non-crimp dry thick fabric was manufactured at the University of Ottawa advanced preforming technology (uOttawa fabric) to cover the growing need for such thick preforms in the aerospace applications. The bending behavior was investigated using significant numbers of tests performed with a new bending apparatus designed and manufactured at University of Ottawa.**

This research paper was aimed to analyze the bending results obtained for samples made from the new uOttawa fabric and samples made from an industrial fabric using a statistical method celled Taguchi method. The Taguchi analysis highlights the most parameters having the stronger effects on testing. The main parameters investigated in bending were the type of fabric, the thickness, yarn orientations, fibre volume fraction and bending cycles. Two plans were used to investigate which parameters have strong effect on bending moment. The Taguchi analysis revealed that the type of fabric, number of cycles and fibre volume fraction have the largest effect on bending behavior of these fabrics.

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

I. INTRODUCTION

The aerospace industry has expressed interest towards thick, net-shape, drapable carbon fibre fabrics that can be used in manufacturing aerospace composite parts. Non-crimp fabrics NCFs have the potential to be used in manufacturing next generations of composite materials [1]. Non-crimp fabrics are manufactured by laying one or more layers of parallel crimp-free fibres that are assembled by means of stitching, knitting or bonding.

A novel non-crimp thick fabric used toward manufacturing aerospace parts is being developed at the University of Ottawa. The fabric, referred to here as University of Ottawa fabric (uOttawa fabric), manufactured from flat, multilayered carbon fibre yarns assembled by stitching, to net-shape, drapable preforms, Figure 1 [2, 3].

Figure.1 uOttawa fabric preforms.

Two types of carbon fibre reinforcements were tested in bending, labeled as type A and B. Type A reinforcements were made from Tenax-J grade HTS40 E13 12K, 800 tex carbon fibre yarns assembled by stitching using University of Ottawa Advanced preforming Technology process (uOttawa). Type B is an industrial stitched carbon textile consisted of stacked layers of Saertex made from Tenax HTS40 12K yarns. Figure 2 shows a flow chart of the tests conducted to investigate the bending behavior of both type of fabrics.

Tests conducted using type A reinforcements were classified into test groups A1, A2 and A3. Groups A1, A2 and A3 featured 8, 12 and 8 layers respectively. Stitch lines ran at 0° and 90° in test groups A1 and A2, and at 45° in test group A3. Test groups A1, A2 and A3 were further classified into sub-groups based on fibre volume fraction (v_f) and thickness. For groups A1 and A3, thicknesses of 2.0 mm and 1.5 mm were used leading to nominal v_f values of approximately 45% for sub-groups A1/45 and A3/45, and approximately 60% for sub-groups A1/60 and A3/60. For group A2 thicknesses of 3.0 mm and 2.0 mm were used leading to nominal v_f values of approximately 45% for sub-group A2/45 and approximately 66% for sub-group A2/66.

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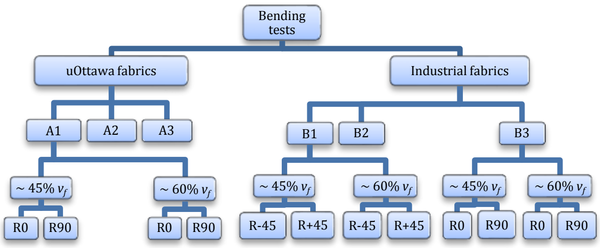

Figure 2. Flow chart of bending tests.

Type B tests were classified into sub-groups based on v_f and thickness, similarly, to type A tests described above. For groups B1 and B3, thicknesses of 2.0 mm and 1.5 mm lead to nominal v_f values of approximately 45% for sub-groups B1/45 and B3/45, and approximately 58% for sub-groups B1/58 and B3/58. For group B2, different thicknesses of 2.7 mm and 1.8 mm lead to nominal v_f values of approximately 45% for sub-group B2/45 and approximately 63% for sub-group B2/63, enabling the same comparisons as above. Type B tests were further classified into sub-groups based on stitch line orientations. Tests were conducted with stitch lines running reference directions R–45 and R+45 for groups B1 and B2 and along reference directions R0 and R90 for group B3.

For type A and B reinforcements, 3 different physical samples were used for every testing configuration and sub-group, with each sample bent for 3 consecutive cycles leading to 216 bending tests performed for both type of reinforcements.

To investigate the bending behavior of such new thick fabric six main experimental parameters were used. The first parameter investigated the effect of type of fabric, the second parameter investigated the effect of thickness, the third parameter investigated the effect of different fibre volume fractions, the fourth parameter investigated the effect of stitch orientations, the fifth parameter investigated the effect of roving orientations, and the last parameter investigated the effect of number of cycles.

The analysis introduced here in this work was to identify which of the six parameters has the most significant effect on the bending behavior of the new fabric based on a previous experimental work published in Part I of this paper [4]. Data analyzed in this work was generated from results obtained in Part I of this paper and listed in Tables I, II, IV and VI.

II. TAGUCHI METHOD

Taguchi method was developed by a statistician and engineer called Dr. Genichi Taguchi who was born in Japan in 1924. His method was aimed to improve quality of manufactured goods and reduce the costs. The method has been used in the field of design of experiments to determine parameters that affecting the response, which is in our case the average (*AVG*) and standard deviation (*STD*) values of the bending moments. Parameters such as type of fabric, thickness, stitch orientation are affecting the response of the bending moment. Also, the number of levels that the parameters should be varied at must be specified. In this research paper, there is two levels for each parameter. As an example, the type of fabric parameter has two levels either Type A fabric or Type B fabric [5-10].

The quantitative analysis of bending results was performed using 2-level, 5-parameter Taguchi plans for analysis. The responses analyzed with both plans are the average (*AVG*) and standard deviation (*STD*) values of the bending moments (M_B) [4].

The FIRST PLAN compared the effect of the 5 following parameters and their interactions, with 2-levels on 2 quantitative responses that are the average (*AVG*) and standard deviation (*STD*) values:

- Parameter A: small thickness (-) vs. large thickness (+);
- Parameter B: uOttawa fabric (-) vs. industrial fabric (+);
- Parameter C: low v_f (-) vs. high vf (+);
- Parameter D: R0/R90 (-) vs. R+45/R-45 (+);
- Parameter E: cycle 1 (-) vs. cycle 3 (+).

The SECOND PLAN compared the effect of the 5 following parameters and their interactions on the same 2 quantitative responses the average (*AVG*) and standard deviation (*STD*) values:

- Parameter A: roving bent at 0°/90° vs. -45°/+45° ;
- Parameter B: uOttawa fabric (-) vs. industrial fabric (+);
- Parameter C: low v_f vs. high v_f ;
- Parameter D: R0/R90 (-) vs. R+45/R-45 (+);
- Parameter E: cycle 1 (-) vs. cycle 3 (+).

The first plan focuses on the effect of the thickness along with other parameters on the response in bending. Data analyzed in this plan was generated from tests listed in Tables 1, 2, 4 and 5.

The second plan focuses on the effect of the orientation of the yarns along with other parameters on the response in bending. Data analyzed in this plan was generated from tests listed in Tables 1, 3, 4 and 6. Whilst the structure of the data precluded it from being all analyzed within a single plan, the two distinct plans featuring mostly common parameters and sharing 50% of common experimental results enable a clear comparison of the effect of reinforcement thickness and yarn orientations, which are two important preform parameters.

The plans are fully factorial hence each plan quantifies independently the main effects of parameters A, B, C, D and E, as well as all the effects of all interactions between the five parameters All tests were replicated on 3 samples which enabled the quantitative evaluation of inner-group variability and comparison with between-group variability; the statistical significance of the effects of parameters could be assessed through multi-factorial analyses of variances and calculation of F-ratios [5].

Tabel 1. Average and standard deviation bending moment values obtained for group A1 samples made from uOttawa reinforcements

Type	Sub-group	Sample	*Bending moment M_B (N.mm)*			
			AVG		*STD*	
			C1	C3	C1	C3
uOttawa - 8 Layers - $[90/0]_S$ - Snitched 0°	A1/45/R0	S1	45.81	36.34	13.39	12.50
		S2	61.04	42.31	14.15	16.64
		S3	81.54	26.10	19.34	12.46
	A1/60/R0	S1	177.88	85.38	64.66	42.90
		S2	248.38	66.87	32.46	28.11
		S3	170.84	113.24	72.79	58.21
	A1/45/R90	S1	74.60	45.19	8.04	8.56
		S2	159.19	83.49	12.24	2.86
		S3	136.97	80.28	7.90	3.76
	A1/60/R90	S1	222.57	141.13	70.55	33.71
		S2	202.40	106.04	29.55	14.90
		S3	190.84	148.63	37.44	49.87

Table 2. Average and standard deviation bending moment values obtained for group A2 samples made from uOttawa reinforcements.

Type	Sub-group	Sample	*Bending moment M_B (N.mm)*			
			AVG		*STD*	
			C1	C3	C1	C3
uOttawa - 12 Layers - $[90/0]_S$ - Snitched 0°	A2/45/R0	S1	100.62	42.34	17.77	19.72
		S2	92.29	65.17	15.38	13.48
		S3	81.51	31.03	19.45	13.02
	A2/66/R0	S1	110.73	67.08	15.40	17.73
		S2	144.42	41.17	21.46	7.56
		S3	139.17	59.43	20.26	21.52
	A2/45/R90	S1	140.46	59.68	25.64	7.60
		S2	109.88	50.40	7.43	10.27
		S3	99.67	85.12	10.98	16.93
	A2/66/R90	S1	183.43	115.25	47.26	22.49
		S2	211.56	149.47	33.30	22.65
		S3	174.06	177.54	49.61	25.96

Table 3. Average and standard deviation bending moment values obtained for group A3 samples made from uOttawa reinforcements.

Type	Sub-group	Sample	*Bending moment M_B (N.mm)*			
			AVG		*STD*	
			C1	C3	C1	C3
uOttawa - 8 Layers - $[90/0]_S$ - Snitched 45°	A3/45/R0	S1	112.27	43.94	42.72	29.64
		S2	52.53	24.37	60.01	53.77
		S3	140.83	77.26	89.05	60.51
	A3/60/R0	S1	55.51	16.32	7.62	7.70
		S2	40.00	34.44	4.76	8.78
		S3	22.20	35.83	13.73	5.20
	A3/45/R90	S1	161.32	65.71	46.62	11.83
		S2	89.76	50.66	9.05	7.88
		S3	99.30	49.64	12.46	6.49
	A3/60/R90	S1	28.88	43.90	6.40	5.57
		S2	44.68	37.83	5.31	2.13
		S3	42.56	27.19	3.60	4.05

Table 4. Average and standard deviation bending moment values obtained for group B1 samples made from industrial fabrics.

Type	Sub-group	Sample	*Bending moment M_B (N.mm)*			
			AVG		*STD*	
			C1	C3	C1	C3
Saertex - 6 Layers - $[(0/90)]_3$ - Stitched 45°	B1/45/R-45	S1	49.00	6.58	5.43	5.02
		S2	33.58	12.70	5.28	6.06
		S3	61.02	28.79	4.49	1.83
	B1/58/R-45	S1	72.34	23.72	8.69	6.86
		S2	46.41	24.74	6.32	3.62
		S3	64.98	35.39	11.15	5.80
	B1/45/R+45	S1	60.32	17.71	3.59	2.03
		S2	23.31	18.47	5.69	2.46
		S3	54.10	13.38	3.13	2.14
	B1/58/R+45	S1	83.03	24.36	20.19	3.15
		S2	61.95	20.67	19.47	7.85
		S3	81.68	30.74	9.44	4.58

Table 5. Average and standard deviation bending moment values obtained for group B2 samples made from industrial fabrics.

Type	Sub-group	Sample	*Bending moment M_B (N.mm)*			
			AVG		*STD*	
			C1	C3	C1	C3
Saertex - 8 Layers - $[(0/90)]_4$ - Stitched 45°	B2/45/R-45	S1	57.91	37.94	8.55	3.33
		S2	57.07	26.08	6.61	10.72
		S3	51.74	32.42	9.35	4.65
	B2/63/R-45	S1	128.18	62.26	20.60	8.26
		S2	134.05	57.86	11.61	11.st88
		S3	122.37	67.89	17.76	6.42
	B2/45/R+45	S1	40.23	12.54	8.03	9.49
		S2	45.35	19.52	4.17	5.67
		S3	22.17	46.57	11.88	2.51
	B2/63/R+45	S1	112.02	28.79	14.67	13.47
		S2	143.27	20.93	14.17	10.17
		S3	129.68	50.52	6.98	5.43

Table 6. Average and standard deviation bending moment values obtained for group B3 samples made from industrial fabrics.

Type	Sub-group	Sample	*Bending moment M_B (N.mm)*			
			AVG		*STD*	
			C1	C3	C1	C3
Saertex - 6 Layers - $[(0/90)]_3$ - Stitched 45°	B3/45/R0	S1	75.52	24.06	4.56	7.31
		S2	21.37	28.38	8.13	6.01
		S3	50.67	49.10	5.60	3.36
	B3/58/R0	S1	39.87	38.24	26.44	12.47
		S2	79.78	40.99	8.80	7.59
		S3	76.27	47.21	8.62	8.19
	B3/45/R90	S1	39.76	65.71	5.18	11.83
		S2	25.07	6.50	1.42	3.92
		S3	26.76	38.67	6.68	4.04
	B3/58/R90	S1	47.21	27.24	11.68	11.22
		S2	75.58	23.36	5.22	6.03
		S3	47.45	43.90	8.40	5.87

The average values of bending moments characterize the general resistance to bending shown by a sample during a given test, whilst the standard deviation value characterizes the extent to which this resistance fluctuates. The labels AVG and STD represent the average and the standard deviation of the values of bending moment M_B

respectively, whilst the labels S1, S2 and S3 identify the sample number. Therefore, one value of the average AVG of M_B and one value of the standard deviation STD of M_B is reported for each specific bending test, cycle number and sample number.

The first step consists in performing a one-way analysis of variance (ANOVA) [5] over the data collected as a whole, for each plan and for each of the responses collected in each plan, leading to calculate a value of an F-ratio in each case. The value of the F-ratio is then compared with tabulated values, indicating that the value of the F-ratio obtained is significant in the case where the value derived from the data is superior to the tabulated value, or not significant in the opposite case. A significant F-ratio indicates that differences between values for given subgroups are sufficiently large to be detected despite noise present in the data; in other words, 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. The one-way ANOVA does not, however, provide any indication as to which parameters or interactions of parameters may be significant [5].

Quantities pertaining to the four one-way ANOVAs performed as part of the analysis of the bending data. *LAVG*(AVG), $LSTD^2$(AVG), *LAVG*(*STD*) and $LSTD^2$(*STD*) represent the line average and the line standard deviation of either *AVG* or *STD* values for each run, or the average and variance of values of *AVG* and *STD* collected for the 3 samples associated with a given run. Equations [5] for these quantities are as follows:

$$LAVG(AVG) = \frac{S1\ AVG + S2\ AVG + S3\ AVG}{3} \quad (1)$$

$$LAVG(STD) = \frac{S1\ STD + S2\ STD + S3\ STD}{3} \quad (2)$$

$$LSTD^2(AVG) = \frac{1}{2}\left[\left(S1\ AVG - LAVG(AVG)\right)^2 + \left(S2\ AVG - LAVG(AVG)\right)^2 + \left(S3\ AVG - LAVG(AVG)\right)^2\right] \quad (3)$$

$$LSTD^2(STD) = \frac{1}{2}[(S1\ STD - LAVG(STD))^2 + (S2\ STD - LAVG(STD))^2 + (S3\ STD - LAVG(STD))^2] \quad (4)$$

Table 7. One-way ANOVA for 1st plan (N.mm).

	Response	*AVG*	*STD*
First Plan	**Average**	**359.25**	**60.70**
	Variance	**8879.82**	**569.12**
	F-Ratio	**24.718**	**9.375**

Considering response *AVG* for the first plan with data reported in Table 7 evaluating the effect of the thickness along with other parameters, variances between subgroups and within subgroups were calculated as 8879.82 and 359.25 respectively for an F-ratio equal to 24.718. The calculated and tabulated values [5] of the F-ratio obtained from the one-way ANOVA conducted for response *AVG* and the first plan, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Considering response *STD* for the first plan with data reported in Table 7, variances between subgroups and within subgroups were calculated as 569.12 and 60.70 respectively for an F-ratio equal to 9.375. Here again, the calculated and tabulated values [5] of the F-ratio obtained from the one-way ANOVA conducted for response *STD* and the first plan, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *STD*.

Considering response *AVG* for the second plan evaluating the effect of the orientation of yarns along with other parameters with data reported in Table 8, variances between subgroups and within subgroups were calculated as 6607.55 and 458.04 respectively for an F-ratio equal to 14.426. Yet again the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG* and the second plan, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Finally, considering response *STD* for the second plan with data reported in Table 8, variances between subgroups and within subgroups were calculated as 871.61 and 93.67 respectively for an F-ratio equal to 9.305. The same conclusion is reached from this last one-way ANOVA: the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *STD* and the first plan, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *STD*.

Table 8. One-way ANOVA for 2nd plan (Nmm).

	Response	*AVG*	*STD*
Second Plane	**Average**	**458.04**	**93.67**
	Variance	**6607.55**	**871.61**
	F-Ratio	**14.426**	**9.305**

Given the above conclusions, the next step in analyzing the effects of the parameters on bending consists in calculating contrasts associated with each parameter and interaction of parameters, for each response and each plan. Contrasts, which are quantified comparisons of responses obtained under opposed effect of a given parameter or interaction of parameters, are calculated as follows. Given k subgroups, a contrast defined upon the subgroup averages μ_1, μ_2, … , μ_j, … , μ_k by the coefficients c_1, c_2, … , c_j, … , c_k can be estimated using equation (5):

$$\hat{C} = \sum_{j=1}^{k} c_j \bar{X}_j \quad (5)$$

where values X_1, X_2, …, X_j, …, Xk are averages associated with each subgroup, which are estimates of means.

An F-ratio may be calculated for each individual contrast as the ratio of the sum of squares for the contrast *SS*(*C*) and mean square within for all the data, *MSW*:

$$F - ratio = \frac{MS(C)}{MSW} = \frac{SS(C)}{MSW} \quad (6)$$

Term *SS*(*C*) is calculated as:

$$SS(C) = \frac{(\hat{C})^2}{Adjustment\ Term} \quad (7)$$

$$Adjustment\ Term = \sum_{j=1}^{k}\left(\frac{c_j^2}{n_j}\right) = \frac{1}{n}\sum_{j=1}^{k} c_j^2 \quad (8)$$

Term *MSW* is the average of variances for all contrasts, values for both plans, for each response appear in Table 9. It may be noted that the average of contrast F-ratios presented in Table 8 are equal to the one-way ANOVA F-ratios presented in Tables 9, as expected.

Table 9. Contrasts for MSW

Plan	*MSW* *AVG* Response	*MSW* *STD* Response
First Plan	**359.3**	**60.7**
Second Plan	**458.0**	**93.67**

Calculated contrast F-ratios must be compared with tabulated values. The tabulated value indicating significant differences between groups is 7.07 [5]. Values of contrast F-ratios superior to 7.07, deemed be significant. Results reveal that 12 main effects and interactions of parameters have a significant effect on response *AVG* in the first plan, 8 main effects and interactions of parameters have a significant effect on response *STD* in the first plan, 12 main effects and interactions of parameters have a significant effect on response *AVG* in the second plan, and 7 main effects and interactions of parameters have a significant effect on response *STD* in the second plan. Significant main effects and interactions of parameters are summarized in Figures below, along with the associated contrast sign.

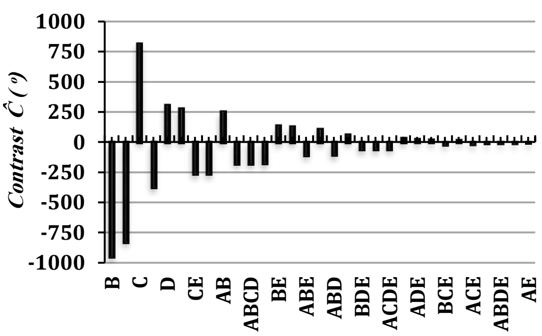

Figure.3 Main effects and interactions of parameters in decreasing order, response *AVG*, first plan.

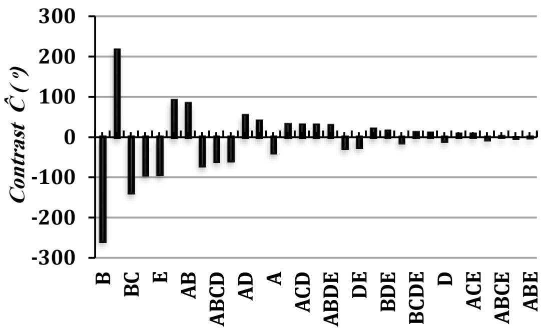

Figure.4 Main effects and interactions of parameters in decreasing order, response STD, first plan.

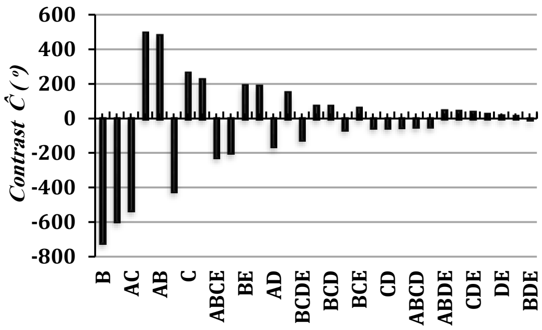

Figure.5 Main effects and interactions of parameters in decreasing order, response AVG, second plan.

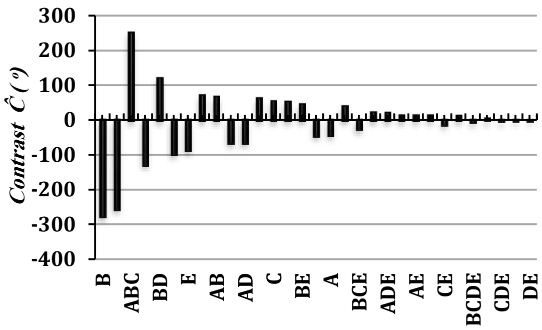

Figure.6 Main effects and interactions of parameters in decreasing order, response STD, second plan.

Where for <u>FIRST PLAN</u> the main 5 parameters are:
⇒ Parameter A is small thickness vs. large thickness;
⇒ Parameter B is uOttawa fabric vs. industrial fabric;
⇒ Parameter C is low v_f vs. high v_f;
⇒ Parameter D is setup in rig 1 vs. setup in rig 2;
⇒ Parameter E is: bending cycle 1 vs. bending cycle 3.

Where for <u>SECOND PLAN</u> the main 5 parameters are:
⇒ Parameter A is rovings bent at 0°/90° vs. -45°/+45° ;
⇒ Parameter B is uOttawa fabric vs. industrial fabric;
⇒ Parameter C is low v_f vs. high v_f;
⇒ Parameter D is setup in rig 1 vs. setup in rig 2;
⇒ Parameter E is: bending cycle 1 vs. bending cycle 3.

III. CONCLUSIONS

The above systematic Taguchi plans identify very clearly that the most important significant. Differences in bending behavior arise when comparing uOttawa and Saertex industrial textiles. This was to be expected given the different means of assembly used for each type of reinforcement fabrics. This highlights the effect of relative displacements between layers on the bending behavior. The stitching type is therefore a crucial factor that affects the mobility of yarns and the ability of fabrics to bend and drape. Bending analysis shows that Saertex fabrics are more flexible than uOttawa fabrics, because of the nature of stitching in Saertex fabrics. It has been found that Saertex fabric gained their compliant nature from the type of stitching threads. This confirms that stitching through the thickness of the reinforcement stacks has a strong effect on the observed bending moment.

The second most important main effect on the average bending moment is the cycle number. Such effect of cycling is not surprising as reorganization of fibres upon successive loading and unloading lead to changes in mechanical behavior. However, it is worth noting that cycling generally has a stronger effect than other parameters related to the architecture of the fabric stacks, namely the fibre volume fraction, thickness, yarn orientations and setup orientations. The effect of different fibre volume fractions appeared clearly on the values of the bending moment recorded in bending tests. The bending moments recorded for all samples made from both types of fabrics at 60% v_f were higher than those recorded at 45% v_f. The same conclusion was reached from the Taguchi analysis conducted here.

Two setup roving orientations, 0°/90° roving and -45°/+45° roving, were investigated in bending tests for samples made from both types of fabrics. Taguchi analyses conducted on both types of fabrics showed that roving orientations had little effect on the bending behavior for both types of fabrics.

The overall conclusion here is that Taguchi analysis shows clearly that the novel non-crimp thick fabric developed at the University of Ottawa has ability to deform under very low bending force despite the fact that the industrial fabric has different assembling and stitch configuration.

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