EFFECTS OF STITCHING PARAMETERS ON THE ENERGY ABSORPTION OF FLAT COMPOSITE PLATES

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ABSTRACT

The aim of this work was to identify methods of maximising the energy absorbing capabilities of fibre reinforced composite plates for use in low-cost, weight-critical energy absorbing structures. It has been shown that the interlaminar shear properties can significantly affect the crushing energies of composites [1].

The research therefore was aimed at improving the energy absorption of the flat plates, measured as specific sustained crushing stress (SSCS) in kJ/kg, by increasing the interlaminar fracture toughness properties through the use of stitching.

To optimise the stitching process with respect to the SSCS, a design of experiments (DOE) technique using the Taguchi approach was applied; the optimised laminate was then compared in another DOE with equivalent unstitched laminates to assess the overall improvement.

It was found that, from the initial seven factors selected, the four prime factors that influenced the crushing of the stitched composites were the fibre orientation, resin type, stitch separation and stitch type. In the final comparisons, it was shown that stitching increases the SSCS and a stiffer composite can be used providing a 31% improvement in the SSCS. The best factors discovered in this research were $[\pm 45/0_3]_s$ carbon fibre/epoxy longitudinally stitched at a separation of 10mm with carbon thread in a modified lock stitch where the loop is formed on the top surface.

1. INTRODUCTION

Research into the crash energy absorption of composite structures has shown that they are superior to the equivalent metal crash structures. This is mostly because metals crush by a series of folding mechanisms, while, when designed properly, composites crush through a process of splitting and brittle fracturing [2, 3].

It is these mechanisms that contribute to the high energy absorption of composite materials. The crushing process is initiated through a trigger which is typically a chamfer or ply drop-off. This helps in the formation of a central crack that limits the initial peak load such that the structure would initiate crushing before the collapse of the composite by buckling or compressive failure. Further to the formation of this initial crack, the crushing can proceed in a stable manner.

The crushing process is controlled by various forms of energy dissipation that are: central crack growth, splitting of fronds, delaminations within the fronds, fibre fracture, friction in the laminate and with the crushing platen, bending of fronds and tearing [4].

It stands to reason therefore, that improving the interlaminar and intralaminar properties of the composites should also improve the energy absorption. Stitching has been shown to dramatically improve the Mode-I delamination resistance of composite materials, while potentially stabilising Mode-II crack growth [5]. Additionally, some preliminary work on z-pinning and stitching has shown that these methods can indeed improve the energy absorption of composite structures [6].

The aim of this work was to identify the optimal stitching parameters that would improve the energy absorption of composite crush structures. Flat plates were chosen as the test specimens since these types of specimens can be easily manufactured and stitched with a conventional industrial lockstitch sewing machine. Furthermore, previous research has shown that the specific energies absorbed in crushing by stabilised flat plates are comparable to the specific energies absorbed by tubes [7, 8].

2. THEORETICAL BACKGROUND

Optimisation of stitching parameters

Preliminary investigation [9] into the crushing of composite plates has shown that for a range of materials based on glass fibre multi warp-knit non crimp fabrics (MWK), there was no significant influence of fabric architecture, resin type or fibre orientation between quadriaxial or triaxial orientations.

For this reason, it was difficult to select an optimum material for the investigation of the stitching parameters. Furthermore, it is essential to identify the optimum stitching parameters that will enhance the energy absorption capability of the composites. Hence, to study the effects of stitching on the energy absorption properties of composite plates, carbon and glass fibre laminates in triaxial and quadriaxial orientations having both polyester and epoxy matrices were investigated.

Since the investigation required the investigation of multiple factors, a Taguchi Method of DOE approach was utilised since it minimises the amount of experiments that need to be performed while allowing the relative influences of each parameter to be statistically determined.

Optimisation of the crushing characteristics of composite plates is a complicated affair. Previous work [9] identified some possible parameters, however , the influence of stitching on crushing has not been thoroughly investigated, mostly since stitching is a relatively ‘modern’ method of improving the interlaminar properties of composite components. For the improvement in the crushing of plates, several control factors can be selected, however, the more factors to be examined, the more complicated the optimisation process. Due to the desire to closely examine the stitching process, as well as compare the best stitched material with its unstitched counterpart, two separate arrays with separate factors were used.

With regard to the stitching parameters, the type and thickness of the thread, the stitching method, stitching density, thread Tex tension and break strength, sewing machine pressure foot tension as well as the direction of stitching are all significant. It has been shown that too high a foot pressure would adversely affect the final properties of the laminate [10], while too high a thread tension would result in large resin pockets between the stitched strands [5]. It is generally accepted that carbon thread is superior to Kevlar thread.

The factors that were investigated and the different levels within the factors can be seen in Table 1. Orientations of $[\pm45/0]_{2s}$ and $[90/\pm45/0_2]_s$ were identified as ideal orientations for investigation. Two sheets of 0° fibres were used in the quadriaxial arrangement since using just one 0° ply on each side resulted in panels being thinner than the minimum 3mm thickness suitable for the plate crush rig. The $[90/\pm45]_{2s}$ fibre orientation was added to the orientation factor to avoid having too many dummy parameters, since it is predicted to possess a poor SSCS and poor fracture toughness results.

The reason for avoiding too many dummy factors is that the dummy factor is investigated more thoroughly than the other factors and this can confuse the results. The only factor having a dummy level is the stitching orientation, and the transverse stitching was selected; this is indicated by Transverse’ in Table 1.

One of the recommended orthogonal arrays, the $L_{18}(2^1\times3^7)$ was selected since any interactions between the factors are uniformly distributed among the columns, thereby allowing the main effects to be studied without the interactions confounding the results [11-13]. The assignment of the factors into the $L_{18}(2^1\times3^7)$ orthogonal array is shown in Table 2. The fifth column was left blank.

In all experiments, four specimens were tested per experiment run so that estimation of the error using S/N ratio analysis could be performed. This type of analysis gives more accurate results since the error within and between experiments can be analysed.

Table 1. Control factors and their levels used in preliminary experiments (DOE1)

	Levels		
Factor	1	2	3
A – Sewing thread	Kevlar	Carbon/PBO	
B – Stitch type	LS[a]	ModLSt[b]	ModLSb[c]
C – Reinforcement fibres	Carbon	Glass	Carbon & Carbon/PA (Rino)
D – Stitch separation	5mm	10mm	15mm
F – Fibre orientation	$[\pm45/0]_{2s}$	$[90/\pm45/0_2]_s$	$[90/\pm45]_{2s}$
G – Resin type	UP[d]	Shell Epikote 828	Cycom 823
H – Stitch orientation[e]	Longitudinal	Transverse	Transverse’

[a] LS implies Lockstitch
[b] ModLSt implies Modified Lockstitch with the loop/lock at the top
[c] ModLSb implies Modified Lockstitch with the loop/lock at the bottom
[d] UP implies Unsaturated Polyester
[e] The stitch orientation is longitudinal or transverse to the crushing direction

Table 2. Parameters for each experiment in the DOE1 using the $L_{18}(2^1\times3^7)$ orthogonal array.

	Factor							
Expt. no.	Thread	Stitch type	Fabric	Stitch separation	*	Fibre orientation	Resin type	Stitch orientation
1	Kevlar	LS	Carbon	5mm		$[\pm45/0]_{2s}$	UP	Longitudinal
2	Kevlar	LS	Glass	10mm		$[90/\pm45/0_2]_s$	Epikote 828	Transverse
3	Kevlar	LS	Rino	15mm		$[90/\pm45]_{2s}$	Cycom 823	Transverse'
4	Kevlar	ModLSt	Carbon	5mm		$[90/\pm45/0_2]_s$	Cycom 823	Transverse'
5	Kevlar	ModLSt	Glass	10mm		$[90/\pm45]_{2s}$	UP	Longitudinal
6	Kevlar	ModLSt	Rino	15mm		$[\pm45/0]_{2s}$	Epikote 828	Transverse
7	Kevlar	ModLSb	Carbon	10mm		$[90/\pm45]_{2s}$	Epikote 828	Transverse'
8	Kevlar	ModLSb	Glass	15mm		$[\pm45/0]_{2s}$	Cycom 823	Longitudinal
9	Kevlar	ModLSb	Rino	5mm		$[90/\pm45/0_2]_s$	UP	Transverse
10	Carbon/PBO	LS	Carbon	15mm		$[90/\pm45/0_2]_s$	Epikote 828	Longitudinal
11	Carbon/PBO	LS	Glass	5mm		$[90/\pm45]_{2s}$	Cycom 823	Transverse
12	Carbon/PBO	LS	Rino	10mm		$[\pm45/0]_{2s}$	UP	Transverse'
13	Carbon/PBO	ModLSt	Carbon	10mm		$[\pm45/0]_{2s}$	Cycom 823	Transverse
14	Carbon/PBO	ModLSt	Glass	15mm		$[90/\pm45/0_2]_s$	UP	Transverse'
15	Carbon/PBO	ModLSt	Rino	5mm		$[90/\pm45]_{2s}$	Epikote 828	Longitudinal
16	Carbon/PBO	ModLSb	Carbon	15mm		$[90/\pm45]_{2s}$	UP	Transverse
17	Carbon/PBO	ModLSb	Glass	5mm		$[\pm45/0]_{2s}$	Epikote 828	Transverse'
18	Carbon/PBO	ModLSb	Rino	10mm		$[90/\pm45/0_2]_s$	Cycom 823	Longitudinal

Comparison between Stitched and Unstitched panels

Once the first stage of the DOE had been completed and the optimum stitched factors were identified, another DOE had to be designed to compare the stitched to the unstitched parts and evaluate the improvement in the crushing energies.

This final DOE was intended to be a very simple comparison, so an $L_4(2^3)$ array was selected. This allows for three 2-level factors to can be tested in four experiments. In addition to simple stitching, it was decided to add another orientation where there were more 0° plies, so both the optimum orientation and this orientation would be analysed. This was based on a presumption that since stitching improves the Mode-I properties, a stiffer laminate could have enhanced SSCS while not simply splitting like a pure UD laminate would. The optimum stitching parameters selected in the first stage were utilised for the stitched specimens. Table 3 and Table 4 show the control factors and the levels selected for further optimisation and the assignment of the factors into the array.

Table 3. Control factors and their levels for DOE2.

	Levels	
Factor	1	2
A – Stitching	Stitched	Unstitched
B – Orientation	$(90/\pm45/0_2)_s$	$(\pm45/0_3)_s$
C – Fabric	Carbon	Carbon & Rino

Table 4. Parameters for each experiment in the DOE2.

	Factor		
Expt. no.	Stitching	Orientation	Fabric
1	Stitched	$(90/\pm45/0_2)_s$	Carbon
2	Stitched	$(\pm45/0_3)_s$	Carbon & Rino
3	Unstitched	$(90/\pm45/0_2)_s$	Carbon & Rino
4	Unstitched	$(\pm45/0_3)_s$	Carbon

It should also be noted that another factor – the fabric type factor was added. However, the location of this factor in the array means that it might be confounded with interaction effects since the third column of an $L_4(2^3)$ can be used to represent the effects of the interaction between the first and second column. Also, since only one ply of ±45 material is used on each side of symmetry, the relative effects of the Rino should be insignificant.

Materials and manufacturing

The crush test specimens used in this research are manufactured from MWK fabrics supplied by Saint-Gobain BTI and Sigmatex. In order to negate the effects of ply thickness ratios, the MWK fabrics were chosen such that the ratio of UD to ±45° fabrics was kept constant. The UD carbon fabric was a Sigmatex Constructex at 312 g/m^2, the biaxial carbon was a Saint-Gobain BTI CBX-440 (440 g/m^2). For the glass fibre laminates, the UD was ELpb-412 (412g/m^2) while the biaxial was EBX-602 (602g/m^2). The ratio of UD to ±45° was 0·7 for the carbon and 0·68 for the glass fibre laminates 0·68. The hybrid biaxial fabric (Rino) was an experimental fabric supplied by Saint-Gobain BTI containing 15% by weight of nylon fibres and 440g/m^2 of carbon fibres.

All the laminates were manufactured using a resin-infusion process to keep processing costs down. The resins available that could be infused were Crystic PAX-701 – a pre-accelerated unsaturated polyester resin designed for resin-infusion, Shell Epikote 828 – an unmodified epoxy resin that is quite viscous at room temperature, and Cycom 823 – a very low viscosity epoxy resin designed for RTM. Both epoxy resins had to be heated up to 60°C before infusion, with the Shell Epikote 828 needing to be infused under temperature.

In previous research [9], it had been determined that the plate crush rig knife-edge separation (KES) normalised for the thickness (KES/t) of the plate is crucial for comparing the SSCS of the individual materials. This KET/t ratio was kept constant at 16; the value was dictated by the limitations of the crush rig and thickness of the specimens.

Kevlar 29 120Tex thread from Atlantic Thread and Supply having a tenacity of 185cN/Tex and stretch broken carbon/PBO thread having a tenacity of 53cN/Tex was obtained from Shappe Techniques. Stitching was performed on a Juki LU-563 industrial sewing machine equipped with DP/17 size 160 Groz-Beckert San-5 needles for technical textiles. The dry preform was stitched in parallel lines with 5, 10 and 15mm separation. The pitch, i.e. the distance between stitches in the same line was kept constant at 5mm. This gave a stitch density of 9, 6 and 3 stitches/cm^2 respectively.

Furthermore, the stitching was performed in three different ways – the standard lockstitch, and two variations of a modified lockstitch. The modified lockstitch was adjusted in two modes – with the loop on the top (ModLSt) or with the loop at the bottom (ModLSb). The reasoning is that when the loop is at the bottom, the needle thread, which forms the loop, is passed through the fabric and around the bobbin head, and hence could be degraded. On the contrary, when the loop is at the top, the thread in the fabric would have simply been pulled from the bobbin through the fabric and hence suffer very little degradation.

The SSCS is calculated by obtaining the average sustained crushing stress and dividing that average by the density of the material as obtained via the Archimedes principle.

3. RESULTS & DISCUSSION

Crush testing charts

The charts obtained from crush testing are divided into the different fabric orientations, which are then divided into the stitch orientations. The reason for choosing such a way of displaying the charts is because in the Robust Design analysis that will be presented later, the orientation is the factor that most influences the crushing response of the composite plates. The charts plot the specific stress vs. the crushing stroke; displaying the results in such a manner allows for easy comparison of the crushing pattern between each series.

It can be noted that for the $[90/\pm45]_{2s}$ orientations (Fig. 1) the actual crushing process was stopped after 25 to 35mm of crushing distance. This was because these specimens did not crush, but rather, compacted themselves as can be seen in the photographs of the crushed specimens (Fig. 2). In the case of series 3, 5, 7 and 16 the specimens compact themselves without tearing.

Specimens in the series 11 and 15 that both have a stitch separation of 5mm broke at one of the stitch lines and the energy that was absorbed subsequently was due to the tearing and sliding of the broken specimen over itself. This effect could be the explanation of the particularly low specific crushing stresses; specimens in the series 15 were stitched in a longitudinal manner.

Specimens having fibres arranged in a $[90/\pm45/0_2]_s$ orientation (Fig. 3), all crushed properly with the exception of series 9. In this series, the initial stage of the crush was stable, but after approximately 15mm, the specimens broke and squashed (Fig. 4 left). The laminates seem either unable to tear, or have been destabilised by a possible combination of the close transverse stitching, and the use of a polyester matrix. Series 4 also had in problems during crushing, where 50% of the specimens crushed properly while the others broke and slid over themselves as for specimens having a $[90/\pm45]_{2s}$ orientation. This series is similar to series 9 with the exception that the matrix is Cycom 823.

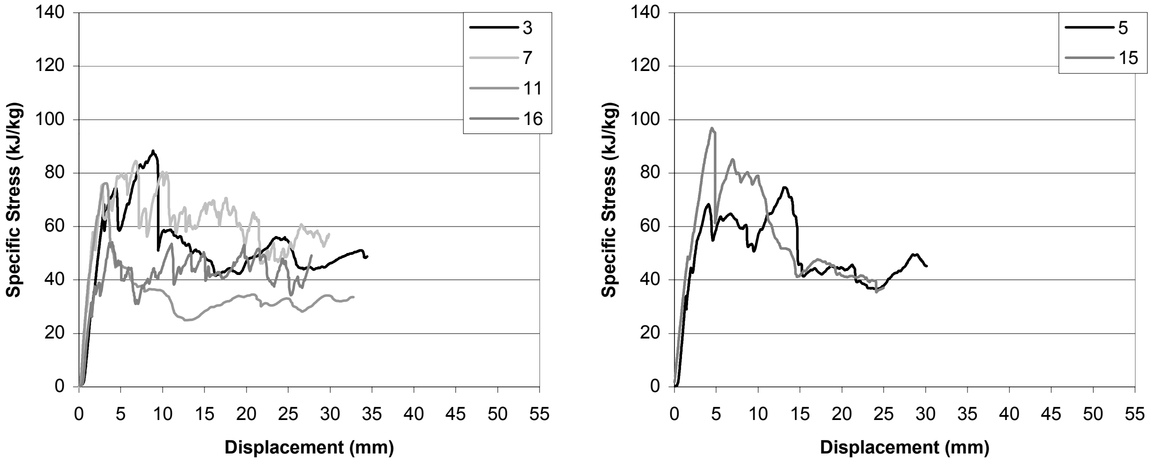

Fig. 1. Sustained crushing charts of $[90/\pm45]_{2s}$ specimens stitched in transverse (left) and longitudinal (right)

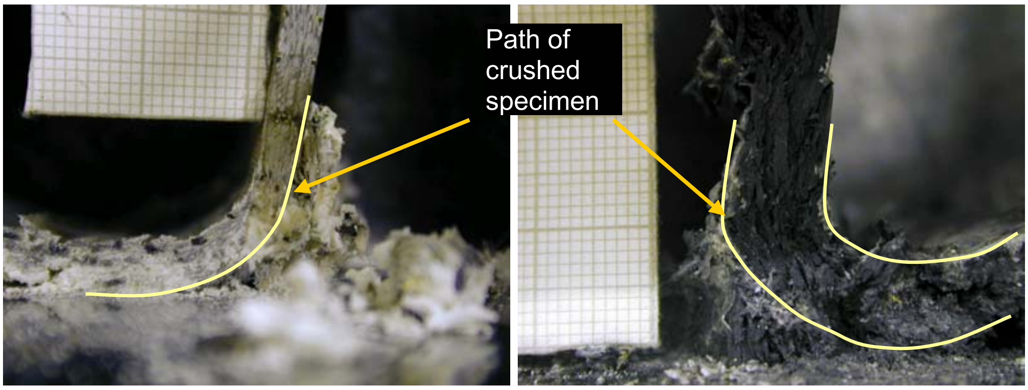

Fig. 2. Photos of 'as crushed' specimens having a $[90/\pm45]_{2s}$ orientation and stitched in transverse – series 11 (left) and longitudinal – series 15 (right)

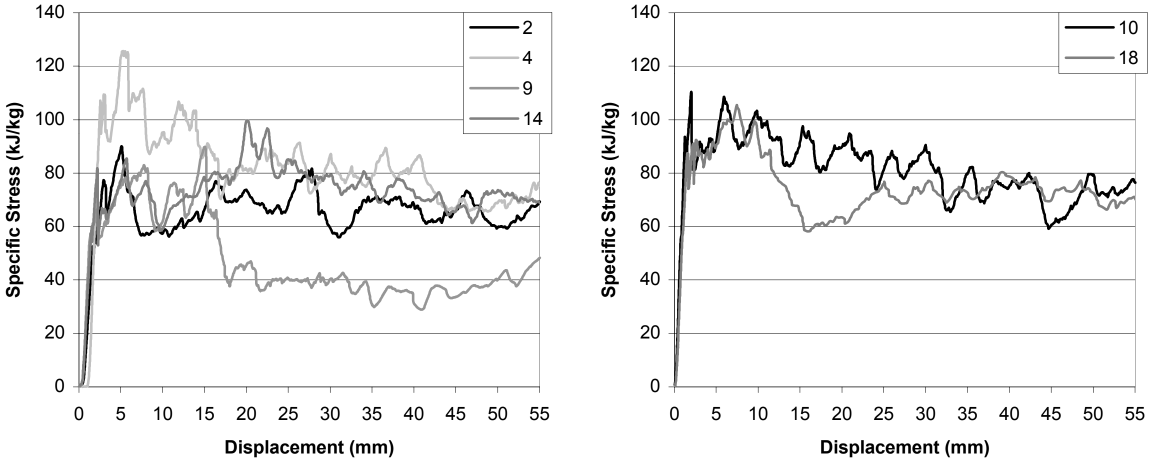

Fig. 3. Sustained crushing charts of $[90/\pm45/0_2]_s$ specimens stitched in transverse (left) and longitudinal (right)

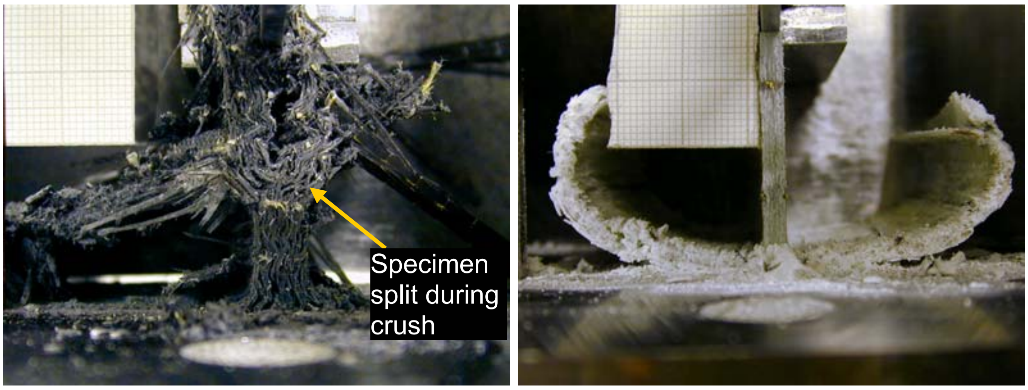

Fig. 4. Photos of 'as crushed' specimens having a $[90/\pm45/0_2]_s$ orientation and stitched in a transverse orientation – series 9 (left) and series 14 (right)

For specimens with the fibres in a $[\pm45/0]_{2s}$ orientation (Fig. 5), the results are peculiar. Series 1 specimens squashed without tearing (Fig. 6 right); this series had tightly stitched rows of longitudinal Kevlar thread in a polyester matrix. It is possible that the traditional lockstitch where the loop is located within the laminate distorted the fibres thus lowering the compressive strength. In fact, in Fig. 5, the series 1 chart reveals peaks that approximate to the 5mm stitching pitch. Series 12 specimens had a stable initial crush, then after a short crush stroke, broke and buckled. These specimens were also stitched in a traditional lockstitch manner, but in a transverse orientation.

It is possible that some stitch lines introduced a defect, although it is plausible that the polyester matrix could have influenced the breakage. The specimens of series 13 all started to crush properly, and then broke during the crush with most of the energy being tearing energy and friction as the broken specimen slid over itself. No particular reason could be discovered, except the possibility that the stitch lines were too tight or distorted the fibres excessively at certain points. The remaining specimens all crushed properly. It should also be noted that in the graph of series 6 (Fig. 5) there are peaks that, similar to series 1, are separated by approximately the 15mm stitch line separation for that particular series.

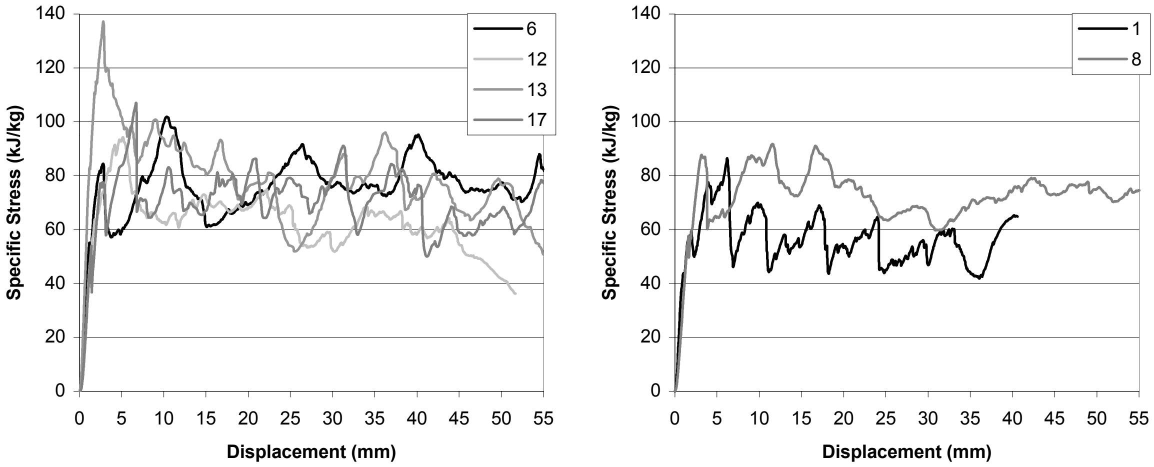

Fig. 5. Sustained crushing charts of $[\pm45/0]_{2s}$ specimens stitched in transverse (left) and longitudinal (right)

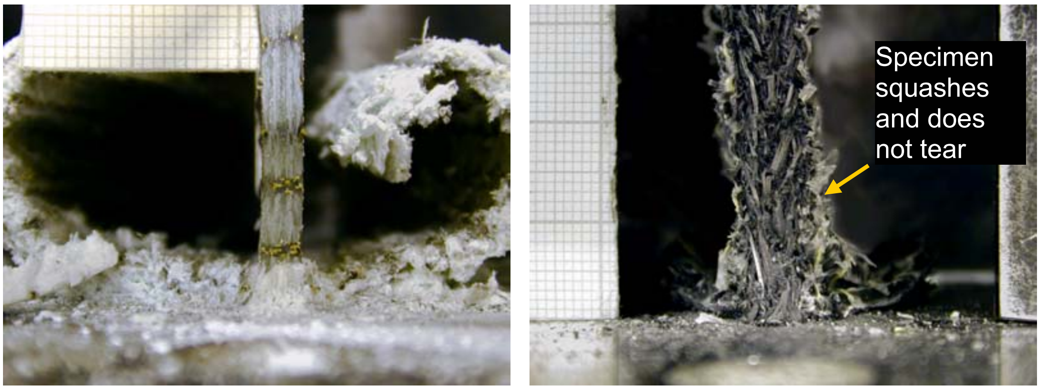

Fig. 6. Photos of 'as crushed' specimens having a $[\pm 45/0]_{2S}$ orientation and stitched in transverse – series 17 (left) and longitudinal – series 1 (right)

Crush Testing DOE Data Sheet

The averages for the results from the above experiments are calculated for a larger-is-better S/N ratio criterion. These results are then implemented in the experimental datasets for analysis (Table 5); the dummy results are italicised and underlined.

The results show that the main factor that influences the crushing, as identified by the "Difference" row in Table 5, is the orientation of the fibres. This factor has approximately twice an influence as the next most important factor – the resin type. It is possible that the selection of the $[90/\pm 45]_{2S}$ orientation was poor since it seems to have confounded the results, especially since the other two orientations are not much different in themselves. The other important factors that emerge are the

- **resin type** – epoxies are obviously superior to the polyester resins
- **stitch separation** – the 5mm separation seems to adversely affect the properties
- **stitch type** – the generic lockstitch is the worst, while the modified lockstitch where the loop is at the top is the best
- **stitch orientation** – longitudinal seems superior although there seems to be a great deal of error in the dummy factor.

The other factors, specifically thread type and fibre type do not seem to influence much the crushing energy.

This is further confirmed by the ANOVA results, where all the F-ratios are all greater than the 95% f-probability distribution. However, in the ANOVA results, the stitch orientation results have been pooled into the error since that particular factor showed a high degree of error within itself. This does have the adverse affect of increasing the total error to 17·67%.

The S/N ratio results are practically identical to the analysis of means for the unpooled factors. In both cases, the orientation is the most significant parameter while the pooled error proves to be greater than the influences of the remaining parameters. This implies that there was a reasonable degree of error, although much of this error was contributed by the dummy factor.

Table 5. Response table for differences method and ANOVA of calculating SSCS by S/N ratio

	Thread	**Stitch type**	**Fabric**	**Separation**	**Orientation**	**Resin**	**Stitch orientation**
Level1	35·65	34·96	35·80	34·68	36·56	34·62	36·22
Level2	35·71	36·41	35·58	36·31	36·75	36·48	*34·82*
Level3		35·67	35·67	36·05	33·73	35·94	*36·00*
Level2 & 2'							35·41
Difference	0·06	1·44	0·22	1·63	3·02	1·85	0·81
Rank	7	4	6	3	1	2	5
Optimum	**Carbon**	**ModLSt**	**Carbon**	**10mm**	**$[90/\pm45/0_2]_s$**	**Epikote 828**	**Longitudinal**

Characteristic Type	**Experimental Mean**	**Predicted Mean**	**Confirmation**
Larger-the-better	35·68 dB	38·72 dB	38·40 dB

ANOVA

Source	**Pool**	**Sq**	*v*	**Mq**	**F-ratio**	**F crit**	**Sq'**	**rho %**
A	Y	0·01	1	0·01	0·02	4·84		
B		6·26	2	3·13	4·59	3·98	4·90	7·17
C	Y	0·14	2	0·07	0·10	3·98		
D		9·21	2	4·60	6·74	3·98	7·84	11·49
F		34·39	2	17·19	25·18	3·98	33·02	48·35
G		10·92	2	5·46	8·00	3·98	9·56	13·99
H	Y	2·63	1	2·63	3·85	4·84		
eH (error H)	Y	4·21	1	4·21	6·16	4·84		
error	Y	0·52	6	0·09				
Pooled error		7·51	11	0·68	1·00	2·82	12·97	19·00
Total (St)		68·29	17	4·02			68·29	100·00
Mean (Sm)		22917·26	1					
ST		22985·55	18					

Confidence Intervals

Factor	**A**	±0·61	**Predicted Mean**	±0·64	**Confirmation Experiment**	±0·86
	B-G	±0·67				
	H1	±0·74				
	H2	±0·53				

The response graph (Fig. 7 left) shows that there are clear differences in between the best and worst parameters in the four important factors. Hence, it is easy to choose the best parameters for crushing. Fig. 7 right, plots the percentage contribution of the best of each important parameter to the improvement of the SSCS. The error can be seen to be significant, and the stitch type is not as important in improving the SSCS as the selection of an epoxy resin matrix and the selection of a reasonable separation between the stitch lines.

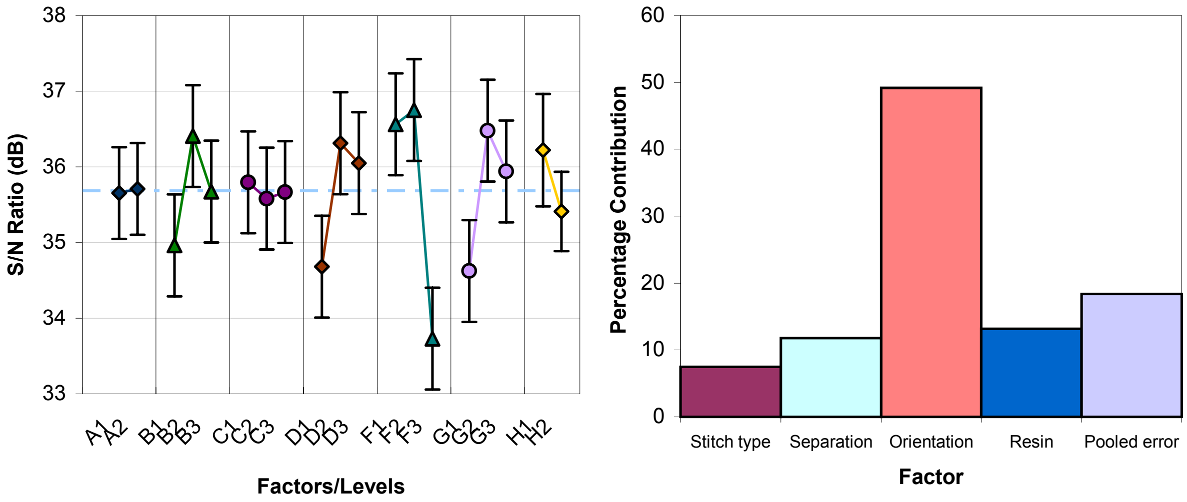

Fig. 7. Response graph for all factors (left) and the percentage contribution of important factors (right)

Crushing of stitched and unstitched panels

The charts obtained from the final DOE are plotted on one chart (Fig. 8) for easy comparison. The unstitched carbon fibre composite (series 4b) has crushing properties that are almost similar to the stitched carbon/Rino fibre composite (series 2b). However, once the carbon fibre composite in the $[\pm 45/0_3]_s$ alignment is stitched, the SSCS increases by 30%.

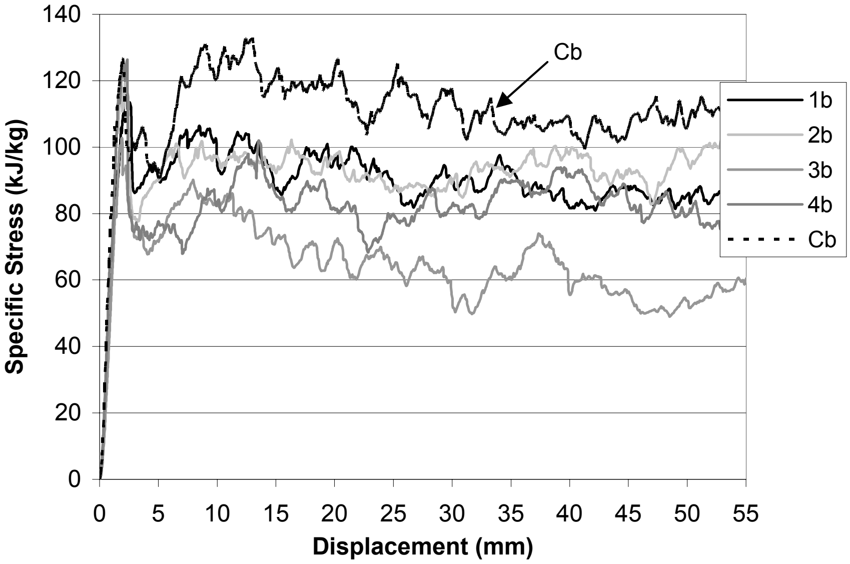

Fig. 8. Comparison of SSCS charts for the selection of the optimum condition (Cb refers to the confirmation experiment)

Table 6 gives the response table for analysis by the S/N ratio. Both show that the stitching is the factor that mostly influences the crushing properties of the composites. The orientation with a greater number of 0° fibres, and hence the stiffer composite shows a great influence on the crushing properties. It should be noted that the fibre type also showed significant influence on the crushing properties, but since the influence was not significant, the results were pooled to obtain the confidence intervals. This accounts for the big degree of error in the confidence intervals, especially since the fibre type accounts for 7·44% and 11·98% of the total results for the analysis of means and the S/N ratios respectively.

Table 6. Response table for differences method and ANOVA of calculating SSCS by S/N ratio

	Stitch /Unstitch	**Orientation**	**Fabric**
Level1	39·11	37·43	38·63
Level2	37·27	38·95	37·75
Difference	1·84	1·52	0·88
Rank	**1**	**2**	**3**
Optimum	**Stitched**	**$(\pm 45/0_3)_s$**	**Carbon**

Characteristic Type	**Experimental Mean**	**Predicted Mean**	**Confirmation**
Larger-the-better	38·19 dB	40·32 dB	40·81 dB

ANOVA

Source	***Pool***	***Sq***	***v***	***Mq***	***F-ratio***	***F crit***	***Sq'***	***rho %***
A		3·38	1	3·38	4·36	10·13	3·38	52·22
B		2·32	1	2·32	2·99	10·13	2·32	35·80
C	**Y**	0·78	1	0·78	1·00	10·13		
error	**Y**	0·000	0	0·00	0·00			
Pooled error		0·776	1	0·776	1·000		0·776	11·977
Total (St)		6·48	3	2·16			6·48	100·00
Mean (*Sm*)		5834·84	1					
ST		5841·32	4					

Confidence Intervals

Factor	**A**	±1·98	**Predicted Mean**	±1·09	**Confirmation Experiment**	±1·58

Fig. 9 plots the percentage contributions from the ANOVA calculations and the percentage contribution of each factor. Effectively, all factors can be considered to influence the crushing properties. It could also be that there exists an interaction between stitching and orientation and this has become confounded by the inclusion of a fibre type in the experiment.

Fig. 10 compares the results from the Robust Design experiments to the best results generated in previous research [9]. The DOE1 series represents the data from the first set of experiments, while DOE2 is the result of further optimisation. It can be seen that non-optimal stitching can significantly reduce the energy absorption properties of the composite plates. Optimal stitching would however, increase the energy absorption capacity significantly, by as much as 31% over the equivalent unstitched composite.

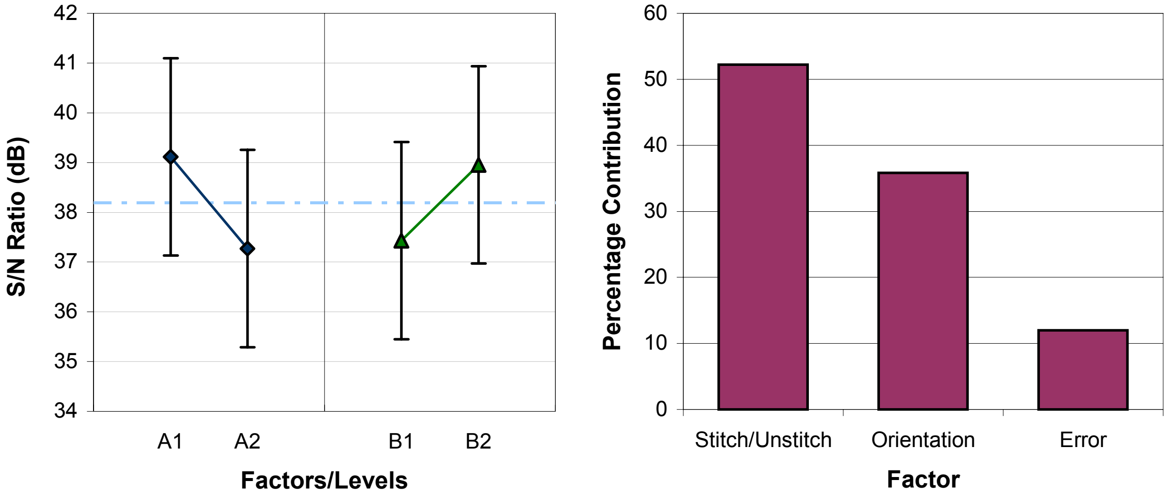

Fig. 9. Response graph for DOE2 (left) and the percentage contribution of the main factors (right)

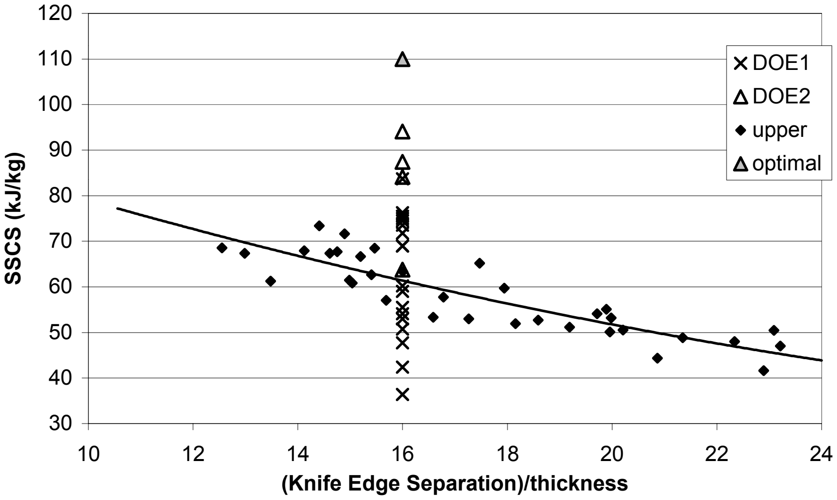

Fig. 10. Results from the optimisation of the stitching parameters compared to results from the crushing of flat glass-fibre reinforced plates.

4. CONCLUSIONS

Estimation of the influence of the important effects by the differences method (Table 5) can still be used to indicate the relative importance of the parameters investigated. Based upon the current research, therefore the optimal parameters are:

- **fibre orientation** – $[\pm 45/0_3]_s$
- **fibre type** – the best fibre has been shown to be the carbon fibre; however, it seems that with stitching, the benefits of the carbon fibre over glass fibres would not warrant their selection unless the design was weight limited
- **resin type** – epoxy resin – most likely due to interfacial compatibility to the carbon fibres
- **stitch separation** – 10mm separation provided the optimal balance between fracture toughness properties and improvement in the SSCS
- **stitch type** – the modified lockstitch with the loop formed on the bag side of the mould

- **stitch orientation** – longitudinal stitching helps prevent lines of stress forming perpendicular to the crushing direction, and hence prevents failure along the stitch lines
- **thread type** – carbon thread seems to be better than the Kevlar thread; however, the benefits are not that great and therefore the most cost-effective thread can be selected.

The results further show that it is not sufficient to stitch composites to improve the crushing of composite plates. Non-optimal stitching can actually serve to degrade the crushing properties, while careful selection of the stitching parameters with respect to a laminate orientation can dramatically improve the SSCS.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the EPSRC and ORS for funding this work, Saint Gobain BTI for supplying the MWK fabrics, Scott Bader and Cytec Fiberite for the resins.

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