INVESTIGATION INTO OPTIMISED COMPOSITE SCARF REPAIRS WITH PRACTICAL CONSTRAINTS

S.V. Neilson*, A.C. Orifici*, C.H. Wang*
***School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University**
GPO Box 2476, Melbourne, Victoria, Australia 3001
samuel.neilson@rmit.edu.au;adrian.orifici@rmit.edu.au;chun.wang@rmit.edu.au

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Abstract

This paper focuses on using a genetic algorithm to optimise composite scarf repairs subject to tensile loading by minimisng the normalised shear stress in the adhesive.

Several parameters are modified to investigate their role in the effectiveness of the optimisation, including constraints to the optimised stacking sequence to increase the practicality of the design. These include enforcing a symmetric and stiffness-matched optimised layup to the parent structure.

The studies show that additional constraints do reduce the effectiveness of the optimisation; but still provide adequate reduction in the maximum normalised adhesive shear stress.

1 Introduction

Composite materials are widely used in the aerospace industry for their high specific properties and are now being used in structurally critical components, whereby total failure of the component would lead to catastrophic failure of the aircraft [1]. Designing with composite materials allows for large structures to be manufactured in one piece, such as an entire fuselage section [2]. However, such a component becomes more difficult and expensive to replace when damaged, making repair the likely course of action. Therefore it is necessary to have suitable repair techniques which can return the damaged component to its original design requirements [3].

The standard scarf repair procedure involves removing material from a region surrounding a detected flaw in order to accommodate the repair. The repair plies are then layered and cured *in situ*, using identical materials, lay-up and curing method to the host structure [4]. For isotropic components, using repair material properties identical to those of the host structure will lead to uniform shear stress along the bondline. For composite materials due to their orthotropic nature and the change in directional properties through the laminate thickness, there are stress concentrations along the scarf bondline, coinciding with the location of 0° plies. In order to increase joint strength the stress concentrations in the bondline must be reduced and the shear stress made more uniform [5].

Optimisation of the repair ply stacking sequence has been previously researched [6]. Optimisation led to a stronger repair compared to a conventional design. The optimised layup was not balanced or symmetric and did not match the stiffness of the parent structure. This may have implications on the practicality of the design. For optimisation of composites, a genetic algorithm has been used successfully in stacking sequence optimisation in the literature [7-10]. A genetic algorithm is akin to evolution, whereby a generation of candidates are subject to a test of ‘fitness’. Each candidate has a chromosome comprised of genes which affect its fitness. The candidate’s chromosome is comparable to a scarf repair laminate stacking sequence and each gene to the individual ply angles. The fittest candidates of the generation are selected and then produce a subsequent generation by way of cross-over and mutation [11, 12]. Cross-over involves the recombination of genes from two selected candidates to from another. Mutation is the random change of a candidate's gene. The process is repeated until convergence is achieved or a pre-set number of generations have been achieved.

The aim of this research is to further investigate the effectiveness of scarf repair optimisation for minimum adhesive shear stress concentration by way of a genetic algorithm. Several key parameters are studied, number of plies, scarf angle, and optimisation constraints, with focus on the practical aspects of the constraints.

2 Analysis

2.1 Finite Element Model

The scarf repair shown in Fig. 1 was modelled and analysed using the finite element analysis (FEA) packages MSC.PATRAN 2008 R1 and MD.NASTRAN R3c respectively. A meshing strategy similar to that proposed in [13] was utilised to ensure a quality mesh at the adhesive centre, despite highly skewed geometry at the adhesive bondline, as shown in Fig. 2.

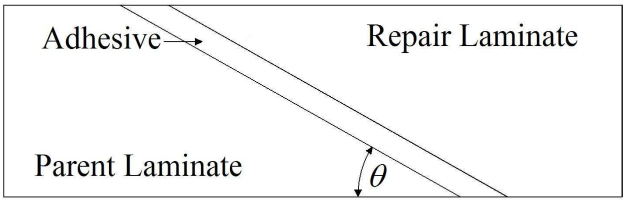

Fig. 1. Scarf repair geometry.

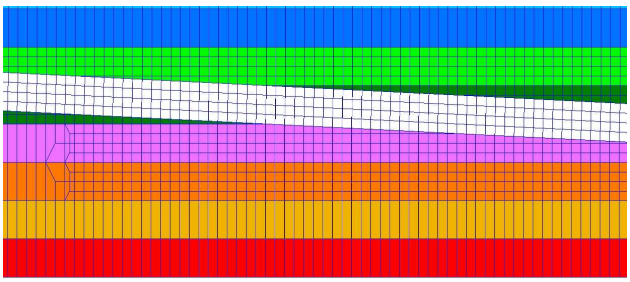
Fig. 2. FEA model mesh generated from PCL script.

The repair was modelled as a 2D scarf joint under plane strain conditions. Three different scarf angles were modelled: 3°, 5° and, 10°. Five laminate thicknesses were also modelled; the layup of each parent structure is shown in Table 1. There are three quasi-isotropic layups and two stiffer layups with additional 0° plies. PATRAN command language (PCL) was used to create a script to generate FEA input files based on these two variables.

Table 1
Parent laminate stacking sequences for different laminate thicknesses

Label	No. plies	Layup
Q-8	8	$[45/0/-45/90]_S$
S-10	10	$[45/0/0/-45/90]_S$
Q-16	16	$[45/0/-45/90]_{2S}$
S-20	20	$[45/0/0/-45/90]_{2S}$
Q-24	24	$[45/0/-45/90]_{3S}$

A carbon/epoxy laminate was employed, with material properties shown in Table 2. The boundary conditions applied to the model simulated clamping at either end, with freedom in only the loading direction for the loaded end.

A unit tensile load was applied and the shear stresses along the centre of the adhesive were measured (stress at a distance) so as to avoid the singularity arising from the double and triple material interfaces [13]. The normalised shear stress distribution along the centre of the adhesive is shown in Fig. 3 and is comparable to work done in the literature [13].

Table 2
Material properties for unidirectional (UD) composite ply and epoxy adhesive

	Carbon/epoxy UD ply	Epoxy adhesive
E1 (GPa)	120	
E2 (GPa)	7.47	3
E3 (GPa)	7.47	
G12 (GPa)	3.94	
G23 (GPa)	2.31	1.1
G13 (GPa)	2.31	
v12	0.32	
v23	0.33	0.35
v31	0.02	

2.2 Optimisation Model

The optimisation model was constructed in modeFRONTIER, using the multi-objective genetic algorithm (MOGA) solver present within the package. The FEA input file was imported into modeFRONTIER and each ply angle was modified as a variable. This was implemented by calculating the Young's modulus, shear modulus and Poisson's ratio of each ply based on its angle using classical laminate theory. The modified FEA input file was then analysed in MD.NASTRAN R3c and the maximum normalised shear stress was calculated and treated as the objective function.

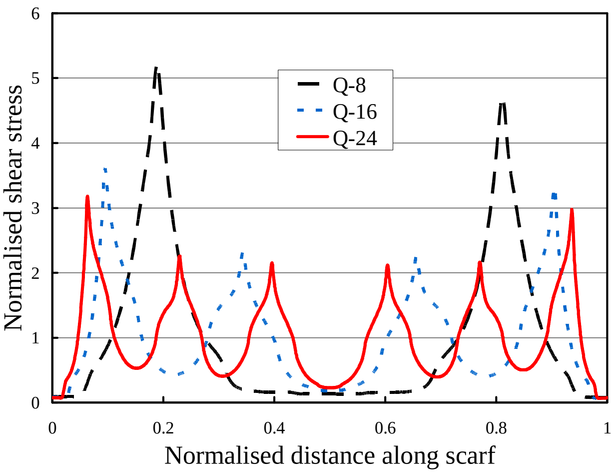

Fig. 3. Normalised shear stress distribution along adhesive for different number of plies.

An initial generation size of *2n+1* was used, where *n* is the number of variables (ply angles). The first generation was based on the parent laminate layup with permutations to each of the individual ply angles.

Three different constraints to the optimisation were studied.

- Unconstrained layup (U); each ply angle was independent of the others.
- Symmetric layup (SY)
- Stiffness-matched layup (ST); symmetric and also matched to the stiffness of the parent structure within ±10%.

All designs were compared to a conventional layup (C) i.e. a repair ply layup that matched that of the parent structure, to measure their effectiveness. Refer to Fig. 4 for the optimisation process flowchart.

3 Results and Discussion

3.1 Effect of Constraint

Due to the large volume of results (45 analyses), the Q-8 layup with 3° scarf angle will be discussed. For a parent laminate with the layup [45/0/-45/90]s, the optimisation analyses yielded the following optimised repair layups:

- Unconstrained [-89/73/-87/-40/-1/-1/22/14]
- Symmetric [-9/-89/4/0]s
- Stiffness-matched [8/60/-8/0]s

Fig 5. shows the shear stress distribution along the bondline for each layup. The unconstrained optimisation analysis gives the greatest reduction in maximum normalised shear stress of 51%, however the stiffness-matched constraint also allows for a significant reduction in shear stress, 43%.

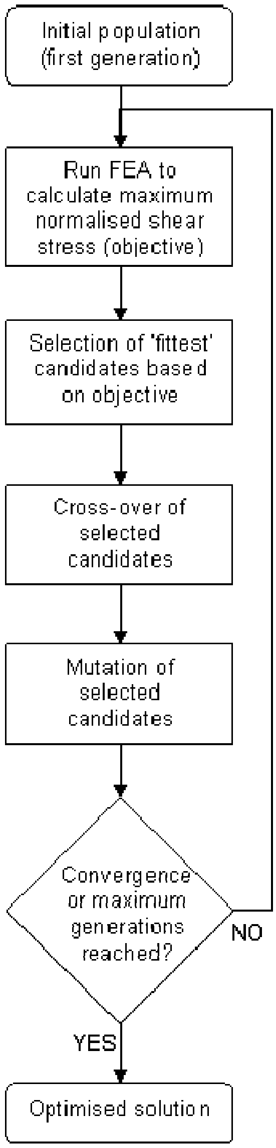

Fig. 4. Optimisation flowchart.

Common to all three optimisation constraints, the repair laminates tended to have high ply angle lamina (low stiffness) adjacent to the parent 0° plies (high stiffness). Similarly, the optimised repair laminates tended to have high stiffness plies adjacent to the low stiffness plies of the parent structure. The effect of this is seen in Fig. 5 whereby the distribution of adhesive shear stress is spread towards the centre of the 8 ply laminate, which was very lowly stressed in the conventional repair, due to the presence of adjacent 90° plies.

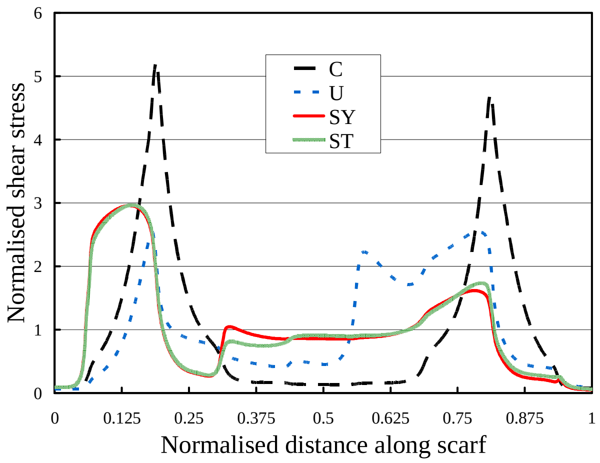

Fig. 5. Normalised shear stress distribution along the adhesive for the Q-8 layup with 3° scarf angle.

3.2 Effect of Scarf Angle

Fig. 6 and Fig. 7 show the normalised shear stress distribution for the Q-8 layup with 5° and 10° scarf angles respectively. It can be seen that the increase in scarf angle reduces the maximum normalised shear stress.

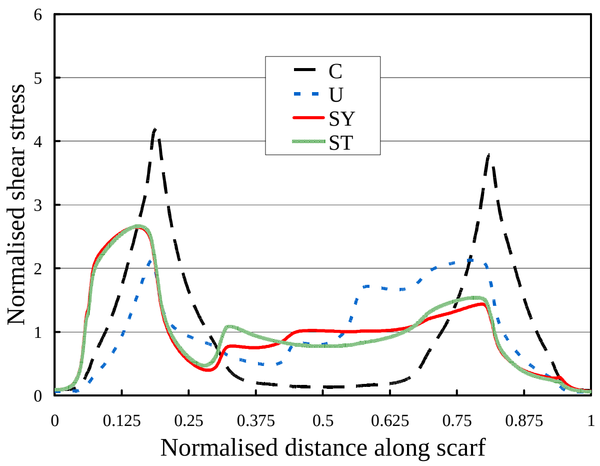

Fig. 6. Normalised shear stress distribution along the adhesive for the Q-8 layup with 5° scarf angle.

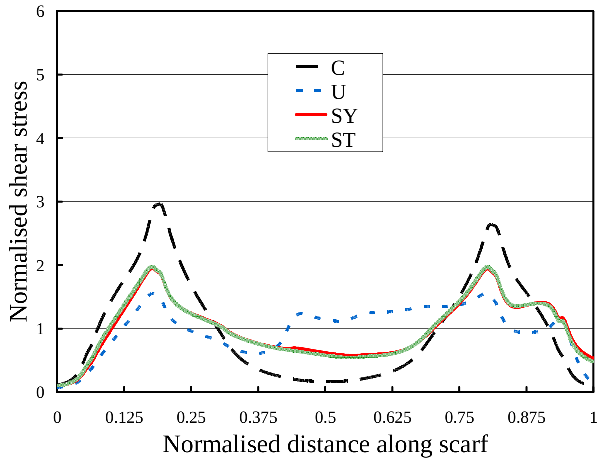

Fig. 7. Normalised shear stress distribution along the adhesive for the Q-8 layup with 10° scarf angle.

As shown in Table 3 the effectiveness of the optimisation to reducing the maximum normalised shear stress is decreased as the scarf angle is increased.

Table 3
Effect of scarf angle on optimisation performance; objective is the maximum normalised shear stress in the adhesive

Repair type	C	U	SY	ST
		3° scarf		
Objective	5.22	2.54	2.96	2.96
Reduction	-	51%	43%	43%
		5° scarf		
Objective	4.20	2.13	2.65	2.66
Reduction	-	49%	37%	37%
		10° scarf		
Objective	2.96	1.55	1.95	1.97
Reduction	-	48%	34%	33%

3.3 Effect of Number of Plies

Referring to Table 4, the number of plies has no distinct trend in terms of varying the effectiveness of the optimisation. The same is seen for the S-10 and S-20 layup, which contain additional 0° plies compared to the Q-8 and Q-16 layups respectively.

Table 4
Effect of ply number on optimisation performance; objective is the maximum normalised shear stress in the adhesive

Repair type	C	U	SY	ST
	Q-8			
Objective	5.22	2.54	2.96	2.96
Reduction	-	51%	43%	43%
	S-10			
Objective	3.67	1.78	1.85	1.86
Reduction	-	51%	50%	49%
	Q-16			
Objective	3.61	1.66	1.75	1.83
Reduction	-	54%	51%	49%
	S-20			
Objective	3.01	1.38	1.46	1.55
Reduction	-	54%	52%	48%
	Q-24			
Objective	3.18	1.57	1.71	1.93
Reduction	-	51%	46%	39%

4 Conclusions

The conventional composite scarf repair contains stress concentrations within the adhesive adjacent to the 0° plies. It has been shown that such stress concentrations can be reduced by optimising the ply stacking sequence via the genetic algorithm.

By optimising without constraint to the ply angles, a greater reduction in shear stress can be achieved. However, a more practical solution may be obtained by limiting the design space to repair stacking sequences that closely match that of the parent structure, without severe penalty to the efficiency of the optimisation.

The scarf angle of the repair and the number of plies within the repair do not significantly affect the efficiency of the optimisation analysis.

Further analytical and experimental work is required to validate the optimised layups and to assess further practical considerations such as sensitivity due to manufacturing variability and plastic failure of the adhesive.

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