Tensile Behavior of Composite Patched Cracked Metallic Structures

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ABSTRACT: Composite patches of epoxy-based unidirectional carbon and woven glass prepregs were adhesively bonded on uncracked and center cracked standard specimens of aluminum sheet, and patched specimens were evaluated by tensile testing. The effect of various surface treatments, patch length, and number of plies on the tensile strength was studied. Surface preparation of the specimens by sandblasting had a pronounced effect on strength improvement compared to other physical or chemical treatments. The strength of the cracked specimens increased up to 79% for unidirectional carbon patched specimens and 75% for woven glass patched specimens. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 68: 2063–2068, 1998

Key words: tensile behavior; composite patched metallic structure; tensile strength

INTRODUCTION

Aircraft structures are prone to fatigue cracks due to cyclic loading conditions to which they are subjected to during their lifetime. Different inspection methods are usually employed to detect these cracks. When the crack size reaches a critical value, the component must be replaced or repaired. Conventional repair procedures are based on mechanically fastened metallic patches.

The "damage tolerance" design philosophy is now widely accepted in the design of aerospace structural components. Recently a new method of repairs has been introduced based on using fiber-reinforced plastic (FRP) patches that are adhesively bonded to the cracked metallic structural components.

The new repair procedure has several advantages over the traditional methods.[1–5] High performance composite materials offer many advantages as patch materials in comparison to conventional metallic materials.[6,7] The repair procedure can be implemented in the field during normal servicing, thereby shortening the unavailability of the aircraft.

Several studies have been carried out on repairing the actual components of an aircraft's structure[1–6]; except for Rose[8] and Nahas,[2] no attention has been given to the study of the behavior of the repaired material on specific laboratory test specimens. The present work was undertaken as a first step toward developing test data for such a repair technique. Standard test specimens of aluminum were machined to develop a crack at the center of the specimen, and composite patches of carbon unidirectional and woven glass prepregs were adhesively bonded on cracked and uncracked specimens. The specimens were subjected to tensile loading conditions to investigate the effect of the composite patch repair on the tensile strength of the specimens under considerations.

EXPERIMENTAL

Materials

Aluminum alloy of 2024 T3 ALCLAD (core composition of 4.5% copper, 1.5% magnesium, and 0.6%

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manganese) and cladding with 93.4% aluminum was used as the substrate. The properties of this alloy are 470 MPa ultimate tensile strength, 371 MPa yield strength, 11% elongation, and 287 MPa shear strength. The prepregs used were epoxy based unidirectional carbon prepregs (carbon UD; VICOTEX NCHR 914/34%/158T 300) and glass woven prepregs (VICOTEX 1452 GM/43%/664-120 cm or VICOTEX 633 GRI SO2-120 cm) obtained from Ciba Composites (France). The resin content (epoxy) was 34 and 43% by weight, and the curing cycle was 60 min at 175°C and 43 min at 165°C, respectively, for these prepregs. The shelf life of both prepregs was 12 months at −18°C. The carbon UD prepreg was bonded to aluminum specimens using the elastomeric modified epoxy adhesive FM-61 (American Cyananid Co.) along with BR 227 primer. The glass woven prepreg was bonded onto the specimen using the phenolic polyvinyl formal adhesive REDUX 775.

Specimen Preparation

Using a shear cutter (Lodge and Shipley, Cincinnati model 0216-32), aluminum sheet metal was shear cut to the required dimensions of 200 × 25 × 1 mm and a crack was machined using a milling machine (Cincinnati model F 3) at the center and parallel to the width of the specimen. The crack length was 5 mm. Composite patches of carbon UD prepregs and glass woven prepregs were adhesively bonded using FM 61 and REDUX 775, respectively, on center cracked and uncracked aluminum specimens.

The effects of the following variables on specimen preparations were considered for this study:

1. Surface treatments: Physical [trichloroethylene (TCE) degreasing], electrochemical (chromic acid anodizing), and mechanical (sandblasting) techniques were employed to prepare the substrates.
2. Patch length: The effect of patch lengths of 10, 20, 40, and 60 mm were studied.
3. Number of plies: Composites were prepared with 5 and 10 plies to study the strength variation. The plies were arranged in the order of 0, −45, 90, +45, and 0 for 5 plies and 0, 90, −45, +45, −45, +45, −45, +45, 90, and 0 for 10 plies.

The carbon UD/FM61 specimens were cured at 175°C for 60 min and glass/REDUX 775 specimens were cured at 165°C for 45 min in a Fontune platen press. After curing the specimens were cooled to 50°C using water cooling and then subjected to testing.

Evaluation

The fabricated uncracked and center cracked, untreated unpatched, treated unpatched, and treated patched specimens were evaluated by tensile strength measurement according to ASTM D 638 using a universal testing machine (RDP Howden Ltd., S20 EV type) at a testing speed of 6 mm/min. The results given are averages of 12 experimental values. The scatter of the results was less than ±1%.

RESULTS AND DISCUSSION

The tensile strengths of uncracked and cracked aluminum specimens with different surface treatments such as TCE degreasing, chromic acid anodizing, and sandblasting are given in Table I. There is no marked change in tensile strength of uncracked (445 MPa) or cracked (237 MPa) aluminum specimens with respect to surface treatments except for the sandblasted ones. Sandblasted test specimens showed very good tensile results compared to other surface treated specimens. These variations are shown in Figures 1–

Table I Tensile Strength of Uncracked and Cracked Unpatched Aluminum Specimens

Type of Treatment	Tensile Strength (MPa)		Reduction in Strength (%)
	Uncracked	Cracked	
Untreated	445	237	46.74
Trichloroethylene treated	445	237	46.74
Chromic acid anodized	445	237	46.74
Sandblasted	460	237	48.47

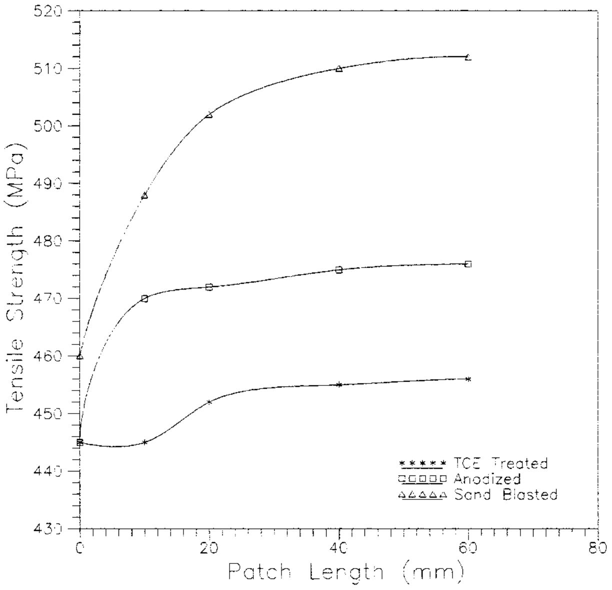

Figure 1 Tensile strength of uncracked specimens patched with 5 plies carbon UD prepregs.

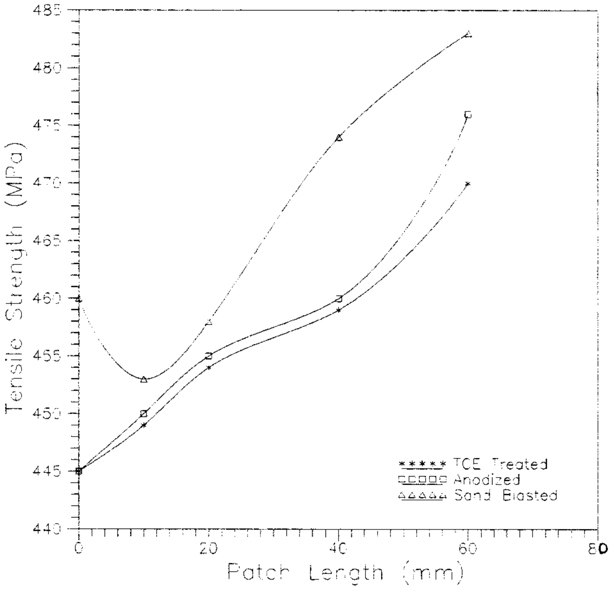

Figure 3 Tensile strength of uncracked specimens patched with 5 plies woven glass prepregs.

4. This is because in sandblasting particles are deposited on the specimen that contribute to the roughening of the surface that is very high compared to that of anodizing and TCE. In the anodizing and TCE treated test specimens there is no roughening or chemical change on the surface of the substrate; hence, it will not contribute to a greater increase in strength. The reduction in strength for cracked specimens was about 47% because of the stress concentration effect of the crack.

Tensile strengths of the patch materials are shown in Table II. The carbon unidirectional prepreg showed a tensile strength of 420 and 980 MPa for 5 and 10 plies, respectively. For the glass woven prepreg the values were 325 and 618 MPa, respectively. An increase in the number of plies increased the strength as expected.

The tensile strengths of the uncracked patched

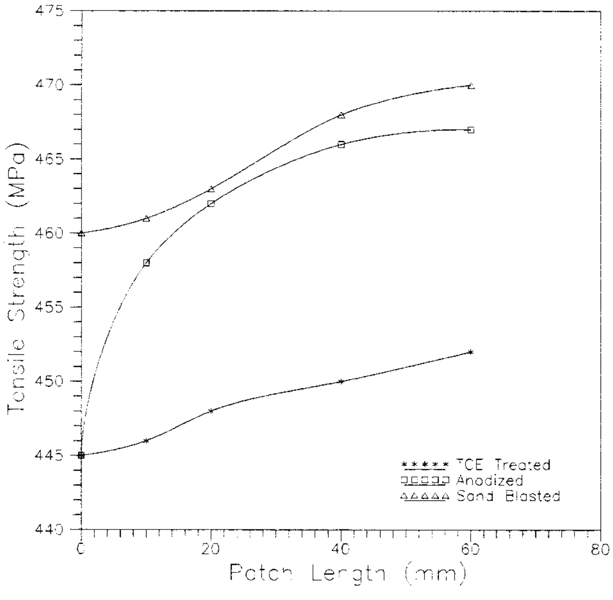

Figure 2 Tensile strength of uncracked specimens patched with 10 plies carbon UD prepregs.

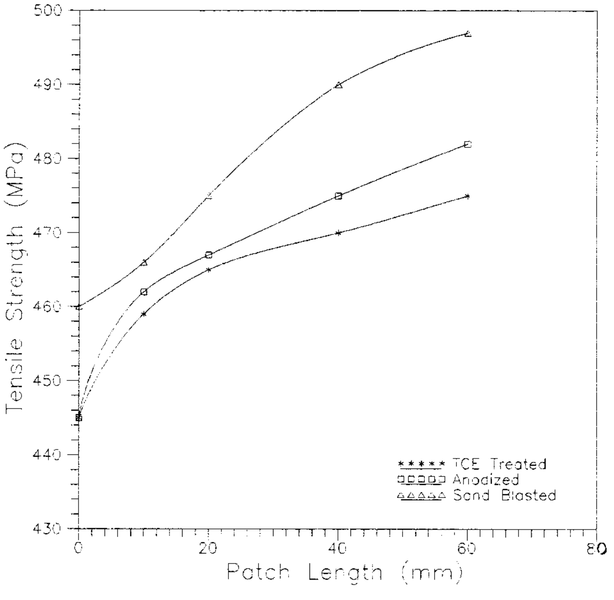

Figure 4 Tensile strength of uncracked specimens patched with 10 plies woven glass prepregs.

Table II Tensile Strength of Carbon UD and Glass Woven Prepregs

	Tensile Strength (MPa)	
Patch Material	5 Plies	10 Plies
Carbon unidirection	420	980
Glass woven	325	618

specimens using both the prepregs with different patch lengths are shown in Table III. The uncracked patched specimens were tested in order to find the limiting patch length beyond which there would be no increase in strength.

Figures 1–4 show the variation of tensile strength of uncracked specimens patched with 5 and 10 plies of carbon UD and woven glass prepregs with different patch lengths and surface treatments. It is observed from these plots that the tensile strength increased up to a patch length of 40 mm; there was a considerable increase up to 20 mm, and beyond 40 mm the variation was negligible. This indicates an optimum patch length between 20 and 40 mm. It is also observed from Figures 1–4 that sandblasted specimens possessed higher tensile strength compared to other treatments. In Figure 3 a minor reduction in tensile strength was observed for a patch length of 10 mm; this reduction in the value lies in experimental error ($<1\%$) and hence can be overlooked. The strength variation followed the same trend in all cases.

The strength leveled off for the 40-mm patch length for uncracked aluminum specimens patched with composites. This is in accordance with adhesive bond joint theory[3] that states “[T]here is a proportional increase in strength with the increase in width, but increasing the overlap beyond a certain limit has very little effect on the strength.”

Further, the strength improvement depends on the adherend surface preparation. The strength of the uncracked aluminum specimen patched with composites lies in the order of TCE degreasing < anodizing < sandblasting surface treated samples. This variation in values indicates that the sandblasting technique is the most effective surface treatment for adhesive bonding between the patch material and the metal surface. A slight variation was observed with an increase in patch length, but an increase in ply numbers does not follow any specific trend. This indicates that the strength depends on the interaction between aluminum suface and the prepreg but not on the number of plies.

The effects of surface treatments on the tensile strength of the cracked patched specimens were calculated and are shown in Table IV for 5 and 10 plies. The same trend of variation in strength as in the case of uncracked patched specimens (shown in Table III) was observed in the cracked specimens patched with composites. The tensile strength was greatly increased with an increase in patch length of the composites. Figures 5–8 show this variation graphically. Figures 5 and 6 give the variation in tensile strength for specimens patched with carbon UD prepregs of 5 and 10 plies, respectively. Sandblasted specimens show better improvement in tensile strength compared to TCE degreasing and anodizing, confirming the superiority of this surface treatment over the others, which was observed even with uncracked specimens. It showed an improvement of 74% for a 5-ply composite patch of 60-mm length. The value increased from the 237 MPa for un-

Table III Tensile Strength of Uncracked Patched Aluminum Specimens

		Tensile Strength (MPa)					
		TCE		Anodized		Sandblasted	
Patch Material	Patch Length (mm)	5 Plies	10 Plies	5 Plies	10 Plies	5 Plies	10 Plies
Carbon UD	10	445	445	470	460	488	460
	20	452	448	472	462	502	463
	40	455	450	475	466	510	466
	60	456	452	476	467	512	470
Glass woven	10	449	459	450	460	453	462
	20	454	465	455	467	458	468
	40	459	470	460	475	474	490
	60	470	475	476	482	483	497

Table IV Tensile Strength of Cracked Patched Aluminum Specimens

Patch Material	Patch Length (mm)	Tensile Strength (MPa)					
		TCE		Anodized		Sandblasted	
		5 Plies	10 Plies	5 Plies	10 Plies	5 Plies	10 Plies
Carbon UD	10	294	250	295	279	306	294
	20	336	262	360	329	373	357
	40	342	303	385	395	396	412
	60	350	346	397	413	412	425
Glass woven	10	246	245	265	295	280	290
	20	268	260	320	330	330	355
	40	281	300	360	380	380	400
	60	306	320	369	400	400	415

patched to 412 and 425 MPa for 5- and 10-ply composite patches. For TCE degreased and anodized specimens this improvement was 48 and 68%, respectively. The number of plies did not show much of an effect on the strength improvement that was about 46, 74, and 79%, respectively, for TCE degreased, anodized, and sandblasted specimens for the 10-ply composite patch. This could be due to the lower adhesive forces associated with the increased patch thickness, because the adhesion strength depends on the amount of interaction between the surface treated aluminum substrate (active surface area) and the matrix. Hence, the adhesion bond does not depend on the thickness of the patch but on the surface area of the patch. The same kind of variation was observed in the case of composite patches of woven glass prepregs. Figures 7 and 8 show the variation of tensile strength with patch length for 5- and 10-ply glass composite patches. However, the extent of improvement was lower for the glass composites compared to the carbon composites. This was due to the superior mechanical properties of carbon fibers over the glass fibers. But a 10-ply glass composite patch of 60-mm length was comparable to a carbon composite; the strength was improved for the sandblasted specimen from 237 to 425 MPA (about 75%).

Carbon prepreg patched specimens showed higher tensile strength, percent increase in

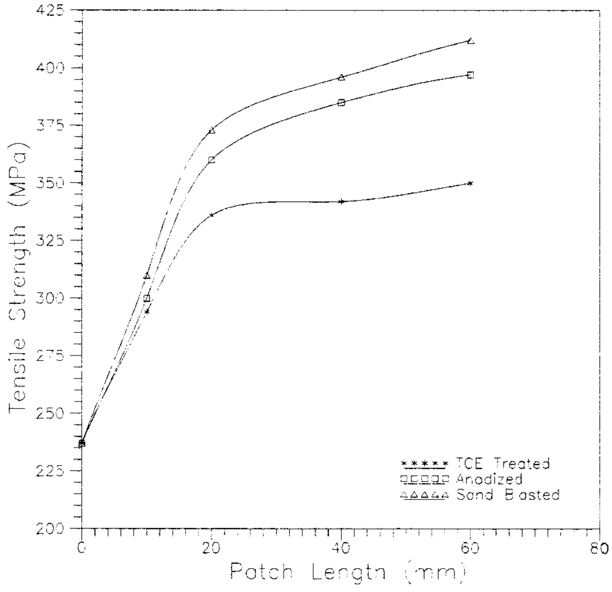

Figure 5 Tensile strength of cracked specimens patched with 5 plies carbon UD prepregs.

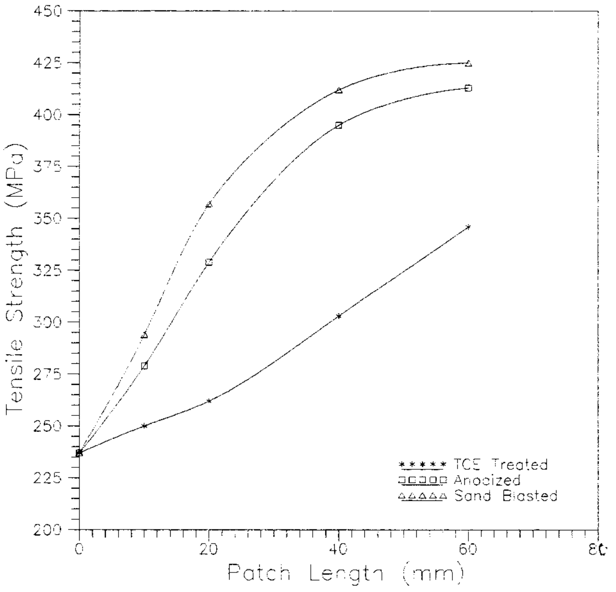

Figure 6 Tensile strength of cracked specimens patched with 10 plies carbon UD prepregs.

strength, and percent of original strength restored than glass prepreg, even though the weaving was different. This can be attributed to the inherent superior properties of carbon fibers. This indicates that the strength is independent of the number of plies and depends on the nature of matrix or interaction between the matrix and aluminum surface. There was also about a 75% increase in strength of the cracked patched specimens compared to the cracked aluminum specimens.

Throughout this study it was observed that all the specimens fractured in the cracked resin along with debonding. None of the failure was due to debonding alone. The fracture never occurred in the composite.

CONCLUSION

This study gave a clear indication of the strength improvement for cracked aluminum specimens repaired with composite patches. Mechanical surface preparation of the substrate yielded superior strength improvement due to better adhesion than the physical and electrochemical surface treatments. Carbon UD composite patches showed better improvement in tensile strength compared to glass composite patches. It was also observed that the strength was independent of the number of plies.

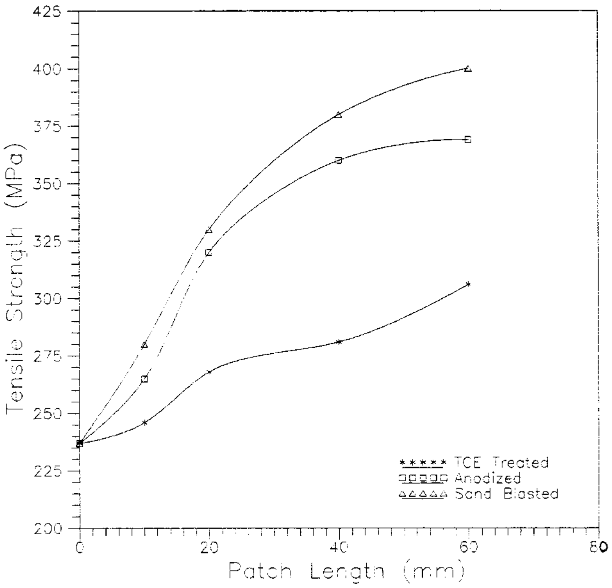

Figure 7 Tensile strength of cracked specimens patched with 5 plies woven glass prepregs.

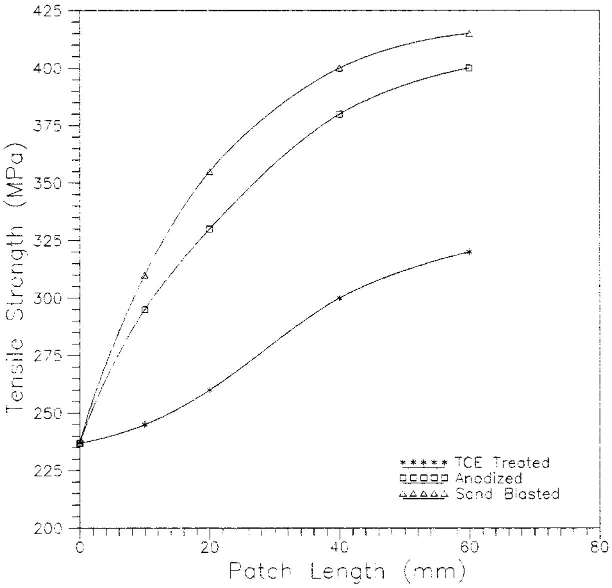

Figure 8 Tensile strength of cracked specimens patched with 10 plies woven glass prepregs.

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