Article

JOURNAL OF REINFORCED PLASTICS & COMPOSITES

Journal of Reinforced Plastics and Composites
30(9) 749–755

DOI: 10.1177/0731684411403021
jrp.sagepub.com
SAGE

A study on curing processes and environmental effects for rapid composite repair

Faruk Elaldi[1] and Pelin Elaldi[2]

Abstract

This article focuses on scarf joint comprised of vacuum-precured, vacuum-cocured, autoclave-procured, and autoclave-cocured composite patches bonded to autoclave- and vacuum-precured parent laminates. Autoclave- and vacuum-cured parent laminates and scarf joints were prepared and exposed to the same temperature and moisture environment for comparison. All specimens were loaded in tension at three temperatures. Interlaminar shear strength (ILSS) tests were also carried out for the parent materials. As noted, the tensile strength and ILSS decrease when the material has been exposed to moisture and tested at elevated temperature. But, no significant difference was reported for either tensile strength or ILSS between autoclave- and vacuum-cured materials. The room temperature repair efficiencies are reported for single-scarf repairs comprised of vacuum-cocured and vacuum-precured patches. These vacuum-cured repair efficiencies were found to be similar to the efficiency of the autoclave-precured patch repair. This result supports the feasibility of scarf joint repairs with precured or cocured patches under vacuum curing conditions in field-level facilities. Therefore, repairs with vacuum-precured or vacuum-cocured patches requiring less equipments seem to be a serious potential alternative to the composite patch repair requiring autoclave conditions which might be only available at depot-level maintenance centers.

Keywords

composite, repair, scarf, joint, cocure, precure, environmental, effect

Introduction

Composites are increasingly being used for aircraft structures because of their superior structural performance such as high strength, high stiffness, long fatigue life, and low density. Some recently developed military aircrafts like helicopters and unmanned air vehicles have nearly all-composite airframe structures. Battle damage repair (BDR) becomes to be significant for these structures, as they are vulnerable to ballistic impact damage from small arms fire. Therefore, a rapid repairing technique is quite important either to keep the aircraft operational with a minimum level of mission capability or otherwise to send it back to depot-level maintenance center. As a matter of fact, the effectiveness of BDR, in general, depends on several factors such as repairing technique, geometry, patching material, adhesive material, curing cycle, and environmental conditions.

In conjunction with repairing techniques, earlier efforts to repair composite structures have generally resorted to an external lap joint patch concept that requires autoclave facility. But, this concept may suffer from high shear and peel stresses at the ends of the patch area because of non-flushing surface.[1] By contrast, a scarf repairing technique shown in Figure 1 seems to be more suitable for rapid repairing of composite structures, since it does not require

[1]Department of Mechanical Engineering, University of Baskent, Turkey.
[2]Department of Industrial Engineering, Bilkent University, Turkey.

Corresponding author:
Faruk Elaldi, Department of Mechanical Engineering, University of Baskent, 06530 Ankara, Turkey
Emails: elaldi@baskent.edu.tr; farukelaldi@gmail.com

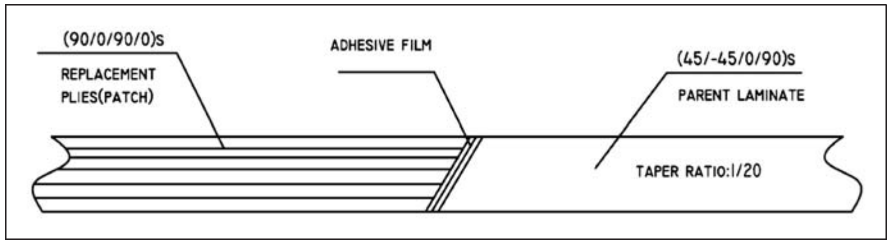

Figure 1. Repair of a flat laminate with single-scarf technique.

depot-level capability instead it requires only a few simple hand tools. As a general rule, the flush scarf repair has the following advantages over an external patch. They are as follows:[1–13]

- Strength,
- Aerodynamic smoothness,
- Weight,
- Stiffness,
- Appearances
- Durability.

However, this repair technique still needs to be improved for fully qualified applications. Investigations, therefore, are being done to determine the environmental effects of oil, fuel, paint striper, and absorbed moisture on the repaired laminates[14–16] and also to determine the differences between the properties of vacuum bag-cured and autoclave-cured laminates.[4,5] The geometric effects including laminate material thickness, stacking order, structural form, and accessibility and protrusion limitations are also being investigated. It has been revealed that significant savings can be made to the amount of material removed when adopting optimum repairs over conventionally designed repairs. It has also been highlighted the importance of having self-similar repair geometry to avoid local stress concentrations.[1,3,13,17] Some of the researchers[18] noted that quick determination of the appropriate precured patches for different thicknesses and damage characteristics could be made by predetermined reference table which contains parent material thickness and damage diameter.

The majority of the studies on scarf repair technique were based on depot-level capabilities, i.e., autoclave curing. But, there are considerably limited studies on vacuum curing technique for scarf repair that could be advantageous to rapid BDR in field.

By maintaining repairing technique same as scarf repair and excluding the other affecting parameters, this study specifically aimed to focus only on how curing process and environmental conditions are affecting the effectiveness of the repair. Therefore, the first objective was to determine the effects of vacuum bag and autoclave curing processes on the mechanical properties of scarf-repaired parent materials to indicate how these two techniques differ from each other. The second one was to determine the environmental effects, i.e., moisture uptake and service temperature, on the tensile and interlaminar shear strengths (ILSS) of repaired laminates.

Test materials and processes

Prepreg materials

The material used in this study was Ciba Geigy Fiberdux 913G/7781 fabric prepreg which consisted of woven reinforced glass impregnated with epoxy resin. A film adhesive, (FM73), manufactured by American Cyanamid, was used in scarf joint-type repairs and the repairs were cured under vacuum at a temperature of 125°C.

Curing processes

The mechanical properties of laminates and adhesives are expected to be affected by the curing process. In this study, two curing processes for repair (autoclave and vacuum bag cure) have been used to process parent materials and patches. Patches were also processed by vacuum curing *in situ* with cured parent laminates, which was generally called cocure. The effects of each curing process and environmental exposure on the material properties have been investigated. The curing procedures developed for these two processes are given in Figure 2.

Specimen preparation

Parent material specimen. Glass fiber-reinforced epoxy laminates which consisted of eight plies of fabric prepreg were processed in either an autoclave or a vacuum bag. The stacking sequence of the laminates was $[+45/-45/0/90]_s$. After cure, the panels were machined into tensile specimens with a configuration of $200 \times 25 \times 2\,mm^3$ and ILSS specimens with a configuration of $20 \times 10 \times 2\,mm^3$ according to ASTM D3039 and ASTM D2344, respectively.

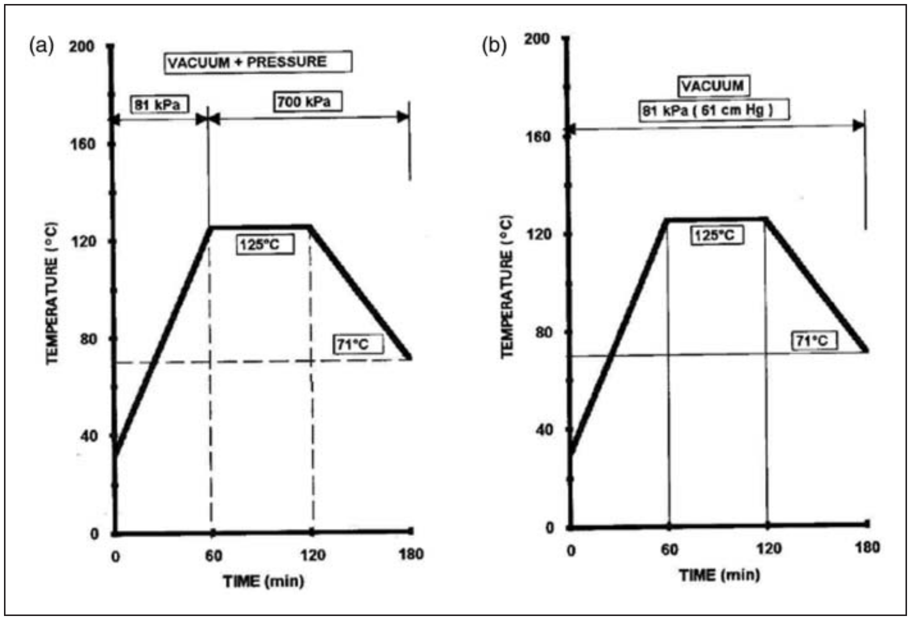

Figure 2. Cure cycles for 913G/7781 prepreg material: (a) autoclave cure cycle and (b) vacuum cure cycle.

Table 1. Types of repair

SCARF repair	Combination	Repair process
Repair with precured patch, A	a + FM 73 + a*	Vacuum
Repair with precured patch, B	b + FM 73 + b⁺	Vacuum
Repair with cocured patch, C	a + FM 73 + cˣ	Vacuum
Repair with cocured patch, D	b + FM 73 + cˣ	Vacuum

*a means autoclave-cured 913G/7781 laminate.
⁺b means vacuum-cured 913G/7781 laminate.
ˣc means the patch material (913G/7781) to be cured with parent material.

Scarf repair specimen. The above parent laminates were used to evaluate repair techniques based on procured and cocured patches. Precured scarfed patches and tapered plies of prepreg were bonded to parent laminates under vacuum cure conditions.

In the preparation of a scarf joint, the scarfing of the parent laminate was accomplished with a portable power-driven sander. Patch patterns with a stacking sequence of $[90/0/90/0]_s$ which were almost identical to the parent laminate (since the reinforcements were woven fabric) were pre-cut, and some of the patches were precured as required. A layer of film adhesive (FM 73) was used for both types of the patches (Figure 1). The patches were easily fitted into the scarfed cut-out. The cocured patches always provided a flush and smooth repair surface after cure. Finally, the panels were machined into tensile specimens according to ASTM D3039 (Table 1).

Moisture conditioning of specimens

To determine the effects of moisture uptake on the mechanical properties of the parent materials and repaired specimens, some of the specimens were conditioned in an environment controlled at 70°C and 85% relative humidity until they were saturated.

For the moisture conditioning, tension and ILSS specimens were kept in a sealable glass vessel that contained saturated calcium chloride solution. The specimens were supported from the cover plate in the humidified air space above the solution. The glass vessel was placed in an oven which operated at the conditioning temperature with a variation of less than 1°C.

The specimens were weighed before, during, and after conditioning. They were removed from the vessel at predetermined intervals and placed in a transient storage box until they cooled to the ambient temperature, then they were weighed to the nearest 10^{-3} g. After weighing, the specimens were returned immediately to the vessel. This weighing process was repeated until the equilibrium values of moisture uptake in the specimens were obtained. The weight gains were recorded as a function of time and the moisture uptake, determined as percent weight gain, was plotted vs. the square root of time (Figure 3).

The average moisture uptakes in terms of weight gain percentages for ILSS specimens and tension specimens were 1.3% and 1.2% respectively. For the repair tensile test specimens, the average moisture uptake was approximately 1.8%. It is shown that higher moisture content was obtained for the repaired parts. This was probably due to higher void content of the repaired area.

Testing

No matter if it is repaired or not, the airframe materials are mostly exposed to combined or individual loading conditions such as tension, compression, and shear, uniaxially or biaxially. But, for experimental simplicity, only tension and shear tests were carried out to determine the mechanical properties of the repaired area. Compression and fatigue tests were left for future studies.

Tension tests

The tests were conducted according to ASTM D3039. A strain gage was bonded to each specimen to measure the longitudinal strain. The specimens were installed in an Instron universal testing machine using wedge grips. The strain gage and load cell outputs were collected by a computer-controlled data acquisition system. A cross-head loading rate of 1 mm/min was used. Tension tests were carried out at three temperatures; room temperature (RT), 70°C, and 100°C. For the tests at elevated temperatures, an environmental chamber was used. The test temperature was pre-set and the testing was initiated when the specimen reached the test temperature which required approximately 5 min.

The stress–strain plot for each specimen was obtained from the test data. The linear portions of the stress–strain curves were used to calculate the elastic modules. The nominal thickness and width of each specimen were used for calculating the strength. The ultimate strengths for autoclave- and vacuum-cured specimens were obtained and utilized to calculate the efficiency of repairs at different temperatures. Repair efficiency is defined as the strength of the repair expressed as a percentage of the dry parent laminate strength at RT. Data obtained from all tests were normalized to 60% fiber content by volume, so that comparison between two cure procedures could be made.

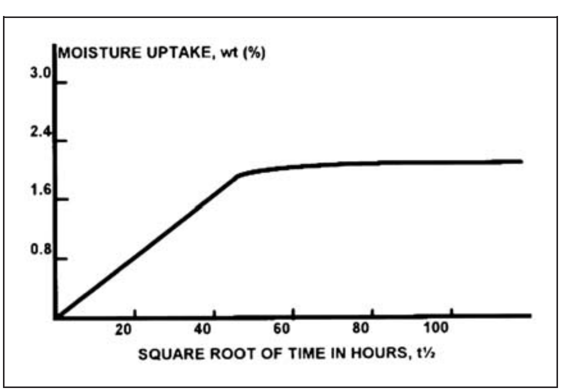

Figure 3. Typical moisture uptake vs. square root of time.

ILSS testing

For the ILSS tests, specimens were placed in a specially designed fixture to apply three-point bending. Ultimate loads for calculating ILSS were determined from the load vs. displacement chart of the test machine.

Results and discussion

Tensile strength

Considering the data obtained from the static tests of parent material performed at RT, 70°C, and 100°C on dry and conditioned specimens for both autoclave and vacuum cure cycles, it can be seen that the average ultimate tensile strength (UTS; 343 MPa) of dry specimens at RT for the autoclave cure is 10% higher than the strength (309 MPa) of dry specimens at RT for the vacuum cure. The wet specimens had differences in tensile strength between the autoclave and vacuum cures of 9% and 6% at 70°C and 100°C, respectively (Figure 4). These differences were considered insignificant and they indicated that vacuum-cured patches could be an alternative to autoclave-cured patches for repair in the field-level maintenance facility.

It was also noted that moisture (wet) conditioned specimens showed a decrease in tensile strength of up to 8% (from 343 to 316 MPa) at a test temperature of 70°C and up to 23% (from 343 to 268 MPa) at 100°C for autoclave-cured material. Similar results were also obtained for vacuum-cured specimens. The maximum decrease in strength was about 23%, which came from the effect of combining moisture, temperature, and curing process (Figure 5). Therefore, it is important in

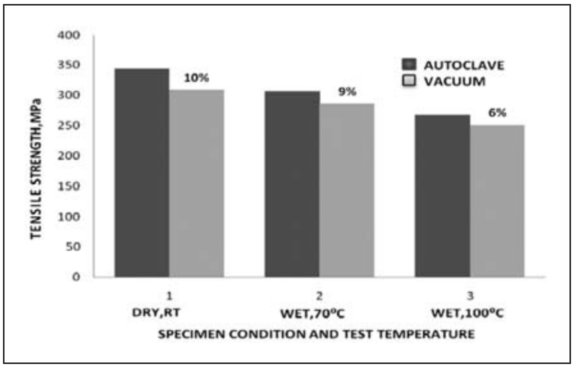

Figure 4. Effect of curing process on tensile strength.

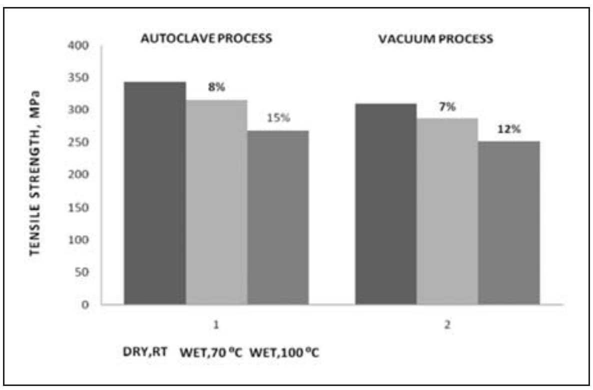

Figure 5. Effect of moisture and temperature on tensile strength.

design to take the elevated temperature strength for this material into account as the RT strength is significantly higher.

No significant change in strain at failure was observed in tension loading at different temperatures after moisture exposure, but a slight decrease of modulus was found to occur for both curing processes as the test temperature increased.

On the other hand, the UTS of repair specimens dropped rather drastically at elevated temperatures (70°C and 100°C). It is considered that this might have been due to debonding between parent material and patches. However, the difference in tensile strength between precured (A and B in Table 2) and cocured (C and D in Table 2) repair specimens was not significant at RT (Table 2), since bonding strength does not change with the curing technique.

At RT, the highest repair efficiency (81%) was obtained for the dry scarf repair (A) with an autoclave-precured patch (Table 3), in which the baseline data is based on dry parent material strength. With a vacuum-precured patch (B), the repair specimens used in the study were capable of retaining 75% of the parent material strength (Table 3). The repair efficiency with cocured patches (C and D) was also found to be approximately 75% at RT.

At elevated temperature (70°C and 100°C), repair efficiencies were low, and all the failures occurred in adhesives (FM73). When examined the fracture

Table 2. Scarf repair UTS results

	Ultimate tensile strength (MPa)		
	Specimen condition and test temperature		
Repair	Dry (RT)	Wet (70°C)	Wet, 100°C
Precured scarf repair A	281 ± 2.0	–	45 ± 2.0
Precured scarf repair B	228 ± 2.0	–	29 ± 2.0
Cocured scarf repair C	245 ± 2.0	97 ± 25	34 ± 0.06
Cocured scarf repair D	236 ± 0.4	136 ± 9.0	41 ± 06

Table 3. Repair efficiencies and failure modes for specimens tested at three temperatures

	Repair efficiency (%)				
Specimen condition and test temperature	Precured Scarf repair A	Precured scarf repair B	Cocured scarf repair C	Cocured scarf repair D	Failure mode
Dry (RT)	81	75	71	76	Material tension
Wet (70°C)	–	–	28	44	Adhesive
Wet (100°C)	13	10	10	13	Adhesive

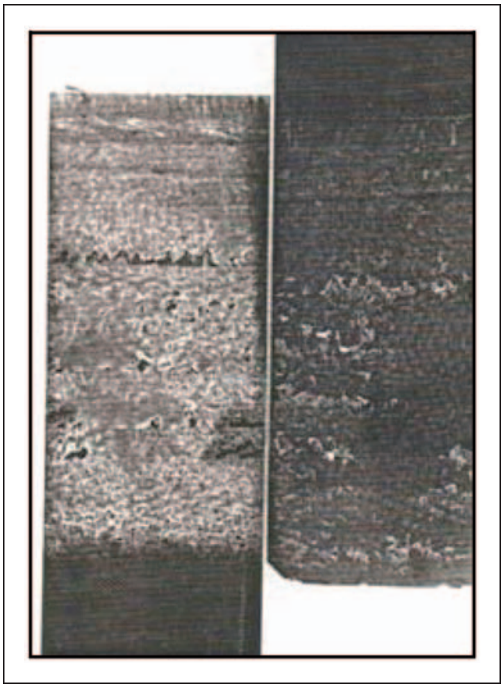

Figure 6. A typical fracture surface of test specimen at elevated temperature.

Table 4. ILSS of repaired specimens for two cure conditions

	Interlaminar shear strength (MPa)	
Specimen condition and test temperature	Autoclave process	Vacuum process
Dry (RT)	59 ± 0.20	57 ± 2.7
Wet (70°C)	39 ± 1.4	36 ± 2.7
Wet (100°C)	26 ± 2.7	27 ± 2.0

surfaces (Figure 6), a considerable number of voids and blisters can be observed. These defects may have been caused by the entrapped moisture during the conditioning. The presence of the voids is expected to contribute to the degradation of the shear strength of the adhesive. The shear strength obtained from these specimens was found to be relatively low.

On the other hand, scarf repair efficiency is generally affected by factors such as matching of plies, quality of adhesive, scarf angle, and tolerance between scarfed surfaces. In all cases, the plies in a patch must be carefully cut so that they match the surrounding laminate orientation. As a matter of fact, there is a trade-off between precured and cocured scarfed patch repairs. A precured scarfed patch repair (A and B) is easy to install against the prepared parent surface, it gives excellent aerodynamic smoothness for flat surfaces and it permits a high-strength patch to be incorporated into the repair. However, the precured patch repair is not suitable for contoured surfaces. On the other hand, cocured scarfed patch repair (C and D) in general is useful for both flat and contoured surfaces, but it may also be suitable for repairs where access is limited to a single exposed surface.

Interlaminar shear strength

The ILSS values measured at RT, 70°C, and 100°C are presented in Table 4. The results of the short-beam three-point bend tests show that the ILSS of saturated specimens dropped considerably at test temperatures of 70°C and 100°C, but no significant difference was observed between the ILSS of the autoclave- and vacuum-cured materials.

As indicated in 'Tensile strength' section, voids and blisters caused by the entrapped moisture during the conditioning phase may contribute to this degradation of the shear strength of the bonding at elevated temperatures.

Conclusions

From this investigation of glass fabric-reinforced epoxy, it is concluded that the tensile strength and ILSS decrease considerably when the material has been exposed to a combination of moisture and elevated test temperature. The maximum decrease with respect to the values at dry, RT test results also including curing processes is about 23% for tensile strength and about 55% for ILSS.

But, no significant difference was found for either tensile strength or ILSS between autoclave- and vacuum-cure repairing techniques. Single-scarf repairing technique with a vacuum-cocured or vacuum-precured patch gave a repair efficiency of 75%, which was quite close to the efficiency of the autoclave-precured patch repair (81%) at RT.

It is concluded that the repair techniques investigated in this study, specifically scarf repair with precured or cocured patches under vacuum curing conditions can be performed in field-level maintenance facilities. Vacuum curing process requiring less equipments and not any autoclaving facility seems to be a serious potential alternative to the composite patch repair requiring autoclave conditions which might be only available at depot-level maintenance centers. However, these repairs are still not qualified since only limited testing has been conducted and other properties, e.g., fatigue and compression, were not investigated yet.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1. Hart-Smith LJ. Adhesive bonded double lap joints. NASA Langley Research Center report, NASA CR-112235, 1973.
2. Labor JD and Myhre SH. Repair guide for large area composite structure repair. AFFDL-TR-79-3039, Northrop Corp., March 1979.
3. Wang CH and Gunnion AJ. Optimum shapes of scarf repairs. *Composites Part A* 2009; 40: 1407–1418.
4. Myhre SH and Beck CE. Repair concepts for advanced composite structures. *J Aircr* 1979; 16(10): Article No. 78-479R.
5. Vilsmeir JW. Composite repair of aircraft structures. AGARD Report No. 716, 1984, Italy.
6. Wang J, Zhou Z, Vodicka R and Chiu WK. Selection of patch and adhesive materials for helicopter battle damage repair applications. *Compos Struct* 2009; 91: 278–285.
7. Harman A and Wang CH. Improved design methods for scarf repairs to highly strained composite aircraft structure. *Compos Struct* 2006; 75: 132–144.
8. Wang CH and Gunnion AJ. On the design methodology of scarf repairs to composite laminates. *Compos Sci Technol* 2008; 68: 35–46.
9. Kieger RW and Myhre SR. Large area composite structure repair. AFFDL-TR-78-83, Northrop Corp., July 1979.
10. Myhre SH. Advanced composite repair-recent developments and some problems. In: *26th National SAMPE Symposium*, Los Angeles, CA, April 1981.
11. Hall SR, Raizenne MD and Simpson DL. A proposed composite repair methodology for primary structure. *Composites* 1989; 20(5): 479–483.
12. Wang J, Stankiewicz M, Zhou Z and Baker A. Battle damage repair of a helicopter composite frame-to-skin junction-A sole external repair approach. *Compos Struct* 2010; 92: 936–949.
13. Baker AA. Development of a hard-patch approach for scarf repair of composite structures. Defense Science and Technology Organization-TR1892, 2006.
14. Douglas CD and Pattie ER. Effects of moisture on the mechanical properties of glass/epoxy composites. Army Materials and Mechanics Research Center, Massachusetts, USA.
15. Myhre SH, Labor JD and Aker SC. Moisture problems in advanced composite structural repair. *Composites* 1982; 13: 289–297.
16. Clark G, Saunders DS, Blaricum TJ and Richmond M. Moisture absorption in Gp/Ep laminates. *Compos Sci Technol* 1990; 39: 355–375.
17. Mall S and Conley DS. Modeling and validation of composite patch repair to cracked thick and thin metallic panels. *Composites Part A* 2009; 40: 1331–1339.
18. Marioli Riga ZP and Tsamasphyros GJ. Design of emergency aircraft repairs using composite patches. *Mech Compos Mater Struct* 2001; 8: 199–204.