# INNOVATIVE REPAIR TECHNIQUE FOR POLYMER COMPOSITE LAMINATES

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## ABSTRACT

During the last few decades, the use of lightweight composite materials has increased dramatically. They are widely used for a variety of applications including aerospace, automotive, wind turbine blades and numerous others. Usually, these composites are exposed to various types of loads like axial, flexural, fatigue, impact, etc. Out of these loadings, the impact loading causes severe damage to the composite laminate which may prove catastrophic. Thus, when laminates are damaged, there needs to be an effective methodology to repair these damages. Composite repairs are normally considered as a cumbersome process. Hence, this paper proposes a novel repair technique to address this issue. This paper focuses on the study of composite laminates subjected to impact loading, and then replacing the damaged area with various shapes of cutouts to facilitate the load transfer after repair and reduce the loss of compressive strength significantly in the process. Composite laminates of carbon fiber with epoxy resin were fabricated using Heated Vacuum-Assisted Resin Transfer Molding (HVARTM) method. The laminates were subjected to low-velocity impact loading. The resulted damage areas were cut using a water jet cutter and replaced with innovatively designed shapes of cutouts. The compressive strengths of the repaired laminates were compared with undamaged and impact damaged laminates.

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## 1. INTRODUCTION

Carbon Fiber Reinforced Composites (CFRC) have many advantages over conventional materials like steel and aluminum. High strength-to-weight ratio, ease of molding, superior tensile properties and many other structural advantages [1]–[3] have made them popular in the aircraft industry. In the beginning of early 1980's, composite parts were repaired using bolted joints just like metal parts. Later, bonded patch repair became the common repairing technique followed by tapered scarf repair, which is more common nowadays. However, there are still some challenges this industry is battling. Effective technology for joint and improvement in maintenance and repair techniques are some of those challenges to be addressed [4]–[6]. The technological progress in maintenance and repairing could not keep the same pace as the rapid development of composite products [7]. To make up for this drawback, the safe and efficient operation of the currently available parts made of composites are largely dependent on prevalent repair and maintenance techniques at a high frequency, which is very common in modern aviation industry [8]. Of these frequently encountered damages in composite, low velocity impact [6], [9]–[13] possesses significant threat because of various factors. Firstly, unlike metals, which are ductile and hence capable of absorbing energy, both fibers and matrix in the composite gets fractured (matrix-cracking and fiber-breakage) in the process of absorbing energy [14]. In addition to that, although the fibers exhibit superior in-plane characteristics, they are vulnerable to transverse loading due to their directional properties. Moreover, at high velocity impact, through-thickness penetration results in localized damage but at low velocity, the subsurface nature of damage (e.g. delamination) makes the detection difficult [15], which eventually results into catastrophic failure later during cyclic loading. This low velocity impact causes significant deterioration of properties in tensile, shear and compressive strength [16], [17]. As a result, after the damage has taken place, the composite needs to be thoroughly studied to find out the exact position and extent of the damage to determine the feasibility of either repairing or replacing the damaged component. In case of damages that aren't widespread, repairing might be the better option as it saves the remaining material and also the time and labor for the replacement of the component [18], [19].

The vast majority of the composite materials used in aerospace and aeronautical applications are made of thermosetting polymers [20]. Also, there is variation in the manufacturing procedures resulting in different composition in terms of components, tow size, direction etc. Thus, there is dearth of an easy and cost-effective common method of repairing for composites; unlike metals, where riveting and welding is the usual practice [21]. The same conclusion was given by Loomans et. al [22] stating that there is no universally recommended surface treatment that would be compatible for all types of composites. In the earlier approach of repairing of mechanically joining the parts with bolts and screws, the holes ultimately become the source of stress concentration compromising the integrity of the material and adding to the weight due to the fasteners. More advanced bonding technique like the "Patch" and "Scarf" have performed better than the fastener. However, the industries are looking for improvements in the existing bonding techniques which would be more suitable considering the limitations of the onsite conditions like the storage condition, curing time and temperature, availability and readiness of the composite materials, eliminating the usage of complicated equipment like autoclave etc. Although, the composite materials have been in extensive use for a few decades, this area is still not fully explored, and researches are persistent in this regard. Soutis et al [23] has found out that more than 80% of the undamaged compressive strength is recoverable through carefully designed external patch repairs. Gong et. al [24] has defined an optimal strength ratio R* and a parameter K for the optimization in patch repair. Cheng et. al [25] has studied the tensile properties of the repaired composite. Kessler et. al [26] have compared the performance of Bisphenol E, Cyanate Ester in composite repairing and compared it with similar processes using BMI and Epoxy. Wu et. al [27] has concluded that filling out and complete re-bonding of the delaminated plies by adhesive can enhance the repair efficiency by as high as 98% and satisfy the repair requirement. From all these studies it is eminent that, there is still a lot of room for improvement in the existing repairing technique of composite materials.

In this study, an innovative technique is applied to repair the plain weave CFRP composite panels subjected to low velocity impact damage using patches of two different geometries. The repaired samples are then subjected to the compression after impact loading to study the compressive strength retained. The results found for these two different geometrical shapes are then compared with the compressive strengths found for nonimpacted panels and impact-damaged panels without repair.

# 2. EXPERIMENTAL PROCEDURES

## 2.1 Materials

Plain weave carbon fabric with a tow size of 3K (3000) acquired from Fibre Glast® Development Corporation was used in this study. HEXION Incorporation supplied the EPON™ 862 Resin and EPIKURE™ Curing Agent W hardener.

## 2.2 Sample preparation

A flat glass mold was used to conduct the manufacturing through HVARTM process. 20 layers of carbon fabric were placed on the peel-ply. Two layers of plastic vacuum bags were then used to seal the whole setup carefully and then examined for any leak to prevent air from passing in.
The mixture is prepared by vigorous stirring of resin and hardener at a ratio of 1: 0.264 by weight followed by heating and degassing in a vacuum oven at 80 °C and -30 psi respectively. Throughout the infusion, the temperature at the top and bottom plate is maintained at 45 °C. After the infusion was completed, the laminate was put into an oven with vacuum at 131 °C for 4 hours for curing. Circular patch (CP) of 5.5 cm diameter and Circular Patch with Radial Projections (CPRP) with projection of 1.5 cm, all were produced using a waterjet cutter (Mach 2 1313b).

## 2.3 Repair

Two different geometries were used for the repairing process to study the effect of different shapes in the repaired samples. The first one is CP with a diameter of 5.5 cm and the second type is the circular patch with 16 radial projections of the same diameter and outward projections of 1.5cm. These patches and all the 152.4 mm ×101.6 mm samples (for compression after impact test according to ASTM D7137 [28]) were cut off from the same panel to ensure the homogeneity of the properties. In practical application it is important to utilize the same parent material to repair the damage which assures structural integrity of the repaired panel. Use of different material may result in mismatch of both thermal and mechanical properties causing inferior repair of panels. The composite panels were impacted from a height of 38 cm. The amputated portion of the damaged samples and the patches for replacement were cut in the same geometry to exactly match together. After matching the cut-section in the sample with the patch of same shape, the voids were filled up by injecting the same resin-hardener mixture with a plastic syringe and the curing process was repeated as stated previously.

## 2.4 Impact test (ASTM D7136) [29]

The Drop Weight Impact Tests were performed by the Instron® Dynatup 9250G. The samples were clamped using an ASTM D7136 standard fixture. The weight of the impactor was 18 kg. The velocity of the impactor was calculated using the formula $v = \sqrt{2gH}$ (g =acceleration due to gravity, H = drop height). The actual impact force was measured by a machine integrated load cell.

## 2.5 Compression after impact test (ASTM D7137) [28]

This test was done in an ASTM D7137 fixture using the Instron® 3384 Universal Testing Machine. Specimen axis was carefully aligned with compression load axis to minimize buckling.

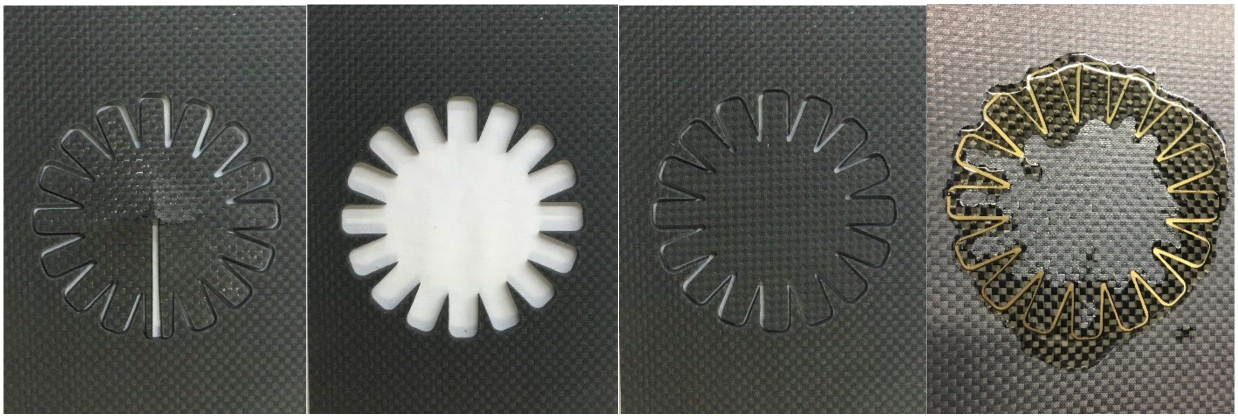

Figure 1. Steps involved in repairing the panels subjected to impact damage with CPRP: a. Cutting off the damaged part. b. Panel after amputation of damaged region c. Replacement of the damaged region with intact patch d. Repaired panel after curing.

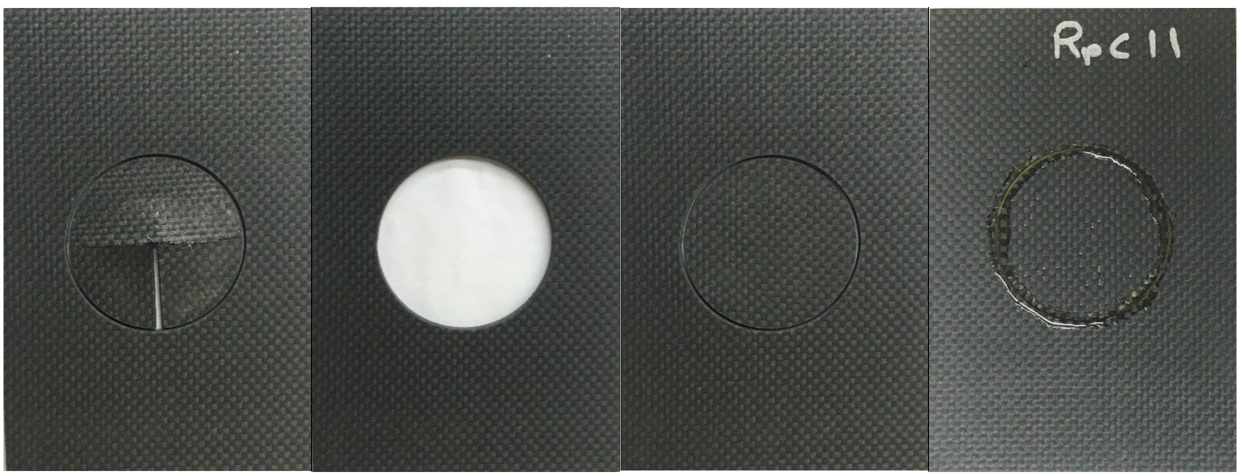


Figure 2. Steps involved in repairing the panels subjected to impact damage with CP: a. Cutting off the damaged part. b. Panel after amputation of damaged region c. Replacement of the damaged region with intact patch d. Repaired panel after curing.

## 3. RESULTS AND DISCUSSION

CFRP samples were subjected to drop weight impact test (impactor mass = 18 kg) from various drop heights i.e. with different impact velocities. From these test results, it was found that insipient damage for the sample occurs at a drop height of 5 cm (impactor velocity of 1 m/s) and the impactor starts to penetrate the sample at a drop height of 38 cm (impactor velocity of 2.73 m/s). Therefore, all the specimens for this study were subjected to an impact from 38 cm drop height. Figure 3 shows the plots of peak load and absorbed energy against impact time. Fluctuations of the peak load data can be interpreted as major fiber damage occurred during impact (Figure 3).

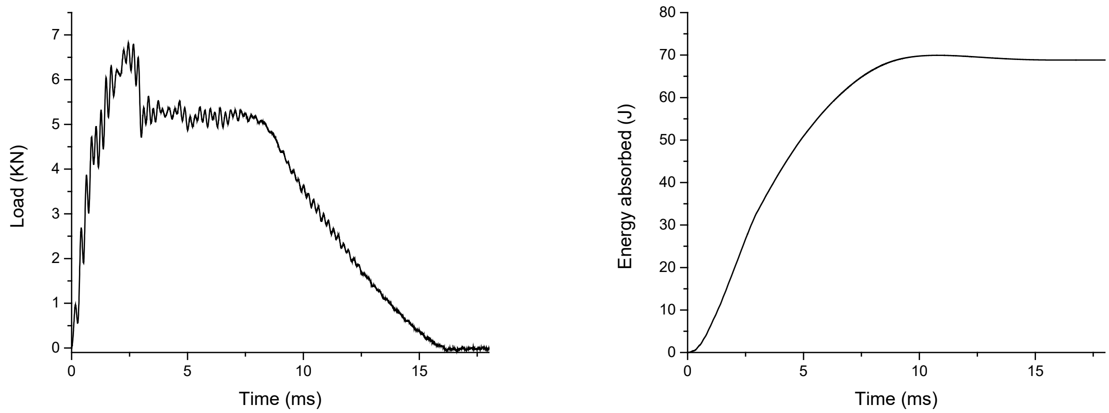


Figure 3 Peak load (Left) and energy absorption (Right) plot against impact time.

After impact, the damaged region was cut out and replaced with an intact patch. The repaired specimens were subjected to compression after impact test according to ASTM D7137. Obtained results are listed in Table 1 and compressive stress plotted against compressive strain is shown in Figure 4.

Table 1 Parameters obtained from compression after impact test

| **Sample** | **Compressive Strength (MPa)** | **%Retained Compressive Strength (%)** |
|---|---|---|
| Not Impacted | 220.7 ± 16.9 | - |
| Impacted | 128.3 ± 2.9 | 58.1 |
| Circular patch (CP) | 159.6 ± 3.6 | 72.3 |
| Circular patch with radial projection (CPRP) | 177.6 ± 3.8 | 80.5 |

From Table 1, the specimens that were impacted but not repaired shows a compressive strength of 128.3 MPa, which is 58.1% of the undamaged specimen. Even though CP specimens shows good recovery (72.3% retention), CPRP samples exhibited significantly more compressive strength (80.5% retention). With other parameters kept similar, incorporation of radial projection in CPRP resulted in nearly 12% more compressive strength than the CP sample (Figure 5).

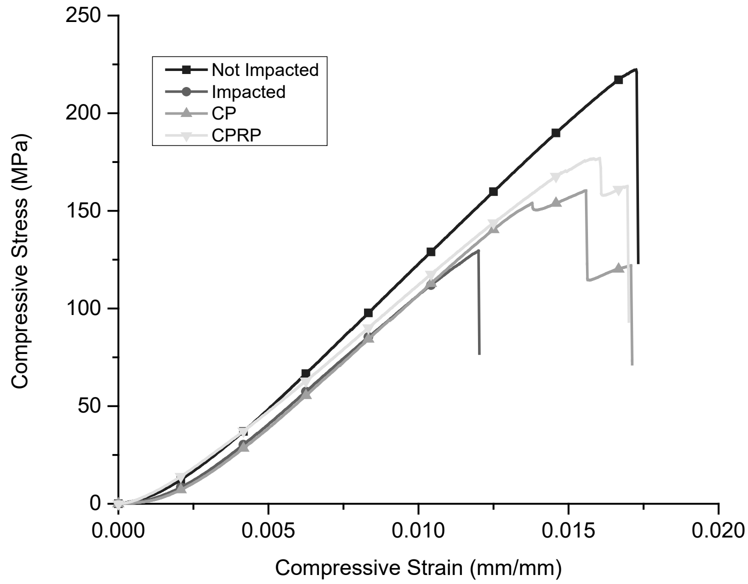


Figure 4 Compressive stress responses of specimens as a function of compressive strain.

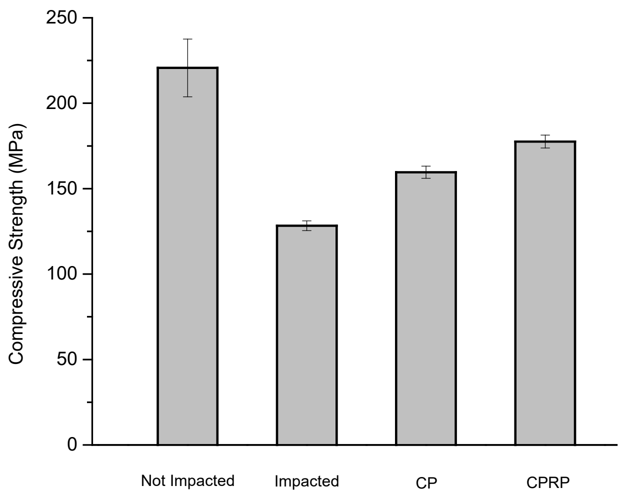


Figure 5. Comparison of compressive strength after impact in related samples.

Figure 6 shows the fractured specimens of CP and CPRP after the compression test. The CP specimen shows damage in the resin along the repair joint whereas the patch popped out intact. Obviously, when the CP sample was under compressive stress, the repair joint failed to transfer load to the patch keeping it undamaged. In contrast, CPRP sample shows prominent failure of the patch, which means bonding in the joint area was strong enough to successfully transfer the load to the patch. This is an important discovery in a sense that the strength of the patch is irrelevant if enough load is not transferred to it, and from this point of view, CPRP sample has shown much better promise than the CP sample.

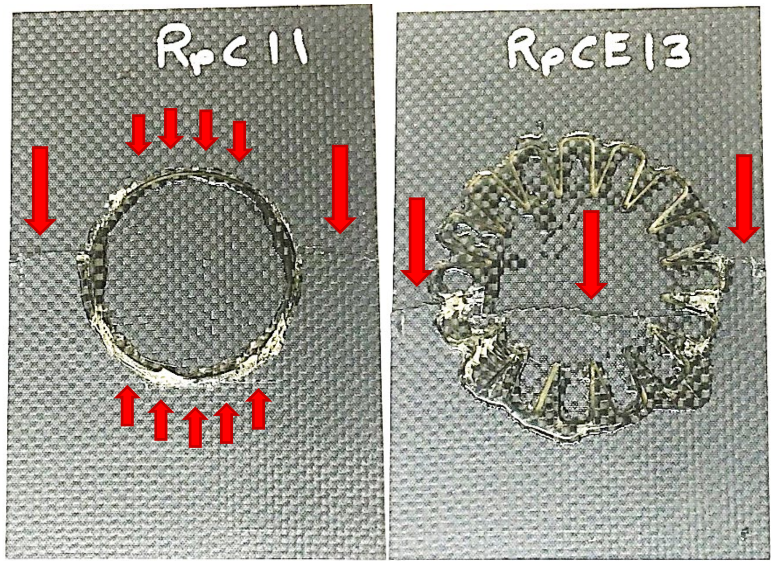


Figure 6 Failed specimens of CP (Left) and CPRP (Right) (Arrows showing the fracture progression).

## 4. CONCLUSION

This article discussed the potential of a novel repair technique of CFRP composite laminates. Two different shapes (CP and CPRP) were studied to compare the effect of patch geometry on the effectiveness of load transfer. Results indicated that the CP and CPRP samples showed compressive strength recovery of 72.3% and 80.5% respectively. CPRP specimens exhibited ~12% more compressive strength than their CP counterparts. More importantly, failure mode distinctively shows that CFRP specimens have much better load transfer between laminate and patch than CP specimens. A Full 3D finite element model of the repaired joints can provide better understanding of the load transfer mechanism. Currently, more research is underway to further improve the compressive retention and effective load transfer.

## 5. ACKNOWLEDGMENT

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