Sustainable and Effective Composite Repairs Using Novel 3D Printed Patch Designs

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Executive Summary

Major changes have occurred in the automotive and aerospace industry over the last few decades where aircraft and high-performance automobile structures are increasingly based on composite materials. Composites are lightweight, have exceptional strength, and provide design flexibility. For high performance composites more carbon fiber-based designs are being used. When they are damaged, they need repair, and typically the resin systems like epoxies, unsaturated polyesters dissolved in styrene and others are used. In the aerospace market especially for aircraft/UAV repairs, rapid return to flight is critical to minimize ground time and ensure safety.

The current composite repair systems have certain limitations.

a) Unsaturated polyesters dissolved in styrene: They are not environmentally friendly; styrene is considered a potential carcinogen and exposes the repair workers to health risks. It has a very pungent odor and generates about 10% to 30% of the resin waste which needs proper disposal leading to environmental challenges.
b) Epoxy systems: Standard epoxy systems are slow reacting and typically takes about 6 to 48 hours to cure. For aerospace grade epoxy it takes days to develop full strength. Some of the amines used in crosslinking have a very pungent odor and eye irritation.
c) For high performance composite substrate repairs which needs the use of carbon fibers, the carbon fiber mats must be layered very slowly followed by soaking in the resin and vacuuming the whole system to avoid voids. This increases the repair time significantly for hours and days.

The current work that we have done is designed to address both the issues and has the following salient features: a) Styrene free and does not use any raw materials/ chemicals of concern b) System with very fast cure time; 20 to 60 minutes very quick turn-around time c) Very minimum waste and avoids pollution at landfills d) Very minimum odor e) Improved worker safety f) Rapid turn around time for time-critical applications

Our novel design is as follows:

a) Development of a 3D patch design that can be customized and printed with standard low-cost FDM printers
b) Use UV curable resin infill for the patches that can cure in a few minutes using low-cost LED or UVA black light lamps
c) Mix matrix concept of adjusting the patch and infill depending on the composite substrate like size, shape, substrate, market needs and performance

Industry Overview

The current composite repair process has the following deficiencies or limitations, and our new design and system developed will address to resolve these limitations.

Deficiency 1:

The repair worker inspects the damaged area, cleans it and prepares the substrate to be repaired. Depending on the size and thickness of the damaged composite fiber glass mats, fillers, backing materials etc. are lined to cover the damaged area followed by application of the resin filling system. Sometimes the matte is soaked with the resin system and placed in the damaged area. In certain high-performance applications, the carbon fiber needs to be layered very slowly, and vacuum bagged to remove trapped air to get uniform distribution of resins to cure. This adds time and leads to significant labor costs. Also, in the typical epoxy and unsaturated polyester system, when they are mixed, they immediately start to react slowly leading to 20-30% resin wastage at the end of work. The innovative idea is to use a resin system that will not cure until it is taken out of the can and exposed to UV light.

Our design and concept are to custom 3D print a patch in a three-dimensional structure and place it in the damaged area with ease. Various design models were studied, and the optimum planar design was developed for the right balance of performance. The advantage of this 3D printed patch versus layering approach is that it provides similar strength as the fiber matte layering with significantly lower time when repairing high performance composites like carbon fiber-based ones. The details will be explained in the next section.

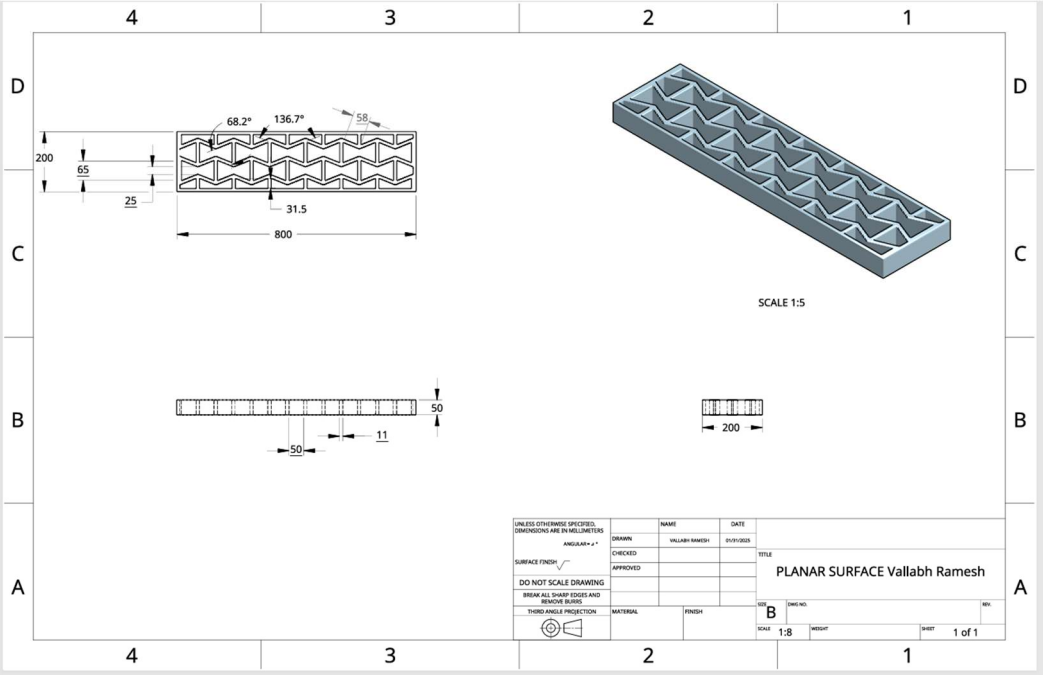
Deficiency 2:

Typically for high performance composites like the ones made of carbon fibers (used in aerospace and high end automotive for exceptional strength and performance). When they are

damaged it is relatively difficult to repair. As explained earlier the carbon fiber mats need to be layers, followed by resin infill and cure which takes time. There are newer emerging technologies like UVA light and LED cure resins that can cure faster and reduce the return to service time. But unfortunately, the carbon fibers block the UV light source, and this fast cure resin technology cannot be used in the current technology setup. This is the problem that our new design will solve, mainly the use of carbon-fiber reinforced polymer filaments that can be 3D printed in precise patch models that will still let UV radiations penetrate and provide the curing. The patch design will provide the structural outline, integrity and strength in combination with the infill but significantly cures faster than the current system (e.g. reduce the cure time from 1-2 days to less than an hour.

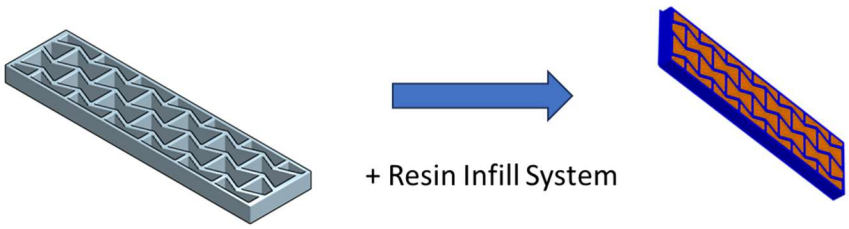
Design, Functionality and Durability

The planar surface of the reentrant hexagonal structure design is shown below and the STL files are attached in the zip folder for reference.

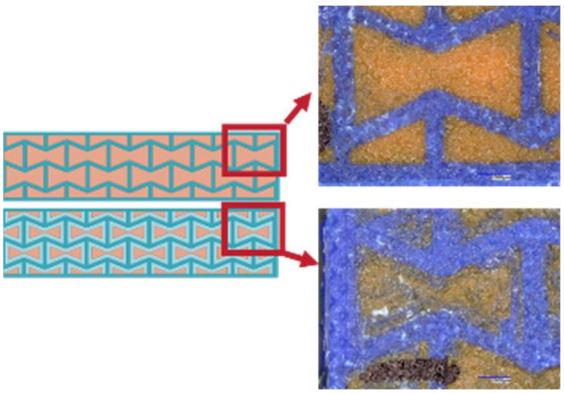


The designed structure was 3D printed using a FDM (Fused Deposition Modeling) filament printer as shown below.

Various structural designs like grid, gyroid etc were tested for real world repair patch type scenarios. The planar lattice reentrant hexagonal design was found be the most effective. The model design was printed using TPU filament and different infills using unsaturated polyester, epoxy and UV curable resin were studied. The process is schematically shown below.



Here is the zoomed image of the filled structure.

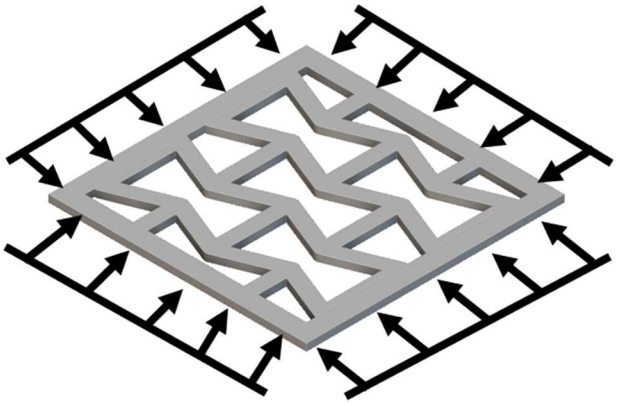


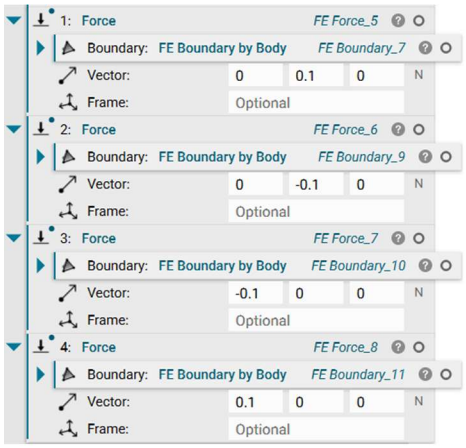
The dimensions of the novel model patch created with a thermoplastic urethane (TPU) filament and infilled with control epoxy resin (standard used in the industry) and the new UV curable infill resins are shown below.

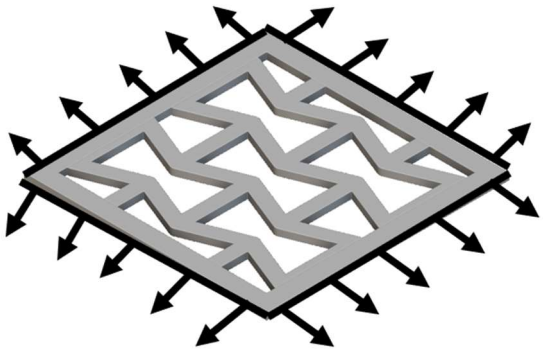
Lattice Type	Planar
Lattice Design	Re-entrant Honeycomb
Unit Cell Size	12x12x12
Thickness, mm	1.1
Weight, g (Hard Thermoplastic)	4.52
Surface Area, mm^2	6270
Mixed Matrix (Sequential 3D Printing)	

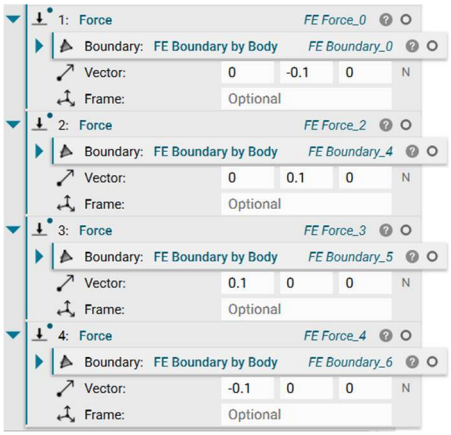
The hard thermoplastic volume is 3116.06 mm^3 (grey region) and the resin infill volume is 4882.5 mm^3 (blue region).

FEA simulation of the models was done for compression and stretch conditions. The images are shown below.









The filled models were then tested for impact strength using ASTM D2794 impact strength tester shown below.

In this study high modulus carbon fiber reinforced TPU filament (purchased from Smart Materials) was used to prepare the planar reentrant hexagonal patch.

Comparing the durability and performance against the current system in the market:

The proposed novel design and patch solution was compared against current repair systems (unsaturated polyester with styrene and fillers) and epoxy. Typically, these systems are very durable to 5 to 10 + years and meet various specifications prescribed by the Automotive and Aerospace industry. Standard impact strength measurements are done to make sure the repaired

part is equal or even better than OEM manufactured composite substrates. The reentrant hexagonal patch with UV curable resin system passed the 160/160 lbs-inch impact strength as measured using ASTM D2794. This is equal or sometimes exceeds the actual composite OEM substrate itself that is being repaired. Example of our test results in various composites is shown in the next section.

Design Integration and utilization of DDM materials and processes

The designed patches were tested in real world conditions. Automotive and Aerospace composite panels were purchased from commercial vendors like Rock West Composites etc..

A typical composite repair and the new and innovative process is explained schematically in the slides below.

Repair of Composite Panels

Current field repair technique: Casting of an ambient/ thermally curable resin and fiber mat infusion

- Average of 24-48 hour curing period, and full-strength development in 7 days
- Some resin systems require elevated cure temperatures
- Fire risks of using heating blankets
- Limitations:
  - Layup of fibers
  - Vacuum bagging process
  - Skilled technicians

Source: Aviation Maintenance Magazine (AVM-MAG.com)

Novel Approach

Use a thermoplastic and thermoset combination to develop the ideal strength to match the original specifications and performance of aircraft or UAV substrates.

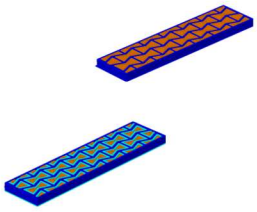
Thermoplastic-Thermoset Hybrid Combination

- **Thermoplastic polymer** provides easy printable options using FDM filament printer
- Excellent flexibility and toughness of the structure
- Various intricate designs can be developed

- **Thermoset polymer** provides wide range of combinations to infill
- Extends the performance and adjusts the properties
- Cure rate can be tuned for specific applications
- Operator friendly during repair situation

CAD Models of Composite Sandwich Panels

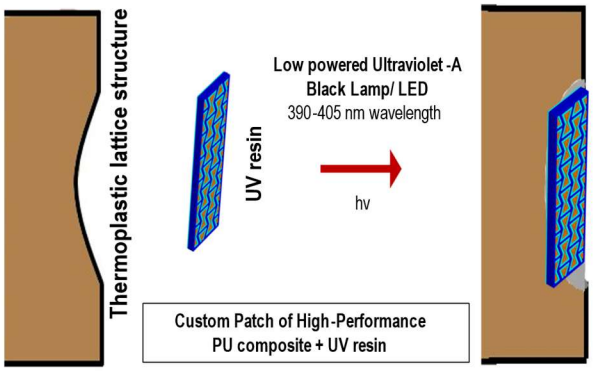
- Various infill designs were created and tested



Ultra Fast Aircraft/UAV Composite Repair

New Method of Return-To-Service: Use emerging technology that is being developed to stencil paint logos on aircraft and high-end professional automobiles. This technology can be used to assist the patch repair curing process.

Source: UV/EB Course ACS June 2021



Rapid advancements in lamp technologies and LE source in the 390-405 nm range will make these curing mechanisms safer and more efficient.

With the right photoinitiator(s) combinations, these resins can even be cured by sunlight, so people in remote military operations can also util this repair method.

Situation: surface damage (indentation or holes)

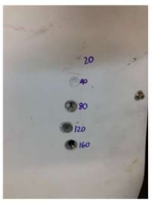
Customized process takes less than one hour

Lab Demonstration of the New Process

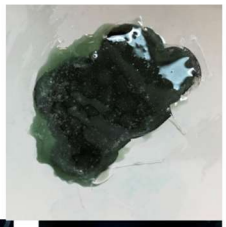
Excellent results were obtained with Ultra-Fast cure Thermoplastic Thermoset (UV cure) combination on the repair system.

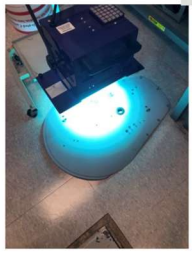
Different grades of aircraft panels beingrepaired in the lab

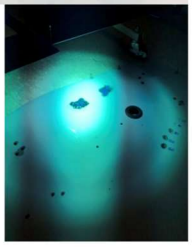
Lab Demonstration of the New Process



Actual large Predator MQ series damaged part by bullet holes and the damaged areas are beingrepaired in the lab







Casting resin matrix into the printed design

Casting resin matrix into the printed design - UV cured resin system

Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean and continuous improvement

The following will be the distribution of this technology for the composites market.

The FDM printer manufacturers like Pulse printers (US made – high end) can provide quality machines for about $1000 and medium range printers from Asia sell for about $300 to $600 that can be used for printing. Ideally this patch design can be distributed by the printer manufacturers as part of their license agreement, or it can be sold separately for an annual fee with upgrade features etc.

The manufacturers of the UV curable devices like LED producers and UVA lamp producers in the automotive and aerospace industry will be excited about this opportunity. This is because it will help them sell more units - they can sell one portable or stand mountable unit for each repair shop and service them for parts. E.g. of vendors are Phoseon LED, H&S Autoshot etc…

The 3D filament producers like Ninjaflex, SmartMaterials, Creality etc. can supply these carbon fiber reinforced filaments, and they can expand their portfolio to new offerings as the customer demand and requirements goes up.

A preferred partnership with the printer manufacturer and any of the resin system provider and filament maker can also make this technology penetrate the market faster.

Last option is to make it open source and let any new technology enthusiasts, hobbyists and entrepreneurs experiment and evaluate this technology and take it to new areas.

Cost Benefit/Value Analysis

Economical Advantage:

By adopting this new design and approach the productivity of the repair shop increases dramatically. E.g. In a very simplified scenario if you are repairing an automotive car body made out of carbon fiber, your typical repair time is 6 to 12 hours per vehicle (that involves the downtime for curing of the resin system etc. By applying this 3D patch followed by UV curing cuts the repair time by at least 6 hours. So for the repair shop the number of automobiles repaired per day can be doubled (typically 3-4 cars are repaired by a crew)a. Assuming the labor rate of ~70$/hour, a four-person crew i.e. about (70x8x4=$2240) productivity improvement per day in a repair shop. Multiplying this by thousands of repair shops in the US and around the world this will have significant improvement in the economy.

Here are some reference cost figures for the raw materials:

The cost of the high end FDM printer is $1000

The cost of the carbon fibre reinfored thermoplastic polyurethane (TPU) 1.75 mm diameter standard size filament roll = $80

Cost to print a patch including parts, labor etc. = $2 to 3 per unit

Cost of the UV curable infill ($100 per gallon of fully formulated system). Assuming using 50 to 100 grams per patch the cost of infill = $2 to 3 per repair area

So combined with the patch and infill = $4 to $ 6 for raw materials cost.

This cost is similar or lower on the cost of square foot per repair job since the UV curable resin does not have any wastage when compared to the traditional epoxy or unsaturated polyester mixed in styrene.

Environmental/Social/Regulatory advantages:

This patch system will have improved worker safety, lower regulatory hazardous labels on their container, does need to wear complex masks and suits to operate, and reduce about 30% resin in mixing.

Conclusions

Novel 3D printed patch designs were successfully developed for sustainable and effective composite repairs. This innovative reentrant honeycomb design will help the repair worker to:

- customize the repair process to the specific job
- significantly reduce the downtime
- lower the environmental footprint by reducing wastage and eliminating the use of hazardous raw materials

The work also successfully demonstrated the use of this repair patch in aerospace and automotive composite repair applications. The work can be expanded to other large volume markets like windmill blades. Technology improvements in additive manufacturing and digital scanning will further seamlessly integrate and customize the repair patches to large and complex repair areas.

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