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Programmable laser curing of carbon fiber laminate structures

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ABSTRACT

Carbon fiber composites have revolutionized various industries due to their exceptional mechanical properties and lightweight nature. However, the conventional curing processes used in their manufacturing are often time-consuming and energy-intensive. In this study, we propose an alternative approach utilizing blue and red lasers for the selective curing of carbon fiber-reinforced polymer (CFRP) laminates, enabling the development of deployable structures. Laser curing offers several advantages over traditional methods, including precise control over curing parameters, rapid heating and cooling rates, and localized energy delivery. This fabrication method is ideal for applications in deployable design. Deployable structures have become increasingly popular due to their ease of assembly and compact storage capabilities. They are often made from lightweight and durable materials and are designed to be assembled quickly with minimal tools and expertise required. Origami principles have been used to design deployable structures that can be collapsed and deployed along the same path, and pop-up design techniques have also been used to create articulated three-dimensional structures that can be fabricated starting from a flattened state. In this context, two laser fabrication methods are presented and a deployable, pop-up carbon fiber reinforced polymer (CFRP) lattice structure is developed, as well as a ruled surface structure. For the first strategy,a blue laser is used to selectively cure parts of the flattened CFRP design, creating hinges that allow the entire structure to be deployed in a pop-up manner. In the second strategy, a red laser is used to ablate epoxy from the prepreg carbon fiber, leaving areas that are more flexible than the surrounding areas once the entire structure is cured. This design and fabrication method yields a deployable structure with many potential applications in aerospace fields.

Introduction

Carbon fiber composites are highly regarded in various industries due to their exceptional mechanical properties and lightweight nature. The curing processes traditionally employed in their manufacturing, however, can be time-consuming and energy-intensive. To address these challenges, we present an alternative method utilizing a lasers for selective curing of CFRP (Carbon Fiber Reinforced Polymer).

The concept behind laser curing involves using high-intensity laser beams to induce curing reactions in the resin matrix of carbon fiber composites (Figure 1). This method offers several advantages over conventional curing processes. Firstly, it allows for precise control over curing parameters, enabling manufacturers to tailor the curing process to specific requirements. This control enhances the overall quality and consistency of the cured composite.

Secondly, laser curing enables rapid heating and cooling rates. By selectively applying the laser beam, the desired regions of the CFRP laminate can be heated quickly, promoting rapid curing, while leaving other areas unaffected. This rapid curing capability not only reduces production time but also minimizes the energy required for the overall process.

Another benefit of laser curing is the localized energy delivery it offers. Unlike traditional methods that rely on convection or conduction to transfer heat, laser curing provides a focused and controlled energy source. This localized delivery of energy allows for the precise targeting of curing regions, avoiding potential damage to adjacent areas and reducing thermal stresses.

To illustrate the potential of laser curing, we develop deployable structures. By selectively curing the CFRP laminate, specific regions are left uncured, effectively creating hinges within the structure. This hinge mechanism enables the lattice to fold or unfold, resulting in a deployable configuration.

Deployable structures are designed to be quickly and easily deployable into their load-bearing form, and they can also be stored in a compact, folded configuration. This makes them suitable for applications where speed and ease of erection are desired, such as in large apertures for space[1], space enclosures[2], and solar arrays[3]. Deployable structures are often made from lightweight materials that are strong and durable, allowing them to be transported easily while also providing a stable and secure structure once erected. They are designed to be assembled quickly, with minimal tools and expertise required, making them an ideal solution for rapid deployment scenarios. Origami is one well-studied method of developing deployable

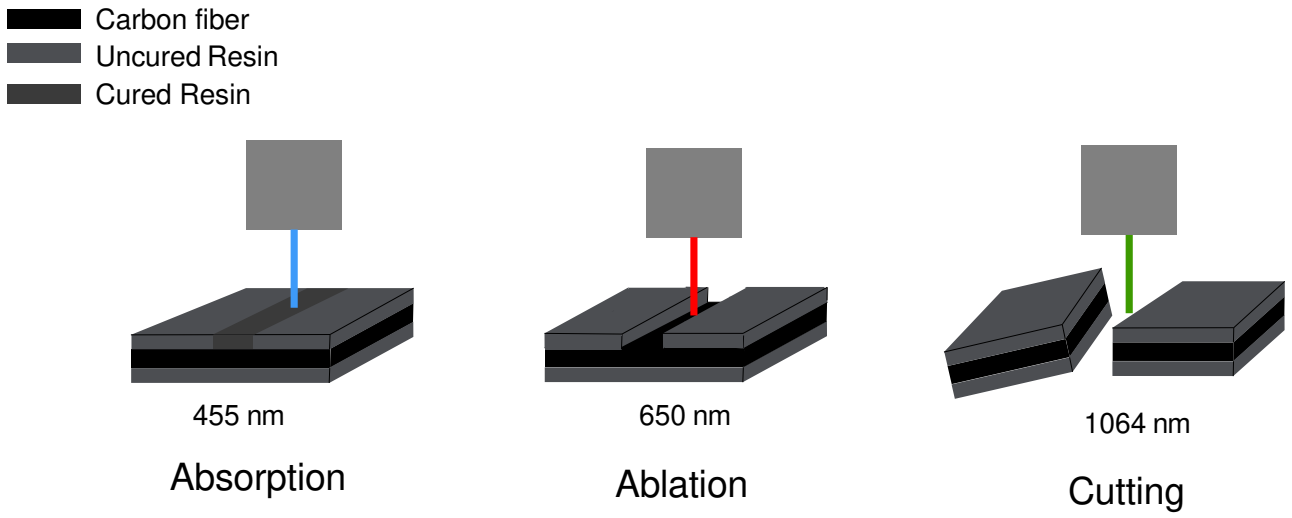


Figure 1. Different laser treatment methods for carbon fiber composites.

structures[4–6]. One of the key advantages of using origami principles in the design of mechanical metamaterials is that the resulting structures can be easily collapsed and deployed along the same path. This flexibility allows the structures to be easily transported and deployed in a variety of different settings. Another possible avenue for deployment is pop-up design. For example, with pop-up MEMS[7], articulated three-dimensional structures are able to be fabricated starting from a flattened state. This fabrication technique has also been used to develop metamaterials[8] that also deploy from an initially flattened position. Here, we present two fabrication strategies that can be utilized to develop (CFRP) structures. CFRP composites have become increasingly popular in recent years due to their unique properties and simple design. One of the key advantages of CFRP composites is their high strength-to-weight ratio. This property makes them ideal for use in applications where weight reduction is important, such as in aerospace. The first method presented here uses a blue laser is used to selectively cure parts of the flattened CFRP design. This creates hinges, allowing the entire structure to be deployed in a pop-up manner. In the second method, a red laser to ablate epoxy from a woven carbon fiber prepreg. Overall, these design and fabrication methods yield deployable structures that have many potential applications in aerospace fields.

Results

Here, we present two laser treatment methods for use on CFRP laminates (Carbon fiber Hexcel AS4/Epoxy Newport 321, Rockwest Composites). In the first, a blue laser (xTool D1 Pro Laser 20W version) is used to selectively cure regions of the CFRP laminate. Hinges can then be created by leaving certain regions uncured and curing the surrounding area with the laser. Conversely, an infrared laser (Thunder Laser) is used to selectively remove epoxy from specific regions.

DMA bending tests

To compare the stiffnesses of the carbon fiber treated with the blue laser, red laser, and carbon fiber cured in an oven, a dynamic mechanical analysis (DMA) test was performed. Samples that were cured in the oven were cured in the following process: first, oven ramp up temperature from room temperature to 149 ℃ at a rate of 3 ℃/min, maintained at 149 ℃ for 30 minutes, and naturally cooled down to room temperature.

Samples created with the red laser and blue laser were treated with a range of power and speed settings to determine trends in these settings. The dual cantilever clamp bend test was then carried out with a ramp of 17 N/min, and the stress strain data are collected at a rate of 5 points per second. To determine Young's Modulus, the linear region of the data is first computed. For a series of data from (x_1, y_1) to (x_n, y_n), data is taken from (x_{n-24}, y_{n-24}) to (x_n, y_n) (i.e., the last five second of our test). Then, linear fitting of the data points is conducted to get a slope and y-intercept of k and b. Then for the rest of the data, the estimation value $y_{estimate}$ is calculated based on x_m through $y_{estimate} = kx_m + b$, i.e. $1 \leq m \leq n - 24$. By comparing the residue value $\frac{|y_{estimate} - y_m|}{y_m}$ with 0.05, the linear range of our data can be determined.

To calculate the specific work applied to the sample in Mega Joules per square meter, we applied the following two methods to red laser samples and blue laser samples. For the red laser sample, the laser used has a maximum power P of 80 W. The blue laser has a maximum power of 20 W. In the process of making the samples, we applied various settings of power percentage α

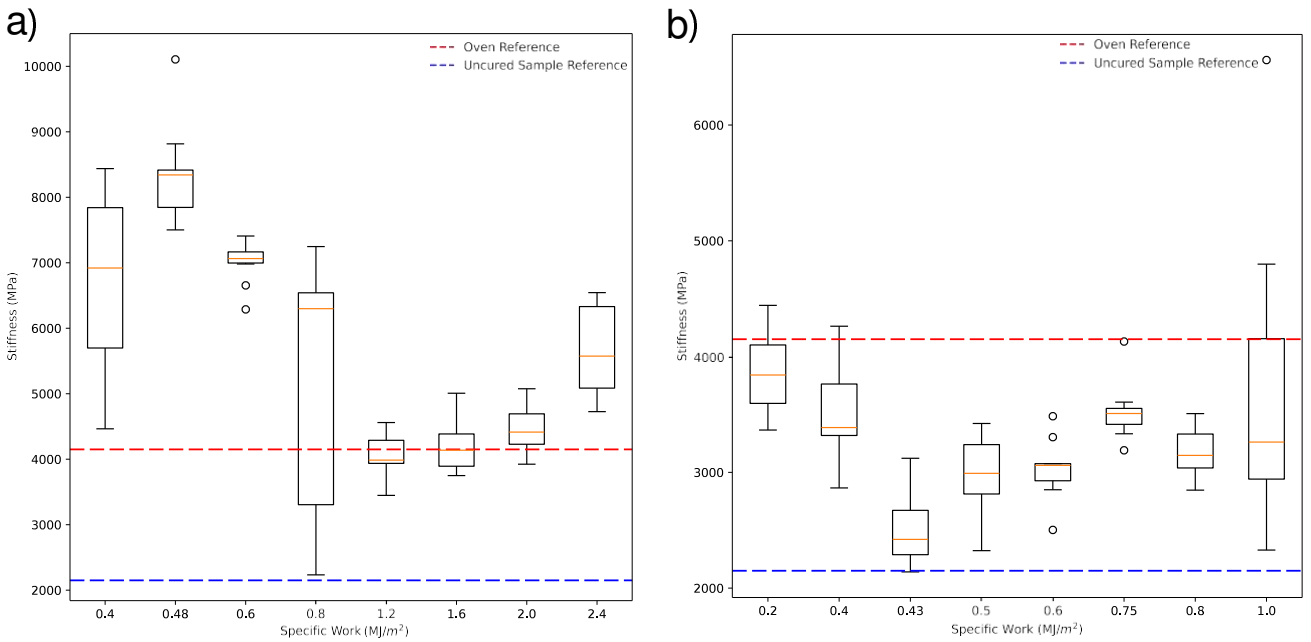


Figure 2. Stiffnesses of laser treated prepreg carbon fiber. a) Red laser treatment stiffness as a function of specific work. b) Blue laser treatment stiffness as a function of specific work.

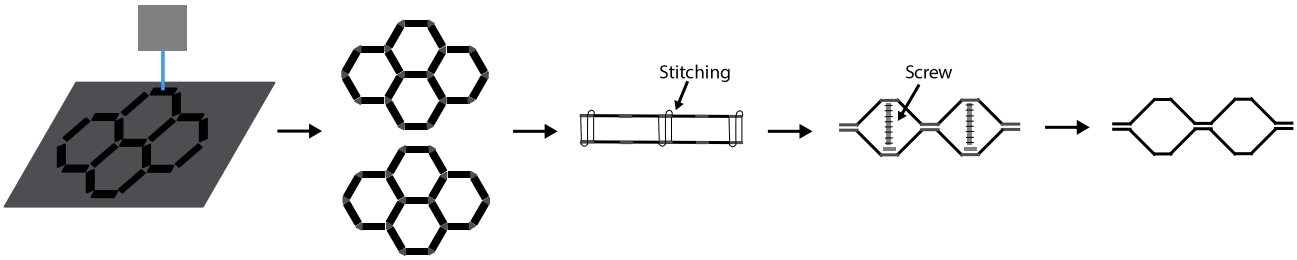


Figure 3. Manufacturing process for deployable lattice structures.

and speed v. The diameter of the laser is expressed with the line density parameter, N, in units of lines per centimeter. N is usually 100 lines/cm. Therefore, the specific work w for the laser emitted onto the sample is calculated by

$$w_{\text{laser}} = \frac{\alpha PN}{v} \tag{1}$$

Note that the specific work of laser is different from the total energy observed by the sample.

As is shown by the plots in Figure 2, the stiffness of the carbon fiber can be determined as a function of specific work. A comparison to oven curing is shown as well. As compared to oven curing, the stiffness of the carbon fiber can be tuned using the laser parameters to generate stiffer or less stiff samples.

Deployable lattice fabrication

As aforementioned, a blue laser can be used to selectively cure regions of carbon fiber. This allows for the more flexible, uncured regions to act as hinges. Once the design is selectively cured, the outline of the design is cut away from the surrounding material using an X-acto knife. In future iterations, this step could be automated and cut with a specialized cutting machine. Once two designs are cut out, selected nodes are sewn together using carbon fiber tow. This process could also be automated in future iterations. The structure can then be opened up into a lattice shape. To keep the design opened up, screws are used as spacers to prop open the nodes that aren't sewed together. To keep the screws in place while the entire structure is cured in an oven at 230°C, hot glue is used. Once the entire structure is cured after 5 minutes in the oven, the screws can easily be removed,

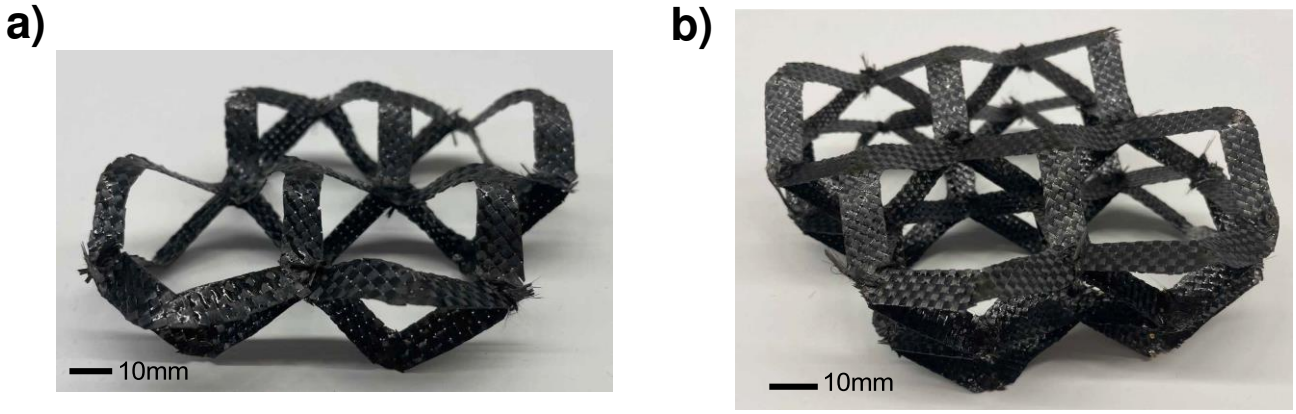


Figure 4. Examples of deployable lattice structures. a) Lattice with a single unit cell in height. b) Lattice with two unit cells in height.

as the hot glue melts in the oven. This process is shown in Figure 3. Once completed, this process yields a fully deployed lattice structure, as shown in Figure 4.

Red laser sample fabrication

In order to make a ruled surface that can transform into a given shape, a red laser is used to selectively ablate the resin in regions of a sheet of carbon fiber. These regions are stiffer than the surrounding material when cured, effectively making score marks that allow the sheet to bend into a curled shape, as shown in Figure 5. This manufacturing process is shown in Figure 6. The parameter settings for the laser curing needs to be carefully selected to achieve different goals for each laser type. For the red laser, the specific work needs to be set to the region where the stiffness will be higher than the oven reference. For the blue laser, the specific work needs to be set so that the resin is cured as much as possible. The resin can alternatively be cured by employing the oven. The extra flexibility of the carbon fiber sample occurs due to the slight difference in stiffness on the two sides of the sample, allowing for the ruled surfaces to be created.

Discussion

Here, fabrication methods for developing a deployable lattice structure are developed. A red laser is used to remove epoxy in hinge regions. Conversely, a blue laser is used to selectively cure a CFRP laminate, leaving uncured regions to act as hinges. With two of these selectively cured laminates, these layers can be sewn together, fully cured, and deployed. The use of origami principles and pop-up design techniques to create such a structure allows for easy deployment and compact storage, making it ideal for applications where space is limited. This design and fabrication method offers many potential applications in aerospace fields, such as in the development of lightweight and compact solar panels, antennas, or deployable structures for space exploration missions. It also has potential applications in other fields, such as architecture, where lightweight and easily deployable structures could be used for temporary or emergency shelters. Overall, the use of CFRP and pop-up design techniques to create deployable lattice structures offers a promising solution for weight-sensitive applications where ease of assembly and compact storage are crucial factors.

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a)



b)

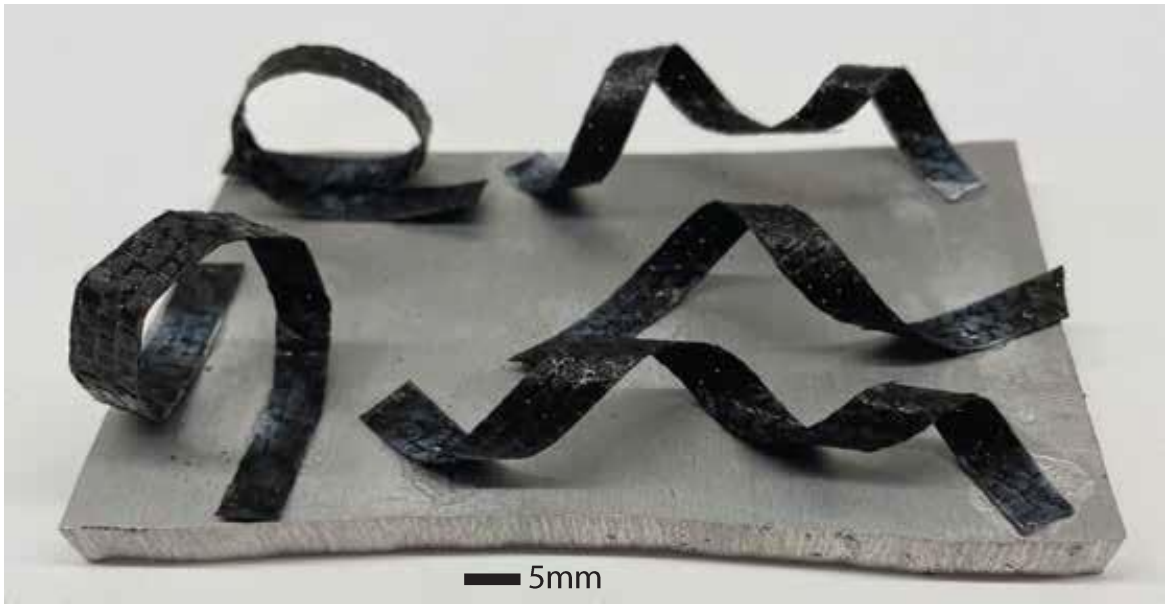


Figure 5. Examples of structures made using a red laser. a) Cylinders with varying radii. b) A variety of curved surfaces made using different scoring patterns.

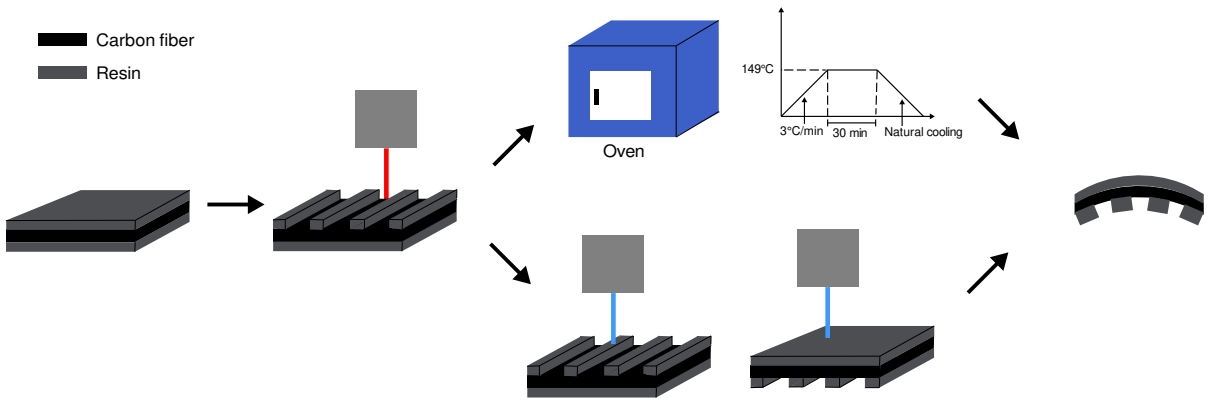


Figure 6. Manufacturing process for curved structures made with the red laser.

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Author contributions statement

H.M. and H.L. conceived the experiment(s), H.M., Y.D., and M.S. conducted the experiment(s), H.M. and Y.D. analysed the results. All authors reviewed the manuscript.

Competing interests statement

The authors declare no competing interests.

Data Availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.