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# Investigation of embedded resistive heating for high strength adhesive bonding of modular space structures

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**This research examines high strength adhesive bonding using carbon fiber embedded heaters to fabricate large, rigid structures in space from smaller, easy-to-transport modules. The use of carbon fiber embedded resistive heaters can be used to produce high quality adhesive bonds under vacuum bagging. This study shows that this technique has similar results when done in higher vacuum conditions with a method of applying external pressure to the adherends. The advantages of this bonding method, as opposed to fastening, are the minimal use of extra materials as the embedded heater becomes part of the composite structure, and energy efficiency due to the targeted heating at the bondline. Such embedded-heater-based joining could be a key enabler for modular manufacturing and repair of space structures.**



## I. Introduction

One of the primary difficulties and costs associated with space exploration is the limitations imposed by the current necessity of sourcing materials, supplies, and structures from Earth. Payload fairings are small by necessity, and range from about 3 to 10 meters in diameter.[1] For example, the record setting launch of 104 satellites by the Indian Space Research Organization (ISRO) on February 15th, 2017, was done with a 3.2 meter diameter payload fairing. Limitations on fairing size has encouraged the design of space structures to include a variety of solutions so that rigid structures can be transported with a small footprint, and then expanded when deployed. Some examples of this include inflatable structures,[2,3] and origami-inspired expanding booms.[4,5] Considering the cost of putting a payload into space, and size limitations, it is important to have high strength, low weight, and cost effective ways of joining rigid materials in space after deployment.

Techniques for joining are important for initial construction, as well as for repair. This research examines one such technology, which is high strength adhesive bonding using carbon fiber embedded heaters. There are a number of advantages of bonding as a method of joining. Minimal material is added to the structure when compared to fastening, and the bond becomes part of the structure, which equates to less weight to bring to space. It does not require drilling into materials, which for composites can cause damage and stress concentrations in the adherends, requires heavy tooling, and drill heads that need replacement.[6,7] However, there are downsides to adhesive bonding. Some high strength adhesives require cold storage before use, elevated and controlled temperatures for curing, and skilled technicians for application.

The use of carbon fiber embedded heaters for bonding has been shown to produce bonds of comparable strength to more traditional methods, such as heat blankets or ovens.[8–10] Embedded heaters for bonding would be particularly well suited for space applications due to its minimal need of large specialized equipment, and it is extremely efficient by targeting heating to the bondline. The adhesives and carbon fiber used for embedded heating can also be chosen to match the materials in the adherends, thereby reducing stress concentrations.

This paper investigates the feasibility of adhesive bonding in space using carbon fiber embedded heaters. In normal Earth operating conditions, a vacuum and over-pressure are applied by vacuum bagging. The combination of vacuum and pressure is necessary to minimize voids within the bond.[11,12] This process requires extra equipment such as a vacuum pump, and materials used once and discarded. The advantage

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of attempting this in space-like conditions is that there is a natural vacuum. However, using the natural vacuum of space introduces new problems to be investigated, two of which this study will seek to address. The first is whether the high vacuum of space would cause improper curing and a weakened joint due to outgassing. The second is that it becomes necessary to apply an external source of over-pressure to the joint. This study will look at whether space-like vacuum with the addition of over-pressure can produce a bond of similar quality to bonding with vacuum bagging.

## II. Methods

This experimental study examines the ability of embedded heaters to form a high quality adhesive bond in a vacuum chamber with an apparatus applying external pressure. The quality of the bond will be compared to specimens created using an embedded heater with the standard vacuum bagging technique. The cure profile for both experiments was a ramp up rate of 3 °C per minute until reaching 177 °C, hold at this temperature for 2 hours, then ramp down at a rate of 3 °C per minute. A single-lap joint configuration was used for this study, with specimens created to the ASTM standard D5868.[13]

The heater configuration which was used for the vacuum chamber and vacuum bag experiments can be seen in Fig. 1. Extra fabric was added on all sides of the bond area to minimize edge effects. After curing, this extra fabric can be removed. Voltage was applied to copper tabs at either end of the heater, with current flowing in the long direction of the heater. An Arduino based controller with solid state relays (SSRs) modulated voltage to the embedded heater, with power provided by a Variac power supply. Full details of this controller can be found in previous work.[9]



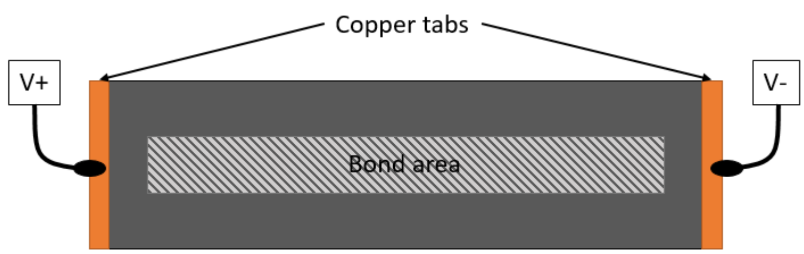



Figure 1: Schematic of an embedded heater, with AC voltage (V) applied at both ends. The bond area, which is smaller than the heater, is marked with cross-hatching.

The rest of this section will describe in more detail the two different methods used to create single-lap joints, bonding in a vacuum chamber, and bonding under a vacuum bag.

### A. Bonding experiment in a vacuum chamber

A bonding experiment was done in a vacuum chamber, which was brought to a vacuum pressure of 1% of atmospheric pressure. In addition to this vacuum, over-pressure of 33.86 kPa was applied using a fixture of plates and screws, which can be seen in Fig. 2. The joint was placed between the silicon rubber spacers. Using pressure sensors (FlexiForce A401-25) under the pressure plate, the screws were adjusted to get uniform pressure across the bond area.

The layup of the single-lap joint to be bonded in the vacuum chamber can be seen in Fig. A. This consisted of an embedded heater, surrounded by film adhesive on both sides, all placed inside a bottom and top adherend. Non-porous teflon sheet was placed between the embedded heater and adherends to avoid electrical shorting.

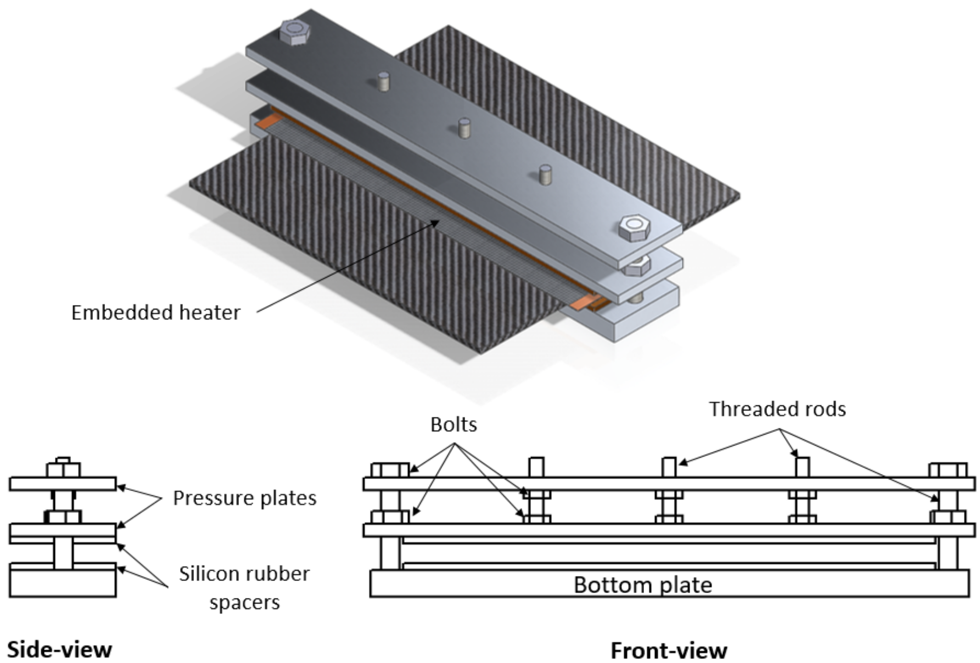



Figure 2: Schematic of fixture to apply over-pressure to single-lap joint during bonding in a vacuum chamber.

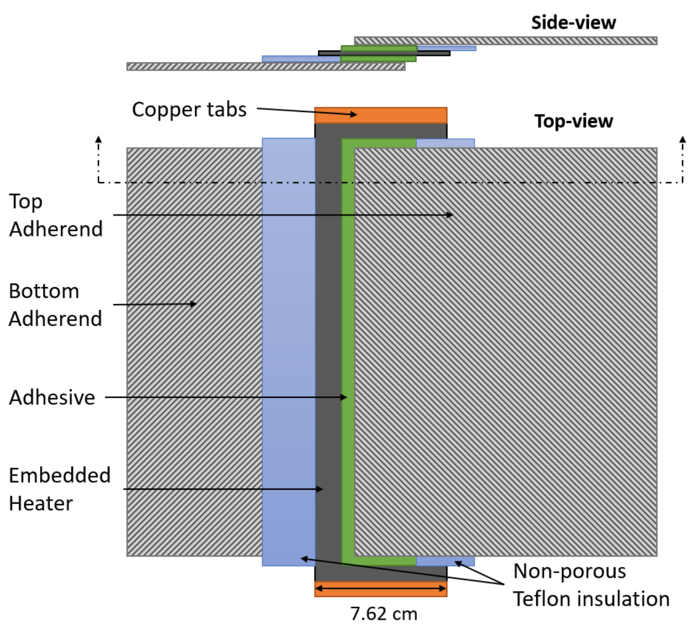



Figure 3: Side and top views of the embedded heating layup with adherends. This layup was used in the vacuum chamber and for vacuum bagging.

### B. Bonding experiment under vacuum bag

A bonding experiment was done using an embedded heater under a vacuum bag. The layup was similar to the experiment done in the vacuum chamber. The layers for this bonding can be seen in Fig. 3. Vacuum pressure of 33.86 kPa (approximately 66% or atm) was applied using a vacuum pump. This pressure is the same pressure applied via the pressure apparatus in the vacuum chamber.

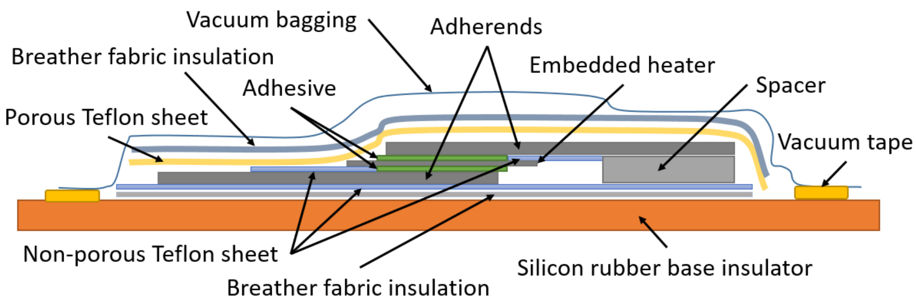



Figure 4: Side view schematic of bonding with embedded heater under vacuum.

## III. Materials

The single-lap joints produced in this study are comprised of two carbon fiber composite adherends, bonded together with a single layer of carbon fiber prepreg, sandwiched between two layers of film adhesive. Both the adherends and embedded heater were made with graphite/epoxy plain weave prepreg produced by HEXCEL (BMS8-168), and the adherends were 8 layers with a stacking sequence of $[0, 90]_{2s}$.

The film adhesive was the Master Bond polymer system FLM36-LO. This adhesive did not have a carrier film, but carrier film is recommended when using embedded heaters to reduce the chance of shorting between the heater and adherends. A noteworthy characteristic of the chosen adhesive is its low outgassing conformity to the NASA ASTM E595 specification. It is electrically insulating, and can be stored at room temperature. The recommended cure temperature is 1-2 hours at 177 °C.

## IV. Results

The specimens created in the vacuum chamber and under a vacuum bag were compared by first examining specimens under a microscope, and then through tensile testing. Before testing, the specimens were cut out of the 22.86 cm specimens into approximately 2.54 cm samples, as shown in Fig. 4.

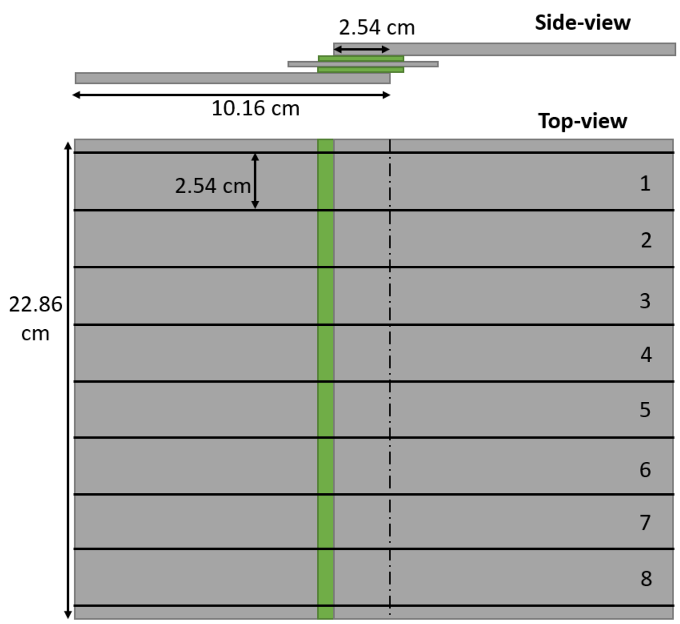
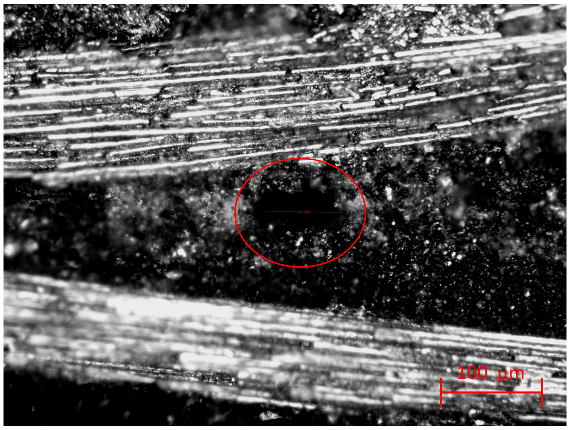
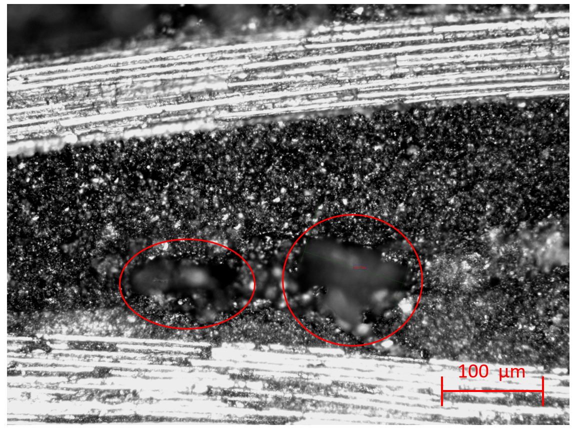


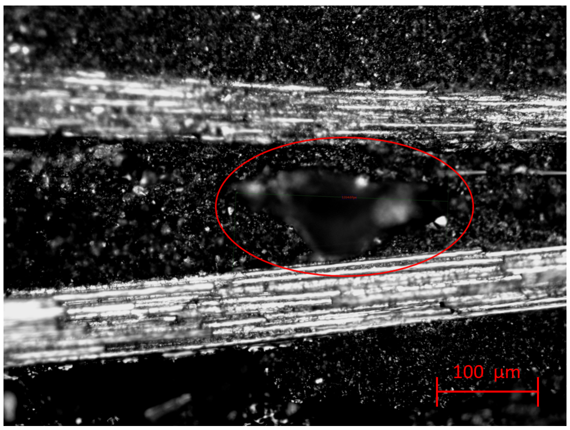

Figure 5: Schematic of a bonded single lap joint, to be cut into 2.54 cm wide specimens for tensile testing.



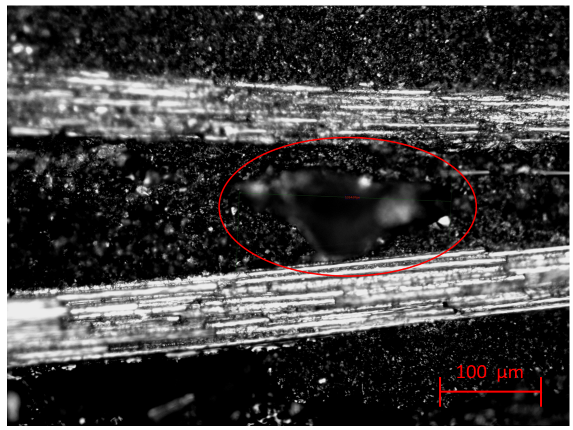

(a) Vacuum chamber sample 2




(b) Vacuum chamber sample 4




(c) Vacuum bag sample 2




(d) Vacuum bag sample 4

Figure 6: Photos of the bondline from samples of each bonding method. Photos were chosen where voids were found, which are circled in red.



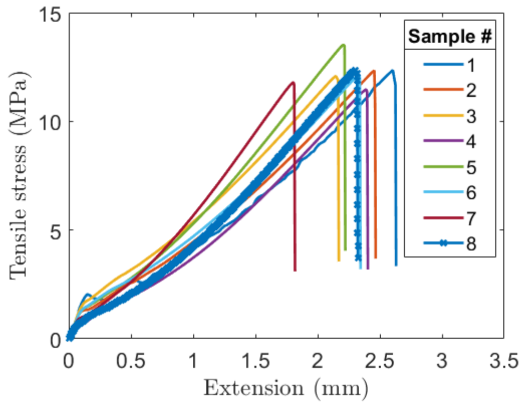
### A. Bondline under the microscope

After each set of adherends were cut into 8 tensile specimens, 2 samples from each were examined under a microscope. The samples examined are numbered 2 and 4 as shown in Fig. 4. After cutting, the edges of these samples were sanded consecutively with 240, 800, and 1200 grit sandpaper. They were then wiped with paper towels and acetone for cleaning. On the two cut edges of these samples, the center 1.27 cm of the bondline was scanned with a microscope to look for void content.

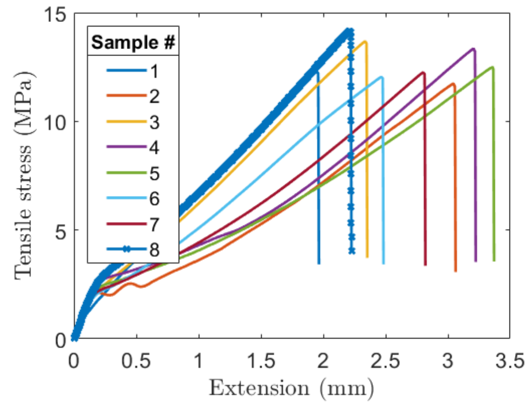
Quantitatively, both the vacuum chamber and vacuum bagging specimens appeared to have comparable void content, though these voids did not make up a significant fraction of the bondline. A snapshot of the bondline for each sample can be seen below in Fig. 5. Photos were selected where voids were found, which are highlighted by red circles in the photos.

### B. Tensile testing

Using the prepared samples produced from bonding in the vacuum chamber and vacuum bagging, tensile tests were performed in a 100 kN capacity Instron test frame. The raw results can be seen in Fig. 6, with the maximum loads listed in Table 1. The plots in Fig. 6 show that the vacuum chamber produced samples with noticeably less scatter, and on average had less displacement at failure. However, the mean load at failure was about 5% lower for the samples produced in the vacuum chamber. Taking a two sample $t$-test on this data, it cannot be said that these samples are statistically different, with $p = 0.14$. This indicates that the results show that the tensile strengths of the two methods are similar. After the samples were broken,




(a)




(b)

Figure 7: Tensile testing results for a) vacuum chamber, and b) vacuum bagging

the fracture surfaces were examined, and adhesive was found on both sides of every fracture surface. This implies good adhesion and cohesive failure.

Table 1: Table of tensile test results for each method, with maximum tensile load at failure, mean maximum load, and standard deviations.

| Sample (#) | Vacuum Chamber Max Load (N) | Vacuum Bag Max Load (N) |
|---|---|---|
| 1 | 7489.4 | 7608.5 |
| 2 | 7459.8 | 7217.2 |
| 3 | 7550.8 | 8445.3 |
| 4 | 7194.4 | 8339.1 |
| 5 | 8414.3 | 7872.1 |
| 6 | 7595.2 | 7615.6 |
| 7 | 7372.7 | 7686.8 |
| 8 | 7719.9 | 8924.2 |
| Mean | 7599.6 | 7963.6 |
| Std. Dev. | 364.1 | 558.7 |

# V. Conclusion

This study examined the feasibility of using embedded resistive heaters made of carbon fiber for high strength adhesive bonding in space. This was done by bonding a test specimen in a vacuum chamber at around 1% of atmospheric pressure, which was compared to bonding under a vacuum bag at 66% of atmospheric pressure. A pressure apparatus was used in the vacuum chamber so that equal over-pressure was applied for both methods. No significant difference in void content was found by looking at the bonds under a microscope, or by tensile testing. While it did appear that the samples bonded at a higher level of vacuum did have lower variation in bond strength, and a slightly lower average load at failure, these difference were not statistically significant. An additional comparison was made with samples made in an autoclave, which can be found in the primary author's thesis.[14] This work used relatively few samples, and could benefit from a larger sample size. Future work could look at higher levels of vacuum, as well as other common high strength adhesives.

# Acknowledgements

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