Resistive Embedded Heating for Homogeneous Curing of Adhesively Bonded Joints

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Adhesively bonded single-lap joints with laminated composite adherends were cured using heat generated by passing an electrical current through a carbon fiber fabric embedded in the bondline. Resistance heating using the embedded fabric resulted in a uniform temperature distribution in the bondline, as compared to temperature fields typically generated using more conventional surface heating methods such as heat blankets or heat lamps. Composite single-lap joint specimens were created using the proposed embedded heating approach, via an oven cure under a vacuum and through the use of an autoclave. The bond strengths of all specimens were measured and found to be comparable. The proposed embedded curing technique results in bond strengths that equal or exceed those achieved with conventional methods, and at potentially lower cost.

Keywords: Adhesively bonded joints, resistive heating, homogeneous curing, composite repair, DIC in bonded joints

1. **Introduction**

Composites have better strength-to-weight and stiffness-to-weight ratios when compared to metals, and therefore, composite structures enable aircraft to be more fuel-efficient. The increased use of high-strength Carbon Fiber Reinforced Polymers (CFRP) in passenger aircraft has resulted in an escalation of maintenance issues associated with composite structures. Hence, the repair of damage to composites has become an important issue in the aerospace industry. A common requirement is to rapidly repair a composite structure without removing it from the aircraft. Repair of thick structures while still on the aircraft can be difficult to achieve. For example, the thermal energy necessary to cure the repair adhesive must diffuse through the composite layers to reach the joint repair interfaces, resulting in long and expensive processing times as well as wasted energy [1-3]. Surrounding heat-sensitive materials or equipment may also be damaged. The most popular approach to is to use a surface heater such as heat blanket(s) and/or heat lamps to generate the heat needed to cure the repair adhesive. In these approaches the entire structure is heated to initiate cure of the repair adhesive, typically a high-strength thermoset such as an epoxy. CFRPs typically exhibit poor thermal conductivities and consequently the temperature of the heated surface can be much higher than the temperature at the subsurface repair bondline. Large thermal gradients are inevitably created, resulting in an inefficient repair process.

We propose to overcome these difficulties by passing an electrical current through a carbon fiber fabric sandwiched between two layers of structural adhesive film and embedded in the bondline. The carbon fabric serves as an embedded a resistance heater. A substantial advantage of this approach is that the carbon fibers that initially serve as heating elements remain in the bondline as reinforcing materials. Since many types of carbon fibers have already been certified for use in transport aircraft (e.g., AS4 or IM7 fibers), which could facilitate certification of the proposed approach for use in commercial aircraft. The epoxy adhesive electrically insulates the embedded heater from the electrically conductive adherends. Moreover, it will be shown that bonded joints cured via an embedded resistive heating method have single-lap shear strengths comparable to the strengths of samples cured in an autoclave.

In the past literature, efforts have been reported to reduce the cost of producing thermoset/thermoplastic composites by avoiding the need for expensive autoclaves or ovens.

These methods could conceptually be used during composite repair, as discussed in reference [1]. As a case in point, UV photo-curable adhesives were utilized in the past and cured through, transmission of the UV light through the laminate [4, 5]. Microwave curing of composite materials has been considered as a highly efficient volume-heating radiation manufacturing process; however, heating efficiency of the microwave depends greatly on the dielectric properties of the material [6, 7]. Inductive heating or welding has proven to be effectively employed in an epoxy adhesive between composite adherends to cure the bond and produce strong joints [2, 8]. Nonetheless there are difficulties associated with edge and local heating effects that have limited large scale applications [1, 8-10]. Studies have been performed in the past to improve cure homogeneity by taking advantage of the conductivity of the carbon fibers embedded in the matrix to cure the carbon-fiber/epoxy pre-pegs internally [11-15]. References [12-14] utilized carbon fibers in the pre-pregs as resistive heaters to cure the composite laminates. In contrast, references [10, 11] reported the use of a carbon-fiber mesh sandwiched between resin/resin saturated fiber layers to create composite parts. The current paper focuses on adapting such use of carbon-fiber resistive heaters to bond composite materials, which can be potentially used in composite repair applications. Resistive heating in bonding applications is a relatively new technique, and very few studies are available in the literature. Rider et al. [1] reported the use of a stainless steel mesh as an embedded resistive heater to achieve shear strength similar to the joints cured by the conventional methods; however, shear strength was proven to be highly dependent on the stainless steel mesh surface treatment. Additionally, Mas et al. [16] cured epoxy resins were cured with Joule heating of dispersed carbon nanotubes (CNTs) which were deposited on the epoxy using a three roll mill. Subsequently, the epoxy resin was used as an adhesive to repair an aerospace composite panel. Composite parts were used as electrodes to pass electricity to the CNTs dispersed in the epoxy in reference [16], which led to very fast heating rates and uniform curing.

In this paper, an experimental investigation examining the cure of a thermoset adhesive film between carbon composite adherends by using resistive heating of an embedded carbon fiber mesh is described. It is shown that the method is energy-efficient and results in low temperature gradients due to the negligibly small distance between the heat source and the repair bondline.

The technique could be applied to large scale composite repairs, or possibly employed during original manufacture of a bonded composite structure.

2. Materials and Methods

2.1 Materials

The single-lap join specimens were fabricated using composite panels manufactured using carbon/epoxy prepreg (Toray T800-HB-12K-40B) with $[0/+45/90/-45]_s$ quasi-isotropic stacking sequence and cured in autoclave according to the curing cycle suggested by the prepreg manufacturer (1.66 °C/min heat-up rate, 130 minutes hold at 176.67 °C with 586 kPa external pressure with vacuum). The composite laminates were then cut to 22.9 cm × 10.2 cm using an abrasive disc. One 22.9 cm edge of each panel was sanded with 240 grit paper, degreased using acetone, and then air dried for two hours.

Unidirectional carbon fabric (12K, 0.1524 mm thick) was purchased from Fibre Glast to be used as the embedded mesh fabric, and is shown in

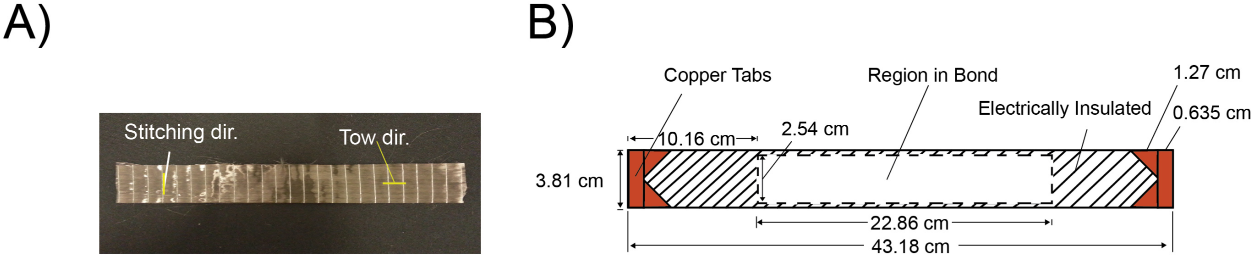


Figure 1A. The fabric was cut to the dimensions depicted in

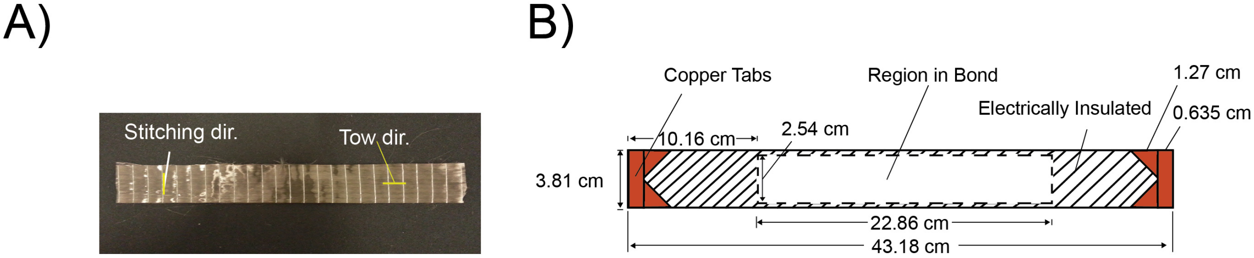


Figure 1B. Flash tape was used to electrically insulate the out-of-bond regions of the embedded fabric from the conductive adherends.

Two layers of structural adhesive film (Scotch-Weld AF 163-2U) with 0.0635 mm thickness were used to bond the adherends. Modulus of elasticity, shear modulus, and poisson’s ratio of the mentioned adhesive were reported by its manufacturer to be 1110 MPa, 414 MPa, and 0.34 at

24°C respectively. The adhesive films were cut slightly larger than the bonding region to ensure no contact between the embedded fabric and the adherends.

2.2 Embedded resistive curing of bonded joints

Carbon/epoxy composite panels are electrically conductive, and might interfere in the resistive heating process in the case of any contact between the embedded fabric and adherends. Therefore prior to any experiments, resistance testing was conducted to ensure complete electrical insulation between the embedded fabric and the composite adherends. In the bond region, a layer of thin adhesive film was placed on each side of unidirectional carbon fabric. As it is shown in Figure 2A a flat plate was used to avoid bending of the top adherend. Several layers of bleeder cloths were used as thermal insulators in order to minimize the transfer of heat to the underlying caul plate during the cure process. Figure 2B shows the experimental setup prior to and after insulation and vacuum bagging. Vacuum pressure was applied to the setup prior to the heating process, and was kept at 33.86 kPa until the sample reached the ambient temperature. A proportional-integral-derivative (PID) Controller (Omega CN7500) was connected to a variable voltage convertor. The standard line voltage of 110 V was stepped down to 50 V before applying to the embedded heater for the resistive curing. The end-to-end resistance of the carbon fabric mesh was measured to be 14.5 Ω, and therefore the maximum power generated was approximately 170 W which is considerably lower than the power consumption of a typical autoclave. The PID controller provided control of the power output with a thermocouple input embedded in the middle of the bond to provide temperature feedbackA thermal camera (FLIR T-640) was used to monitor the temperature distribution in the bond region, as shown in Figure 3A. Figure 3B shows that the temperature distribution was relatively uniform along the bond region, which is a desirable condition in any composite repair systems [3]. Furthermore, no local hot spots were observed on the embedded fabric, where can potentially damage the thin film adhesive through excessive heat.

The embedded resistive heating method can also be applied to the larger bond areas with some changes. For example, in cases where the use of an embedded thermocouple is undesirable, the uniform temperature distribution in the embedded fabric (see Figure 3B) can enable temperature control using thermocouples outside of the bond area. Additionally, internal temperatures could be estimated using external temperature sensors. Moreover, the amount of the heat produced in the embedded heater depends on the geometry, and the tow size of the carbon fiber mesh, which can be optimized for the bond area. For example, it is possible to use multiple, parallel embedded carbon-fiber meshes, with separate heaters to achieve the desired cure temperature for large areas.

2.3 Curing adhesively bonded joints through conventional methods

The shear strength of the bonded joints fabricated using embedded resistive heating was compared to strengths of test samples manufactured in an oven as well as in an autoclave. Vacuum pressure of 33.86 kPa was applied to the oven cured samples. In the autoclave cured samples a 344 kPa overpressure was applied in addition to vacuum pressure, in accordance with the suggested curing pressure from the adhesive manufacturer. Additionally, bonded joints with two layers of adhesive film and without an embedded fabric in the bond were produced to compare with the samples having an embedded mesh inside. Three K-type thermocouples were embedded on the mesh to monitor the temperature inside of the joints. **Error! Reference source not found.** shows the location of each thermocouple located in the bond region. Furthermore, feedback from TC-Middle was used to control temperature during the curing process. Temperature increase rate was 2 °C/min, and temperatures were maintained to at least 120°C for 1hr, as shown on **Error! Reference source not found.**A. Pressures were maintained during cool down to ambient conditions. **Error! Reference source not found.**B presents the temperature data feedback recorded by all three thermocouples in embedded resistive heating method.

Seven single-lap specimens were machined from these panels, as shown in Figure 6. Specimen width was 25.4 mm. Note that the three thermocouples used to monitor and control bondline temperatures were now embedded within the bondline, so these regions of the panel were not used to produce single-lap joint specimens.

2.4 Testing

Uniaxial tensile loading of the specimens were performed in accordance with ASTM D5868-01 standard in a 100kN capacity Instron load frame using displacement control at a crosshead displacement of 12.7mm/min. Subsequently, failure load for each specimen was reported.

2.5 Study of strain gradients in a bonded joint using Digital Image Correlation (DIC)

Experimental measurement of strains in the bond-line of an adhesively bonded joint can play a significant role in the design of bonded structures [17]; however, there are some difficulties associated in obtaining adhesive strains. One of the major difficulties is the small bond-line thickness. Therefore, non-contact optical methods are ideally suited for such measurements [18]. Digital Image Correlation (DIC) is a relatively new optical method that provides full-field displacements and strains while, being relatively simple in preparation and setup [19, 20]. Briefly, a speckled pattern is applied to the surface of interest, and a digital image of the surface is recorded before and after loading. A correlation algorithm is then used to determine displacement fields caused by the loading. The displacement fields are then differentiated to obtain strains. Both two- and three-dimensional versions of DIC have been developed [21].

In this study strains were measured using the three-dimensional DIC method. The Vic-3D commercial package available from Correlated Solutions was used. This package includes two Point Grey digital cameras with a pixel resolution of 2448 × 2048, two Schneider Xenoplan lenses (focal ratio: 1.9 and focal length: 34.9 mm), a stereo camera mounting system, and the Vic-3D post-processing software. To create the speckle patterns on the bonded joints, samples were first lightly coated with white spray paint. After drying, black paint was sprayed quickly past the surface in a sweeping motion using an air brush, creating a high-contrast speckled pattern. Full image correlation requires that the speckle size be small enough in the deformed image such that, each subset contains sufficient unique information [22]. Speckle size was controlled by modifying the nozzle, air pressure, and throttling the spray. Images were taken every 1112 N during tensile testing of the specimens. Post-processing was performed using Vic-3D to calculate deformation and strains in the bonded joints. .

3. Results and Discussion

3.1 Shear strength of single lap joints

Embedded carbon fiber fabric increases the effective stiffness as well as the thickness of the bondline. Consequently, specimens with and without embedded carbon fiber mesh were produced in an autoclave as well as in an oven to understand the potential effect of the embedded heater material on the overall performance of the bonded joint. As shown on Figure 7a, the oven cured joints without embedded fabric exhibited higher average shear lap strength, in comparison with similarly cured specimens with the embedded carbon fiber mesh. In contrast, autoclave cured samples with inclusion of the mesh had higher average strength comparing to the ones without the embedded fabric cured in similar condition. Nevertheless, shear lap testing results have shown that that the average joint performance where the adhesive was cured using embedded resistive heating was similar or higher than the other test samples regardless of their curing condition and inclusion/exclusion of the embedded fabric. Lap shear failure loads for bonded joints cured by embedded resistive heating, cured in oven and autoclaved are presented in Table 1. Figure 7b shows load vs. displacement curves for specimens close to the average strength of every curing method. Moreover, load vs. displacement curves were different with respect to curing method. Figure 8 shows typical failure surfaces for the samples with fabric embedded in the bond-line cured through embedded resistive heating and autoclave. Failure for the electrically and thermally cured joints (autoclave and oven cured samples) was observed to be a combination of interfacial failure and cohesive failure of the adhesive. Moreover, failure for the two specimen types was very similar and occurred partially close to the adhesive and composite inter-face, and partially between the uni-directional fabric and the adhesive. Some carbon fibers were also pulled out from the adherend surface. The failure surfaces were consistent with the similar joint strengths measured for the thermally and electrically cured samples (Table 1).

3.2 Strain measurements by DIC

Figure 9A shows maximum principal strain distribution results for five electrically cured bonded joints at 3336 N load level. Furthermore, maximum strain was observed on the edge as expected, and strain pattern was similar for all of the five test samples as well as the thermally cured specimens. As shown on Figure 9B, adhesively bonded joints that failed at higher loads showed higher joint stiffness than the rest of the samples. Although, the effect of joint stiffness on lap shear strength needs more investigation, this information could be potentially used to compare adhesively bonded joints' strength by non-destructive shear lap tests in the future.

4. Conclusions

This study examined adhesively bonded single-lap joints where the adhesive was cured using heat generated by passing an electrical current through a carbon fiber fabric embedded in the bondline. It was shown that joints cured by embedded resistive heating method can provide equivalent shear strength to oven- and autoclave-cured joints. These results indicate that this technique is capable to adapt to typical repair configurations with complex geometries and adhesives with different physical and chemical properties. Additionally, strain measurements using DIC showed that bonded joints with higher failure loads indicated higher joint stiffness in comparison with other test samples. It was shown rather than heating the entire system to cure the adhesive, controlled heating using an embedded carbon-fiber fabric was targeted at the bond-line. By localizing the heating to where it is needed, the proposed approach can substantially reduce the energy and cost of joining composite components, when compared to the use of autoclaves.

5. References

[1] Rider A.N., Wang C.H., Cao J., Internal resistance heating for homogeneous curing of adhesively bonded repairs, International Journal of Adhesion and Adhesives, 31 (2011) 168-76.

[2] Mahdi S., Kim H.-J., Gama B.A., Yarlagadda S., Gillespie J.W., A Comparison of Oven-cured and Induction-cured Adhesively Bonded Composite Joints, Journal of Composite Materials, 37 (2003) 519-42.

[3] Katnam K.B., Da Silva L.F.M., Young T.M., Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities, Progress in Aerospace Sciences, 61 (2013) 26-42.

[4] Turri S., Sanguineti A., Lecchi R., Novel Glass Fiber-Reinforced Composites Having a UV and Peroxy Curable Fluoropolymer Matrix, Macromolecular Materials and Engineering, 288 (2003) 708-16.

[5] Glauser T., Johansson M., Hult A., A comparison of radiation and thermal curing of thick composites, Macromolecular Materials and Engineering, 274 (2000) 25-30.

[6] Nightingale C., Day R.J., Flexural and interlaminar shear strength properties of carbon fibre/epoxy composites cured thermally and with microwave radiation, Composites Part A: Applied Science and Manufacturing, 33 (2002) 1021-30.

[7] Tanrattanakul V., Jaroendee D., Comparison between microwave and thermal curing of glass fiber–epoxy composites: Effect of microwave-heating cycle on mechanical properties, Journal of Applied Polymer Science, 102 (2006) 1059-70.

[8] Ahmed T.J., Stavrov D., Bersee H.E.N., Beukers A., Induction welding of thermoplastic composites—an overview, Composites Part A: Applied Science and Manufacturing, 37 (2006) 1638-51.

[9] Abliz D., Yugang D., Steuernagel L., Lei X., Dichen L., Ziegmann G., Curing Methods for Advanced Polymer Composites - A Review, Polymers & Polymer Composites, 21 (2013) 341-8.

[10] Carbas R., Viana G., da Silva L., Critchlow G., Functionally Graded Adhesive Patch Repairs of Wood Beams in Civil Applications, Journal of Composites for Construction, 0 (2014) 04014038-1-04014038-11.

[11] Ramakrishnan B., Zhu L., Pitchumani R., Curing of Composites Using Internal Resistive Heating, Journal of Manufacturing Science and Engineering, 122 (1999) 124-31.

[12] Zhu L., Pitchumani R., Analysis of a process for curing composites by the use of embedded resistive heating elements, Composites Science and Technology, 60 (2000) 2699-712.

[13] Santos C., Plaisted T., Arbelaez D., Nemat-Nasser S., Modeling and testing of temperature behavior and resistive heating in a multifunctional composite, Smart Structures and Materials, San Diego, CA 2004, pp. 24-6.

[14] Joseph C., Viney C., Electrical resistance curing of carbon-fibre/epoxy composites, Composites Science and Technology, 60 (2000) 315-9.

[15] Santos C., Plaisted T., Arbelaez D., Nemat-Nasser S., Modeling and testing of temperature behavior and resistive heating in a multifunctional composite, 2004, pp. 24-6.

[16] Mas B., Fernández-Blázquez J.P., Duval J., Bunyan H., Vilatela J.J., Thermoset curing through Joule heating of nanocarbons for composite manufacture, repair and soldering, Carbon, 63 (2013) 523-9.

[17] Ashrafi M., Ajdari A., Rahbar N., Papadopoulos J., Nayeb-Hashemi H., Vaziri A., Adhesively bonded single lap joints with non-flat interfaces, International Journal of Adhesion and Adhesives, 32 (2012) 46-52.

[18] Kumar R.V., Bhat M., Murthy C., Experimental analysis of composite single-lap joints using digital image correlation and comparison with theoretical models, Journal of Reinforced Plastics and Composites, 32 (2013) 1858-76.

[19] Pan B., Qian K., Xie H., Asundi A., Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review, Measurement Science and Technology, 20 (2009) 1-17.

[20] Ashrafi M., Tuttle M., High Strain Gradient Measurements in Notched Laminated Composite Panels by Digital Image Correlation, Composite, Hybrid, and Multifunctional Materials, Springer International Publishing, 2014, pp. 75-81.

[21] Sutton M.A., Orteu J.J., Schreier H.W., Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications, Springer London, Limited, 2009.

[22] Rajan V.P., Rossol M.N., Zok F.W., Optimization of Digital Image Correlation for High-Resolution Strain Mapping of Ceramic Composites, Experimental Mechanics, 52 (2012) 1407-21.

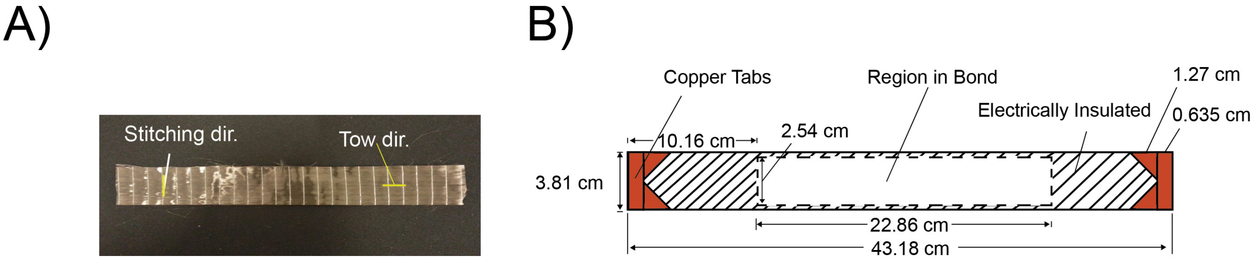
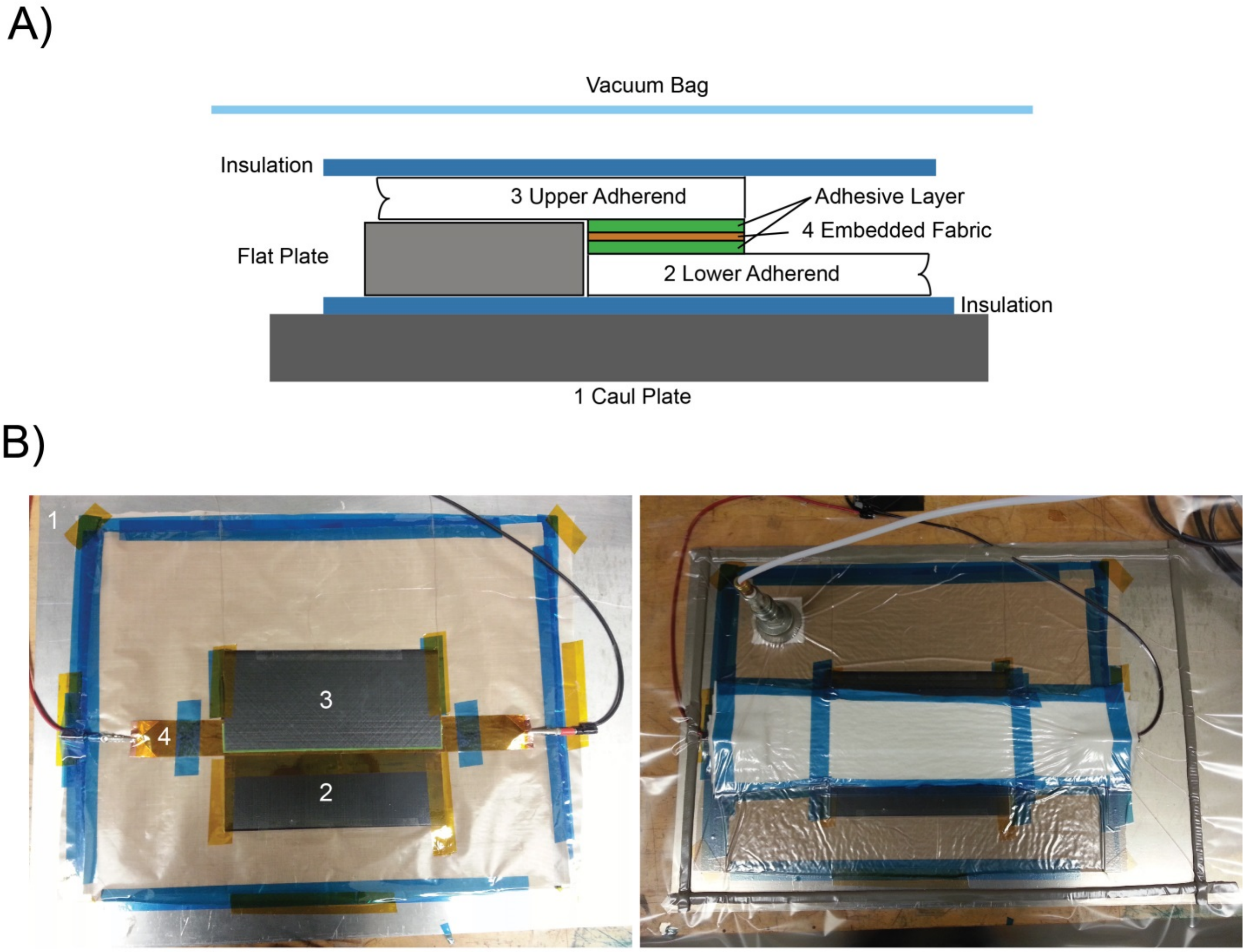


Figure 1- A) Uni-directional carbon fiber mesh used as the embedded heater. **B)** Schematic of the embedded carbon fiber mesh.



Prior to vacuum bagging and insulation

After vacuum bagging and insulation

Figure 2- **A)** Schematic of the experimental setup for embedded resistive curing of a single lap joint. **B)** Photograph of the experimental setup prior to and after vacuum bagging and insulation.

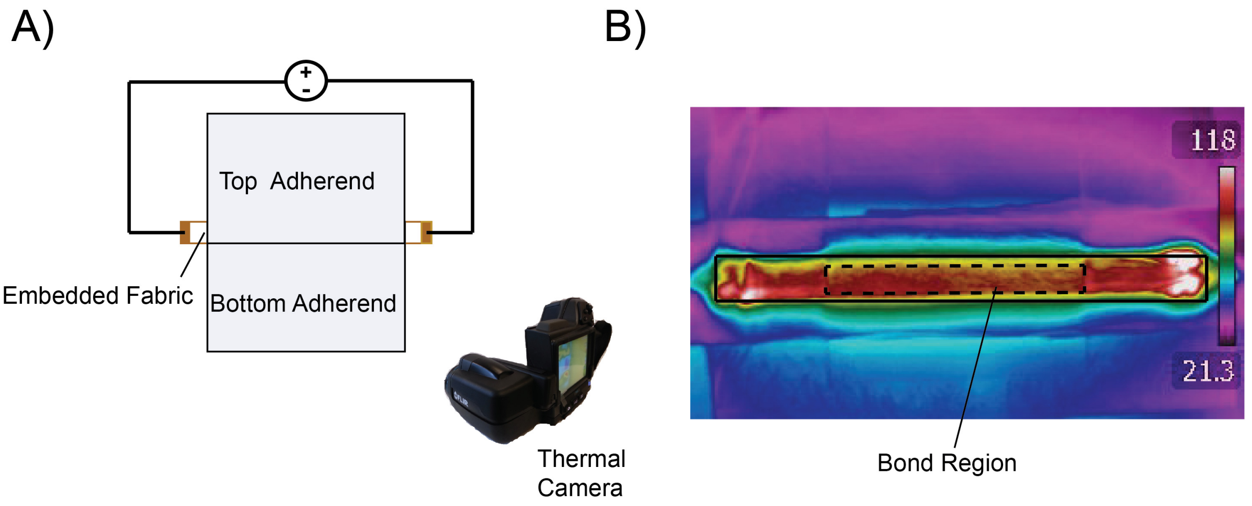


Figure 3- **A)**Schematic of the closed-loop control using an embedded temperature sensor. **B)** Thermal picture of the bond region shows that the temperature range in the overlap was about 15°C.

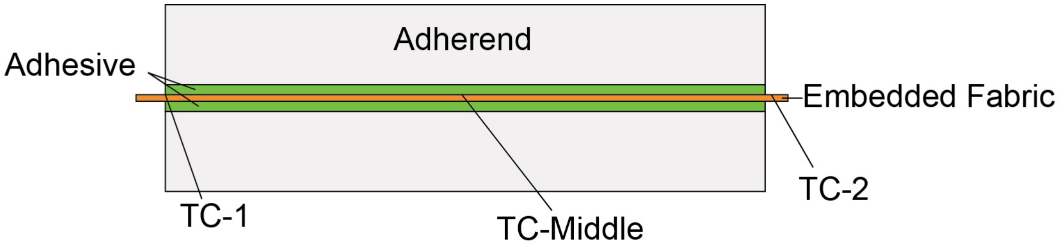


Figure 4- Schematic of the bondline showing the location of thermocouples.

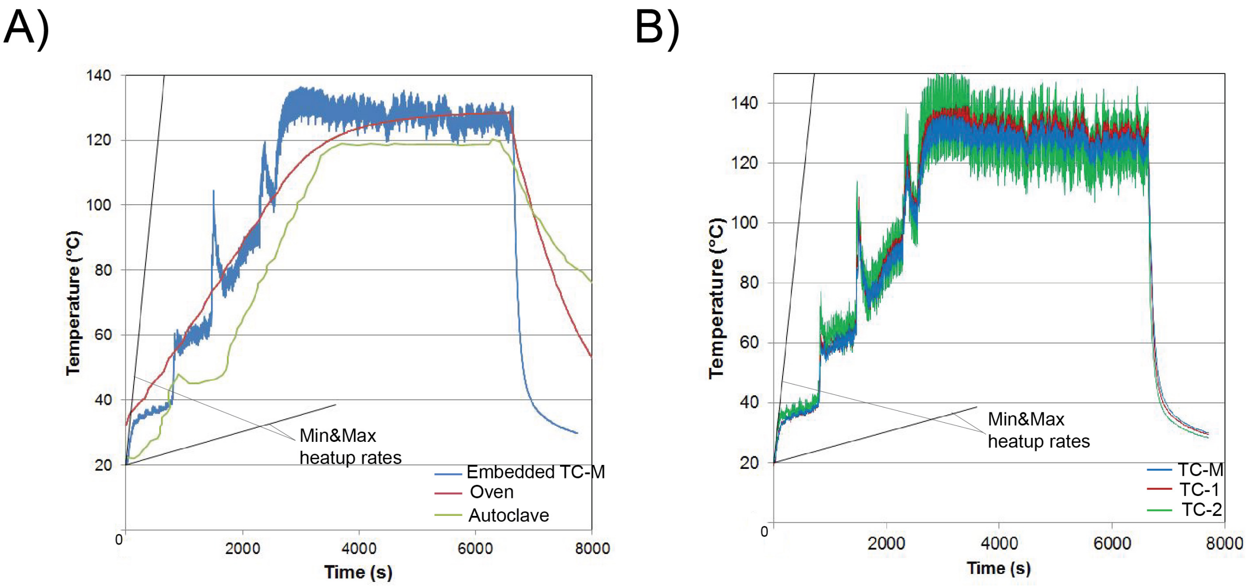


Figure 5- A) Temperature feedback for TC-Middle in all three cure processes. **B)** Temperature feedback for TC-Middle, TC-1, and TC-2 in the embedded resistive heating cure process.

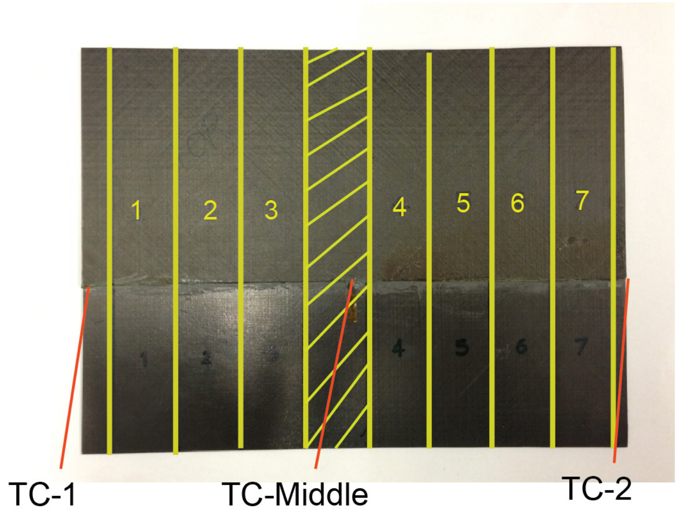


Figure 6- Photograph of cured single lap joint prior to cutting to shear lap specimens.

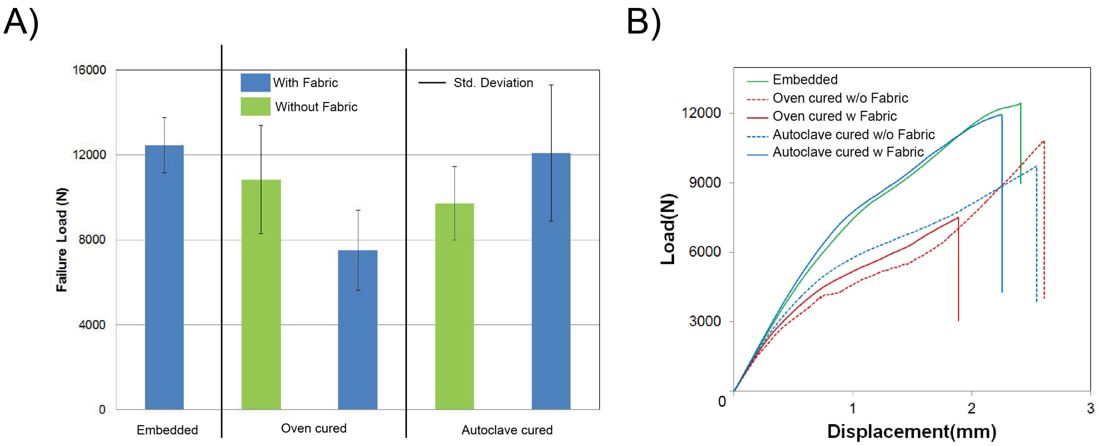


Figure 7- Average lap shear faiilure loads for the single lap joints

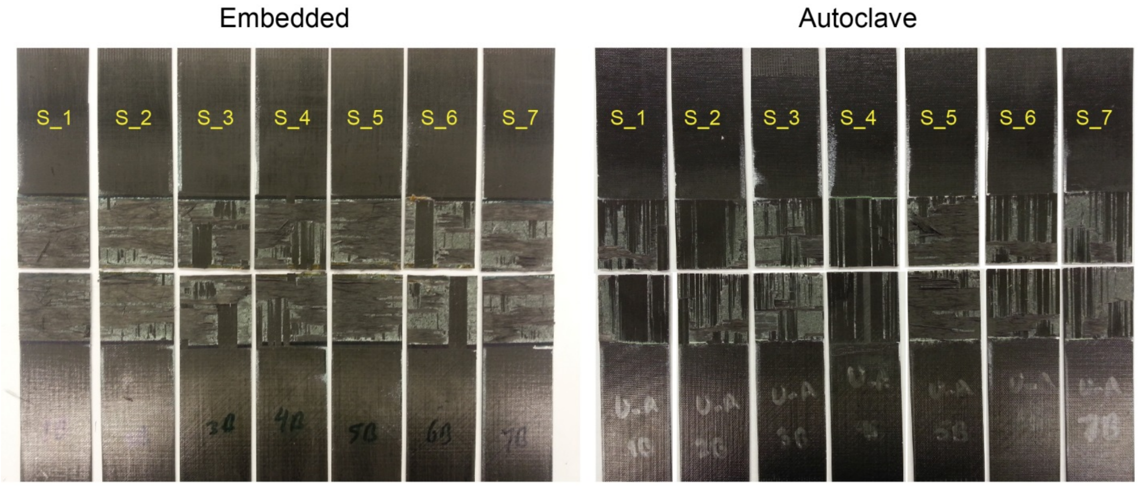


Figure 8- Failure surfaces of the single lap joints with inclusion of mesh fabric

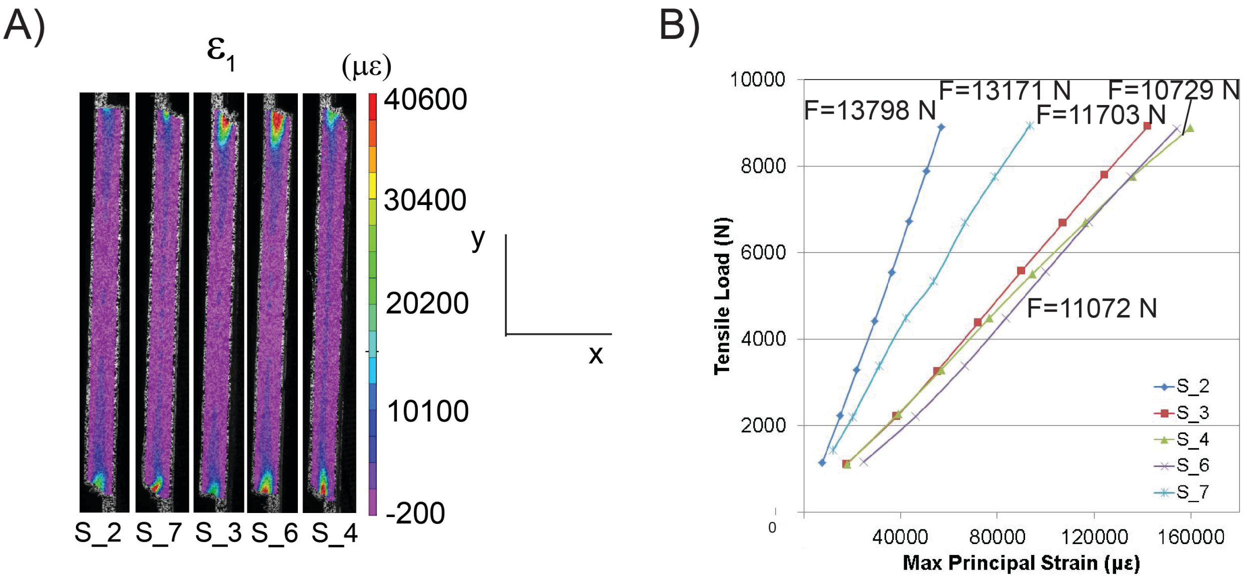


Figure 9- A) Maximum principal strain for samples cured by embedded resistive heating method. **B)** Maximum principal strain for samples cured by embedded resistive heating method

No.	Embedded Fabric (N)	Oven Cured (N)		Autoclave Cured (N)	
		W/O Fabric	W Fabric	W/O Fabric	W Fabric
1	13997	8014	6676	11505	5605
2	13804	11058	4306	10630	11099
3	11708	13200	6401	8910	13064
4	10734	10898	8757	6359	14590
5	12737	14138	9161	9448	15288
6	11077	7118	8727	10251	11951
7	13177	11444	8543	10962	13096
Avg.	**12462**	**10839**	**7510**	**9723**	**12099**
Std. Dev.	1305	2540	1886	1726	3202

Table 1- Lap shear failure loads for all of the single lap test specimens.