FAA Joint Advanced Materials & Structures (JAMS) Center of Excellence
6th Annual Technical Review Meeting May 19–20, 2010

CACRC DEPOT BONDED REPAIR INVESTIGATION – ROUND ROBIN TESTING

John Tomblin and Lamia Salah
National Institute for Aviation Research, Wichita, KS

Curtis Davies
FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ

ABSTRACT

INTRODUCTION

Composites have many advantages for use as aircraft structural materials including their high specific strength and stiffness, resistance to damage by fatigue loading and resistance to corrosion. Thus, extensive use of composites should reduce the high maintenance costs associated with repair of corrosion damage normally associated with conventional aluminum alloys. Similarly, costs associated with the repair damage due to fatigue should also be substantially reduced, since composites do not, in general, suffer from the cracking encountered with metallic structures.

As more composites are increasingly used on aircraft components, new challenges associated with composites are continually arising. These challenges are primarily focused towards the migration of composite repairs, of which the majority was previously in control surfaces and fairings, to the fuselage, wings and other safety critical primary structure. As most repair depots around the world prepare for this migration the philosophy and training necessary to ensure the quality and durability of these repairs will continue to increase. These repairs will affect the new general aviation business jet aircraft and smaller piston driven planes as well as large commercial transport aircraft.

The proposed project will investigate the effects of several bonded repair variables and characterize the strength of the repairs using various experimental methods to determine the effectiveness of the repairs. The repairs will be representative of typical OEM and field repairs in an attempt to characterize the quality of the repair and if any deviations in the processing and repair techniques at the depot can result in poor repair performance. The methods and repair procedures proposed by the Commercial Aircraft Composite Repair Committee (CACRC) will be utilized whenever possible and input will be provided to the FAA which can be used in general guidelines for bonded repair and also placed into training curriculum for short courses on composite repair.

Furthermore, the current NDI methods cannot provide absolute assurance of bond integrity (i.e., may fail to detect a weak bond due to poor surface preparation, pre-bond moisture, under or over-cure, surface contamination, etc.).

As a consequence, a substandard repair is not detected until it actually disbonds, leading to a possible failure of the repaired part. It is therefore essential to quantify the performance of these weak joints and draw attention to the need for appropriate training in the composite repair community. This will help identify the degree of criticality of the different steps within a bonded repair and subsequently lead to more rigorous repair procedures

BACKGROUND

As more composite materials are increasingly used in aircraft structural components, it is important to develop repair philosophies that will restore the structure to its original design capability. This implies development of maintenance procedures that clearly define the allowable damage limit (ADL) for the structure and provide efficient and reliable NDI and repair methods (figure 1).

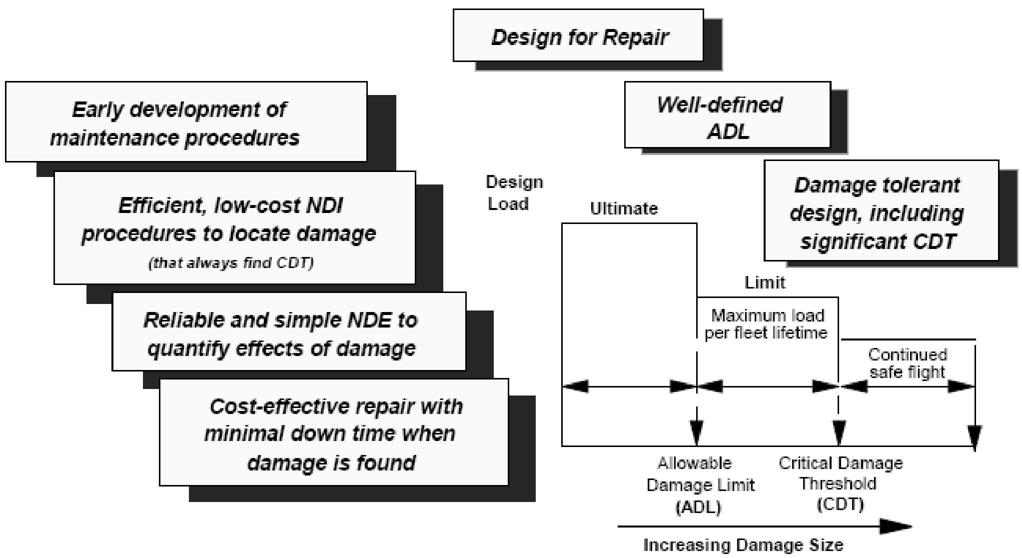


Figure1. Maintenance development philosophy established during the Boeing/NASA (ATCAS) composite fuselage program

Adhesively bonded repairs have significant advantages over bolted repairs. Adhesively bonded repairs can restore a composite structure's original strength, are more fatigue resistant due to the absence of stress concentrations that occur at fasteners and are significantly lighter than bolted repairs due to the absence of fastener hardware. Adhesively bonded repairs have limitations due to the fact that a bonded joint is a single joint thus there is no redundancy in the load path. Furthermore there are no NDI methods that can provide assurance of absolute bond integrity. Adhesively bonded repairs are process dependent and therefore repair technicians must have adequate proficiency to successfully complete the bonding process.

The commercial aircraft composite repair committee (CACRC) developed an industry standard for the certification of composite repair technicians. A previous research program has demonstrated that the quality of training and experience of repair technicians will directly affect the technician's successful completion/ implementation of a repair (Figure 2). This study has indicated the quality and reliability of a composite repair is much more directly linked to the skills/knowledge of the repair technician than was previously believed and specified in the standard. The focus of the proposed research will address this issue to verify if the proposed CACRC standards for composite repair technicians are appropriate and to look into any deviations which may be easily overlooked in the repair procedure which may lead to poor repair performance.

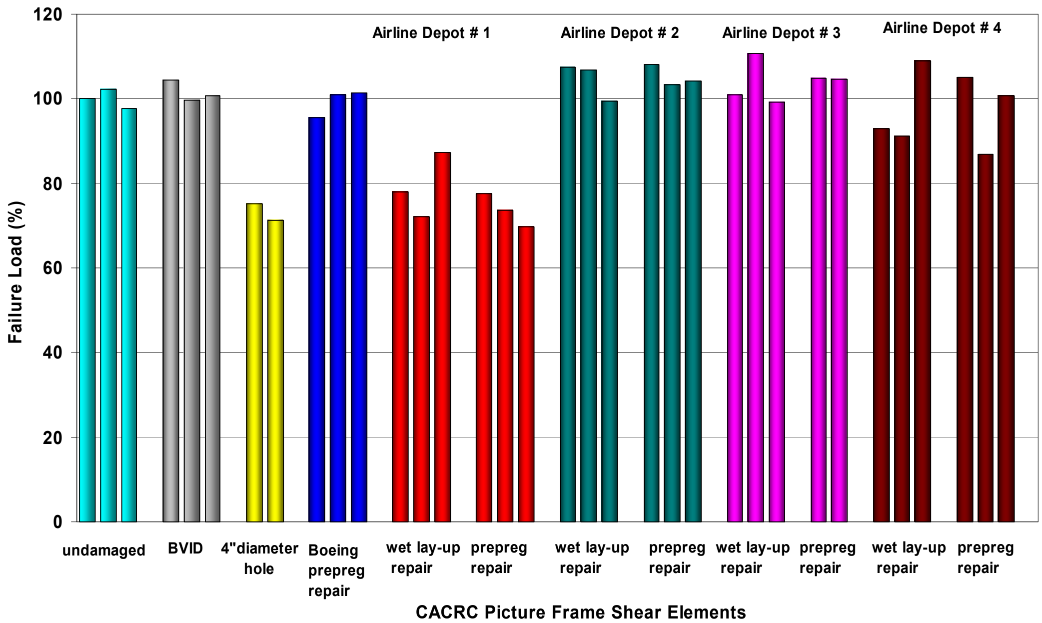


Figure 2. CACRC Investigation Results (ref [1]).

In the previous research program (Ref [1]), the main objective of the investigation was to evaluate the structural performance of picture frame shear sandwich coupons repaired using two different methods, an OEM method using a prepreg repair and a CACRC method using a wet lay-up repair as shown in figures 3 and 4. These repairs were conducted at four different airline depots. For comparison purposes, baseline undamaged coupons as well as coupons repaired at the OEM were also tested. All data presented in Figure 2 was normalized with respect to the average of the failure loads obtained for undamaged coupons.

As shown in figure 2, the picture frame shear elements repaired by the OEM using a prepreg patch restored the original strength. In fact, of all three coupons loaded to failure, two exceeded the average pristine strength (100%) and one reached 95% of this value. This demonstrates that the OEM prepreg repair, if properly implemented, is capable of restoring the structure's original strength capacity.

The same repair concept, implemented by airline depots 2, 3, and 4 exceeded the average strength of the pristine coupons i.e., the 100% value, except one coupon repaired by airline depot 4 which reached only 88% of the undamaged strength. However, using the same repair methodology, the strength values obtained from coupons repaired at airline depot 1 were 25% lower than the average undamaged strength.

When assessing the validity of the wet lay-up repair methodology, it was found that coupons repaired by airline depots 2, 3, and 4 reached at least 92% of the original strength. Of all nine coupons tested, only two of them had strength values below 99% of the undamaged strength. However, the wet lay-up repairs carried out at airline depot 1 showed a strength reduction of about 23% with respect to the baseline undamaged strength.

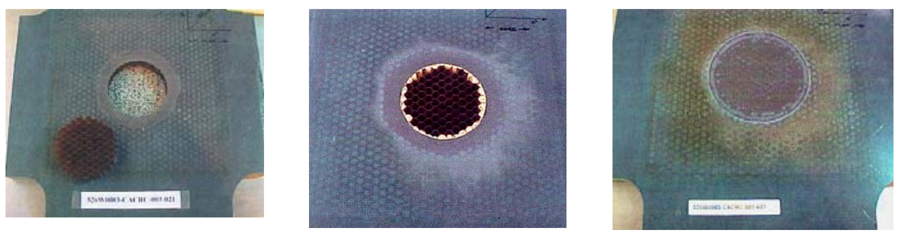


Figure 3. Picture Frame shear elements repaired using the OEM method

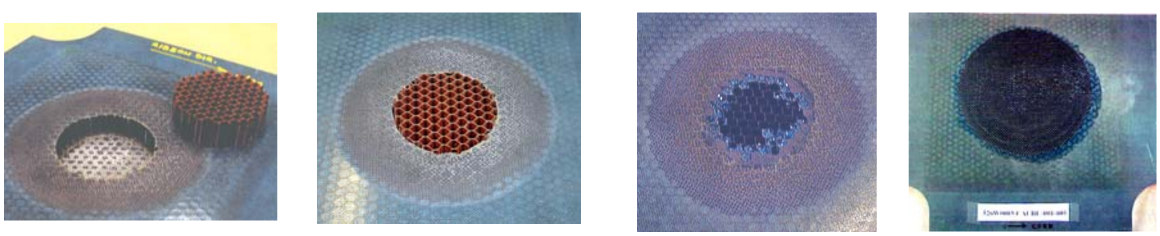


Figure 4. Picture Frame shear elements repaired using the CACRC method

In an attempt to identify what might have caused the premature failure of the picture frame shear coupons repaired at airline depot 1, further investigation revealed that the problem actually stemmed from a failed curing stage due to improper training and/or unfamiliarity of the piece of equipment used for the final curing. This failure was representative of an equivalent open hole, the size of the damage repair site and an indication of an ineffective repair.

Another study has shown that bond contamination will yield a substandard repairs (pre-bond moisture, bond contamination). In this study composite laminates of various thicknesses and moduli were scarfed and subjected to contamination including skydrol, perspiration, jet fuel, paint stripper and water. After contamination, the scarfed panels were cleaned per the OEM specifications and subsequently repaired and cured. After curing, the panels were tabbed and subsequently machined into 4” wide single scarf joints as shown in figures 5 and 6 below.

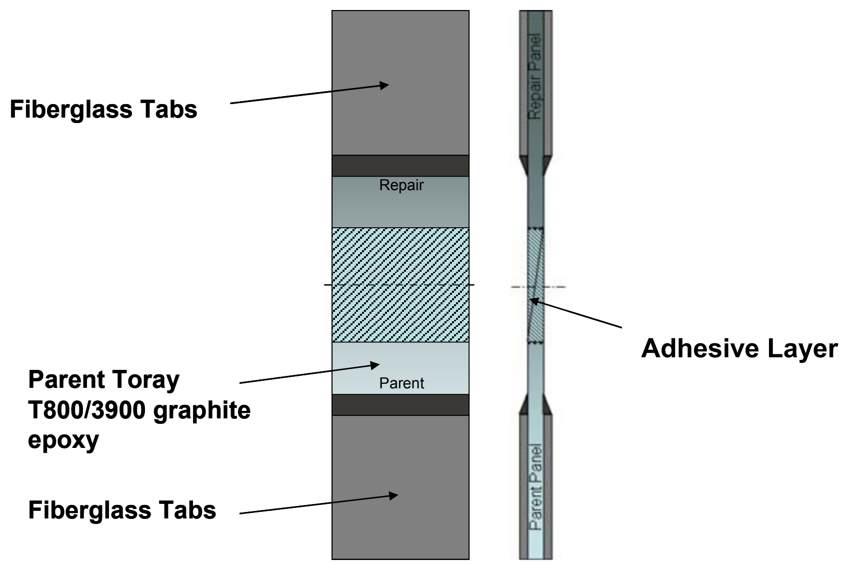


Figure 5. Laminate Scarf Joint Configuration

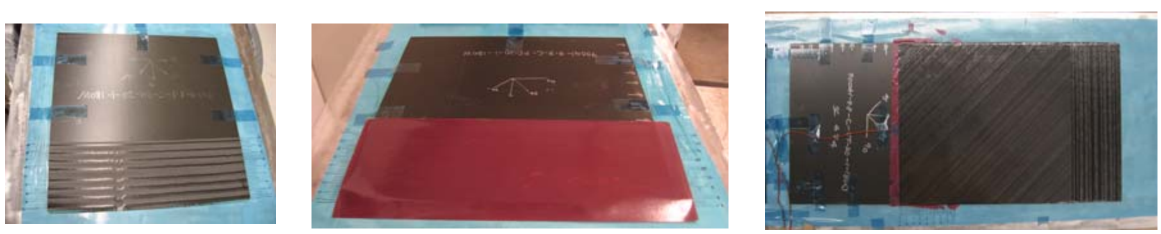


Figure 6. Scarfed laminate preparation and repair procedure

Water contaminated panels were conditioned at 145°F 85%RH until they reached equilibrium. After moisture equilibrium was achieved, these scarfed panels were dried back to achieve 75%, 50%, 25% and 0% saturation. Jet fuel, paint stripper and skydrol panels were subjected to the contaminant for 30 days at RTA.

Figure 7 summarizes the ultimate strength results of WA-0 scarf repairs tested to failure at RTA. The parent substrate for these repairs was conditioned prior to repair at 145°F 85%RH until moisture equilibrium was achieved then fully dried prior to applying the repair. As can be seen in the figure, the ultimate strength of all six specimens tested was lower than the pristine joint capability with a maximum strength degradation of 37.5%.

Absorption and diffusion of water in polymeric material is related to the free volume which depends on molecular packing (degree of cure)[Ref 2]. Water molecules that attach to the polymer through H bonds disrupt the interchain H bonds, induce swelling and plasticize the polymer. Moisture Absorption is a function of degree of cure[2]. Imperfectly cured systems allow moisture ingress due to the relatively loose chemical network structure. Moisture absorption causes irreversible changes in the epoxy network (evidence provided by the study of absorption-desorption cycling)

Figure 8 summarizes the ultimate strength results of PR scarf repairs tested to failure at RTA. The parent substrate for these repairs was scarfed and contaminated with salt water simulating perspiration then cleaned per OEM specifications and repaired. The magnitude of the strength degradation was less severe than that observed for the water contaminated panels at RTA.
A more severe knockdown in the ultimate strength capability was observed for hot wet specimens. Fatigue testing was conducted on these contaminated joints to investigate the durability of these joints as compared with the durability of the baseline uncontaminated joints. Specimens were cycled at a fatigue strain that yielded no failure (165000 cycles) for the uncontaminated configuration.

Both studies conducted have clearly demonstrated that adhesively bonded repairs are process dependent and that adequate technician training, adequate procedures, process control of incoming material, NDI, adequate curing and surface cleaning and preparation are key elements to bond integrity.

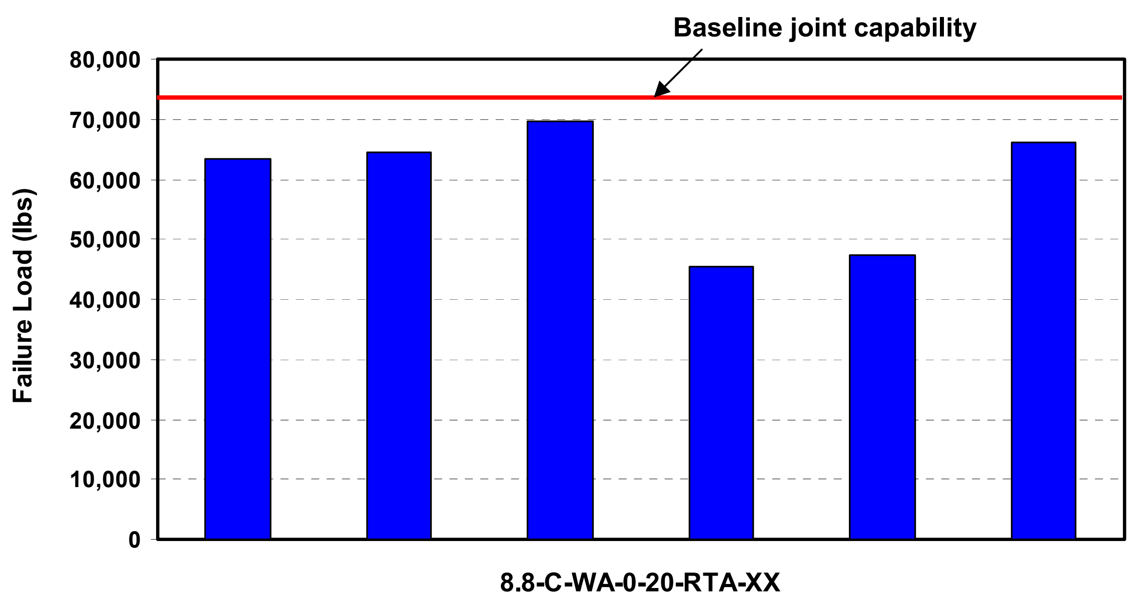


Figure 7. Ultimate Strength of WA-0 Contaminated Specimens

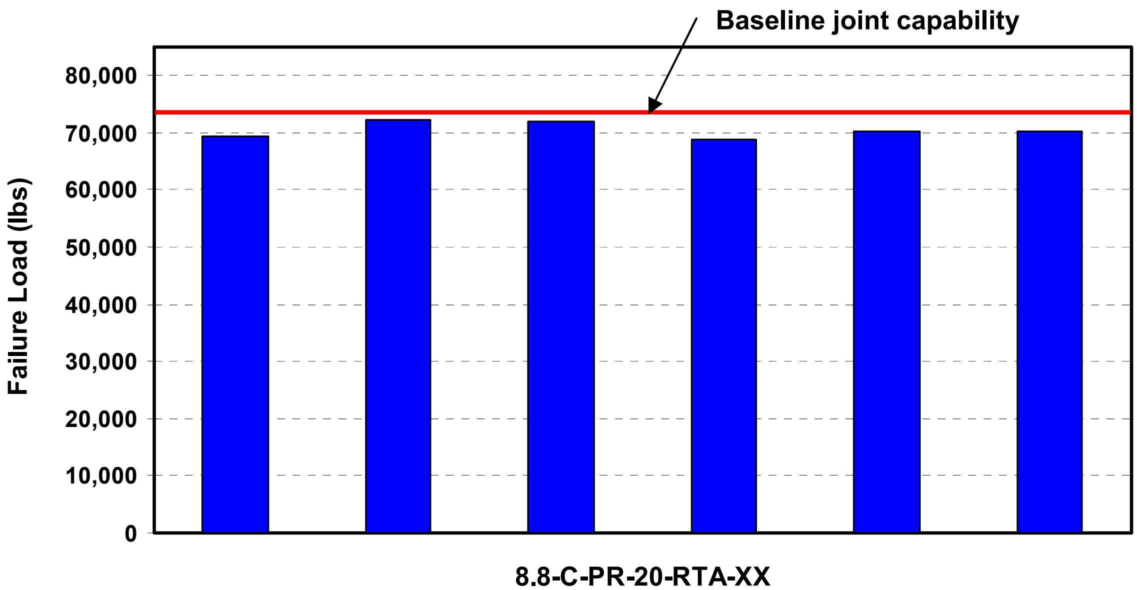


Figure 8. Ultimate Strength of PR (perspiration) Contaminated Specimens

OEM VERSUS FIELD STATION REPAIR INVESTIGATION

The partners involved in the proposed investigation are shown in Figure 9 along with the primary role of the partner and national & international organization interface. All materials, fabrication and repairs will be supplied by an OEM and/or airline CACRC members.

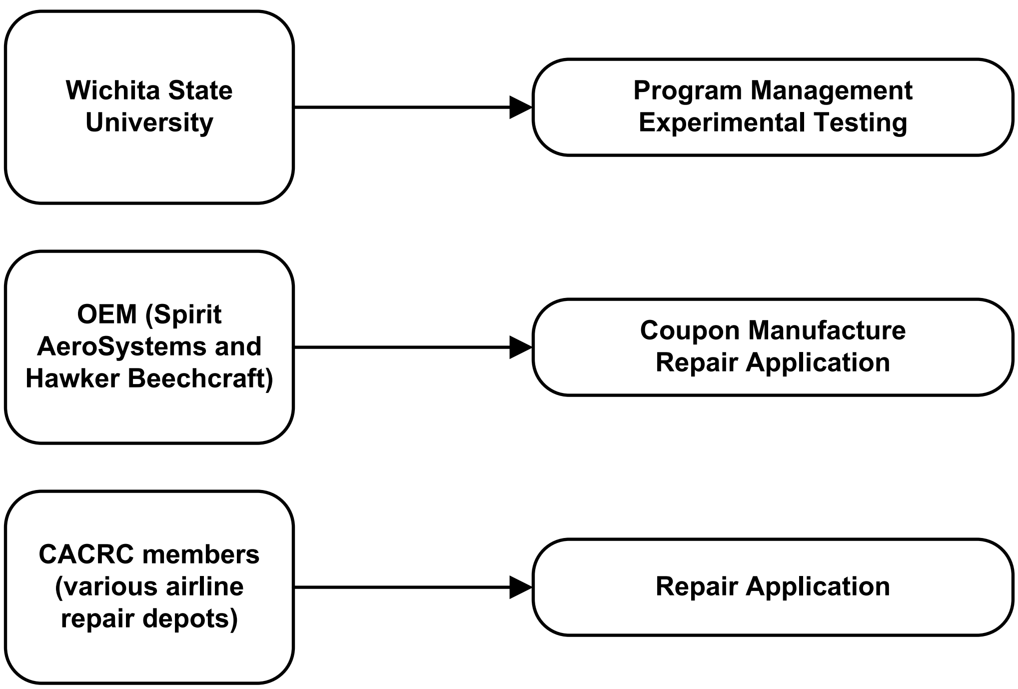


Figure 9. Primary program partners and investigation role.

This task will consist of manufacturing coupons at the OEM using the configuration shown in Figure 10. The primary goal will be to investigate the effectiveness of OEM vs field repairs and the variability due to repair implementation at various operator depots, to identify key elements in the implementation of bonded repairs that ensure repeatability and structural integrity of these repairs and to provide recommendations pertaining to repair technician training and repair process control.

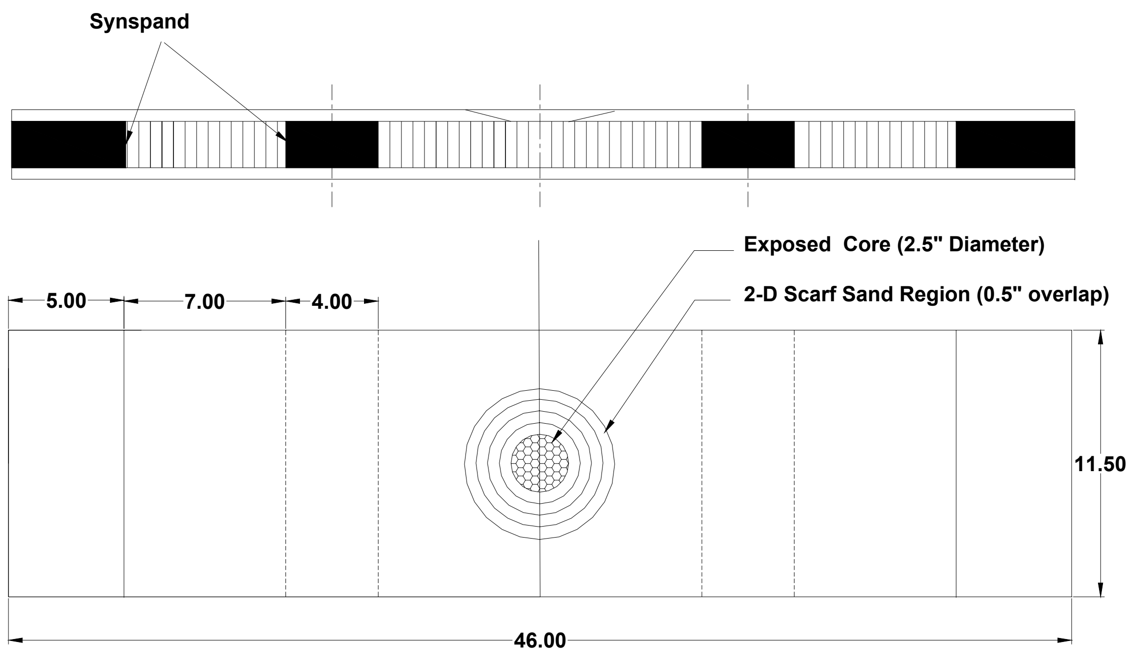


Figure 10. CACRC Coupon Configuration

A total of 78 coupons will be manufactured for the purpose of this investigation. The parent substrate is representative of existing commercial aircraft components and is 3-ply sandwich with 1/8” core cell size, 2” thick. The parent material is T300/934 graphite epoxy prepreg with FM377S adhesive. Three repair systems will be considered, an OEM repair system (labeled as 2D-OEM) using the parent material and adhesive for repair (350°F cure repair, prepreg) and two field repair systems using Hexcel T300/M20 prepreg (250°F cure repair, prepreg) (labeled as 2D-R1) and using Epocast 52A/B (200°F cure repair, wet lay-up) (labeled as 2D-R2). Other alternate wet lay-up resins include EA9390 or EA 9396 laminating resins. The proposed test matrix is summarized in table 1 below.

The two dimensional repairs will be typical of what is done in the OEM factory and field station setting when damage occurs and a repair is accomplished (these two dimensional repairs will be circular in shape). These repair methods will be quantitatively compared to baseline pristine unrepaired coupons, unrepaired coupons with a 2.5” hole diameter and OEM repaired coupons.

Once these repair methods have been formalized, a detailed repair procedure will be forwarded to the OEMs, several airlines/ operators and FAA POCs for review. Upon approval, these specific repair instructions will follow the panels to the repair stations. All coupons, upon repair, will be characterized using non-destructive inspection using various field techniques. After repair and inspection, the repaired beams will be conditioned at 145°F 85%RH until moisture equilibrium to simulate the worst environmental conditions the structure may be subjected to. Specimens will be instrumented with strain gages and tested for ultimate strength or residual strength after fatigue.

Table 1. Characterization of field station repairs.

Repair Station	Coupon Configuration	Repair Type	Number of test Replicates Loading Mode		
			Compression Static RTA	Compression Static ETW	Compression RS ETW
OEM	Pristine/ Undamaged	N/A	6	6	6
OEM	2.5" hole	None		3	3
OEM	2.5" hole	2D-OEM		3	3
Field Station 1	2.5" hole	2D-R1		3	3
Field Station 1	2.5" hole	2D-R2		3	3
Field Station 2	2.5" hole	2D-R1		3	3
Field Station 2	2.5" hole	2D-R2		3	3
Field Station 3	2.5" hole	2D-R1		3	3
Field Station 3	2.5" hole	2D-R2		3	3
Field Station 4	2.5" hole	2D-R1		3	3
Field Station 4	2.5" hole	2D-R2		3	3
			6	36	36

MECHANICAL TESTING

Six specimens from each repair configuration will be repaired at the OEM or a given airline depot. All specimens will be instrumented and tested at elevated temperature for ultimate strength and durability. Fatigue strain will be derived from the static testing and the sandwich elements will be cycled for 165000 cycles followed by residual strength evaluation.

The test fixture used for all testing will be a custom made four point bend fixture shown in Figure 11. The specimen strain gage layout is shown in figure 12. The test fixture is permanently mounted to the test laboratory floor and a custom actuator frame is constructed around it so that the actuator can drive the appropriate part of the test fixture. There are four solid steel rollers (with bearings) for load and support introduction as shown. The diameter of the rollers is large enough to alleviate the need for secondary load blocks to distribute load into the coupon. The test machine shall be verified in accordance with ASTM E4 to an accuracy of ±1% within the test loading range. The test system will also have the capability for multiple strain gage channels as well as load and deflection data (measured using a deflectometer).

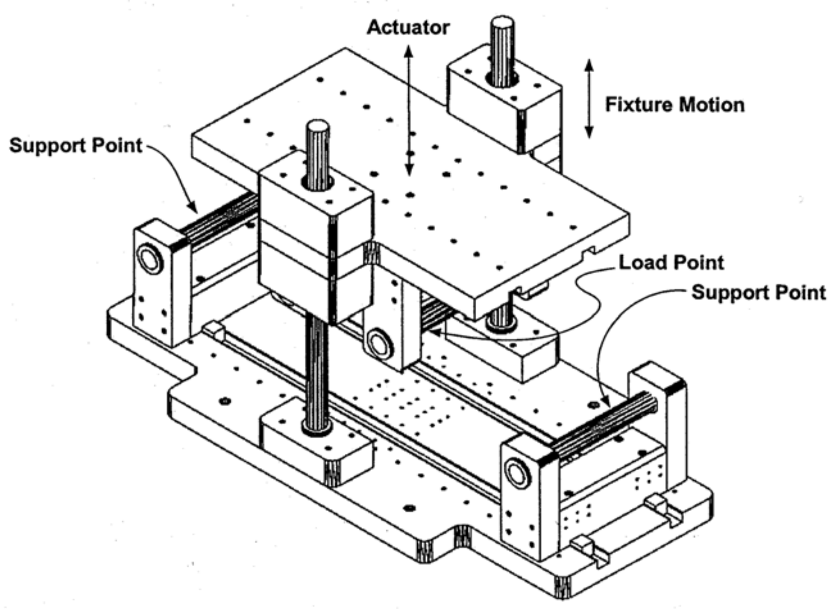


Figure 11. Isometric view of test fixture.

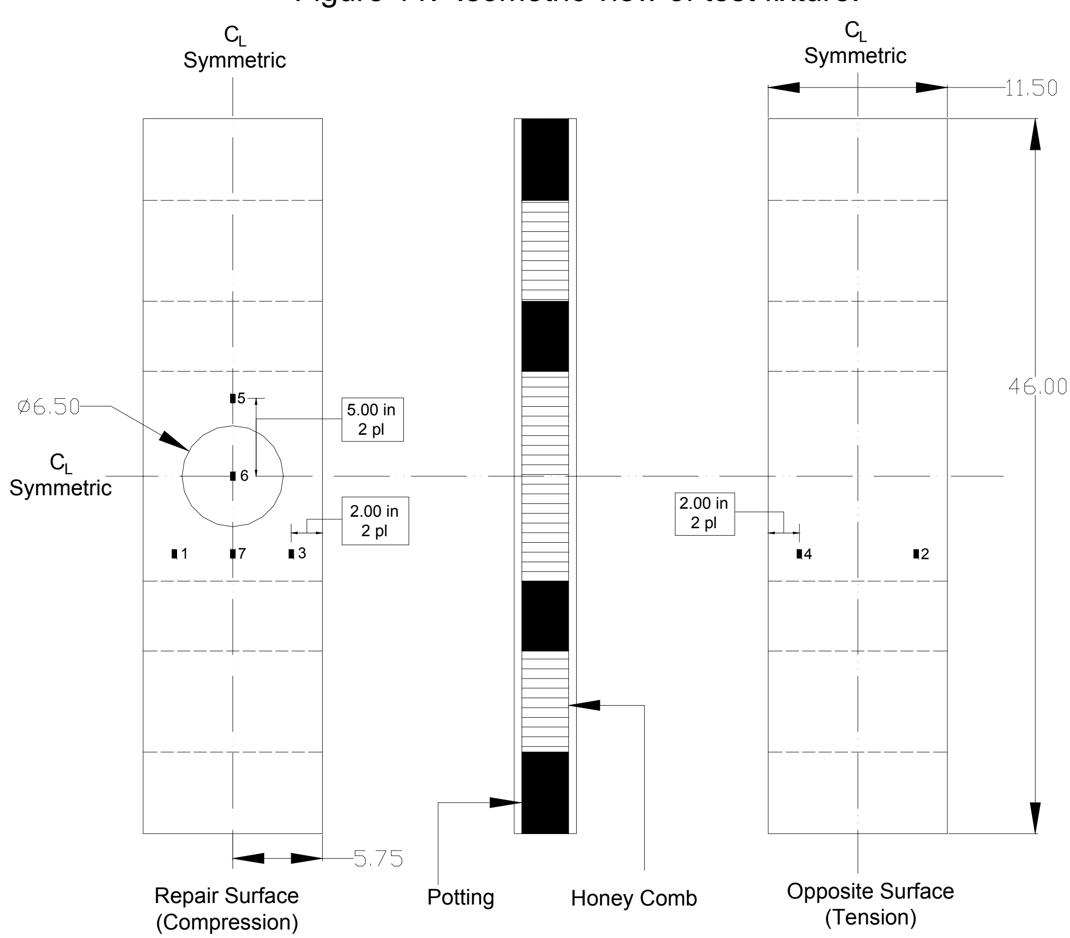
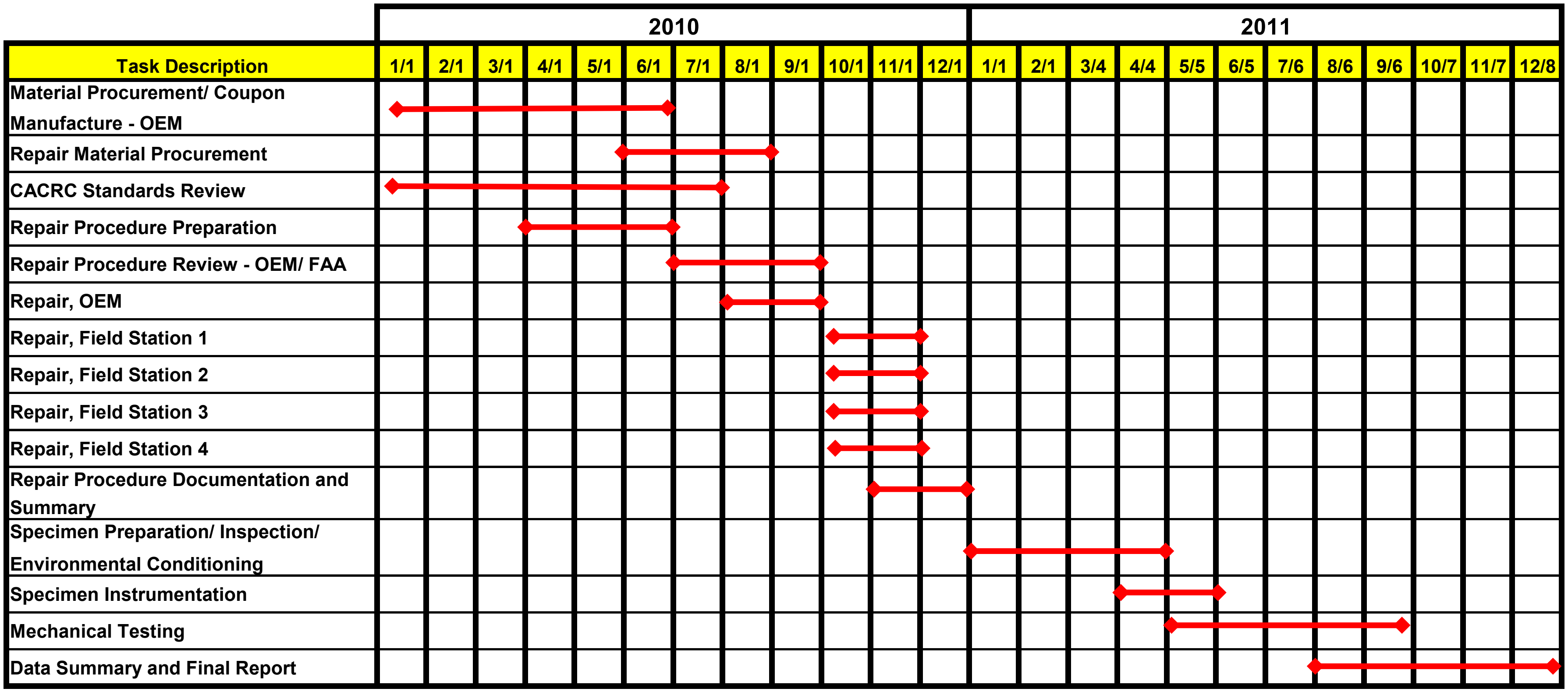


Figure 12. Specimen Instrumentation

RESEARCH PROGRAM TIMELINE/ ACTIVITIES

Table 2. Research Program Timeline



Panel Manufacture Status

- Material Procurement and coupon manufacture planning in progress: expected completion date 6/30/2010

Airline Depots/ OEM participating in Round Robin Investigation/ Testing

- Northwest/ Delta Airlines (Ray Kaiser ray.kaiser@delta.com)
- United Airlines (Eric Chesmar, Eric.Chesmar@united.com)
- US airways (Mike Tallarico, Michael.tallarico@usairways.com)
- Aviation Technology Associates (Marc G Felice mgfelice@avtechemail.com)
- Spirit Aerosystems (Mike Borgman, John Welch)

john.m.welch@spiritaero.com; michael.d.borgman@spiritaero.com

- Airbus (Francois Museux)

francois.museux@airbus.com

REFERENCES

(1) Bonded Repairs of Aircraft Composite Sandwich Structures, Final Report, DOT/ FAA/AR-03/74, February 2004

(2) Tomblin, J. S., Raju, K. S., Liew, J., and Smith, B. L., “Impact Damage Characterization and Damage Tolerance of Composite Sandwich Airframe Structures,” Final Report, DOT/FAA/AR-00/44, 2001.

(3) Tomblin, J. S., Raju, K. S., Acosta, J. F., Smith, B. L., and Romine, N.A., “Impact Damage Characterization and Damage Tolerance of Composite Sandwich Airframe Structures–Phase II,” Final Report, DOT/FAA/AR-02/80, 2002.