Composites Affordability Initiative:

Transitioning Advanced Aerospace Technologies through Cost and Risk Reduction

John D. Russell
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH

INTRODUCTION

In the mid-1990's, the Air Force Research Laboratory (AFRL) recognized that despite the potential of advanced composites to drastically reduce aircraft structural weights compared to conventional metal structures, the aircraft industry was reluctant to implement them in new aircraft. Although composites were used on the F-15, F-16, and F-18 in small percentages, data showed that composite applications had reached a plateau. For example, despite early projections of the F-22 airframe being 50% composite by weight, it settled back to 25% [1]. As a result, AFRL launched the Composites Affordability Initiative (CAI) to address the perceived risks and barriers. What resulted was a team consisting of personnel from the AFRL Materials and Manufacturing Directorate (AFRL/ML) and Air Vehicles Directorate, the Office of Naval Research-ManTech, Bell Helicopter Textron, The Boeing Company, Lockheed Martin Corporation, and Northrop Grumman Corporation. Ultimately, a $152M, eleven year effort was performed to attack the problem.

What Needed to be Done?

The CAI Team found that the key to affordability in composite structures was to reduce assembly costs. State-of-the-art aircraft structures have thousands of parts and hundreds of thousands of fasteners (Figure 1). In addition, drilling holes and installing fasteners has been and still is a major source of labor and rework in aircraft structures. If the number of fasteners is reduced substantially, structural assembly costs and cycle time could be drastically reduced. The CAI team pursued part integration and structural assembly through bonding parts together to achieve this goal. As a result, CAI's objective was to "establish the confidence to fly large integrated and bonded structures". To meet this objective, the technical program was structured to ensure that Department of Defense (DoD) structural integrity goals were met (see Figure 2). This required a multidisciplinary approach: maturation of materials and processes, an understanding of the structural behavior of bonded joints, quality assurance and nondestructive evaluation to ensure bonded joints remain bonded throughout an aircraft's service life, and the approval of DoD aircraft certification authorities.

The CAI business strategy was intended to maximize leveraging of knowledge and funding as well as improve the transition of "game changing" technologies. CAI was a collaborative effort among all parties, each sharing data equally for core technology efforts and delaying data release on specific technology applications (transition demonstrations). The industry partners agreed to a 50% cost share with the government, which increased the leveraging and also created an internal company incentive to realize an acceptable return on the investment by using the CAI technologies in their products. Technology transition demonstration projects ("T"-programs) were also a key feature of CAI. These T-programs focused the development of large integrated and bonded structures technology tailored to specific needs for several DoD weapon systems. Demonstrations were performed for several aircraft, including the X-32 (Boeing JSF prototype), F-35, X-45, and C-17. A key feature of these T-programs was that the integrated product teams (IPTs) were staffed with people from the DoD laboratories, industry development personnel, DoD program office personnel, and industry program personnel. Having representatives from each type of organization greatly improved the lines of communication and ensured the technology being delivered met the needs of the customer.

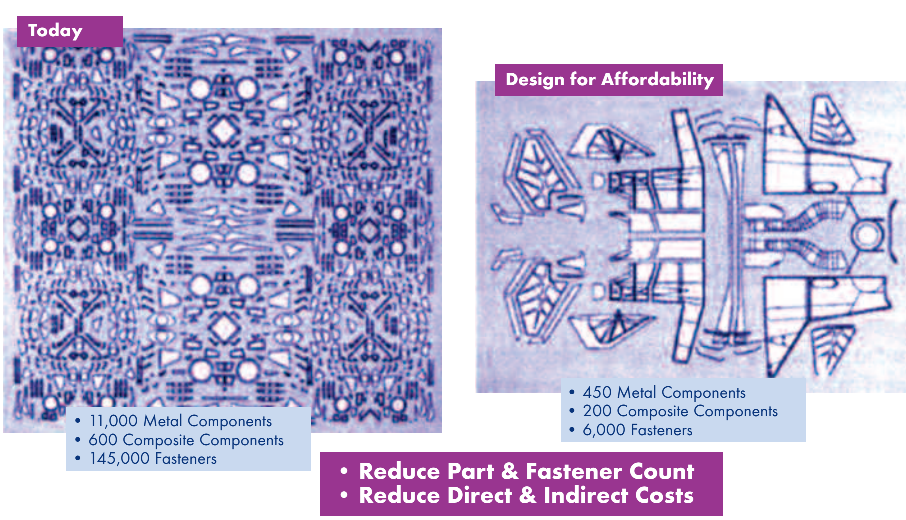

Figure 1. Composites Affordability Initiative's Technical Approach.

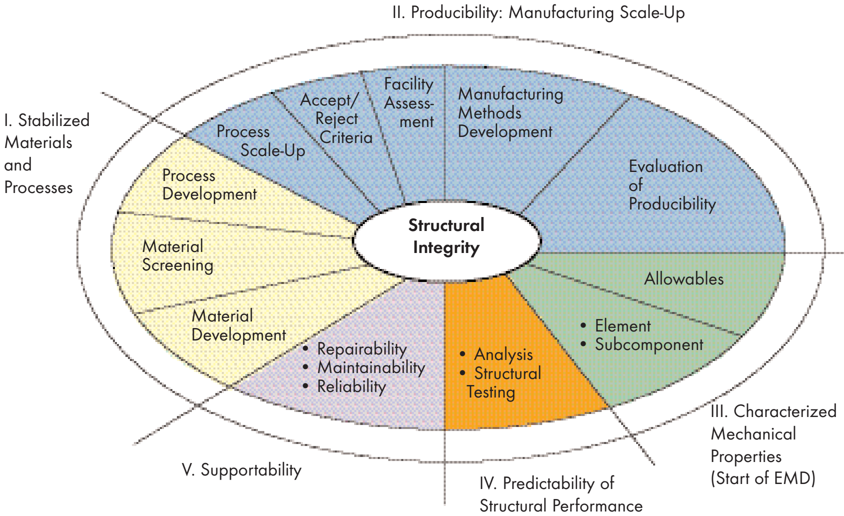

Figure 2. Structural Integrity Areas.

TECHNICAL ACHIEVEMENTS

In light of CAI's goal to "establish the confidence to fly large integrated and bonded structures", the primary technology pursued for integrated structures was Vacuum Assisted Resin Transfer Molding (VARTM). Bonding was enabled by the pi-joint bonded primary structure design and robust manufacturing processes. These technologies, along with the supporting tools and methods used to make certification possible, are described in the following sections.

Vacuum Assisted Resin Transfer Molding

For integrated structures, a nonautoclave process for making large yacht hulls was transitioned to the aerospace industry. VARTM is a process that uses a pressure that is less than atmospheric (typically full vacuum) to pull a liquid resin into a fiber bed. It was made famous in the boatbuilding industry with the advent of the SCRIMP process (Seemann Composites Resin Infusion Molding Process). There are two key advantages of VARTM over conventional autoclave curing. First is that an autoclave is not needed, unlike the conventional processes used for fabricating composite aerospace parts, resulting in reduced capital equipment costs. Furthermore, removing the need for the autoclave provides industry with a much larger supplier base for part fabrication. Second is that the typical VARTM resins cure at a low enough temperature to enable the use of inexpensive tooling such as medium density fiberboard rather than the typical invar tooling used for 350°F (177°C) curing autoclave materials. This also reduces system development costs.

While the aerospace industry dabbled in VARTM over the years, CAI has demonstrated its viability as a valid production method for aerospace parts up to 160 ft^3 (5.4 m^3). As shown in Figure 3, several parts were demonstrated including a replica X-32 one piece cockpit tub (top left)*, a C-17-like fuselage skin with integral stiffeners (bottom left), and a C-17 nose landing gear door (right). CAI's VARTM efforts resulted in fiber volumes and per ply thickness comparable to typical autoclave cured aerospace composite parts. In addition, the process worked with several resins, including EX-1510, SI-ZG-5A, and VRM-34.† Further use of the VARTM process would be enabled through the development of toughened resins with properties similar to the 977-3 resin‡.

Overall, VARTM has enabled reduced part counts (up to 80%), reduced fastener counts (up to 100%), and lower part fabrication costs as compared to conventional structures (30% to 50%). CAI has demonstrated the VARTM process to be versatile in the parts it can create, while achieving acceptable quality and validating its repeatability. VARTM is a production ready process for the aerospace industry.

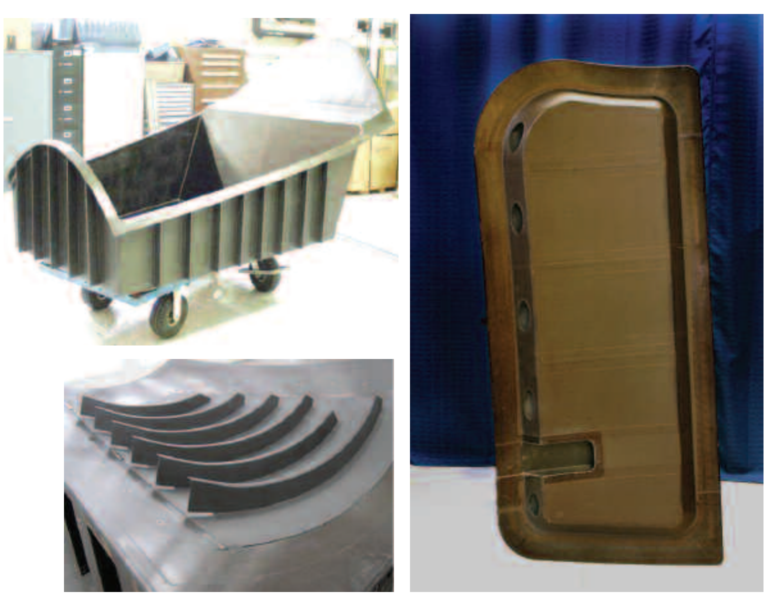

Figure 3. Aerospace VARTM Demonstration Parts.

Adhesively Bonded Structures

While bonded primary structural joints are currently in service on DoD aircraft, including the F-18 and Global Hawk, there continues to be an unease in the DoD airframe certification community with regard to bonded structures. That community has a legitimate concern based on past research programs intended to broaden the use of bonded structures. The inability to discriminate between a good bond and a "kissing" bond (intimate contact between adhesive and structure without adhesion) has been the key roadblock to further use of bonded structures. Despite this unease, bonded structures have tremendous potential for aircraft structures. If designed correctly, bonded aircraft structures have greatly reduced part count and fastener count and also greatly reduced structural assembly times. The CAI attacked each barrier to increase the confidence to fly bonded primary structures.

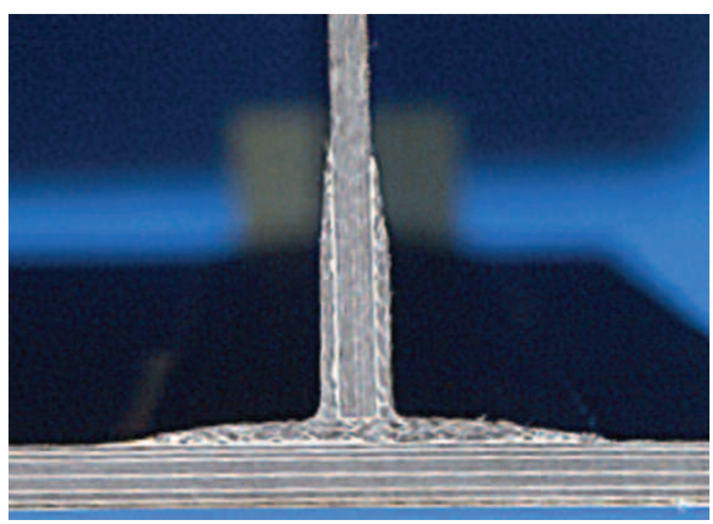

Figure 4. Cross Section of the Pi Joint.

Table 1. **Full-Scale Structural Testing of Pi-Joints.**

Test Article	Testing Performed
F-35 replica wing (Figure 5, upper left)	Static and ballistic tolerance
F-35 replica vertical tail (Figure 5, upper right)	Static, damage and fatigue
X-45A replica wing carry through (Figure 5, lower left)	Static
X-45 wing (Figure 5, lower right)	Static, damage and fatigue (2 lifetimes)

Pi Joint

The first area to be addressed was design of the bonded joint. CAI's bonded structures work centered on the "pi" joint (Figure 4); this stiffener, shaped like the Greek letter π, can be co-cured or co-bonded to the skin. The pi joint has several advantages. First, it provides structural redundancy. The pi joint acts as two independent bondlines, and the joint is stronger than a double lap shear joint. When used with EA 9394 adhesive[§], the pi joint takes advantage of the inherent properties of the material. EA 9394 has excellent shear properties and performs better in shear than in tension loaded bonds. It also paves the way for much reduced assembly times by providing a determinate assembly feature. Tension loaded bonded structures typically have the adhesive spread over the skins and/or spar/rib caps prior to assembly. This leads to adhesive out time[**] issues. They also may require several verifilm cycles to ensure the correct tolerances to get the adhesive thickness required by the designer. Conversely, out time is minimal with the pi joint. It takes much less time to apply the adhesive into the clevis of the pi, and much less surface area is exposed to the air before bonding takes place.

The CAI Team spent considerable energy in analyzing and verifying the design and manufacture of the pi joint. Testing has shown that the joint is very robust and has predictable performance. A key finding from the CAI pi joint studies is that the room temperature paste-bonded pi joint has three to five times more strength than the co-cure joint of the pi stiffener to the skin. Thus, the pi joint will not be the weak link in a primary structural application. It is tolerant of several defects including: thick bondlines; a canted blade; a blade skewed to one side of the clevis; and typical manufacturing defects, such as voids and peel plies that were not removed prior to bonding. This robustness was proved by a series of successful tests ranging from coupons to full scale airframe components (examples are given in Table 1).

The X-45A wing carry through and the X-45C wing were structurally tested to design limit load, design ultimate load, and finally to failure. Both articles failed just above the predicted design ultimate load. These structural and ballistic tests show that bonded structures can meet structural requirements for military aircraft. In addition, these structural demonstrations showed that assembly times are drastically reduced. By filling the pi joints with adhesive rather than mating, drilling, deburring, remating, and installing fasteners, assembly times can be reduced from 50 to 80% depending on the article, translating to a cost savings of 20 to 50%.

Enabling Tools for Bonding

Besides the validation of robust designs and manufacturing processes, several key supporting tools and technologies had to be matured and validated to make the application of bonded primary structures a reality. These included more accurate analysis tools which took into account peel as well as shear stresses in a bonded joint, tools to evaluate damage progression, nondestructive inspection for the production and maintenance of bonded primary structures and finally an acceptable certification approach.

Analysis Tools

Conventional analysis methods for bonded joints were found to be limited in their capabilities and accuracy. For instance, A4EI, a computer code for bonded joint analysis, is only applicable to adhesive failures in shear-loaded joints and does not account for peel stresses or for potential adherend failures. To date, the only alternative to these limitations has been to develop detailed finite element models of a joint. This approach is time consuming and requires great skill and care by the analyst to ensure stresses and strains in critical locations of the joint are properly quantified. Small errors in modeling can lead to substantial errors in joint performance prediction.

To alleviate these problems, the CAI team implemented improvements to the StressCheck®[††] P-version finite element software, including the incorporation of a strain invariant failure theory. The StressCheck® tool handbook function was used to expertly model typical joints, thereby developing reusable joint models including: single lap shear; double lap shear; scarfed lap shear; and step lap joints for in-plane loading; as well as a pi and back-to-back angle joints for out-of-plane loading. These handbooks are parameterized so that similar joints in the future can be modeled by simply updating geometric parameters of the existing model. StressCheck® will then automatically remesh the model, calculate results, check for convergence problems in the new joint configuration, and even post-process the results.

Durability and Damage Tolerance Analysis Methods

Users are also concerned about how the damage would progress in order to understand the full impact of damage and the durability

Figure 5. **Full-Scale Bonded Structure Demonstration Articles.**

http://ammtiac.alionscience.com/quarterly

of the structural design. Software based on a novel implementation of the Virtual Crack Closure Technique (VCCT) was developed under the CAI program and was being applied to the evaluation of delaminations and disbonds in composite structures after the onset of initial failure. VCCT plays an important role by providing unprecedented capability for the design of aerospace structures involving composites. Boeing has filed a patent application for this interface fracture analysis software and ABAQUS, Inc., will market an enhanced version of the technology commercially.

Quality Assurance

One major hurdle inhibiting the application of bonded primary structures has been the lack of a nondestructive technique to assess the strength of a bonded joint. Boeing, a CAI team member, led the quality assurance technology effort and has developed a laser bond inspection technique (patent pending).

High peak-power, short-pulse-length laser excitation generates stress waves that can be used to discriminate between kissing, weak, and strong bonds in graphite-epoxy composite-to-composite bonded structures. The technique is able to discriminate between variations in surface preparation techniques, levels of surface contamination and/or changes in paste adhesive mixing. In more than 3000 laser stress wave experiments this approach has been found to be repeatable and reliable in the detection of weak versus strong bonded joints. Such an approach offers a potentially cost effective method to be certain of a minimum predetermined load-carrying capability of a bonded joint after manufacture or in-service. A production floor laser bond inspection device is being developed and optimized in two Small Business Innovative Research programs with LSP Technologies sponsored by AFRL/ML.

Certification

The CAI team worked with certification authorities from the Air Force, Navy and FAA to understand and eliminate the barriers to advanced bonded structures. The CAI team prepared certification plans for three structures, each with increasing levels of innovation. The plans started with a secondarily bonded rib to a skin/stringer interface. Next up was a vertical tail featuring 3-D pi preforms and z-pinning[‡‡]. The final plan featured a bonded wing that carried fuel with 3-D pi preforms and z-pinning. These plans included the use of CAI-developed analysis tools and their validation, CAI-developed process controls for bonding and guidelines for advanced processes, as well as advanced bondline inspection tools. These tools and technologies, along with a sound certification plan of analysis supported by test, provided the certification authorities with enough confidence that they believe the methods were sound enough to certify an actual structure. This is a major breakthrough to realizing the cost, cycle time and durability benefits of advanced bonded structures.

TECHNOLOGY TRANSITION

CAI tools and technologies have transitioned across the industrial base. AFRL is currently aware of 22 companies and organizations benefiting from CAI-derived technologies. Technologies include VARTM, pi-joints, laser bond inspection, StressCheck® and crack propagation analysis tools, and certification plans. Bonded structures are flying on the F-35 AA-1. StressCheck® and crack propagation analysis tools have become standard industry practices and are being used to design and analyze DoD and commercial aircraft. The C-17 landing gear door (Figure 3) will be fabricated by a first tier supplier for future C-17's and as a preferred spare. This article only covers a portion of the technologies developed under CAI. Other tools include an improved cost model for composites. This cost model is being used by over 10 organizations worldwide. A process maturation database capturing the entire CAI database with a complete pedigree of processing data, environmental exposures, etc., is hosted on AMMTIAC's National Materials Information System (NAMIS) website (https://namis.alionscience.com/CAI/). An exhaustive set of guidelines has been prepared to provide potential users with clear understanding for advanced materials, designs, analysis tools, process controls, fabrication and assembly processes, quality assurance and repair. All of the CAI technologies, reports and data are open to the DoD and DoD contractors.

SUMMARY

The Composites Affordability Initiative was a huge technical success. CAI matured technologies for large integrated and bonded composite structures across the fixed and rotary-wing industrial base. Through this program technology advancements were accelerated and structural performance and cost effectiveness exceeded the current state-of-the-art. Furthermore, technology applications are increasing and are anticipated to continue to expand, as a result of this initiative.

NOTES & REFERENCE

* This piece was designed/manufactured with the Boeing's X-32/JSF concept in mind, but did not include all features required by the program.

† EX-1510 is a cyanate ester resin; SI-ZG-5A and VRM-34 are epoxy resins.

‡ 977-3 is an epoxy resin.

§ EA 9394 is a structural paste adhesive.

** Out time is the working life of the substance, and is an issue considered when applying epoxy adhesives and composite prepregs. If they are left exposed at room temperature for a finite time before the resin cures too much, they can become unusable.

†† StressCheck is a registered trademark of Engineering Software Research and Development, Inc. (ESRD).

‡‡ Z-pinning is a method of orienting fiber bundles in the z-direction and placing them through gaps in a two-dimensional fiber weave. This method is intended to provide enhanced interlaminar strength.

1. F-22 Raptor Materials and Processes, GlobalSecurity.org, http://www.globalsecurity.org/military/systems/aircraft/f-22-mp.htm.

Dr. John D. Russell is a Senior Materials Engineer with the Air Force Research Laboratory's Materials and Manufacturing Directorate. He has a Bachelor of Chemical Engineering degree and a Master of Science degree in materials engineering from the University of Dayton, and a Doctor of Science degree in chemical engineering from Washington University in St Louis, Missouri. At AFRL, Dr. Russell began his research in the processing of advanced composite materials, and in particular, the processing of polyimide composites and dimensional control of composite parts. Since 2000, he has been the government's program manager for the Composites Affordability Initiative (CAI), where he leads a consortium of aircraft manufactures to reduce the cost of composite airframes through the use of large integrated and bonded structures.

http://ammtiac.alionscience.com/quarterly