Prepreg Non-Autoclave Manufacturing Technology: Program Overview and Co-Cure Enablers for Disruptive, Pervasive Use

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Abstract

In 2007, Non-Autoclave Manufacturing Technology was initiated by a Boeing-led team and the U.S. Government (DARPA) under the guidance of the Air Force to enable disruptive, pervasive use of vacuum-bag-only prepreg for reduced recurring cost and cycle time for primary composite structures. This paper will provide a program overview as well as focusing specifically on composite co-curing technology out of the autoclave. Composite co-cures can be complicated and difficult to repeatedly produce with high quality. Factors that can contribute to these difficulties include autoclave pressure and the flow of the resin. By moving to out-of-autoclave systems, improvements in quality by reducing pressure and resin flow are achievable. Through the DARPA/Boeing co-funded, Air Force guided program Non-Autoclave Manufacturing Technology, two different co-cure designs were evaluated. The first was an existing production co-cure utilizing production tooling and engineering but substituting Cytec's toughened epoxy non-autoclave system 5320-1 for the baseline autoclave system. The second non-autoclave co-cure was a new design for a cooling outer aft duct (COAD) that utilized a novel large-scale tooling concept for the co-cured stiffeners. Non-destructive evaluation (ultrasonic inspection) and visual inspection were conducted on both co-cured structures and demonstrated that reduced resin flow and pressure during cure does improve some aspects of co-cure quality.

Introduction

The Non-Autoclave Manufacturing Technology Program was introduced at the Society of Materials and Processing Engineering (SAMPE) Technical Conference in 2008[1], and an update was provided at the SAMPE Fall Technical Conference in 2010[2]. It is a program jointly accomplished by a Boeing-led team and the U.S. Government (DARPA) under the guidance of the Air Force. The program specifically addresses the following goals:

- Autoclave-like properties with an initial cure temperature of 93°C (200°F) with vacuum pressure only and a free-standing post cure at 177°C (350°F)
- Reduced cost/span time tooling family for use in 10-25 units
- Processing and tooling to match production, because the tooling concepts used in development are also production-worthy

The initial program accomplished its milestones in February 2009. As a result of accelerated milestone completion, promising manufacturing demonstrations, and high technical quality, additional effort was exercised in calendar year 2009 (Figure 1).

The Air Force Non-Autoclave Manufacturing Technology Program and Related Efforts

This paper will provide an overview of the program which primarily deals with the hand layup of the CYCOM®5320 and CYCOM®5320-1 families of out-of-autoclave processed toughened epoxy prepregs and associated processing/manufacturing technology development.

This paper contains an overview of the work under the original Phase 1 program (July 2007 – January 2010) and the expanded effort which was authorized in 2009 and which runs into 2012 as well

Phase 1

- Non-autoclave manufacturing technology for polymer matrix prepreg composite structures-including compatible material family, processes, tooling equipment, and design guidelines.
- Non-autoclave processed material met dimensional/geometric needs, achieved autoclave-like primary structure quality with fewer pressure-driven defects.
- Subcomponent and full size hat stiffened skins and 11.6 m (38 ft) wing spar successfully fabricated and evaluated.
- Tooling guidelines published; approaches passed thermal cycling evaluation.

Additional Effort

- Scale up to large structures (more than 15m (50ft).
- Implement high modulus fiber/toughened resin prepregs.
- Demonstrate that there in no reduction in properties.
- Use materials/processes for integrated structures
- Build flight-worthy primary structure.

The developments in this program enable the use of the same materials and processes for both development and production, mitigation risks frequently realized in program life cycles at maturation to production.

Figure 1. Program objectives.

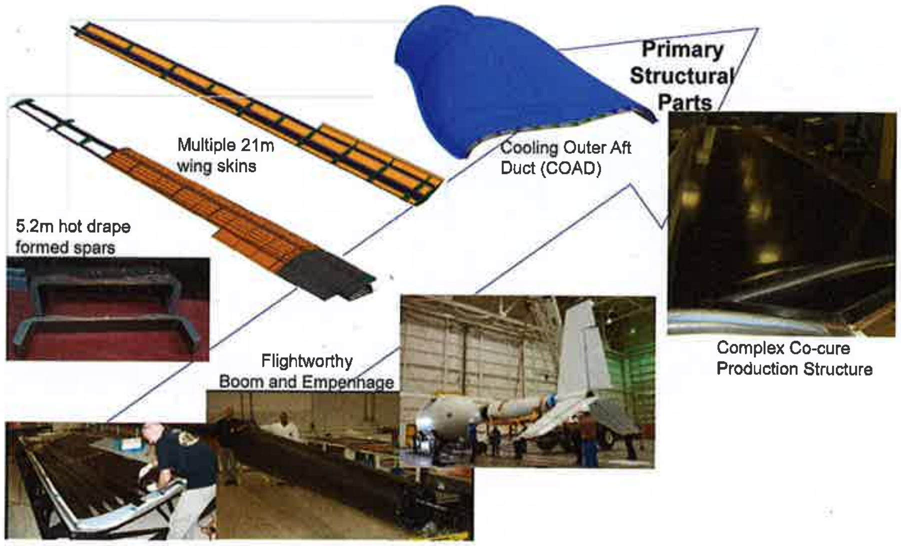

Figure 2. The path to large primary structural parts.

as focusing specifically on co-cure demonstrations. Numerous papers have been published on various activities initiated or supported by the program[3-10] including five companion papers[12-16]. Information included in this paper will cover efforts in the time period of roughly May 2010 through October 2011.

Co-Curing of Out-of-Autoclave Structure

One aspect of the program is to investigate composite manufacturing processes which could be improved by getting out of the autoclave. There are a number of composite structures in aerospace today that are fabricated using a co-cure approach, where two or more uncured composite components are cured together to form one large piece. Numerous issues are common with co-cures including ply thin-out, tool coefficient of thermal expansion issues, and resin-rich/resin-poor regions.

A low flow, low temperature curing non-autoclave material system has the potential to reduce or eliminate many of these common co-cure issues. The program evaluated two specific co-cure designs to examine the impact on part quality by getting out of the autoclave.

Experimentation

Program Developmental Approach

The over-arching philosophy of the program is to fabricate hard-to-fabricate features and thus develop robust manufacturing processes. Small but difficult features such as joggles and rabbets (rebates) evolved to larger and complex manufacturing demonstration articles. A large hat-stiffened skin (and replication at a composite supplier) was followed by a flight-worthy boom and empennage for an unmanned aircraft manufactured under the additional effort. These tasks led to even larger scale parts and three 21 m (68 ft) wing skin configurations were fabricated in 2010 and 2011 as well as multiple co-cure designs.

The Path to Very Large Structures

Figure 2 illustrates the path to very large structures within the Air Force Non-Autoclave Manufacturing Program, all aimed at investigating and exploiting the full envelope of processing capabilities with the CYCOM®5320 and CYCOM®5320-1 out-of-autoclave systems. The images in the lower left side of the arrow in Figure 2 represent efforts for flight-worthy boom and empennage structure[5]. Illustrated are a hat stiffened vertical skin, the tooling used for the boom, and the installation of the boom/empennage itself.

To the upper left of the arrow in Figure 2 are schematics of a 21-m long hat-stiffened wing design and a sandwich wing design which were developed and fabricated in late 2010[6]. Finally, in the upper right, two co-cured structures are shown which will be further discussed in this paper.

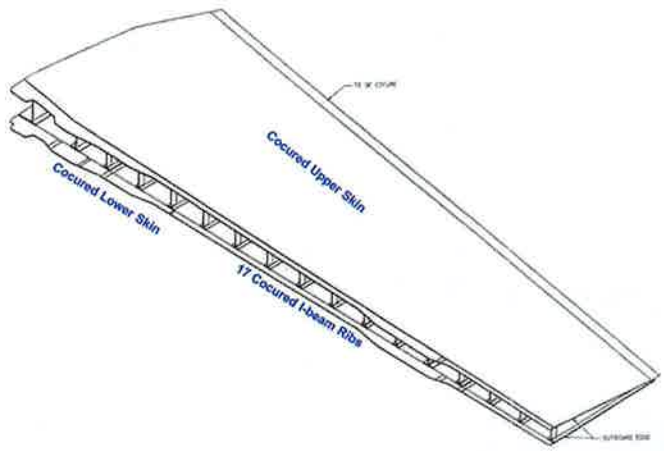

Figure 3. Schematic of complex co-cured production structure (CCPS).

Fabrication of Complex Co-Cure Production Structure (CCPS)

The program fabricated a co-cured torque box (two skins and 17 ribs) based on an existing production design and using production tooling designed for 177°C (350°F) curing autoclave materials. This complex co-cure has been a difficult-to-produce composite part throughout the life of the production program and represented a significant real-world production challenge for non-autoclave manufacturing. The CCPS is shown in Figure 3.

The CCPS was laid up on the production tooling and cured at 121°C (250°F) for three hours. The tooling, despite having been designed for expansion at 177°C (350°F), was able to be removed easily and the CCPS then underwent a free-standing post-cure at 177°C for two hours (Figures 4-7).

Cooling Outer Aft Duct (COAD)

The Non-Autoclave Manufacturing Technology Program also has fabricated a complex co-cured aft duct to demonstrate the use of large low-cost rapid tooling, flexible aluminum honeycomb, and production-relevant shapes and design concepts. The part chosen for this represents a conceptual cooling air duct and is designated as the "cooling outer aft duct" or COAD (Figure 8).

The program designed, analyzed (roughly), and fabricated the upper half of the COAD with two different design configurations for two total skins. One skin was an outer monolithic (Figure 9) while the inner skin used flexible core aluminum honeycomb stiffened skins (Figure 10). The inner skin configuration utilized a fused deposition modeling (FDM) direct digital manufacture process to rapidly make low-cost stiffener tooling; the stiffeners were co-cured with the inner skin.

The COAD configuration was based on the desire to manufacture a complex contoured part approximately 4.6 m (15 foot) in length. The width of the part was driven by available oven size. The final part size of 4.3 m (14 foot) long by 2.9 m (9.5 foot) wide was selected to be compatible with the manufacturing goals. The surface shape was selected to maximize curvature complexity while remaining representative of typical duct structure. Due to budget and schedule constraints, only the upper half (greatest amount of geometric complexity) of the duct was fabricated.

The side flanges are comprised of three planes to simplify the in-

Figure 4. Left – Production tooling consisting of Invar facesheet and aluminum filler blocks; Right – First skin plies being applied (T650/35/5320-1 215gsm unitape).

Figure 5. Left – Film adhesive (FM®209-1K) strips for I-beam flanges; Right – Locating aluminum filler blocks with back-to-back C-channels to make I-beams.

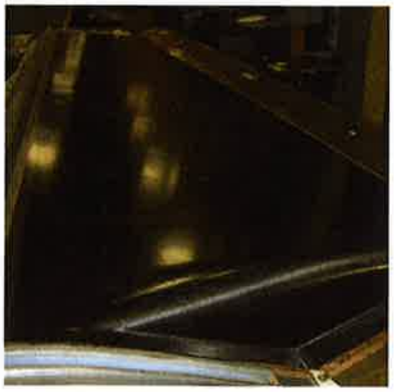

Figure 6. Left – Pre-compacted second skin being applied to filler blocks and uncured composite I-beams; Right – CCPS after cure but before post-cure.

terface between the upper and lower duct halves. The space between the inner and outer skins is determined by the stiffener height which is driven by structural stiffness requirements for the part.

The stiffener C-channel configuration is representative of stiffeners typically utilized in composite structure. The C-channel stiffeners are preferred for ease of fastening during part assembly and fewer tools are required to form the stiffeners during fabrication.

Two COAD configurations were designed to demonstrate the manufacturing capability of different types of composite construction when fabricated on complex curvature. The monolithic configuration utilizes a laminate skin configuration to reduce cost in manufacturing. This leads to a heavier part compared to the sandwich configuration due to the increased skin thickness and number of

Figure 7. CCPS prepared for free-standing post-cure on very low cost support tooling (metal sawhorses).

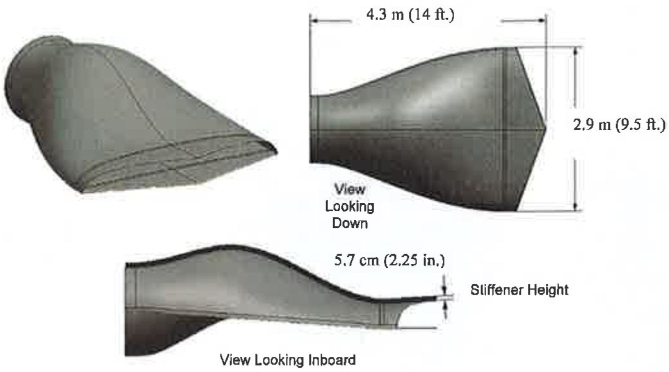

Figure 8. Overall COAD configuration.

stiffeners required. The sandwich configuration is lighter and contains fewer stiffeners but results in a more complex part to manufacture due to the honeycomb core contained in the lay-up.

The monolithic configuration (Figure 9) consists of the following: A monolithic outer skin with three thickness regions of 8, 12, and 20 plies with an estimated weight of 98 kg (217 pounds). A monolithic inner skin also with three thickness regions of 8, 12, and 20 plies and 13 co-cured stiffeners with an estimated weight of 145 kg (319 pounds). The five center stiffeners are 8 plies thick and the outer 8 stiffeners are 16 plies thick. The stiffeners are spaced approximately 16.5 cm (6.5 inches) apart at the forward end and 26.7 cm (10.5 inches) apart at the aft end of the duct.

The sandwich configuration (Figure 10) consists of the following: a sandwich outer skin with three thickness regions of 8, 12, and 20 plies and 6 regions of 1.3 cm (0.5 inch) thick aluminum honeycomb flexible core with an estimated weight of 103 kg (228 pounds). The sandwich inner skin also contains three thickness regions of 8, 12, and 20 plies and 6 regions of 1.3 cm (0.5 inch) thick aluminum honeycomb flexible core with 7 co-cured stiffeners and an estimated weight of 124 kg (274 pounds). The five center stiffeners are 8 plies thick and the outer 8 stiffeners are 16 plies thick. The stiffeners are spaced approximately 33 cm (13.0 inches) apart at the forward end and 53 cm (21.0 inches) apart at the aft end of the duct. Flexible core was utilized to ensure conformity with the complex contour of the part.

After completion of the baseline strength analysis, the skin and stiffener lay-up configurations were tailored to meet the allocated budget for material and fabrication. The following common features were incorporated to reduce the manufacturing cost of the part. The sandwich skins used the same lay-up as the monolithic skins and the honeycomb core parts were the same for the inner and outer skins, permitting reuse of flat patterns for both plies and core. Also, the stiffener configurations for both the monolithic and sandwich parts were the same to make use of the same tooling.

The tailoring resulted in part configurations that deviated from the optimal strength and weight determined by the baseline analysis. The estimated part weights noted do not contain all of the details of the analyzed configuration, and the weight savings that would be realized through the use of the optimum sandwich construction was not reflected in the final manufacturing demonstrations.

However, the features critical to demonstrating the low-cost tooling techniques and manufacturing processes were maintained. Three ply regions were utilized to demonstrate lay-up of plies, honeycomb core, stiffeners, and fused deposition modeling (FDM) tooling on parts with complex shapes and ramps. Two different stiffener thicknesses were used to demonstrate varying degrees of lay-up complexity on the highly curved FDM tooling.

After program and budget reviews, it was decided to only fabricate two skins – one outer and one inner and to make one monolithic and one honeycomb. Both skins (monolithic outer) have been fabricated and are shown in Figure 11 through Figure 15.

Results

Complex Co-Cure Production Structure (CCPS) Results

From visual inspection, the first skin (against Invar tool surface) had significant surface porosity; several resin coats covered the porosity but failed to improve the attenuation. Photomicrographs later confirmed that the skin had significant porosity throughout its thickness (Figure 16).

The CCPS was non-destructively tested (NDT) using ultrasonic through-transmission and pulse echo. NDT also did detect foreign object debris (FOD), later identified as a ply label, in the second skin (Figure 17). However, in general, the second skin looked very good, the first skin had regions of significant porosity, and the rib webs had some areas with some porosity (Figure 18). It is believed that the porosity in the ribs and upper skin may be due to the fact that the tooling was designed to utilize the expansion that occurs at 177°C (350°F), and for the CCPS, the cure only went to 121°C (250°F) (followed by a free-standing post-cure at 177°C (350°F)).

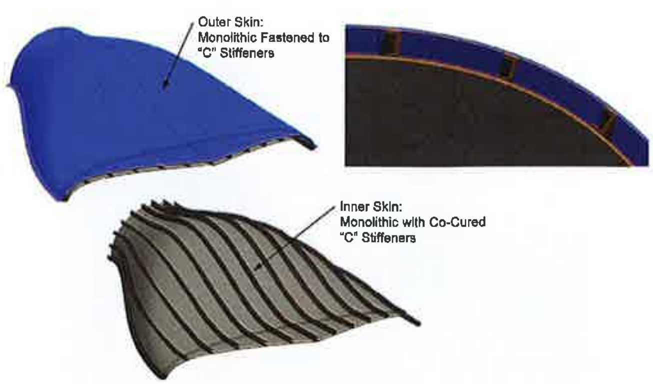

Figure 9. COAD upper half, monolithic configuration (two monolithic skins, one co-cured with stiffeners).

Figure 10. COAD upper half, honeycomb configuration (one honeycomb skin, one co-cured with stiffeners).

Figure 11. Left - First ply of carbon cloth (MMS 5064, Type 1 – T650/35/5320-1 370gsm 8HS) for monolithic outer COAD skin; SurfaceMaster®905M surfacing film was first applied to the tool before the carbon ply was laid up; Right - After 93°C/12 hour cure, COAD outer monolithic skin is removed from bond jig and put into oven for 177°C/2 hour free-standing post-cure.

Figure 12. Left - COAD outer monolithic skin after post-cure; placed temporarily back onto Janicki bond jig until AUSS ultrasonic inspection equipment is ready for it; Right - COAD outer monolithic skin loaded onto holding fixtures at AUSS ultrasonic inspection equipment.

Thickness measurements were also conducted on the CCPS, and results were improved over the typical autoclave results (Figure 19). In particular, the consistency of the rabbet step and lack of thin-out was noticeable. In addition, visual and 10MHz NDT of the skins revealed no ply waviness, which is a non-conforming condition experienced by many of the autoclave-cured production structures.

Cooling Outer Aft Duct (COAD) Results

Visual inspection of the outer monolithic COAD skin showed that while the skin acreage and ply drops looked good and the SurfaceMaster did an excellent job of suppressing surface porosity, the radii at the skin/flange interfaces looked wrinkled, especially in the vertical flange. This was likely due to a poor final (cure) bag application by technicians that allowed bridging in those radii.

Ultrasonic inspection of the COAD skins was still occurring at the writing of this paper.

Visual inspection of the inner honeycomb skin showed that despite some pieces of Aeroglide surfacing film folding over on themselves, the inner (tool) surface looked good. The co-cured C-channels also looked very good, though problems with locating the honeycomb core meant that the C-channels were not located in the center of the "land" regions between the honeycomb.

Conclusions

By carefully building increasingly difficult and larger demonstration articles, components, and elements, the Non-Autoclave Manufacturing Technology Program has provided the base of a launch pad for automation programs, manufacturing very large scale parts, and flight-worthy primary structure fabricated from materials developed and produced for non-autoclave processing.

Figure 13. Left - Park Electrochemical Aeroglide™ surfacing film being applied to COAD inner skin tool; Right – Fused deposition modeling (FDM) polycarbonate tooling for co-cured C-channel stiffeners.

Figure 14. Left - COAD inner honeycomb skin ready for film adhesive and final cloth plies; Right – Lay-up of the cloth prepreg onto FDM tools for co-cured C-channel stiffeners.

Figure 15. Left - COAD inner honeycomb skin with FDM-tooled C-channels ready for final bag before cure; Right – After cure/post-cure, the inner honeycomb skin is trimmed; outer monolithic skin is in background.

Figure 16. CCPS first skin (cured against Invar tool) ultrasonic C-scan; significant areas of porosity likely due to insufficient pressure caused by lack of thermal expansion of tooling details.

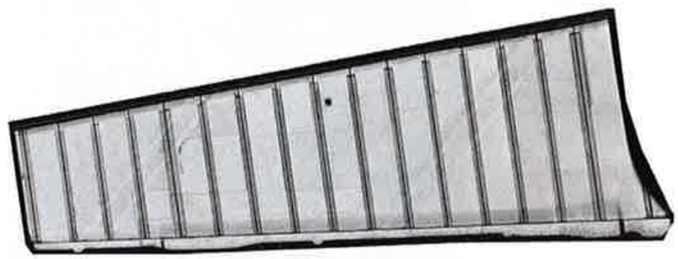

Figure 17. CCPS second skin (cured against composite caul sheet) ultrasonic C-scan; clean scan with exception of foreign object debris (ply label).

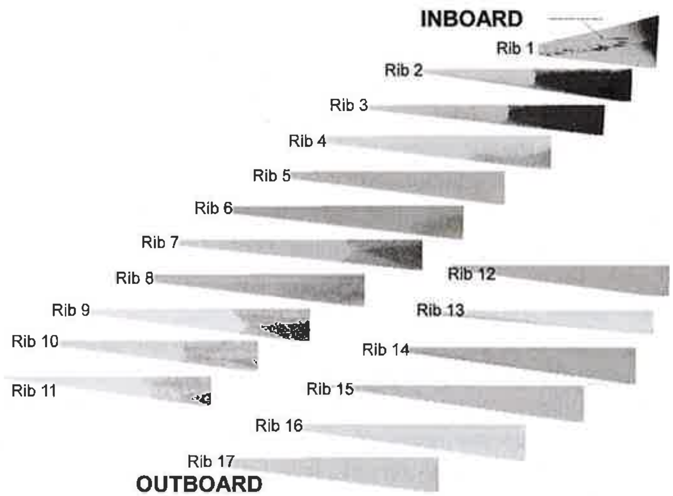

Figure 18. CCPS rib (I-beam) webs ultrasonic C-scans; some areas of porosity; probable cause is again lack of compaction pressure due to lower thermal expansion of aluminum tooling details.

Complex production and large composite co-cures have been successfully fabricated with out-of-autoclave resin systems. A few imperfections were observed due to tool/part incompatibility and poor bagging practices, but, in general, the quality of co-cures can be significantly improved by moving to low-flow resins and reduced pressures. Ply migration, radius thinning/thickening, and dimensional control are just some of the features that were improved with the non-autoclave co-cures.

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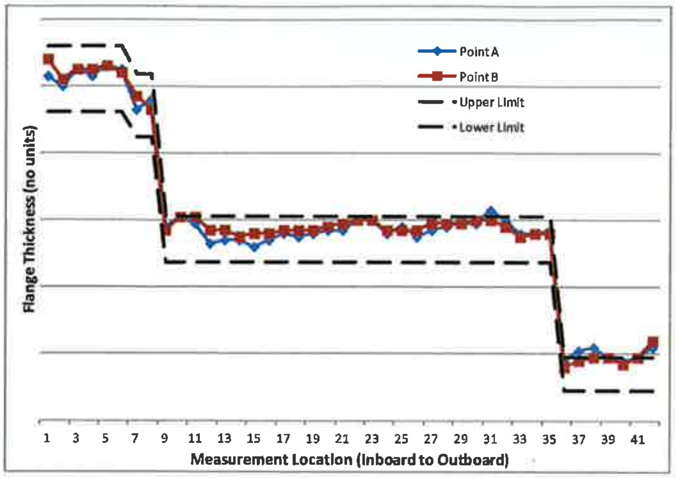

Figure 19. Thickness measurements along length of CCPS flange indicating good thickness control and lack of thinning typically experienced by autoclave-cured structure.

Figure 20. Left - COAD outer monolithic skin after cure showing ply drop region; Right – After cure, the outer monolithic skin had wrinkling in flange radii, particularly in the vertical flange.

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