MANUFACTURING PROCESS DEVELOPMENT FOR ADHESIVELY BONDED JOINTS IN LARGE-SCALE SPACE STRUCTURES

William E. Guin[1], James R. Newton[1], David E. Lawrence[1], Phillip D. Thompson[1], Andrew N. Martin[1], Casey C. Wolfe[1], Justin R. Jackson[1], and Sandi G. Miller[2]
[1] NASA Marshall Space Flight Center, Huntsville, AL 35812
[2] NASA Glenn Research Center, Cleveland, OH 44135

ABSTRACT

In order to take full advantage of the weight savings and performance gains offered by the use of composite materials in large-scale space structures, adhesively bonded joints must be considered. While bonded joint manufacturing at laboratory scale can be straightforward, the same manufacturing processes are not trivial at full scale. Surface preparation becomes particularly challenging (a viable process must yield consistent results over a large application area and be repeatable for multiple application sites), as does the application of heat to cure the doublers and/or bond them to the primary structure (the nature and scale of assembled or partially assembled aerospace structures often necessitates an out-of-oven/out-of-autoclave approach). In this work, bonded joint manufacturing processes are adapted for a full-scale (approximately 30 feet in diameter at the aft end) composite payload adapter at the NASA Marshall Space Flight Center. By iterating across a range of variables, process parameters for adhesively bonded joints on a large-scale composite structure have been developed. Primary findings are presented with respect to overarching bonded joint manufacturing concepts so as to maximize the applicability of this work to similar material systems and structures.

1. INTRODUCTION

Since early 2016, NASA has worked to develop a Payload Adapter (PLA) for use on the Space Launch System (SLS) heavy-lift rocket – specifically, on the SLS Block 1B configuration. Due to a number of design constraints – including the need to conserve mass throughout the rocket to maximize payload capacity, especially among the components that are intended for on-orbit applications – composite sandwich construction has been baselined for primary structure of the PLA. Figure 1 shows a representative schematic of the PLA and how it integrates with an example SLS Block 1B configuration as a whole.

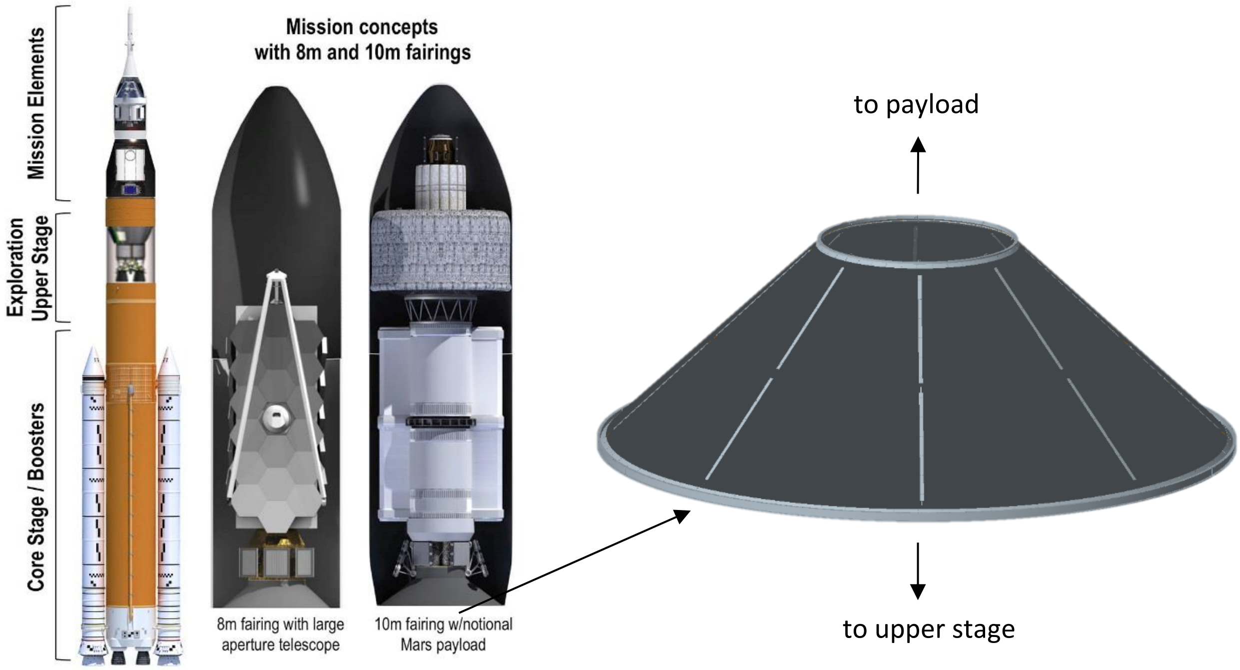


Figure 1. PLA and integration with SLS Block 1B.

Due to facility and general handling constraints, the primary structure of the PLA is comprised of 8 composite sandwich panel segments. These segments are bolted into metallic rings forward and aft which make up the structure's circumferential joints. Though initial designs called for longitudinal (sandwich panel to sandwich panel) joints to be bolted as well, a bonded configuration was eventually selected to further optimize the structure in terms of mass.

In order to further develop manufacturing processes for the PLA at full-scale, a Manufacturing Demonstration Article (MDA) was recently fabricated and assembled at the NASA Marshall Space Flight Center (MSFC). Figure 2 shows PLA MDA manufacturing and assembly in more detail.

(a) (b)

Figure 2. Manufacturing and assembly of Payload Adapter Manufacturing Demonstration Article at NASA MSFC: (a) Facesheet layup via automated fiber placement and (b) Completed article in assembly fixture.

Composite sandwich panel segments were manufactured using automated fiber placement (AFP) and autoclave-cured. The assembly process began as the trade between bolted and bonded longitudinal joints was being carried out in earnest. Given the nature of the PLA MDA – which was not to be tested at full-scale, as it was primarily intended for manufacturing development – the project team chose to further develop both bolted and bonded manufacturing processes for the longitudinal joints. As such, half of the longitudinal joints were bolted and half were bonded. In order to make the most of this opportunity, the authors chose to consider 4 unique bonded joint configurations with respect to manufacturing approach. The key areas of focus for this work included the following:

- continuous doublers (where doublers in a given joint extend uninterrupted from the forward to the aft end) vs. segmented doublers (where a given joint is comprised of multiple doubler segments which are separated by several inches, so as to provide for some degree of fracture control),
- co-bonding (where doublers and film adhesive are cured/bonded to the primary structure in the same process) vs. secondary bonding (where doublers are pre-cured and then bonded via film adhesive to the primary structure), and
- flat doublers (where doublers to be secondarily bonded are cured on flat tooling) vs. curvature-matched doublers (where doublers to be secondarily bonded are cured on curvature-matching tooling).

The manufacturing approaches considered in this work are listed in Table 1.

Table 1. Bonded joint configurations considered for Payload Adapter Manufacturing Demonstration Article.

Configuration	Description	Cure/bond Approach	Notes
1	Gap between doublers	Doublers co-bonded	• Gap between doublers demonstrates fracture control measure
2	Continuous doubler (via step-lap joint)	Doublers co-bonded	• Demonstrates ability to produce doubler larger than available heater blanket size
3	Doublers cured in oven on flat tool; gap between doublers	Doublers pre-cured, then secondarily bonded	• Allows doublers to be inspected after cure/prior to implementation on PLA • Allows for a lower temperature bonding process (by way of using 250°F curing film adhesive) • No specialized tooling needed for doubler layup/cure
4	Doublers cured in oven on curved PLA segment panel; gap between doublers	Doublers pre-cured, then secondarily bonded	• Allows doublers to be inspected after cure/prior to implementation on PLA • Allows for a lower temperature bonding process (by way of using 250°F curing film adhesive) • Precludes potential risk of internal stresses at bond interfaces (by more accurately matching curvatures)

As mentioned previously in this section, the objective of this effort was to further develop manufacturing processes for longitudinal bonded joints to be used on the PLA. This paper aims to summarize said effort, with emphases on lessons learned and overarching bonded joint manufacturing concepts in view of processing at full-scale.

2. DEVELOPMENT WORK

2.1 Bonded Joint Design

The longitudinal bonded joint design used in this effort was leveraged from NASA’s Composite Technology for Exploration (CTE) project. Sleight et al. [1] provide a comprehensive overview of the design, analysis, manufacturing, and testing efforts undertaken to develop this bonded joint concept, which consists of a double strap configuration where tapered doublers are bonded to the primary structure with film adhesive. To maximize the applicability of said bonded joint concept, out-of-autoclave material systems were used for both the doublers and the film adhesive. Figure 3 shows a schematic of the bonded joint design leveraged from NASA’s CTE project and used in the work presented herein.

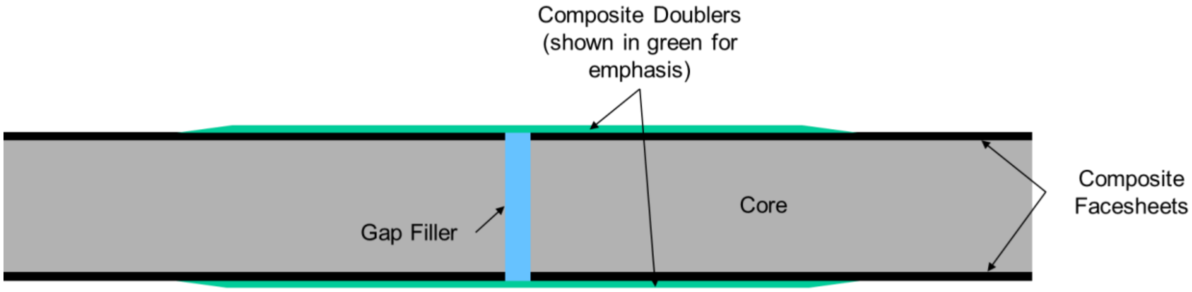


Figure 3. Longitudinal bonded joint concept used herein.

2.2 Surface Preparation

While a range of surface preparation (abbreviated from this point forward as “surface prep”) techniques were considered for use on the full-scale PLA MDA, several constraints heavily influenced the selection of the surface prep technique to be used. When manufacturing began on the composite sandwich panel segments (the first phase of fabrication for the PLA MDA) longitudinal bonded joints were not a primary consideration. As such – although the use of peel ply to provide for surface roughness and eventual mechanical interlock at bonded interfaces (among other potential benefits) is a commonly considered option in developing a surface prep scheme [2–7] – the use of peel ply on the surfaces of the composite sandwich panel segments was not considered at the time. Composite sandwich panel surfaces were instead smooth, as they were cured against tooled surfaces on the outer mold line (OML) and inner mold line (IML) sides. Additionally, the assembly process (and thereby, the bonded joint fabrication process) was to occur in a Class 100,000 clean room. Therefore, surface prep techniques which relied on material removal (i.e. manual abrasion) would necessitate additional processes to sufficiently manage dust/debris (if feasible at all).

2.2.1 Technique Down-select

With consideration given to the aforementioned constraints, a range of basic surface prep techniques was evaluated for use on the PLA MDA. At the onset of technique down-selection, a Surface Analyst was used to measure water contact angle (WCA), which allowed for rapid screening of surface prep techniques and their associated process parameters. Results from this initial screening are shown in Figure 4.

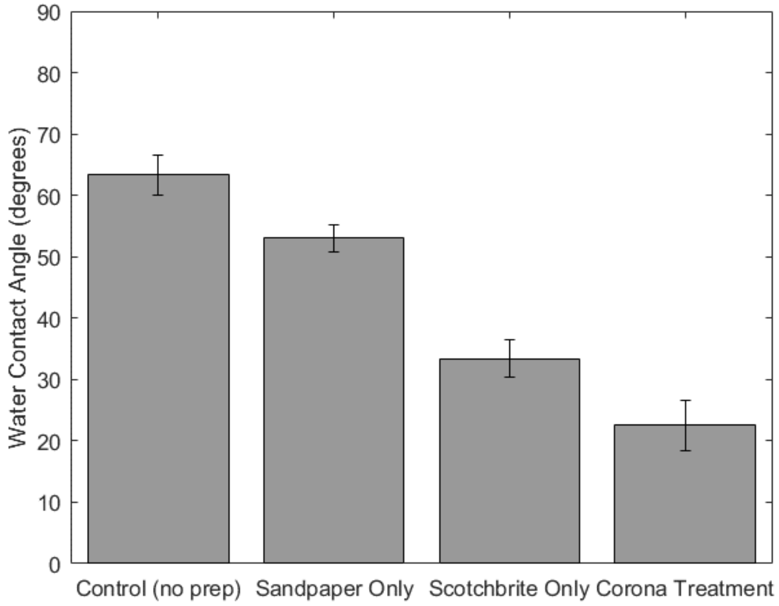


Figure 4. Results from initial surface prep screening.

As seen in Figure 4, corona treatment showed the most promise in terms of WCA. Corona treatment exposes the surface to be bonded to a cloud of ionized air, where electrons collide with the surface with enough energy to break existing molecular bonds. This process leads to an increase in surface energy (which provides for better wettability) and can add functional groups to surfaces that were previously largely inactive. Corona treatment is a type of plasma treatment and is similar to atmospheric plasma in that ionized (or at least partially ionized) air is utilized; however, atmospheric plasma treatment is typically capable of altering surface energy in a more significant and stable manner. Although atmospheric plasma is generally considered to be superior to corona treatment in these respects, at the time this work was carried out, only a corona treatment system was available for use. Given the aforementioned advantages of atmospheric plasma treatment, the authors have since procured an atmospheric pressure plasma treatment system to use going forward.

Though not necessarily reflected in the results shown in Figure 4, corona treatment also proved to provide for operator independence (even though the system considered herein was manually operated). Where manual abrasion techniques were considered, results varied from operator-to-operator, and, in several instances, varied from panel to panel for a given operator. Where corona treatment was considered, results were consistent from operator-to-operator and from panel-to-panel for a given operator. Although corona treatment led to the lowest WCAs in the initial screening, the element of operator independence was among the chief considerations that ultimately led to the selection of corona treatment as the primary process for surface prep on the PLA MDA. Along with the fact that corona treatment (and its counterpart, atmospheric pressure plasma treatment) lends itself to operator independence and the potential for full automation in future work, several additional considerations played a significant role its selection for use on the PLA MDA: it provides for enhanced chemical bonding by adding functional groups on surfaces to be bonded, it provides for some degree of surface cleaning prior to bonding (though this cleaning/removal effect is not applicable to all potential contaminants [6,8]), and it provides for a no-dust solution for clean room/clean work area applications.

Following the selection of corona treatment as the primary surface prep process for the PLA MDA, a complete surface prep approach was developed; this included an initial solvent wipe to clean the surfaces to be bonded, corona treatment, and, finally, verification of the consistency of surface prep via WCA measurements taken by the Surface Analyst. An important distinction should be noted here with regard to the use of WCA measurements in surface prep and bonded joint applications in general. While WCA measurements can provide an indication of the consistency with which a given surface prep technique has been carried out, the wetting behavior of a single liquid is not sufficient to comprehensively characterize surface energy [9]. Furthermore, WCA can be influenced by surface roughness [10,11], and, as such, WCA measurements may be less meaningful on surfaces with inherent roughness (as in peel ply surfaces) or that have been prepared via extensive abrasion/etching. Similarly, where surface prep schemes involving material removal are considered, WCA can change as matrix material is removed and fiber surfaces are exposed (which can lead to confounding WCA results, especially considering the inconsistency inherent to manual abrasion techniques). For these reasons, among others, WCA measurements do not necessarily correlate to the mechanical performance of a bonded interface and, if used, should not be overly relied upon in the development or verification of a given surface prep scheme.

2.2.2 Technique Validation

Following the selection/development of a surface prep approach for the PLA MDA, a series of single lap shear tests were carried out to evaluate the effectiveness of said approach. Coupons were fabricated using the surface prep approach to be used on the PLA MDA. Single lap shear tests were carried out per ASTM D3165. While failure loads were recorded, failure modes/locations were of primary interest. Post-failure images were examined via digital image analysis to determine relative percentages of each failure mode within the bond area. A single post-failure image that contained both mating fracture surfaces was taken for each coupon. Pixel counts were taken for each area representing a given failure mode and compared to the pixel count corresponding to the original bond area to determine relative percentages (based on area) for each failure mode. Table 2 shows failure mode results from the single lap shear testing carried out herein.

Table 2. Failure modes from single lap shear testing using PLA MDA surface prep technique.

Specimen	Failure Mode (relative %, based on area)		
	Adhesive	Cohesive	Substrate
1	0	99	1
2	0	53	47
3	0	72	28
4	0	81	19
5	0	73	27
6	0	17	83
7	0	50	50
8	0	100	0

As seen in Table 2, no instances of adhesive failure (failure at the adhesive/adherend interface) were observed in the 8 specimens considered. Each specimen exhibited a combination of cohesive failure (in the bulk adhesive) and substrate failure (in this case, interlaminar failure within the composite adherend), which showed that the bond interface itself was not the "weak link". This information was used to justify the use of this surface prep technique on the full-scale PLA MDA.

2.3 Doubler Cure

2.3.1 Validation in Oven

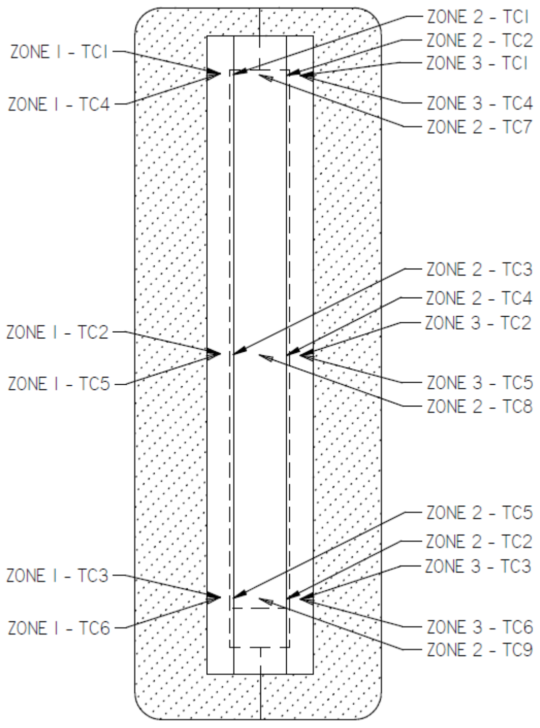
As previously mentioned, both co-bonded and secondarily bonded approaches were considered in this effort. To facilitate co-bonding, an out-of-autoclave prepreg system was selected for the composite doublers. Because out-of-autoclave prepreg systems can be particularly sensitive to processing (specifically, material condition prior to cure and breathing scheme during cure), a series of panels were processed in-oven at NASA MSFC and tested in order to validate the processing approach (i.e. material handling, breathing scheme, bagging procedure, etc.) and cure cycle to ultimately be used on the full-scale PLA MDA. Test panels were manufactured at NASA MSFC and tested at the National Institute of Aviation Research (NIAR). Results were compared to previously validated data on-hand at NIAR. Table 3 shows that results gleaned from the test panels manufactured at NASA MSFC compare well to the NIAR data. As such, the processing approach used for the out-of-autoclave prepreg system was adopted for use on the full-scale PLA MDA.

Table 3. Comparison of out-of-autoclave prepreg mechanical properties used to validate processing approach.

Property	Normalized Mean Values (% of baseline)	
	NIAR	NASA MSFC
Longitudinal Tensile Strength	100	103
Longitudinal Tensile Modulus	100	101
Longitudinal Comp. Strength	100	110
Longitudinal Comp. Modulus	100	100
In-plane Shear Strength (0.2% offset)	100	96
In-plane Shear Modulus	100	100
Short-beam Shear	100	105

2.3.2 Adaptation for Hot Bonder/Heat Blankets

Following validation of the processing approach and cure cycle to be used, the cure cycle was adapted for use with a hot bonder/heat blanket setup so as to provide for in-situ cures on the full-scale hardware. A number of trial runs were carried out on mocked-up assemblies to simulate the full-scale configuration as closely as possible. Several constraints existed in terms of available equipment (which arose in part due to project schedule constraints), namely with respect to heat blankets. In order to accommodate doublers of the width specified by the aforementioned bonded joint design, a combination of heat blankets was required as the widest available heat blanket was the same width as the doubler itself. In order to provide for uniformity in the heating profile across the width of the bond area, supplementary heat blankets (on either side of the primary heat blanket) were used to create a transition area from the extents of the bond area out toward the acreage of the primary structure. In each of the trial runs, temperature data was collected along the backside of the doubler (under the heat blanket) and along the backside of the heat blankets (on top of the heat blankets, toward the vacuum bag). Figure 5 shows this multi-group, multi-zone cure control/monitoring approach in more detail. This data was used to determine temperature lags between the part and the heat blankets. In turn, these temperature lags were used to configure the hot bonder – which was set to control via heat blanket temperatures while part temperatures were simply monitored – to run the cure cycle as desired. In effect, heat blanket set points were configured so as to compensate for the temperature lag between the heat blankets and the part. This configuration proved to provide for much more consistent cure control, as the feedback loop between heat blanket temperature and heat input is predictable cure-to-cure, which leads to better repeatability across a series of cure runs.



TC Locations for Doubler A & Doubler C

TC Map - OML Doublers				
Group	Zone	TC	Placement	Location (from FWD end of doubler)
1	1	1	Part	1"
1	1	2	Part	20"
1	1	3	Part	40"
1	1	4	Blanket	1"
1	1	5	Blanket	20"
1	1	6	Blanket	40"
2	2	1	Part	1"
2	2	2	Part	1"
2	2	3	Part	20"
2	2	4	Part	20"
2	2	5	Part	40"
2	2	6	Part	40"
2	2	7	Blanket	1"
2	2	8	Blanket	20"
2	2	9	Blanket	40"
1	3	1	Part	1"
1	3	2	Part	20"
1	3	3	Part	40"
1	3	4	Blanket	1"
1	3	5	Blanket	20"
1	3	6	Blanket	40"

Figure 5. Cure control/monitoring scheme used for PLA MDA bonded longitudinal joints. Note that the scheme shown herein incorporates heat blankets on both sides of the sandwich panel assembly, so as to cure/bond corresponding doublers in the same run.

3. FULL-SCALE WORK

Following the limited run of development work discussed in Section 2, full-scale bonded joint manufacturing began on the PLA MDA. A total of 4 bonded longitudinal joints were fabricated; 2 joints were co-bonded while 2 joints were secondarily bonded. As previously presented, Table 1 includes additional information on the bonded joint configurations considered herein.

3.1 Gap Filler Injection

As the PLA MDA is comprised of 8 sandwich panel segments, small gaps exist between adjacent segments. To provide for a relatively constant profile from segment to segment (across the area on which doublers would ultimately be bonded), these small gaps were filled with an injectable epoxy. This epoxy material was then allowed to cure at room temperature. Figure 3 (presented in Section 2.1) shows how the gap filler contributes to the overall bonded joint configuration.

3.2 Surface Preparation

Following gap filler injection and cure, surface prep was carried out on the areas to be bonded. First, an area approximately twice as wide as the area to be bonded was masked off (i.e. outlined). Surface prep was then carried out over the entire masked area, with care given to prep the entire area in the same manner. As seen in Figure 6, corona treatment was performed manually (given the lack of an automated process at the time). Following corona treatment, a Surface Analyst was used to check WCA along the extents of the masked area (not in the area to be bonded, so as to prevent potential contamination). As previously discussed in Section 2.2.1, these WCA measurements were taken as an indicator as to the extent to which surface prep had been carried out (and not as an indicator as to the eventual integrity or durability of the joint to be bonded).

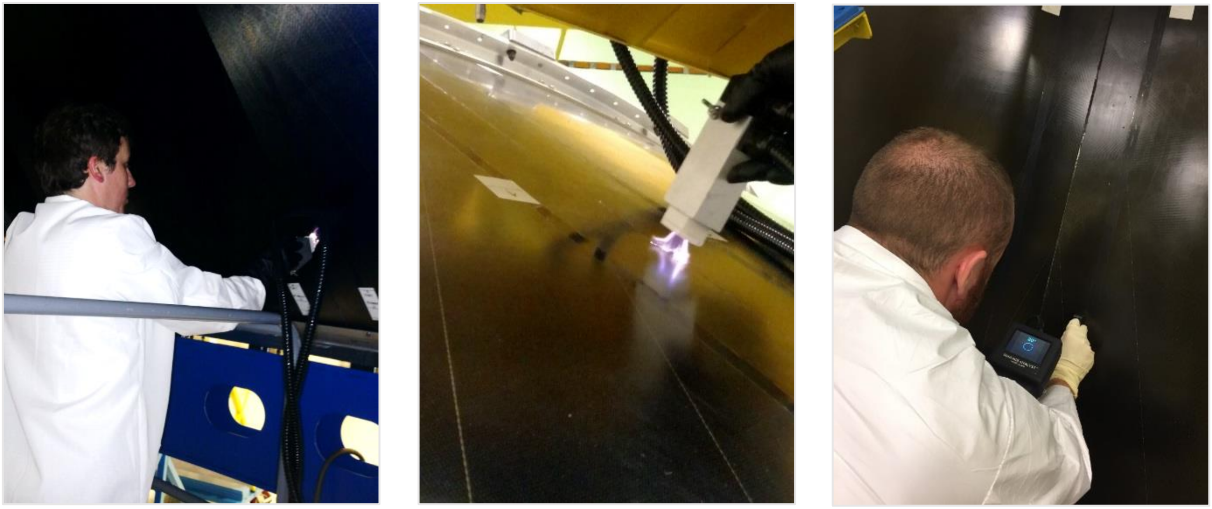
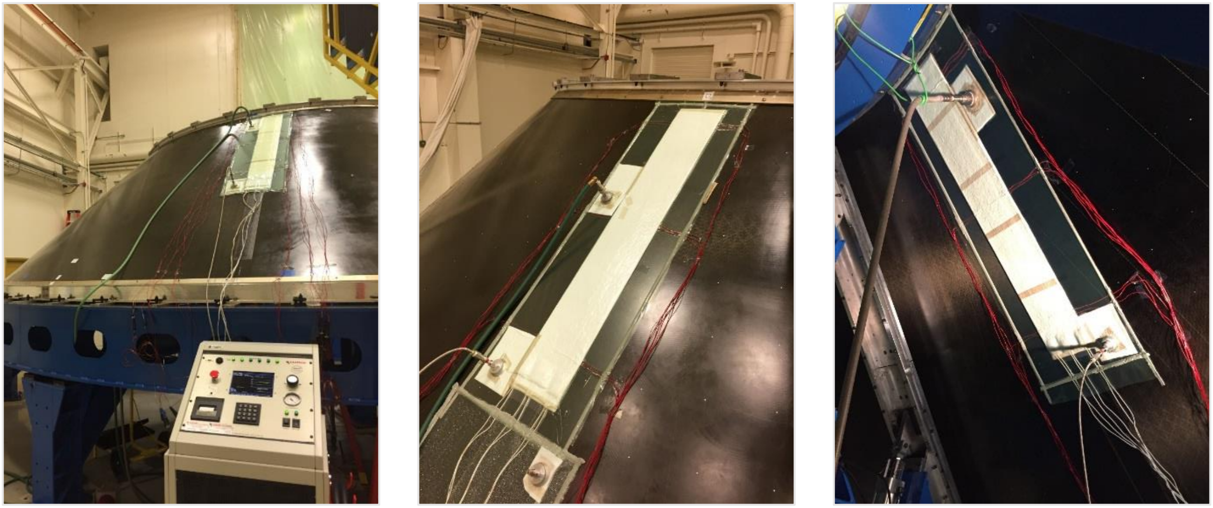

(a) (b) (c)

Figure 6. Surface prep on the PLA MDA: (a-b) surface preparation via corona treatment, which was operated by hand for the work presented herein, and (c) water contact angle (WCA) measurements taken via Surface Analyst.

3.3 Doubler Installation and Cure/Bonding

Upon completion of surface prep, doublers were installed and bagged for cure. Where co-bonding was considered – doublers were laid up, film adhesive was applied, and the assembly was debulked prior to installation, such that doubler installation was simply a matter of placing the entire doubler assembly onto the primary structure in a single step. Similarly, where secondary bonding was considered – film adhesive was applied to the pre-cured doublers prior to installation, such that doubler installation consisted only of placing the entire assembly onto the primary structure in a single step. Following doubler installation, processing materials were applied as necessary (which varied based on whether the doublers were to be co-bonded or secondarily bonded), heat blankets were placed, thermocouples were installed, and the assembly was bagged for cure. Note that for a given joint/joint segment, corresponding doublers were cured/bonded to the primary structure on both the OML and IML surfaces simultaneously. This aided in heat retention through the thickness of the part assembly, as heat was input at corresponding locations on both sides of the primary structure (i.e. heat was not allowed to escape through the opposing side). Figure 7 shows several images of the longitudinal bonded joints during cure.



(a) (b) (c)

Figure 7. Doubler cure/bonding for a forward end joint segment on the PLA MDA: (a) hot bonder/heat blanket setup for forward end doublers, (b) cure/bonding setup for forward end outer mold line doubler, and (c) cure/bonding setup for forward end inner mold line doubler. Note that both doublers shown here were cured simultaneously.

4. CONCLUSIONS

The work presented in this study provided for the development of process parameters with respect to several critical focus areas in bonded joint manufacturing for full-scale applications. While the detailed process parameters developed throughout this effort are generally configuration-specific (and therefore, would be of limited use to the broader community), conclusions are presented herein with respect to overarching bonded joint manufacturing concepts so as to maximize applicability to the broader aerospace community.

4.1 Lessons Learned

4.1.1 Surface Preparation

Although the surface prep scheme considered herein – manually operated corona discharge treatment – proved to be adequate based on a limited run of development and validation work, it is apparent that a fully automated treatment system would be ideal (which aligns with the observations made in previous studies [5,9,12,13]). Two of the most critical parameters in any corona or plasma treatment regime are feed speed and offset distance (from the surface to the corona/plasma source), and both of these parameters can be easily controlled in an automated system. With an automated corona or plasma treatment process, an end user could move one step closer to complete operator independence in the surface prep process. Since surface prep is arguably the most critical process in any bonded joint manufacturing approach, eliminating operator dependence stands to improve reliability of the bonded joint system as a whole.

4.1.2 *Heat Blankets*

In bonded joint applications where hardware scale dictates that an in-autoclave or in-oven cure/bond approach is not feasible, a hot bonder/heat blanket setup (as used in this work) is a viable option; however, the challenges commensurate with this approach should not be glossed over. Uniform heat input into the part is anything but trivial and can be complicated by a number of configuration-specific factors (including part geometry, proximity of nearby heat sinks, substrate thickness, core type, etc.). As such, for a given configuration and cure approach, a heat blanket design unique to said configuration and cure approach should likely be considered. In general, however, a picture frame configuration – as depicted in Figure 8 – addresses several of the issues observed in the work presented herein. The center section is responsible for the primary cure cycle, while the outer section is supplementary; the outer section provides a transition region between the non-heated primary structure and the area to be cured/bonded, thereby reducing the potential for heat loss effects along the edges of the doubler assembly and promoting a more uniform distribution of heat across the area to be cured/bonded. A picture frame configuration can be achieved by using multiple blankets (i.e. with separate cure controls) or by using a single blanket with multiple heating zones (i.e. with separate heat output rates given a constant power input). By curing both doublers within a double strap configuration simultaneously, as was done in this work, heat loss through the thickness of the assembly can be minimized for a given configuration.

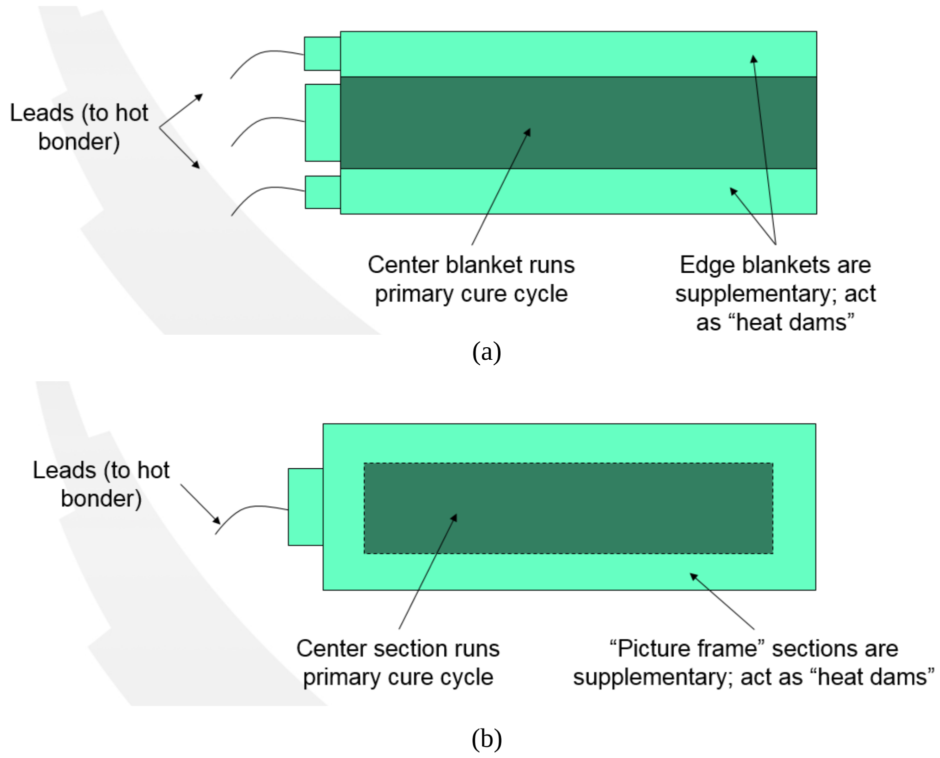


Figure 8. Heat blanket configurations considered herein: (a) heat blanket configuration used on PLA MDA (where 3 separate heat blankets are used in a multi-zone cure) and (b) enhanced heat blanket configuration (which entails a single multi-zone heat blanket) based on lessons learned from full-scale work on PLA MDA.

4.1.3 Co-bonding vs. Secondary Bonding

Both co-bonding and secondary bonding approaches were considered in this work. In part, this was made feasible by the relatively simple geometry of the primary structure considered herein, which dictated that simple tooling could be used to cure the secondarily bonded doublers (if complex tooling had been required for doubler cure in the secondary bonding approach, schedule constraints would have likely dictated that only the co-bonding approach be considered). Through the comparison between co-bonding and secondary bonding carried out in this work, a series of issues common to a range of bonded joint applications was evaluated with respect to manufacturing (for a more general discussion, refer to the comprehensive review by Budhe et al. [14]). A summary of the considerations gleaned from the work presented herein is shown in Table 4.

Table 4. Considerations (in brief) for co-bonding vs. secondary bonding with respect to bonded joint manufacturing on a large-scale composite structure.

Issue	Co-bonding	Secondary Bonding
Surface preparation	Required on one surface (primary structure)	Required on two surfaces (primary structure and doublers)
Doubler/bonding adhesive cure (where part scale exceeds size of available autoclave/oven)	Requires in-situ cure of prepreg material system for doublers and bonding adhesive (if used)	Requires in-situ cure of bonding adhesive only
Verification of doubler quality via NDE	Doubler quality can be verified only via post-cure NDE	Doubler quality can be verified via NDE prior to secondary bonding operation (i.e. ability to reject a doubler if quality is poor)
Verification of doubler quality via mechanical/thermal testing	Difficult to fabricate representative witness panels	Representative witness panels can be cured in same oven run as doublers; can verify material properties for each doubler produced
Bond integrity (in relation to as-built part geometry)	Co-bonding process allows doubler assembly to conform to as-built geometry of the primary structure	Must rely on film adhesive to compensate for irregularities in as-built primary structure geometry
Tooling	Does not require tooling	Requires tooling to match doubler form to that of the primary structure

Note that these considerations are general in nature, and, in a given bonded joint application, one or more of the issues identified may carry more weight than the others. For example, in an application where complex geometries exist in the primary structure, the benefits of a co-bonding approach with respect to tooling and bond integrity (in relation to as-built part geometry) would likely outweigh any of the benefits of a secondary bonding approach. On the other hand, in an application where primary structure geometry is simple and overall scale is manageable, the benefits of a secondary bonding approach with respect to doubler/bonding adhesive cure and verification of doubler quality may outweigh any concerns related to tooling and/or bond integrity (in relation to as-built part geometry).

5. REFERENCES

[1] Sleight DW, Segal KN, Guin WE, McDougal MR, Wolfe CC, Johnston MM, et al. Development of Composite Sandwich Bonded Longitudinal Joints for Space Launch Vehicle Structures. AIAA SciTech 2019 Forum, 2019. doi:10.2514/6.2019-0236.

[2] Kanerva M, Saarela O. The peel ply surface treatment for adhesive bonding of composites : A review. Int J Adhes Adhes 2013;43:60–9. doi:10.1016/j.ijadhadh.2013.01.014.

[3] Bardis J, Kedward K. DOT/FAA/AR-01/8: Effects of Surface Preparation on Long-Term Durability of Composite Adhesive Bonds. 2001.

[4] Bardis J, Kedward K. DOT/FAA/AR-03/53: Effects of Surface Preparation on the Long-Term Durability of Adhesively Bonded Composite Joints. 2004.

[5] Tracey A. Improving Adhesive Bonding of Composites Through Surface Characterization Improving Adhesive Bonding Through Surface Characterization. JAMS 2014 Tech. Rev., Seattle, WA: 2014.

[6] Tracey AC. Effect of Atmospheric Pressure Plasma Treatment on Surface Characteristics and Adhesive Bond Quality of Peel Ply Prepared Composites. University of Washington, 2014.

[7] Williams TS, Yu H, Hicks RF. of Polymers and Composites for Adhesive Bonding : A Critical Review. Rev Adhes Adhes 2013;1:46–87. doi:10.7569/RAA.2013.097302.

[8] Serrano JS. Surface Modifications of Composite Materials by Atmospheric Pressure Plasma Treatment. Universidad Rey Juan Carlos, 2011.

[9] Encinas N, Oakley BR, Belcher MA, Blohowiak KY, Dillingham RG, Abenojar J, et al. Surface modification of aircraft used composites for adhesive bonding. Int J Adhes Adhes 2014;50:157–63. doi:10.1016/j.ijadhadh.2014.01.004.

[10] Kubiak KJ, Wilson MCT, Mathia TG, Carval P. Wettability versus roughness of engineering surfaces. Wear 2011;271:523–8.

[11] Effect of Surface Roughness on Contact Angle Measurements Obtained with the Surface Analyst. Cincinnati, OH: 2016.

[12] Belcher MA, Krieg KL, Van Voast PJ, Blohowiak KY. Nonchemical Surface Treatments Using Atmospheric Plasma Systems for Structural Adhesive Bonding. SAMPE 2013, Long Beach, CA: 2013.

[13] Tracey AC, Belcher MA, Blohowiak KY, Flinn BD. Improving Adhesive Bonding through Surface Characterization: Reverse the Curse of the Nylon Peel Ply? SAMPE 2014, Seattle, WA: 2014.

[14] Budhe S, Banea M., de Barros S, da Silva LFM. An updated review of adhesively bonded joints in composite materials. Int J Adhes Adhes 2017;72:30–42. doi:10.1016/j.ijadhadh.2016.10.010.