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Enabling the manufacturing of the longitudinal butt joint of the world’s largest thermoplastic aircraft structure

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Abstract

With new opportunities for processing, recycling and repair, thermoplastic carbon fiber-reinforced polymers (TCFRPs) offer promising approaches to address the economic and sustainability challenges of tomorrow’s aviation industry. This article describes the manufacturing process of the longitudinal butt joint of the world’s largest thermoplastic aircraft structure, created within the frame of European Union’s Clean Sky 2 project. Using a CO_2 laser source, fully consolidated multidirectional reinforced TCFRP laminates with six plies are welded onto two fuselage half shells to create the longitudinal butt joint in a one-shot process. During welding, multiple parameters are adjusted constantly to achieve a joint with high homogeneity, including laser power, beam shape and feed rate. The chosen process has shown to produce joints with strengths comparable to those of reference samples produced by conventional hot press co-consolidation, without any post-processing after layup and is demonstrated on real-size component scale for the first time.

Keywords: Thermoplastic carbon fiber-reinforced polymer; Multifunctional Fuselage Demonstrator; Layup; CONTIjoin; Consolidation

1. Introduction

During the production cycle of an aircraft, the implementation of joining processes is inevitable due to the size of the components and the complexity of the systems involved. Modern fuselage architectures increasingly rely on the use of lightweight composite materials as they offer high specific strength and stiffness properties. Currently, thermosetting resins reinforced with carbon fibers are the most commonly used composite materials. Since these polymers cannot be remelted once cured, joining methods such as riveting and adhesive bonding are generally employed (Breuer, 2016; Thoppul et al., 2009). However, these techniques come with inherent limitations, including corrosion potential, additional weight or extensive surface and part pretreatment. (Czaban, 2018; Melhem, 2019; Messler, 2004; Pearce et al., 2010)

In contrast, thermoplastic composite materials enable novel design and processing solutions deriving from their ability to be (re-)molten, therefore allowing for welding, thermoforming and recycling operations. To explore the advantages of this material class, which so far has been used only to a limited extent in structural aircraft engineering, the Multi-Functional Fuselage Demonstrator (MFFD) has been manufactured as part of the European Union’s Clean Sky 2 program, incorporating several manufacturing and processing technologies. (Roth et al., 2024)

In this context, this work addresses the solution for the manufacturing of the longitudinal joint of both fuselage half shells which was fabricated using the CONTIjoin technology developed at Fraunhofer IWS Dresden. The longitudinal joint on the left-hand side of the MFFD was designed as a butt joint between the fuselage half shells on both sides of the passenger door cutout as shown in Fig. 1. A stepped joint structure was implemented to expand the effective joint area, especially around the door cutout to accommodate higher local stress levels. The design featured a layup of twelve six-ply laminate straps to create the joint with six straps per side of the door cutout extending to the end of the fuselage barrel. In each step, the width (from 60 mm to 360 mm in 60 mm increments) and length (from 543 mm to 4540 mm) of the straps increased. Additionally,

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the first four straps contain a ply-drop from six plies to one on a 1:200 ramp, whereas the last two straps feature a 45° taper with a decrease in width of 240 mm. The upper and lower shell radii were 1975.00 and 2538.25 mm, respectively. For tolerance management, the steps were designed to be up to 20 mm wider than the straps, leaving gaps to be later filled with thermoplastic neat resin after each welding run (gap filling). Inner positioners made from solid aluminum blocks were installed to bear the radial loads introduced during the layup operation.

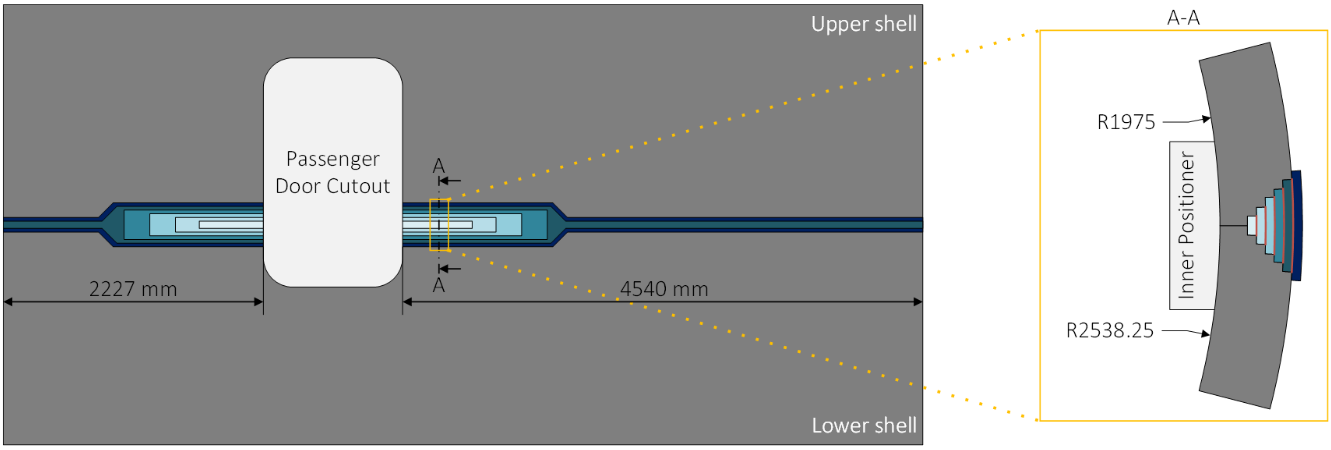

Fig. 1. Geometry of the longitudinal butt joint and dimensions of the laminate straps

2. Materials and tooling

2.1. Materials

The fuselage and laminate straps were made of Toray Cetex TC1225 LMPAEK (Toray Advanced Composites, The Netherlands) with 66 wt% T700 carbon fiber reinforcement. Both fuselage half shells were manufactured using automated fiber placement (AFP) technology. The lower shell underwent autoclave post-processing (Netherlands Aerospace Centre, NLR, The Netherlands), whereas the upper shell was laid in-situ (German Aerospace Centre, DLR, Germany). Likewise, the multidirectional reinforced six-ply laminates were manufactured by AFP (Fraunhofer IGCV, Germany), followed by continuous double-belt press consolidation (Berndorf Band Group, Austria). On the inward-facing side, all laminates were equipped with an additional 60 µm neat resin film (APTIV AE 250 LMPAEK, Victrex, United Kingdom) to increase the polymer thickness in the co-consolidation interface, while the last laminate strap was fitted with a copper lightning strike protection mesh on the outward-facing side.

2.2. CONTIjoin process

To perform the continuous co-consolidation of all laminate straps onto the fuselage surface, the CONTIjoin technology was used (see Fig. 2a). Each laminate strap was guided and centered on the joint line using an adjustable guidance mechanism and is placed underneath a consolidation roller tool. The consolidation tool consisted of multiple adjustable roller segments with elastomeric sleeves, allowing for conformation to the curvature of the fuselage while increasing the interaction length between incoming laminate and substrate material. The forming nip point area at the interface between the joining partners was heated by a CO_2 continuous wave (cw) laser source (DC040, Coherent, Germany) with a maximum laser power of 4 kW. Using a 2D high-speed laser scanning system (AXIALSCAN 30, Raylase, Germany), the raw laser beam (15 mm diameter) was oscillated across the laminate width while being superimposed with a perpendicular wobble frequency, creating a wide-spread temperature distribution field (see Fig. 2b). Simultaneously, a pyrometer (METIS MB35, Sensortherm, Germany) and a second scanning system (IntelliSCAN 14, Scanlab, Germany) measured the temperature inside the nip point area at multiple locations (Fig. 2c). This information was used in a digital PID control loop that adjusted the laser power during co-consolidation to maintain the chosen process temperature. The setup moved at a defined feed rate, enabling continuous processing. During layup, the nip point was constantly flushed with nitrogen gas to inhibit oxidation and the resulting thermal degradation of the material.

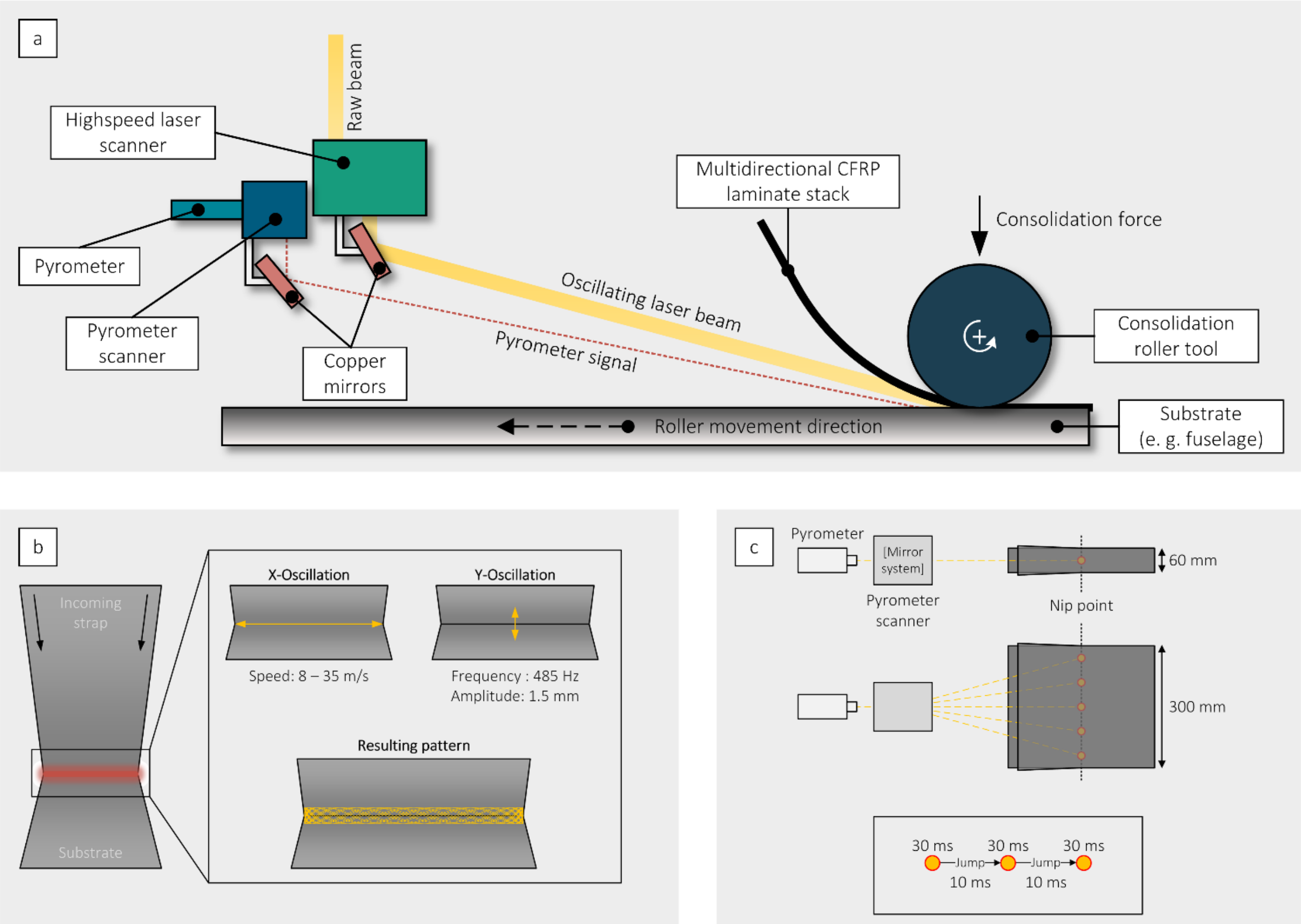

Fig. 2. Process schematic (a), laser beam shaping (b) and pyrometric temperature measurement solution of CONTIjoin layup (c)

2.3. Manufacturing setup

The required CONTIjoin hardware was integrated into tool heads ("end effectors") on two separate linear axes to prevent the translation of vibrations or distortions from the consolidation and guidance mechanisms to the CO_2 laser beam path. The optical end effector (OEE) contained the pyrometer and both scanning systems, whereas the mechanical end effector (MEE) included the strap guidance and consolidation mechanisms, as well as the nitrogen flooding nozzles. The MEE body, strap guidance mechanism, and pneumatic interface, including the control software, were developed by Fraunhofer IFAM Stade (Germany).

2.4. Preparation of the longitudinal butt joint

During inspection of the upper shell surfaces in the area of CONTIjoin-layup of the first four laminate sheets, significant defects were observed, such as delamination and loose carbon fiber rovings, attributed to the upper shell's novel in-situ layup approach of such large structures. This surface condition made it nearly impossible to ensure a sufficient bond quality. Therefore, the scope of the joining demonstration had to be reduced, as the provided components did not meet the required standards for realistic production conditions.

To enable the finalization of the joint, the defective areas were covered. A new surface with sufficient quality was created by adhesive bonding of the first four laminates onto the fuselage (Fig. 3a). The resulting surface for the remaining two laminate straps is shown in Fig. 3b.

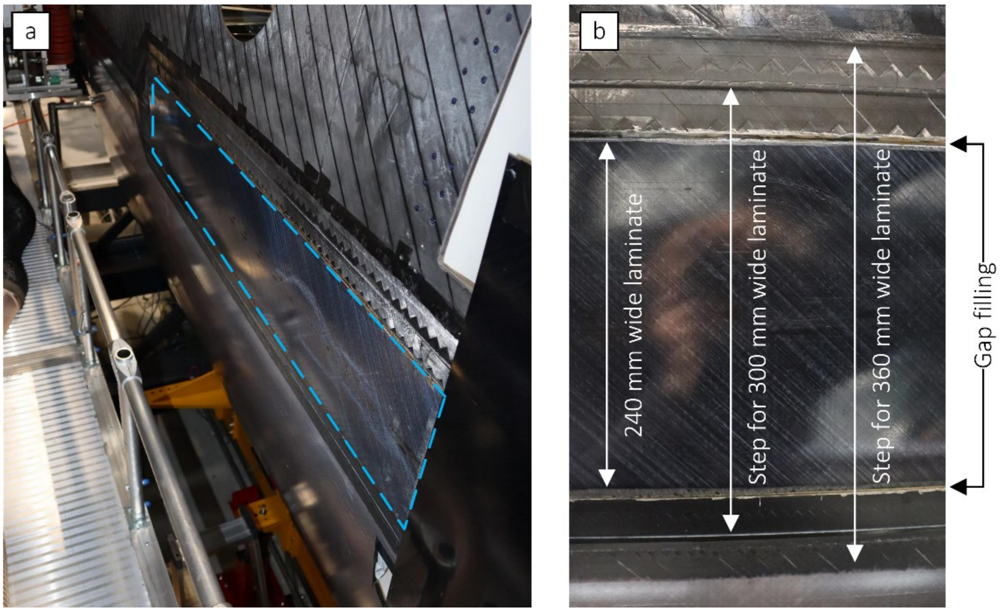

Fig. 3. Area of shimming on the MFFD (a) and prepared surface for welding of the remaining two laminate layers (b)

3. Results

The parameters used for the welding operations at the fuselage were based on experimental process window investigations already reported by (Pohl et al., 2024). On-site, additional welding trials were carried out to determine potential necessary adjustments. It was observed that the set temperature value had to be decreased considerably from 360 °C to around 280 – 290 °C for sufficient bonding and avoidance of thermal degradation. As this temperature is significantly lower than the melting temperature of the matrix polymer LMPAEK (305 °C) it has to be assumed that the pyrometer measurement does not ensure an accurate measurement of absolute temperature during the layup process. Additionally, the layup on the fuselage itself inherently differs from the manufacturing of coupon specimens in a laboratory environment due to the size of the actual components. This has an influence on the characteristics of the thermodynamic system such as heat conduction and heat capacity effects. The parameters used for manufacturing the longitudinal butt joint are displayed in Table 1.

Table 1. Laminate-width dependent CONTIjoin parameters for the longitudinal butt joint

Laminate width	Set temperature	Number of measurement points	Scan speed	Feed rate	Consolidation force
mm	°C	-	$m \cdot s^{-1}$	$mm \cdot min^{-1}$	N
60 ≤ w < 120	290	1	8.8	600	1500
120 ≤ w < 180	290	2	17.6	360	1500
180 ≤ w < 240	290	3	35.2	250	1500
240 ≤ w < 300	280	4	35.2	180	1500
300 ≤ w < 360	280	5	35.2	180	1500
w ≤ 360	280	6	35.2	180	1500

The layup of the laminate straps was concluded successfully. Photographic images of the straps are shown in Fig. 4. Bonding appeared to be sufficient over the large majority of the laminates' surface area, with slight ondulation in the area of the taper feature. The straps followed the curved fuselage geometry across their whole width no significant lift-off effects being visible. No damage of the fuselage substrate structure such as thermal degradation was observed, neither on the edge area of the laminate layup nor on the inside of the fuselage barrel.

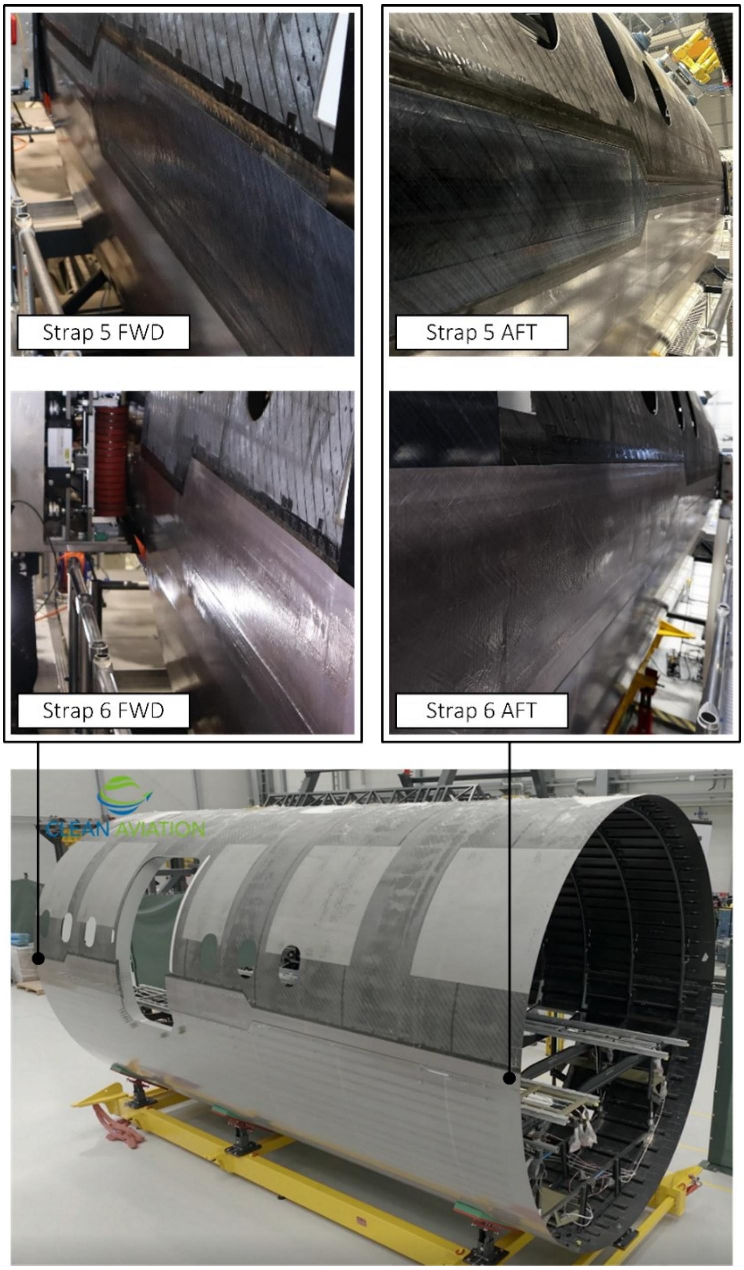

Fig. 4. Photographs of the straps after layup in FWD (a), AFT direction (b) and on the fuselage after extraction from the processing environment (c).

4. Conclusion

For the first time, the CONTIjoin technology was applied on a full-scale demonstrator to manufacture the longitudinal joint of the world's largest thermoplastic aircraft structure. To achieve this, the experimental laboratory setup was transferred into cooperating toolheads (end effectors) on a dual linear axis system, simulating a realistic manufacturing environment. An online process control and monitoring system was developed to enable the continuous co-consolidation of various and complex laminate geometries while ensuring laser safety. The most significant lessons learned can be concluded as the following:

- The CONTIjoin technology enables the manufacturing of complex and continuous joints of large-volume thermoplastic structures. The homogeneity of processing conditions can be achieved with an online process control system.
- Layup onto different substrates (in-situ and autoclave-consolidated material) within a single joining operation is possible.
- Gap filling material does not adversely affect the CONTIjoin process and can be considered as a viable option for tolerance management of such joints.
- The pyrometric measurement approach has to be evaluated regarding the accuracy to absolute temperatures. Alternative temperature measurement options such as thermographic imaging should be considered and verified.

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