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ORIGINAL ARTICLE

Development of innovative automated solutions for the assembly of multifunctional thermoplastic composite fuselage

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Abstract

In this study, the development of innovative tooling and end-effector systems for the assembly of a multifunctional thermoplastic fuselage is presented. The increasing demand for cleaner and new aircraft requires utilising novel materials and technologies. Advanced thermoplastic composites provide an excellent material option thanks to their weldability, low density, low overall production cost, improved fracture toughness and recyclability. However, to fully appreciate their potentials, new manufacturing approaches and techniques are needed. Hence, this project develops three end-effector solutions to demonstrate the feasibility of assembling a full-scale multifunctional-integrated thermoplastic lower fuselage shell, including the integration of a fully equipped floor and cargo structure. The developed assembly solution comprises three individual yet well-integrated tooling systems that allow housing the skin and assembly; picking, placing and welding of the assembly parts, i.e. clips and stringers; and welding of frames and floor beam sub-assemblies. The process of developing these systems including the end-user requirements, technical challenges, tooling and end-effectors design and manufacturing process are detailed in this paper.

Keywords Thermoplastic · Composites · Aerospace · Automation · End-effector · Manufacturing

1 Introduction

It is acknowledged that carbon dioxide (CO_2) emissions increase the greenhouse effect, becoming one of the main reasons for global warming [1–3]. Although the aviation industry brings economic benefits and connectivity, it is estimated that this sector is responsible for 2–3% of global CO_2 emissions; this contribution of CO_2 is expected to double by 2050 [4]. While significant investments in novel technologies are underway to improve the environmental performance of the aviation sector, its rate of growth means faster technological advances are needed [5, 6]. The latest European Aviation Environmental Report states that effective coordination between stakeholders is of the utmost importance to build on existing measures and address the environmental challenges, thus ensuring the long-term success of the aviation sector [7].

It is estimated that up to 600,000 litres of fuel can be saved over the lifetime of an aircraft for every 100 kg weight reduction [8]. Hence, one approach to reduce CO_2 emissions is reducing the weight of the aircraft. This is exploited in the aerospace industry by replacing conventional metallic alloys

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Luka Hans, Chris Worrall, Stuart Lewis, Daniele Negro, Tariq Sattar, Eduardo Ferrera, Elena Blanco and John Wighton contributed equally to this work.

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with composites to reduce weight in many areas, including the heavily loaded primary structure of the wing, fuselage, and smaller, more lightly loaded components, such as ailerons and fairings [9]. For instance, Airbus A350 XWB uses carbon fibre reinforced polymer (CFRP) composite material as much as 52% of its structure by weight [10]. Expanding the applications of composites not only reduces CO_2 emissions but also increases efficiency, payload and or range, as illustrated in Fig. 1.

Thermoset composites, which are most commonly used with continuous carbon, or glass fibre, reinforcing a polymeric matrix, still make the primary structure in advanced aircraft because of their development, competitive pricing, mature manufacturing process and well-established supply chain. However, low energy absorption, labour intensity, long production cycle time, limited recyclability and end of life options question the advantages and sustainability of thermosets in the long run [11–14], especially with the increasing demand for newer and cleaner aircraft.

To meet this increasing demand, there is a need to utilise novel materials and technologies. The alternative to the thermoset matrix is high-performance thermoplastic-based resins. Unlike thermosets, thermoplastic composites do not crosslink or cure, and require no catalyst. They can be moulded simply by heating them to temperatures that exceed their glass transition temperature (T_g), and they retain the new shape once cooled. More importantly, thermoplastics may be heated, welded, press-formed and cooled multiple times without loss of properties [15]. Also, they have low density, improved fracture toughness and in-service damage tolerance, and they can be recycled easily compared with thermosets [12, 14]. These characteristics potentially offer major advantages in terms of manufacturing and maintenance cost reductions and increased environmental friendliness. Hence, it is estimated that the use of thermoplastic composites can reduce manufacturing time by 20–30% [16], and aircraft's total weight and recurring cost by 10% and 20%, respectively [17].

However, to fully appreciate the potential benefits of thermoplastics composites in terms of weight, cost and production rate, new manufacturing approach and techniques are needed; thanks to GKN-Fokker Aerospace [18], these materials have already found their way into commercial-certified aerostructures applications, to name a few: the rudders and elevators of the Gulfstream and Dassault business jets [19], the wing leading edge of the Airbus A380, and the horizontal tailplane of the Leonardo AW169 helicopter [20], as shown in Fig. 2.

To leverage the full potential of thermoplastic composites in aviation and satisfy the need for drastically increasing aircraft production rates, there is a need to innovate completely different build concepts and exploit thermoplastic composites from sub-assemblies to larger assembled structures of the aircraft. To address this, the STUNNING project [22] (smart multi-functional and integrated thermoplastic fuselage) led by Airbus, is set to deliver a double-digit fuel burn reduction for the large passenger aircraft (LPA). The target is to validate high potential combinations of airframe structures, cabin/cargo and system elements using advanced materials and apply innovative design principles combined with the most advanced system architecture for the next-generation cabin [17]. Although joining such complex thermoplastic composite structures seems straightforward as the material is weldable, industrially established joining technologies for metallic and thermosets are not directly transferable to thermoplastic applications. Therefore, a combination of advanced and new production technologies are needed [23].

This study presents the development of three innovative end-effector systems to demonstrate the feasibility of assembling the structural elements of a 180° full-scale multifunctional-integrated thermoplastic lower fuselage shell (shell, stringers, clips and frames), including the system-equipped floor grid (see Fig. 3). The developed solution allows housing the skin and assembly; picking, placing and welding skin stiffening assembly parts; and welding the interfaces between the floor grid assembly and frame

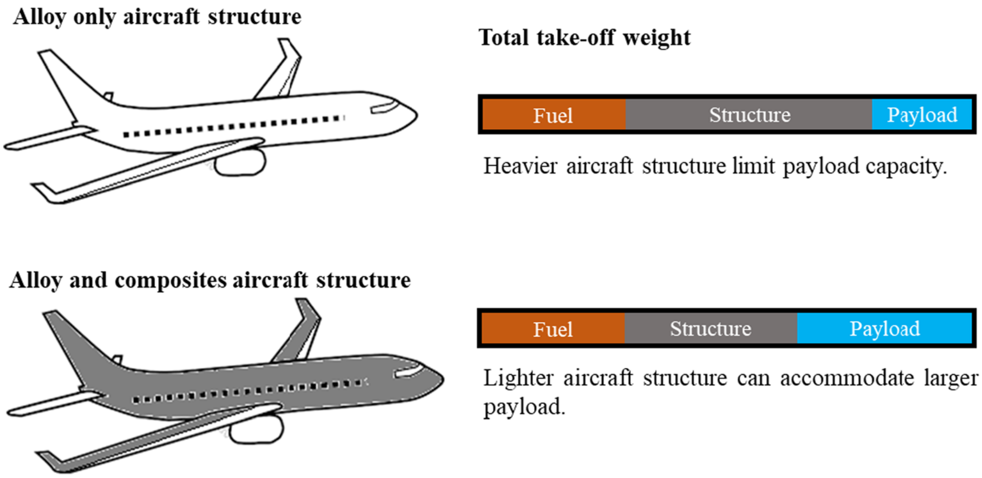


Fig. 1 A representation for the benefits of decreasing the aeroplane structural weight in terms of increasing the payload besides improving fuel consumption and/or flight range

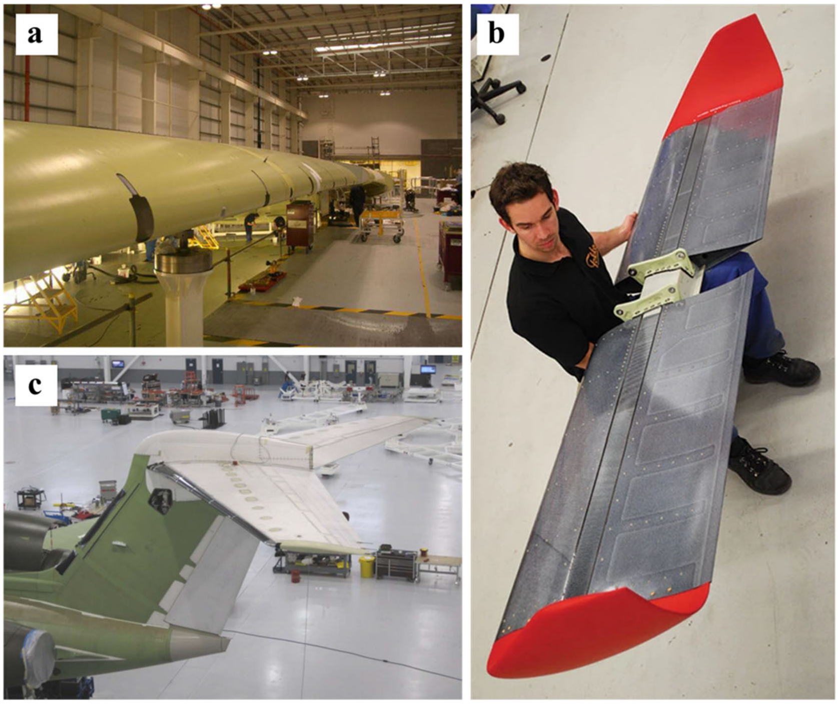


Fig. 2 Aerostructures applications of thermoplastic composites: (**a**) A380 fixed wing leading edge (J-nose), (**b**) a finished tailplane for the AgustaWestland AW169 helicopter [21] and (**c**) elevators and rudder assembled on the prototype Gulfstream aircraft [19]

sub-assemblies. Within this study's scope, several welding and joining techniques are employed to assemble demonstrator's thermoplastic components while considering industrial scalability, and integration with other production processes.

The structure of this study starts with describing the components of the demonstrator and their materials, outlining the demonstrator functional requirements, listing technical design challenges and drives, detailing tooling and end-effectors functions and development, and finally describing the assembly process and sequences. These developments are part of the TCTool project [24] (innovative tooling, end-effector development and industrialisation for welding of thermoplastic components).

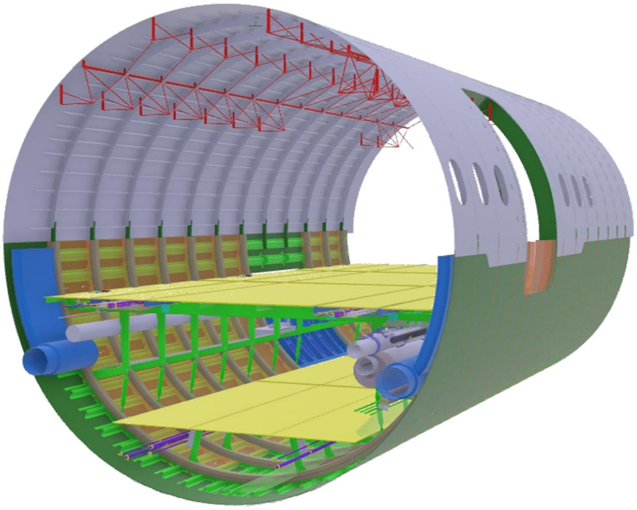


Fig. 3 An overview of the 360° multifunctional fuselage demonstrator from [25]

2 Fuselage components and assembly

The lower half of the multifunctional demonstrator features the asymmetrical Airbus A321 single-aisle aircraft fuselage [26]. The demonstrator section will have a length of around 8 m and a varying radius between 2 and 2.5 m. Although the design and development of the following key elements is not part of this study, they are presented here to outline the elements that will be assembled in this project; further details of these components can be obtained from the STUNNING project [22] and the work reported by Veldman et al. [17].

2.1 Thickness-varying composite fuselage skin

The thickness-varying skin of the demonstrator shown in Fig. 4(a) is manufactured with LMPAEK composite using the automated tape laying (ATL) technique. The laid preforms are transported robotically with suction cups to a female consolidation mould and cold draped in it. Finally, the skin is consolidated in an autoclave [17].

2.2 Composite stringers

A stiffening thermoplastic omega-stringer is used to reinforce the fuselage skin in the aircraft longitudinal axis, as shown in

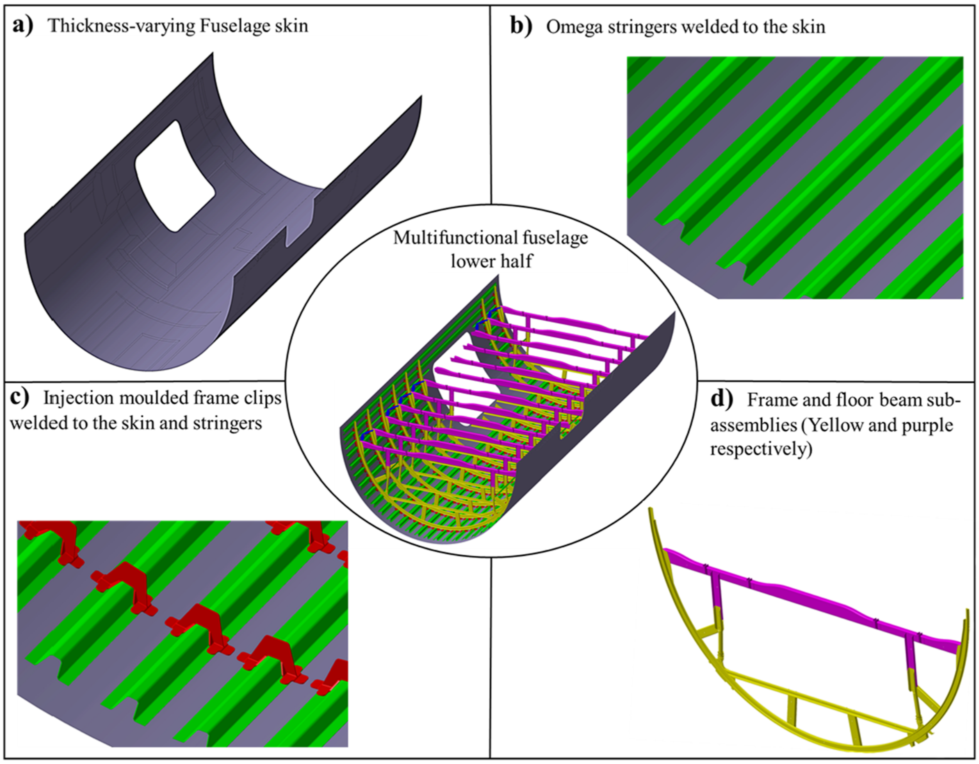


Fig. 4 The key structural components of the multifunctional fuselage demonstrator from Veldman et al. [17]

Fig. 4(b). These stringers will be welded to the skin by a long weld conduction technique developed by GKN-Fokker Aerospace [18] under GB1714799.2 patent [27]. This patented welding tool comprises an elongated flexible heat conductive strip and an elongated heat sink to allow reliable composite welding even with local thickness variation and shallow ramps (such as in the skin) compared with conventional welding tools [27]. To weld, the tool applies heat at the external surface of the stringers' flanges to join the interface with the skin. This weld head is attached to the adaptive tool illustrated in "Long welds adaptive assembly tool." On the other hand, the placement of the stringers on the skin and their tack weld is illustrated in "Jig-less assembly end-effector."

2.3 Composite frame clips

The load is transferred from the internal components of the fuselage to the stiffened skin (skin shell and stringers) using thermoplastic compression moulded brackets reinforced with short fibres; see Fig. 4(c). These clips are welded to the skin and stringers using ultrasonic welding [17]. This technique applies a short cycle of vibrations that cause frictional heat and melting at the weld surfaces. Although the permanent welding of clips is not within the scope of this study, this welding technique is employed for stringers tack welding illustrated in "Stringers tack welding."

2.4 Composite frame and floor beam assemblies

A combination of press-formed, robotic-assisted winded parts and titanium clips are used to form the radial frames sub-assemblies and floor grid assembly, as seen in Fig. 4(d) and described by Veldman et al. [17]. Frame and floor grid are joined in the fuselage following the placement of the frame sub-assembly on the frame clips in "Composite frame clips"; a shorter version of the same conduction welding tool developed by GKN-Fokker Aerospace is used to join the relevant interfaces [27]. The joining process of the two sub-assemblies is detailed in "Short welds end-effector."

In addition to the above key elements, the demonstrator includes other fewer elements such as X-paddles and L stringers used for supporting the floor grid assemblies (see Fig. 16). The sequence at which the above key elements of the multifunctional fuselage demonstrator are assembled is described in "Digital twin and process flow."

3 Demonstrator functional requirements

To ensure industrialisation and scalability feasibility of the innovative assembly tools developed in this project, a set of requirements are defined for each system. This not only assesses the feasibility of the designed solutions but also highlights the areas that require further development. For this purpose, MoSCoW (must have, should have, could have and won't have) prioritisation method is adopted. This method will allow reaching a common understanding between all collaborators on the importance placed on the delivery of each requirement [28]. Some of the key functional requirements and their MoSCoW designation for each system are presented in Table 1.

4 Tooling and end-effectors development

Although thermoplastic components can address the cure cycle roadblock that slows down thermoset parts production because their linear polymer chains do not crosslink and therefore do not require a cure cycle [14]. There is a need to develop and innovate assembly systems, aligned with components' supply chain production rate. As demonstrated earlier, assembly tools and techniques used for thermosets and metallic materials are either not feasible or limit thermoplastics potentials, i.e. adhesive bonding and mechanical fastening. Hence, the weldability of the thermoplastics is exploited with the aim to develop an assembly system that demonstrates industrial scalability and integration to increase the production rate.

Several challenges drive the development of the assembly system in this project. These challenges are divided into four main categories.

- **Scale of components and assemblies.** The demonstrator is a full-scale fuselage section with a length of around 8 m and a varying radius between 2 and 2.5 m, with many of its components having significantly large dimensions, such as the stringers.
- **Assembly space complexity.** In addition to its size, the demonstrator will be assembled under a defined gantry envelope, limiting the available picking space surrounding the demonstrator and systems manoeuvrability above the skin while placing and welding components. Besides, some processes such as short welds are sequenced after the placement of frame and floor beam assemblies in a very confined space.
- **Process compatibility.** The systems defined for the assembly of this demonstrator must work together seamlessly as a single solution, integrating much of their design

Table 1 Examples of the key requirements in accordance with MoSCoW designation for the functionality of each system

	Must have	Should have	Could have	Won't have
Jig-less assembly end–effector	Must be able to pick and place stringers and clips within the defined tolerances. Maximum weight must be less than a defined value. Able to pick and place a stringer and a clip within a defined duration. Allow user access to the coupling screws in order to disarm, clean or repair. Able to position stringers without permanent deformation of the stringers. Able to position and hold stringers in place prior to permanent welding.		Able to recognise parts based on visible tags. The end-effector can be attached to the robotic system by no more than one human operator.	
Short welds end–effector	Able to house the conduction welding element and allow its operation. Able to access parts to be welded. Able to facilitate and withstand the welding forces and radiated heat. Perform all welds within the defined tolerances. Able to position and maintain parallel contact between the welding element surface of the conduction weld head and the anvil. Easily attached to the robot by an operator.	Able to recognise marked points where it will perform welds. The duration that the end-effector needs to move from one position to another should be industrially viable.		
Long welds adaptive assembly tool	Able to move the conduction welding head along the length of the stringers. Able to place the conduction welding element within the defined tolerances. Able to facilitate and withstand the welding forces and radiated heat. Able to operate within the allowable space under the gantry. Able to support the mass of the total demonstrator once assembled.	Provide a possible scaled up production rate. Repositioning the adaptable assembly tool to the adjacent stringer position should occur within a defined duration.	Fully automated functionality	Able to conform to different skin geometries using the same tool.

and functionalities from earlier stages of the project. The designed systems should also satisfy the requirements for other out-of-scope operations such as clips, permanent welding and access for cargo door surrounding structure.

- **Quality requirements.** This challeng is primarily driven by the demonstrator functional requirements presented earlier in “Demonstrator functional requirements.”

The contents of the above categories are presented in more detail in Fig. 5. This figure also outlines the developed solutions to address these challenges in the context of three robotic end-effector systems. The detailed development of these systems within the boundaries of this study is presented in the following sections, while referencing the solutions shown in Fig. 5 where applicable.

4.1 Long welds adaptive assembly tool

The lower half of the multifunctional fuselage demonstrator is treated as a modular unit which will couple with the upper half, forming the fuselage body that will be assembled with other fuselage bodies. Therefore, the components of this system must be housed effectively during the assembly process. To achieve this, a cradle tool that supports the assembly is developed by The Welding Institute (TWI) [29]. The cradle tool is equipped with a welding beam to complete the

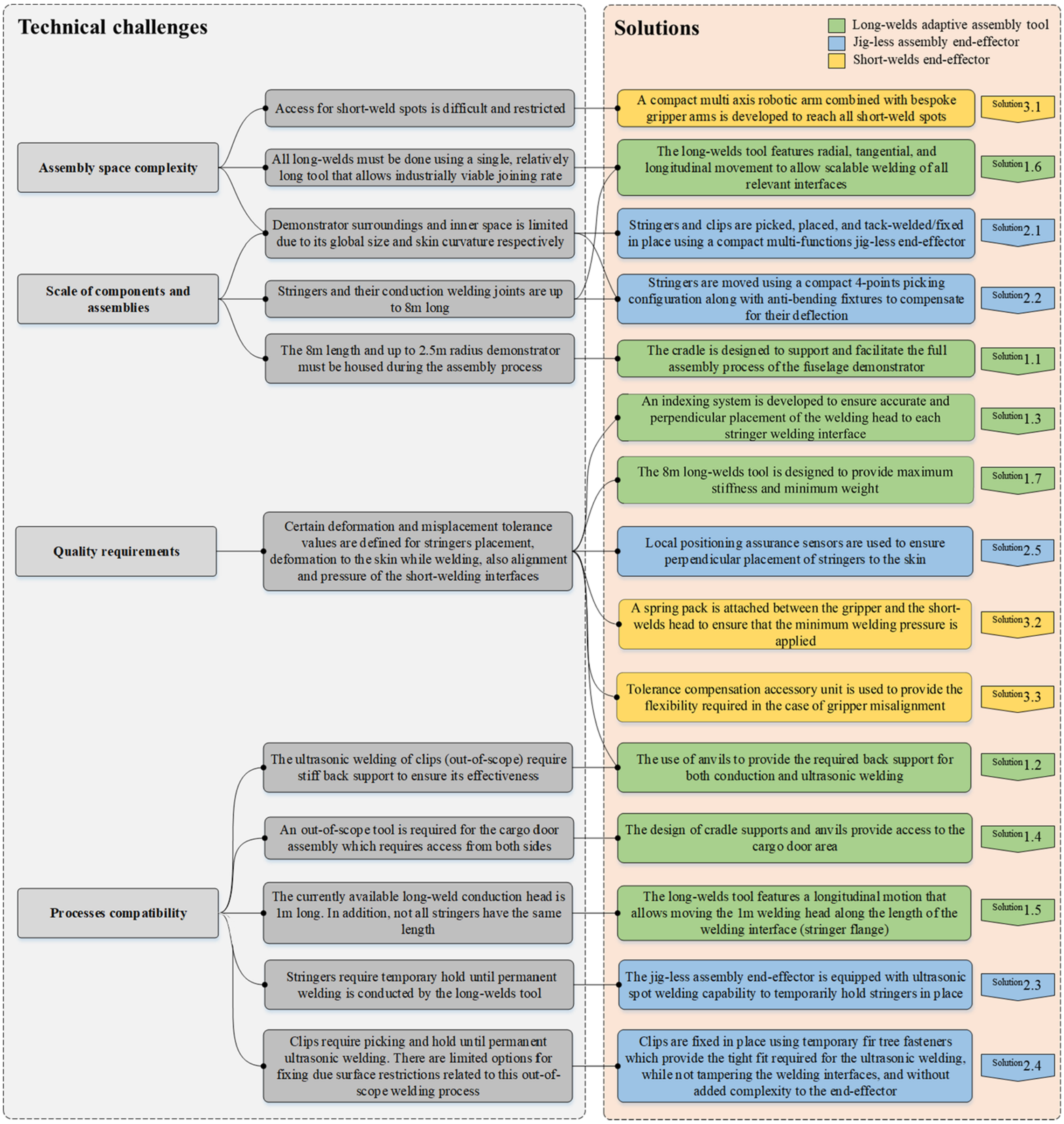


Fig. 5 An illustration of the key technical challenge drives and the developed applicable solutions

assembly of stringers to the skin; see Fig. 6. The development and function of both the cradle and welding beam systems are detailed as follows.

4.1.1 Cradle

The cradle (Solution 1.1) is designed to provide stiff support for the fuselage skin and the fully assembled lower section of the fuselage demonstrator, resisting the transferred large forces applied to the demonstrator because of stringers and clips welding. The cradle assembly consists of the following components.

Backing anvils The cradle contains 34 different styles, longitudinally positioned, backing anvils to suit the different lengths and locations of stringers within the demonstrator. These backing anvils are supported along their length by the lateral support frames. Each backing anvil is designed to support the skin during the stringer and clip welding processes. They are also required to keep the demonstrator such that other operations can be carried out without exceeding the defined quality tolerances; see Table 1.

The width of the backing anvils is larger than stringers' flange weld width to support two operations (Solution 1.2): (1) The welding of stringers. (2) In combination with specially designed clip support fixtures (see Fig. 6(a)), the backing anvils incorporate the support required for the out-of-scope clips' permanent ultrasonic spot welding, which extend beyond stringers' flange width. On the other hand, the depth and thickness of the backing anvils sections are defined based on the stress analysis to meet the maximum allowable deflection requirement at all locations.

Cradle indexing units and plungers At the ends of each backing anvil, there is an indexing unit and plunger assemblies shown in Fig. 6(b). The indexing unit is used as the datum for the conduction welding head such that the weld occurs precisely over the backing anvils and the corresponding welding interfaces (Solution 1.3). This is achieved using a manually operated plunger assembly that index and lock the anvil indexing with the welding beam indexing unit (see "Welding beam indexing").

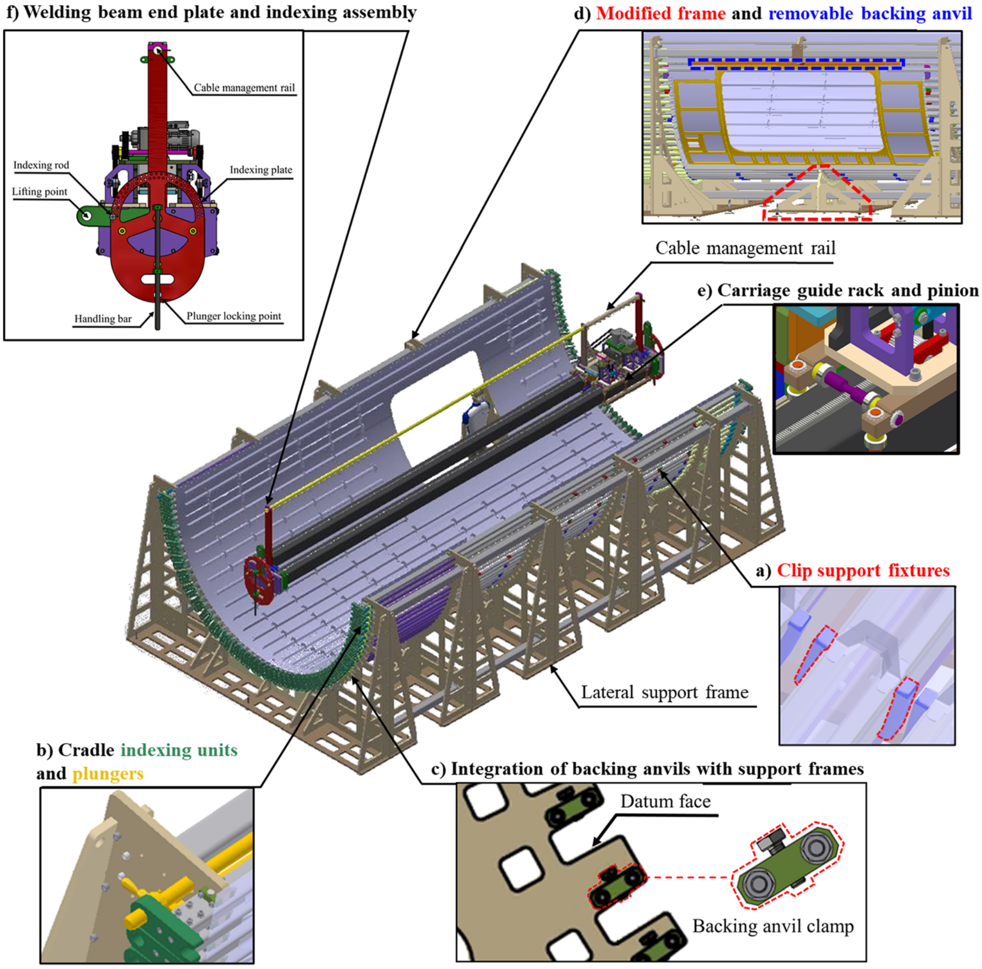


Fig. 6 Illustration of the long welds adaptive assembly tool

Support frames The cradle contains 5 types of support frames necessary to support the backing anvils (Solution 1.1). The support frames are connected using support frame connecting beams. These are necessary to space the support frames the correct distance from one another (see Fig. 6).

On the other hand, each support frame has accurately machined cut-outs to locate the backing anvils profile when inserted accurately. These cut-outs have a datum face that the backing anvils are pressed against to aid the backing anvils' positioning. This is done using a backing anvil clamp (grub screw) to push firmly and fix the backing anvil against the datum face once inserted (see Fig. 6(c)).

As for the cargo door opening, the support frame incorporates removable backing anvils to support the stringer above the cargo door during the welding operation. Additionally, the support frame below the cargo door opening is modified to allow access for this out-of-scope activity, as shown in Fig. 6 (d) (Solution 1.4).

4.1.2 Welding beam

A welding beam that runs longitudinally across the demonstrator's length is developed to carry the 1 m conduction weld head developed by GKN-Fokker Aerospace [18] using a carriage assembly (Solution 1.5). The welding operation which this beam will conduct follows positioning and tack welding stringers in place by the jig-less assembly end-effector presented in "Jig-less assembly end-effector." The components and functions of this welding beam system are detailed in the following sections.

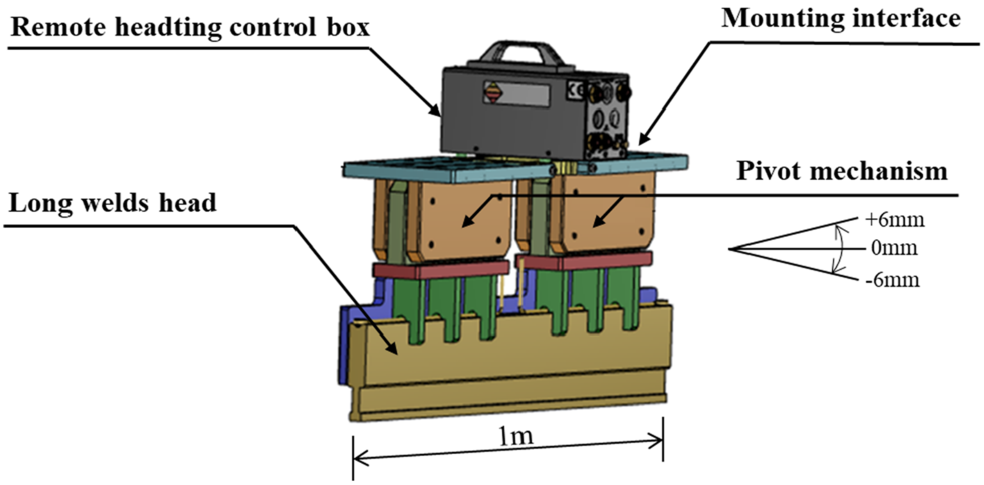
Carriage guide beams The welding beam system is mainly supported on two beams that run across the demonstrator's length. This assembly, the welding beam, is moved from one stringer welding interface to another using a crane system and the manual indexing operation (see "Cradle indexing units and plungers" and "Welding beam indexing"). Due to the length and function of the two guide beams, hollow sections are chosen to provide high stiffness to weight ratio which in turn lessens load requirements for the crane (Solution 1.7). The selected section allows a maximum elastic deflection of 9 mm when the carriage is positioned halfway along with the guides during the welding operation, i.e. pressing against the cradle.

Carriage assembly A carriage system is developed to accommodate moving the 1 m conduction weld head along each stringer's length and apply vertical pressure at the desired positions to perform welding. The longitudinal movement is driven by a rack attached to both square guide beams that engage with a pinion on the carriage to form the automated drive mechanism, which translates the carriage along the welding beam (Solution 1.6), as can be seen in Fig. 6(e).

Whereas the vertical movement needed to deploy and retract the conduction welding head is accomplished using four pneumatic cylinders with a configuration that allows the weld head to pivot (Solution 1.6); see Fig. 7. This pivoting feature supports the welding head's surface adaptivity to buffer the step changes in the skin ("Thickness-varying composite fuselage skin") so that it is normal to the stringer flange surface.

Welding beam indexing To ensure accurate perpendicular placement of the welding head to each welding interface, i.e. each stringer flange, an indexing plate attached to the end of the welding beam is designed to lock with the plunger ("Cradle indexing units and plungers" and Fig. 6(b)). The indexing plate contains several holes, each corresponding to the unique position of a stringer flange weld. This allows the operator to rotate the welding beam to the required angle necessary for the conduction weld head to be normal to the welding surface (Solution 1.3). To ease welding beam manual rotation, the axis of rotation lies on the beam's assembly centre of gravity. After rotation, the indexing rod is inserted through the indexing plate and into the lifting bar to lock the

Fig. 7 Weld head mounting configuration and pivot mechanism



welding beam at the correct angle; see Fig. 6(f). For the welding beam to be directly aligned with each stringer flange, the indexing plunger assembly is deployed through both the anvil end and indexing plate.

4.2 Jig-less assembly end-effector

Accurate positioning of stringers and clips is a critical and exhausting step for the manufacturing of aircraft fuselage due to their quantity and function. Therefore, to decrease assembly time, a multifunction jig-less assembly end-effector supported by a gantry system is needed to conduct two main activities: picking and placing both stringers and clips, respectively. To achieve these activities, the Advanced Center for Aerospace Technologies (CATEC) [30] developed and integrated several systems forming the required jig-less end-effector (Solution 2.1); an overview of this end-effector can be seen in Fig. 8. The development and functionality of the individual systems in this end-effector are presented in the following sections.

4.2.1 Stringer picking and placing

Since the geometry of the stringer presented in "Composite stringers" has flat faces, and its surface is smooth, vacuum technology (suction cups) has been chosen for picking and positioning the stringers on the skin. To define the dimensions of the end-effector, the establishment of picking points and the distance between the suction cups were based on the deflection analysis of the stringers presented in "Stringers anti-bending fixtures." Additionally, to buffer the deflection of the stringers and to have better contact with the stringer's surface, spring plungers have been added to the vacuum suction cups. On the other hand, two machined centring elements are used to guide stringers in position with respect to the vacuum suction cups. The operation of the vacuum suction cups and spring plungers of the vacuum system while performing the stringers' picking is illustrated in Fig. 9.

4.2.2 Stringers anti-bending fixtures

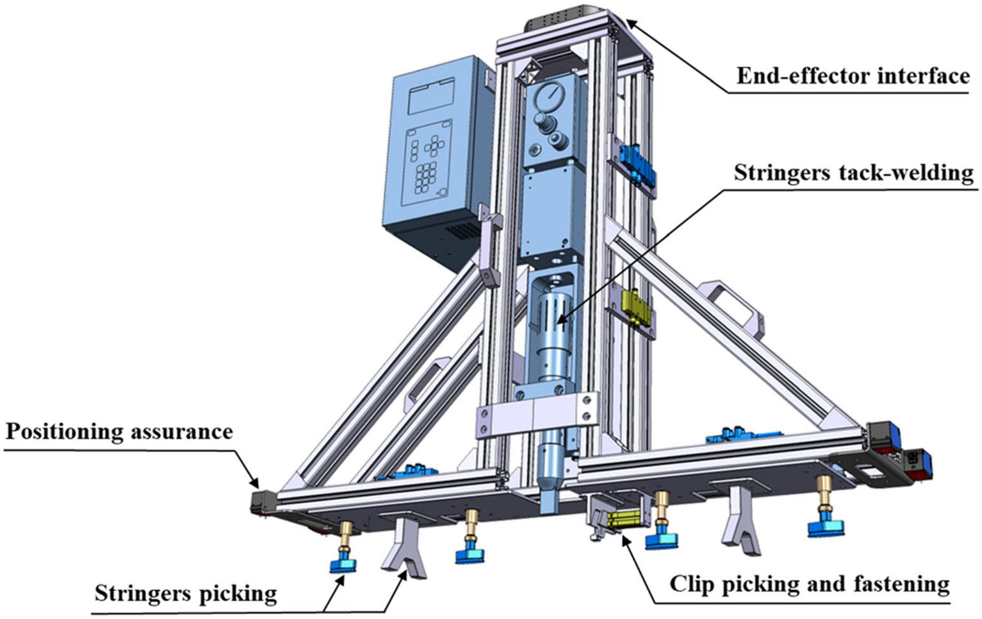
The deflection analysis of the 8 m stringer shows that the combination of stringers stiffness and the distributed four picking points presented in "Stringer picking and placing" will not entirely eliminate the defection of these stringers based on the analysis results seen in Fig. 10, where a maximum deflection of 17.5 mm and 9.78 mm is occurring at stringer ends in the case of horizontal and vertical picking configurations, respectively.

To avoid the deflection of the 8 m stringers and support their weight before conducting the tack welds, the anti-bending fixtures solution is designed to ensure precise placement and subsequent welding (Solution 2.2). These are stringers' housing fixtures positioned on the corresponding anvil indexing unit employing the plunger at the cradle ("Cradle indexing units and plungers") to fix them in place; see Fig. 11.

4.2.3 Stringers tack welding

The period between stringers' placement by jig-less end-effector and performing the conduction welding at each flange will require a temporary hold. Several thermoplastic joining technologies have been considered to provide this temporary hold, such as adhesive tape, adhesive spray, glue, welding and magnets. It was concluded that ultrasonic welding

Fig. 8 The design and components of jig-less assembly end-effector



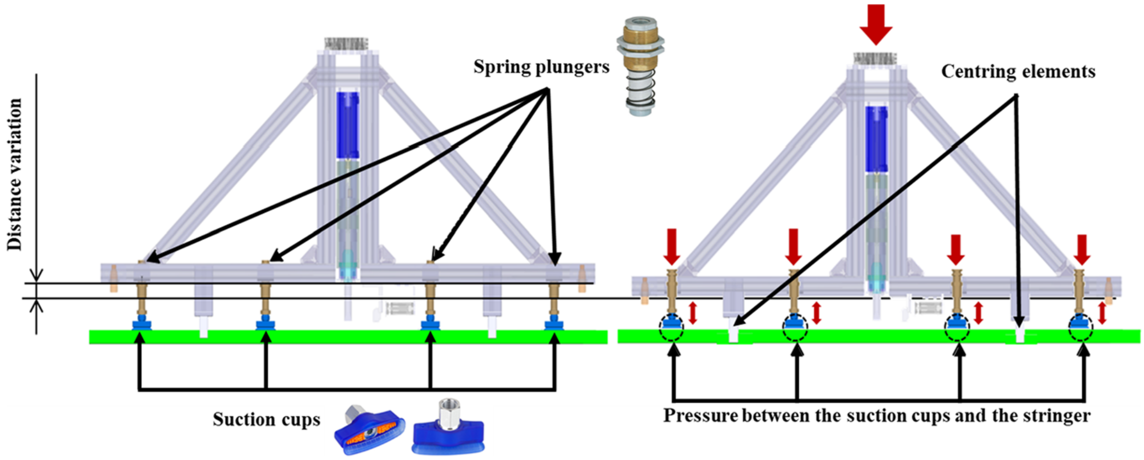


Fig. 9 An illustration of the vacuum system components and operation

is an optimum option for this application as it meets reliability, scalability and production rate requirements (Solution 2.3).

The proposed ultrasonic welding system consists of an SPA20 Rinco ultrasonic welding actuator, acoustic stack formed by the converter, the booster and the sonotrode, and ADG 20 Rinco ultrasonic generator as seen in Fig. 12. The ultrasonic welding tool is positioned at the centre of the jig-less assembly end-effector, with a slight lateral offset

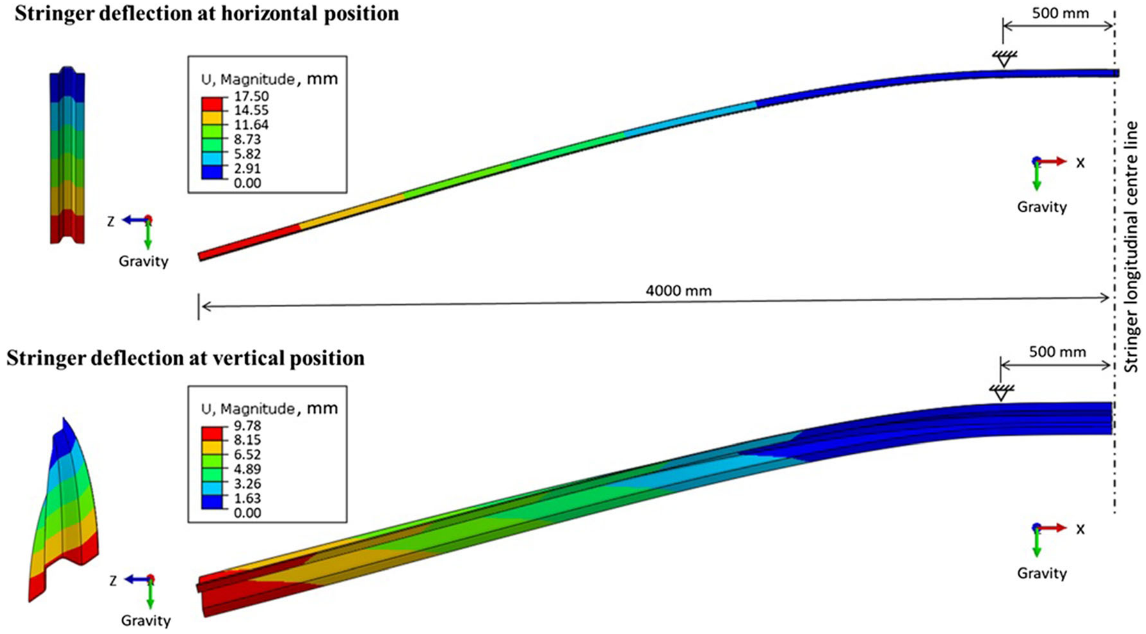


Fig. 10 Deflection analysis of the 8 m stringers in horizontal and vertical picking configurations

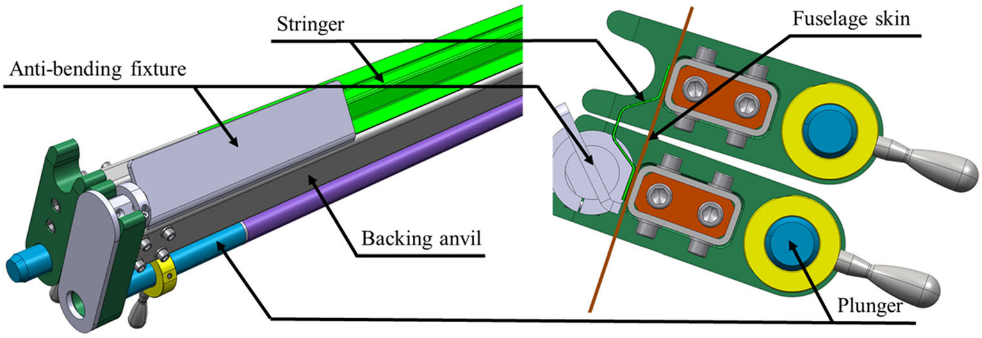


Fig. 11 Stringers anti-bending fixtures supported by the anvils

position that allows it to perform the spot weld following the placement of each stringer. As this completes, the end-effector transits to the corresponding weld spots to secure the stringer adequately.

Following several trials, the energy and force parameters required to conduct a successful ultrasonic weld were identified, avoiding the risking damaging the laminate, nor having a weak weld that can lead to disbond as the end-effector releases the stringer and move to the next tack weld position. The microscopic images in Fig. 13 show an example of an optimum ultrasonic tack weld conducted using the jig-less assembly end-effector on trial sections of the stringer and skin.

4.2.4 Clips picking and placing

The jig-less assembly end-effector employs a pneumatic technology to pick the clips illustrated in “Composite frame clips” (Solution 2.1). The system consists of a pneumatic cylinder that provides the gripping force and a machined part that guides the clip to its proper position while picking it. This can be seen in Fig. 14.

4.2.5 Clips temporary fastening

Similar to the stringers, the clips will require a temporary fix before conducting the permanent weld. A simplified approach was adopted to address this requirement (Solution 2.4). The solution uses a fir tree fastener inserted in pre-drilled holes at the crown of the clip. This in place will be pushed all the way down by the end-effector as it picks the clip. When the clip reaches its destination, the clip with the fir tree fastener will be pushed into the corresponding pre-drilled holes at the crown of the stringer. This operation is illustrated in Fig. 14. It is important to note that holes in both clips and stringers do not exceed the allowable open-hole size.

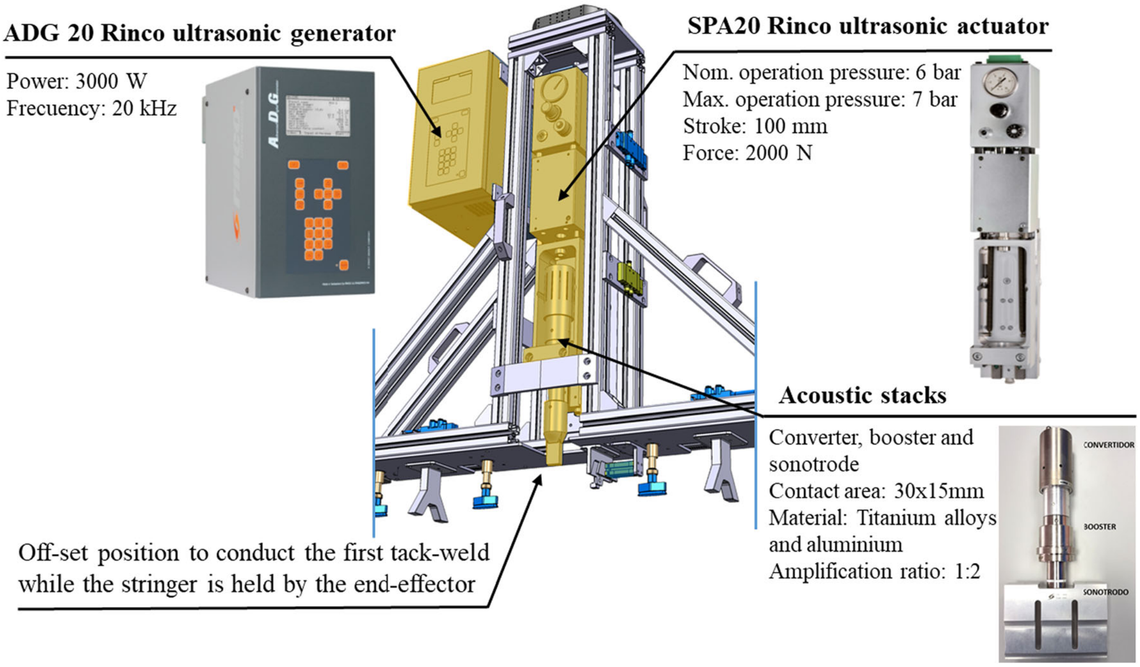


Fig. 12 Ultrasonic welding system for stringers tack welding operation

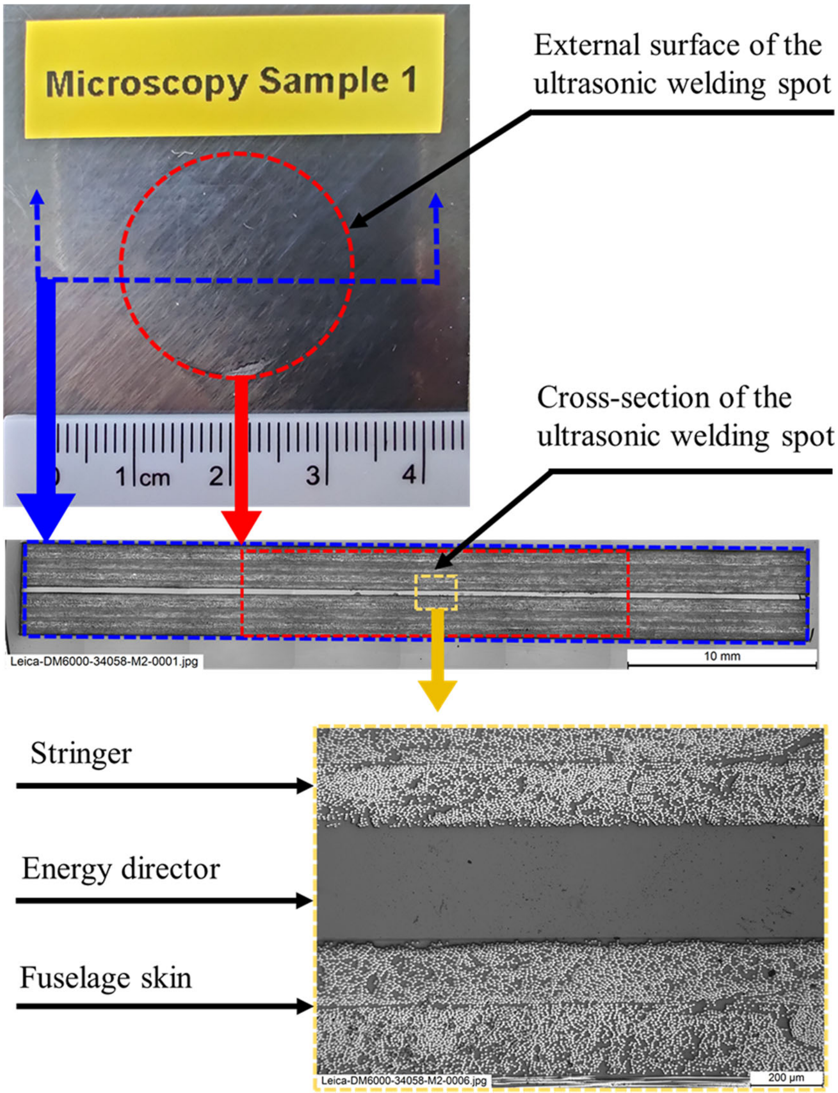


Fig. 13 Microscopic image of an optimum ultrasonic welding spot

4.2.6 Positioning assurance

To ensure meeting the tolerances required in the positioning of stringers and clips within the assembly, four perpendicularity proximity sensors fixed at the far ends of the jig-less assembly end-effector are used (Solution 2.5); see Fig. 8. The measurements collected by all the sensors must be equal, so the end-effector will be appropriately positioned and ready to perform the placement and tack weld of the stringer, also the operation of

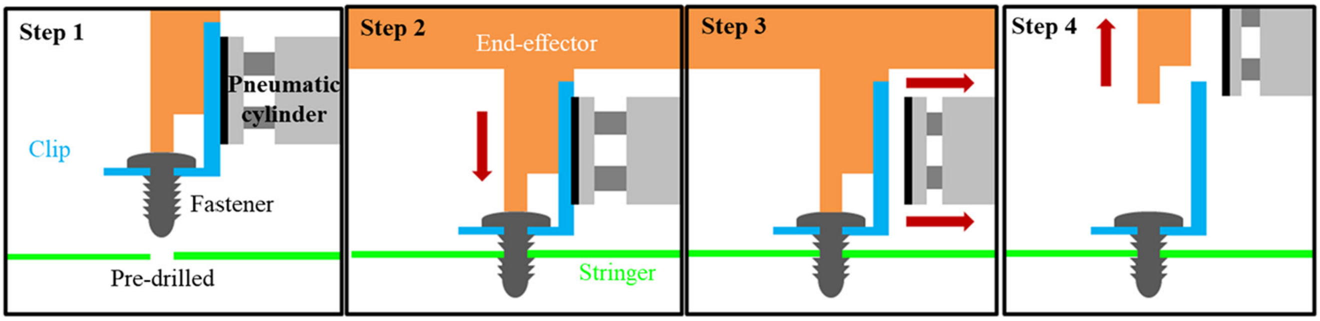


Fig. 14 Clip temporary fastening steps

fastening clips in place. It is important to note that this sensing system is not a substitute for the general positioning system supported by the overhead gantry.

4.3 Short welds end-effector

Frame sub-assemblies and floor grid assembly (see "Composite frame and floor beam assemblies") require joining at several hard-to-reach spots because this operation is sequenced following the assembly of stringers, clips, frames to clips, and and a fully equippedfully equipped floor grid, creating a relatively restricted manoeuvring space. Joining the interfaces at these spots is achieved using an end-effector developed by London South Bank University [31] which facilities and transits a scaled-down version of the same conduction welding technology developed by GKN-Fokker Aerospace [18] that is used in the long welds adaptive assembly tool.

The main development drives of this short welds end-effector are the ability to apply the required pressure to the weld head, manoeuvrability to allow precise positioning for welding, and extended reach capabilities. These targets are achieved in a design that integrates the weld head with a gripping system attached to a robotic arm, as shown in Fig. 15. The development and functionality of these individual systems are presented in the following sections.

4.3.1 Robotic arm

To reach all welding spots required for the floor beam to frame and fuselage assembly, this end-effector uses a robotic arm attached to the gantry system from one end, and to the gripper system from the other end. The robotic arm selected is the small footprint Universal UR16e [32] which provides a reach of 900 mm, six rotating joints degrees of freedom with a working range of 360° and having 16 kg payload capability. These capabilities, combined with machined aluminium grippers' design, allow reaching all welding locations (Solution 3.1); see Fig. 16.

On the other hand, the control boxes of the arm and the heating weld head are supported at the base of the robotic arm (the interface with the gantry system). This can be seen in Fig. 15.

4.3.2 Gripper and welding system

Conduction short welds require applying heat and pressure to the external surface of the welding interface. The thermal energy generated transfers from the laminate's outer surface to the joining interface, melting the thermoplastic matrix to form the join. Like the long welds, GKN-Fokker Aerospace [18] has developed a welding head consisting of two parts, a heating stamps unit and a corresponding anvil. The stamps

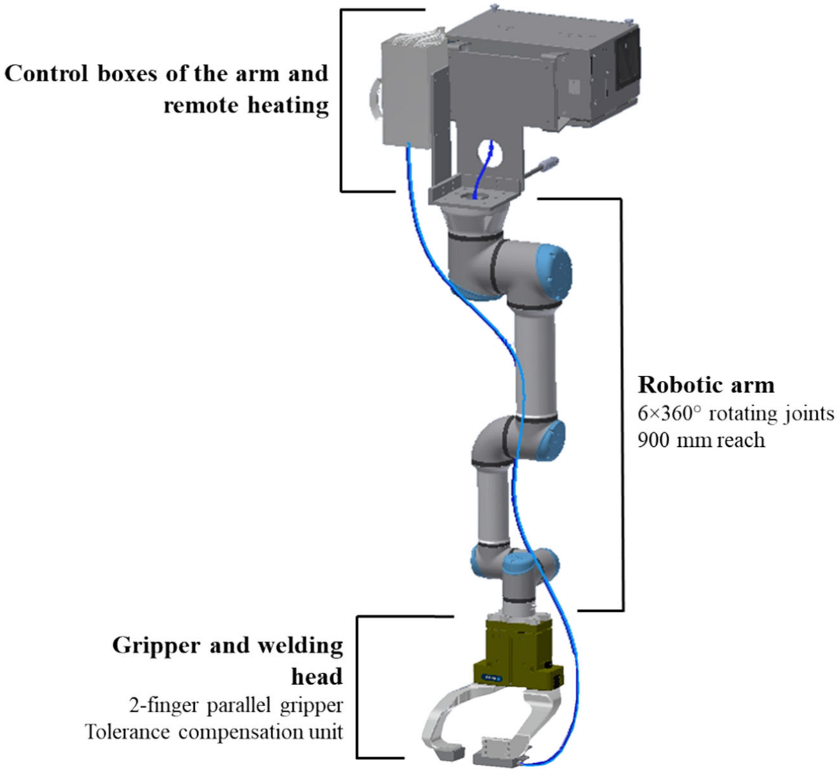


Fig. 15 The design and components of the short welds end-effector

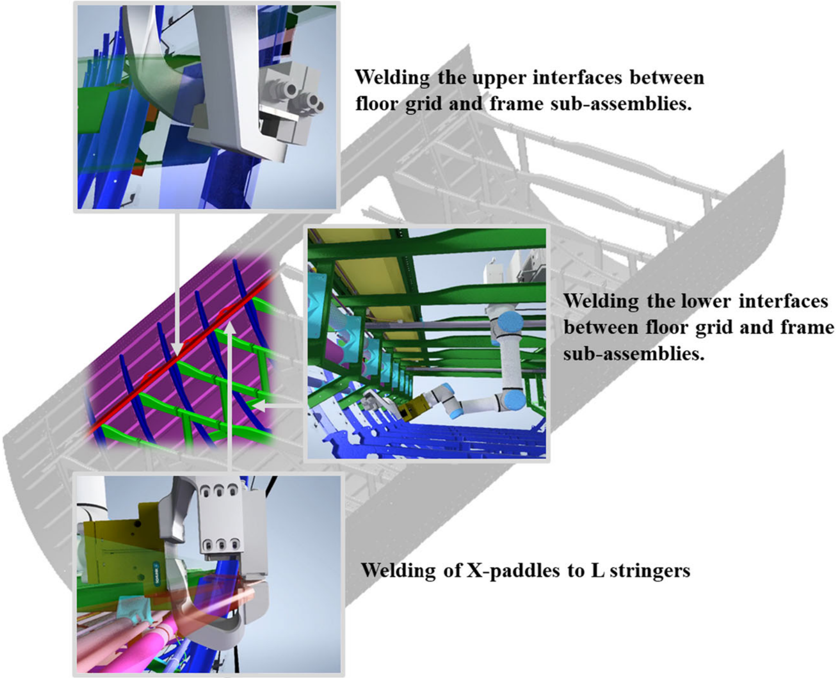


Fig. 16 Key locations of the short welds operation

heat the interface area using the energy provided from the remote heating box. In contrast, the anvil provides the complementary support to obtain the required welding pressure for the defined welding duration; see Fig. 18(a).

One of the main challenges in designing gripper arms that will accommodate the welding head is the ability to clamp and clear off all welding locations inside the fuselage without clashing. This was addressed by starting with a simple gripper arms design, then optimised to have the minimum weight possible while ensuring collision-free clamping operation at all positions shown earlier in Fig. 15. The final geometry of these gripper arms is shown in Fig. 17 and Fig. 18.

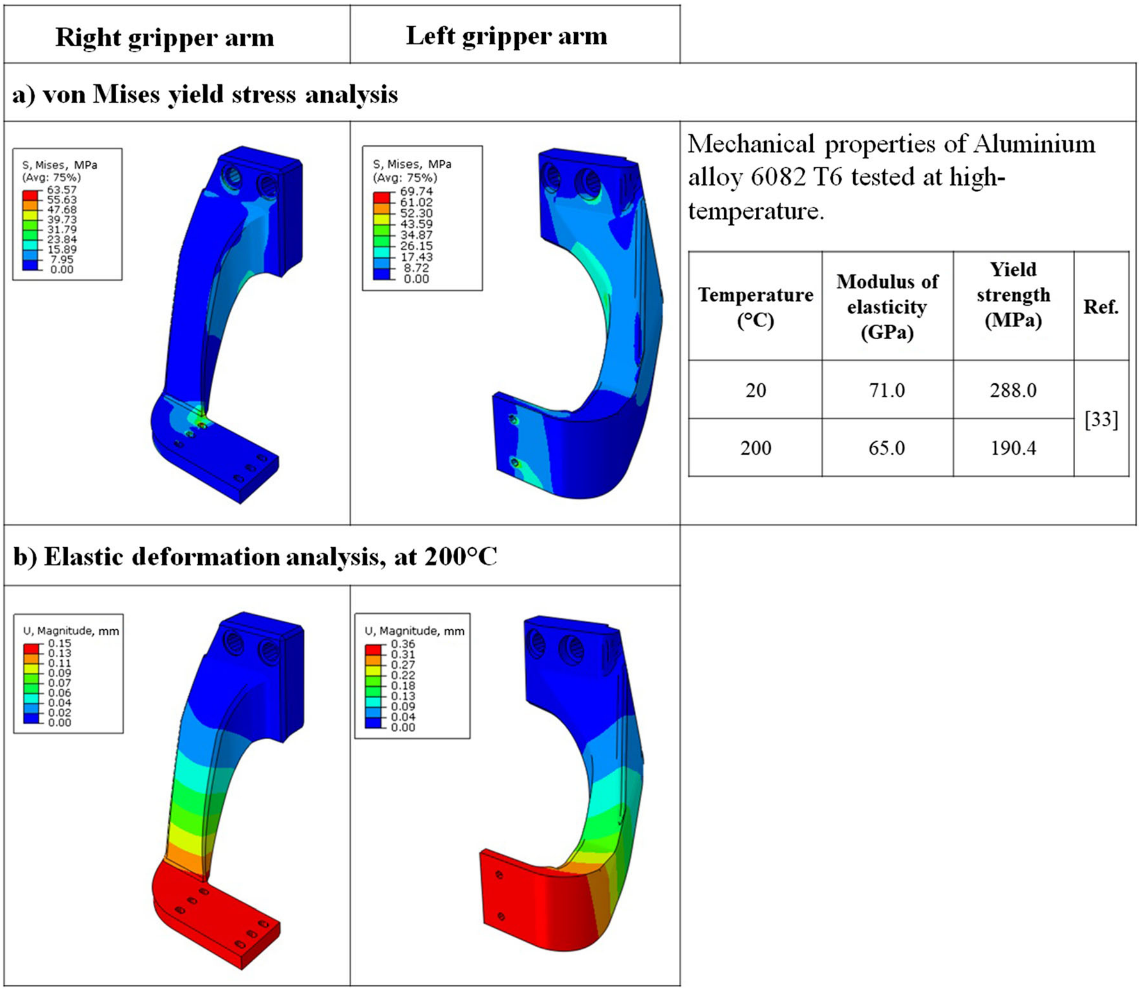
While the welding temperature can exceed 400°C at the joint interface, the maximum temperature at the weld head interface with the gripping system average around 175°C. Therefore, the stress analysis is conducted at 200°C, applying the mechanical properties of Aluminium alloy 6082 T6 tested at a high temperature according to ASTM:E21-09 [33]. The results show that the maximum elastic deformation with the reduced modulus of elasticity at 200°C is 0.15 mm and 0.36 mm for each gripper arm, while von Mises yield stress remains below the lower yield strength at 200°C, ensuring an approximate safety factor of 3, as illustrated in Fig. 17. This stress analysis concludes that the grippers will withstand the applied forces without sustaining excessive elastic or any plastic deformation.

On the other hand, as the system is intended to weld various interface thicknesses, there is a need to ensure that the minimum welding pressure is applied. This is addressed by attaching the heating unit to the gripper arms through a spring pack solution (Solution 3.2). The spring pack consists of four springs housed in two components sliding tool, as seen in Fig. 18(b). Conversely, the welding force via the gripper arms will be applied using Schunk PGN-plus-P 2-finger gripper [34] powered through 6 Barg compressed air supply. This gripper can produce 5000 N of gripping force as a sum for the two claws providing sufficient welding force.

The gripper will be complemented with a tolerance compensation accessory unit Schunk TCU-P [35] that mates with the Schunk PGN-plus-P to provide the flexibility required in the case of gripper misalignment (Solution 3.3), while this unit is attached to the robotic arm interface plate from the other side; see Fig. 15.

5 Digital twin and process flow

The multifunctional lower half of the fuselage's assembly process involves many factors such as equipment condition, process parameters, environmental characteristics and material quality. These factors contribute to the overall quality of the assembly. In the TCTool project, these factors along with production data will be combined in a digital twin to simulate the assembly process. The proposed digital twin will also facilitate the failure mode and effects analysis (FMEA) for the assembly process. FMEA assesses the potential impact of failures, characterises them as minor to serious, applies a statistical approach to establishing the critical components, identifies where failures may occur, how often, and allows pre-emptive action, i.e. provision of spares to avoid downtime. Additionally, the digital twin will allow rapid visualisation of the production line and test solutions in the virtual sphere



Mechanical properties of Aluminium alloy 6082 T6 tested at high-temperature.

Temperature (°C)	Modulus of elasticity (GPa)	Yield strength (MPa)	Ref.
20	71.0	288.0	[33]
200	65.0	190.4	

Fig. 17 Stress analysis of the short welds gripper arms at elevated temperature

before committing to real changes on the production line. On the other hand, the physical assembly-line data captured by the digital twin will enable comprehensive process optimisation in the context of quality by making changes based on the

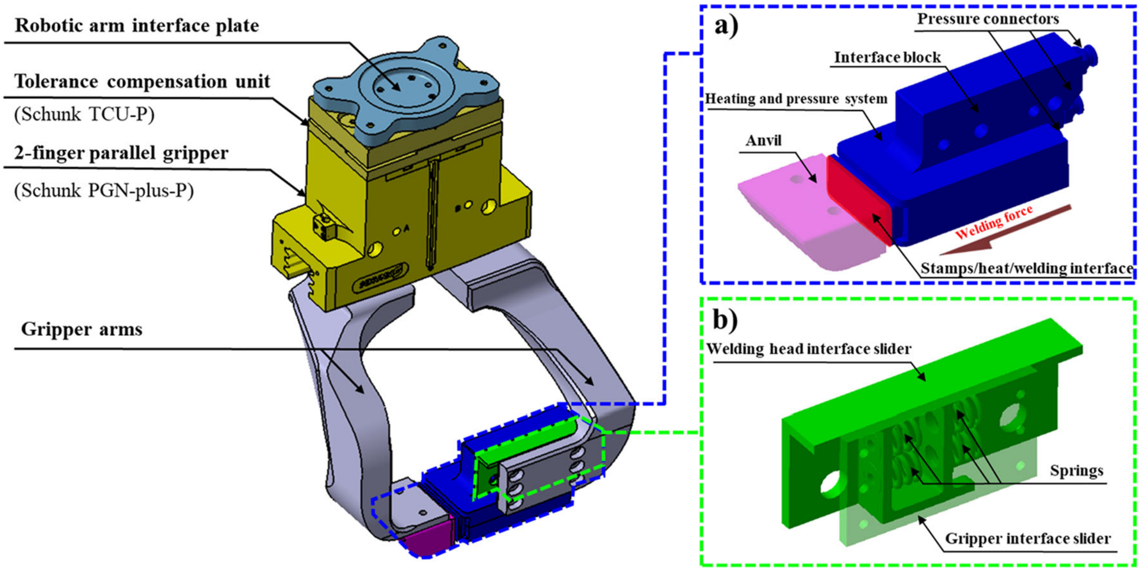


Fig. 18 Short welds gripper and welding system showing (**a**) the conduction short-short welds head and (**b**) the spring pack solution

risk assessment. It can also be used to optimise process steps to reduce energy consumption and identify the optimal sequence of process steps to obtain a higher production rate.

In the development stage of these assembly tools, one of the key objectives was to capture valuable assembly-line data for FMEA and process optimisation utilisation explained above. Therefore, the end-effectors were designed to ensure that most critical steps and processes are automated, allowing obtaining physical assembly-line data to make utmost use of the demonstrator assembly process, which supports concept scaling and industrialisation. These key process steps are listed as follows, which correspond to Fig. 19.

Step 1: Following the placement of the skin on the adaptive assembly tool using a portable gantry, the jig-less assembly end-effector attached to the main gantry starts picking stringers from a picking table that will be updated manually. Yet, when industrialised, the capability to recognise parts based on visible tags could be added; see Table 1. The picked stringer is then transported and placed on the skin relying on the global and local ("Positioning assurance") positioning systems. This is followed by conducting the ultrasonic spot welds required to tack weld the stringer in place. The process continues until all stringers are tack welded in place.

Step 2: The long welds assembly tool starts performing conduction welds for each stringer flange in a sequence of 1 m long weld iterations. The longitudinally and compressive movement of the weld head across the length of the fuselage on the stringers is fully robotic. Yet, the transition of the welding beam from flange to flange (and stringer to stringer) is a combination of an automatic and manual positioning operation. Both the length of the weld head and the manual intervention are feasible to scale for future industrial applications.

Step 3: As all stringers have been permanently welded to the skin, the long welds I-beam will retract, giving space for the jig-less assembly end-effector to start operating again by picking, placing and temporarily fastening clips individually. This process is illustrated in "Clips picking and placing" and "Clips temporary fastening4.2.5." Permanent welding of the clips will be followed using the mobile ultrasonic technique attached to the gantry system, with back support required for this joining process provided by the adaptive assembly tool anvils.

Step 4: In an out-of-scope operation, frame sub-assemblies will be transported using the overhead gantry for positioning and ultrasonic welding with the clips. Following this, the floor beams will be attached temporarily to the frames to form the floor grid with seat rails. This complete floor grid will be removed to complete system integration and reinstalled back on the frames as a fully equipped sub-assembly. At this stage, the scope of this study covers joining the interfaces between the floor grid and frame sub-assemblies (and some of the fuselage L-shaped stringers and X-paddles) using the short welds end-effector attached to the gantry, as illustrated earlier in "Short welds end-effector" and shown in Fig. 16.

6 Conclusion

The increasing demand for more new and cleaner aircraft requires utilising novel materials such as thermoplastic-based composites to benefit from their weldability, low density, low overall production cost, improved fracture toughness and recycling opportunities. Making optimum use of thermoplastic composite materials requires developing new industrially scalable tooling as existing technologies are not transferable. Therefore, this study presents the development of three

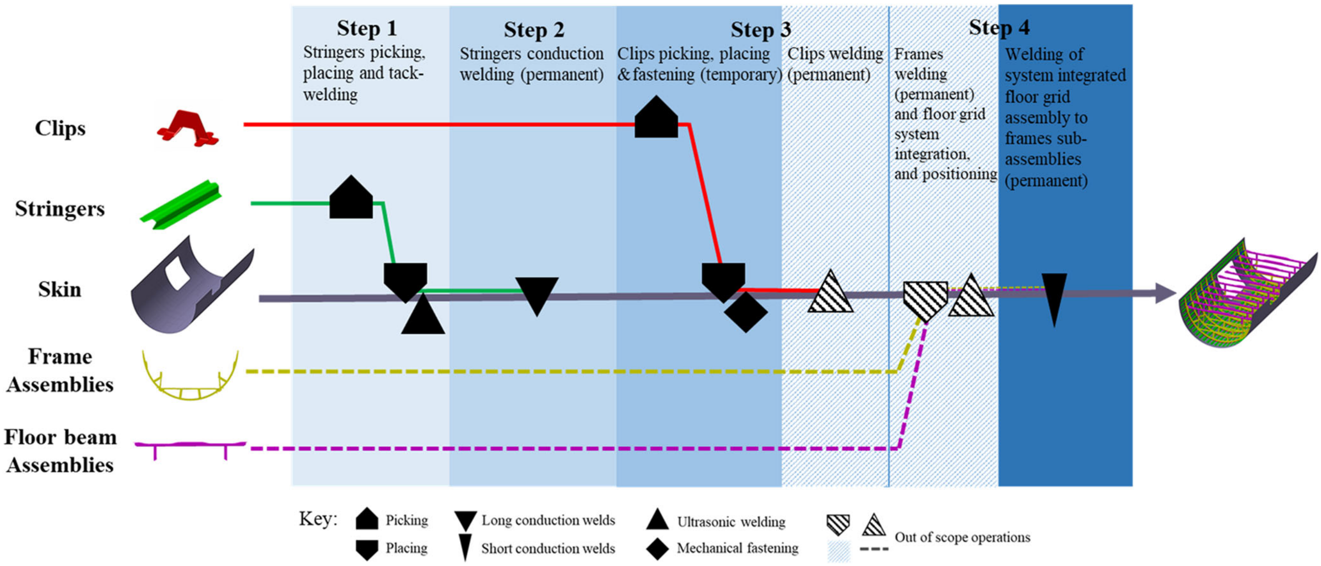


Fig. 19 Methodology assembly sequence diagram

innovative tooling and end-effectors systems for welding multifunctional thermoplastic fuselage components. The key highlights of this study are as follows.

- The development of the assembly tools is directly driven by an identified four main technical challenges: the scale of components and assemblies, space complexity, process compatibilities, and quality requirements.
- The developed adaptive assembly tool supports the fuselage skin for the entire assembly process. Attached to it is the first end-effector that conducts up to 8 m length stringers welding to the fuselage skin using a pre-developed conduction welding technology. This tool allows for scaling the length of stringers welding head while providing the required back pressure of the other end-effectors and joining operations.
- The exhausting operations associated with accurately picking, placing and temporary fixing all stringers and clips are summarised in multifunctional jig-less assembly end-effector design. This solution combines elements such as suction cups, actuators, sensors, ultrasonic welding and more in an innovative single compact package.
- The third end-effector is developed to perform various short welds at hard-to-reach locations within the assembly while being attached to a gantry robot arm. This end-effector uses a pre-developed conduction welding technology, combined with a tailored gripping system integrated with a commercial robotic arm to meet the required welding parameters, manoeuvrability and reach capability.
- The assembly process flow describing the sequence of the key steps required to assemble the demonstrator fuselage is established to allow effective end-effectors operation. These steps, combined with the digital twin that is being developed, will enable visualising quality data and test solutions virtually.

To conclude, this study presents the development of industrially viable innovative end-effectors and tooling systems to demonstrate the feasibility of enabling efficient and dustless assembly of the multifunctional fuselage demonstrator using several thermoplastic composite materials and welding techniques, while taking into consideration industrial scalability and integration with existing production lines.

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Code availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

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Conflict of interest The authors declare no competing interests.

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