Friction Stir Welding (FSW) offers new opportunities for efficient and cost effective airframe.

Authors:

Delphine Allehaux, delphine.allehaux@eurocopter.com Eurocopter
Henri Balthazart, henri.balthazart@eurocopter.com Eurocopter.
Marc Denante, marc.denante@eurocopter.com Eurocopter
Jean Loup Gatti, jean-loup.gatti@eurocopter.com Eurocopter
Robert Re, robert.re@eurocopter.com Eurocopter

Overview

Depending on airframe components, and Helicopter product considered (Military or Civil, Heavy, medium, light) technology evaluation can lead to select composite or metallic materials. During the last thirty years R&T has focused mainly on composite technology. In 2009, EC has launched a research program dealing with advanced concepts for airframe, and after 4 years, working on several light materials and the friction stir welding (FSW) joining technique, we are about to achieve our goal. One can say that this technology offers a breakthrough and reach savings up to 21% in cost and 6% in performance compared to conventional metallic.

1. THE FRICTION STIR WELDING TECHNOLOGIE.

1.1. The Research Program "Fuselage Nouvelle Generation".

In January 2009, Eurocopter launched an ambitious research program on the next generation of helicopters' airframe. With aims, to reduce production costs by 20%, while increasing performances by 10%.
After 4 years the TRL (Technology Readiness Level) was reached, allowing prototypes parts, stemmed from metallic materials assembled with Friction Stir Welding (FSW), to be airborne.
This technology, applied to airframes' beams or skins, allows us to attain the intended objectives of this research program. The TRL process is a formal procedure that validates a new technology on several dimensions: technical, economical, industrial and end-user.

1.2. Introduction to FSW technology

The FSW establishes a continuous link between two metallic pieces to join under solid-state condition with a continuous dynamic recrystallization characterized by a very fine and equi-axed grain structure (typical grain size of 10 microns) without fusion present in conventional Welding.
The thermal input is mainly generated by friction, on and between the pieces to assemble, of the cylindrical welding tool, equipped with a shoulder. The heat generated by friction (rotation of the tool), brings the material into a pasty condition allowing the tool to progress (translation and rotation motions) along the joint line.
The recrystallization generating the material continuity occurs under a specific temperature, strain and strain rate ranges. Due to the high level of strain required to generate this mechanism, the application of an axial load (vertical downforce) is needed for material consolidation and general weld health.

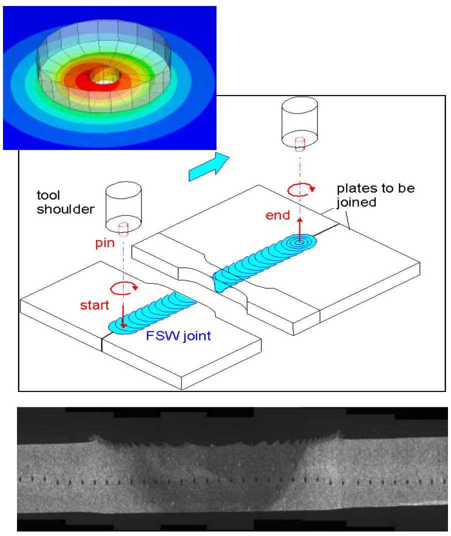


Figure 1, FSW Process

This technique has a large perimeter of applications on aluminum alloys (structural or strain hardening alloys) and lightweight

metals such as magnesium alloys. Hard metals, titanium alloys and steels require higher temperature and vertical downforce ranges to sustain the material flow induced in the stirred zone. As a result, these very demanding materials lead to process optimization and new challenges in the fields of tool materials (wear and strength control) and facility (high precision and stiffness).
Various concepts of machine match with the FSW technology. With a focus on our targeted applications, the two main technical means are described just below.

Figure 2, the specific gantry machine (5 axis mean).

Figure 2 presents the conventional machine architecture, with the welding effector sustained by a gantry. This machine architecture is relevant for the major thinkable applications thanks to its rigidity (up to 80 kN for the gantry).

1.3. Robot with welding effector

The FSW technology can be easily robotized. But currently only KUKA offers a robot capable of meeting the rigidity requirement. More specially the KR500MT robot has been developed for the FSW application by KUKA. Various suppliers can be selected for the welding head. We chose a CYTEC welding head.
This mean has to be considered as the most relevant one for the low thickness range and the 3D welding.
3 main parts compose the industrial FSW mean:

- The robot
- The welding effector
- The control process system.

In many applications it has been difficult to justify the use of friction stir welding (FSW) mainly due to the high capital cost requirements of FSW and the relatively poor productivity that results from the use of standard FSW machines (gantry) for which it is difficult to reach high duty cycles.

Figure 3, Kuka robot installed on a rail (7th axe) equipped with Cytec welding head.

To solve these issues, robotic FSW solution is considered. A robot system is thus expected to enlarge the addressed application range, to improve the flexibility of the robotic system by opening the ability to join other manufacturing steps to the welding one, and to reduce the investment cost.
The introduction of relatively low cost robots with higher payloads allows the robotic FSW deployment in numerous of applications and especially in the field of aluminum alloy thin sheets. Nevertheless critical to the success of robotic FSW, is the development of force control systems to overcome both the needed forge to weld and the lack of stiffness the robot may possess.

1.4. Most promising applications on H/C primary structure.

The three main components of a structure, which are the skins, beams and frames, are all compatible with the FSW technology.
In a first application step we have selected a skin and a beam as scale one demonstrator.

Figure 4, Main structural components of a helicopter

1.5. Where are the savings?

In reference to riveted technologies, skins and beams are composed of overlapping parts, fastened by rivets. The installation of a single rivet requires, piercing, protecting, positioning, placing and installing the rivet.

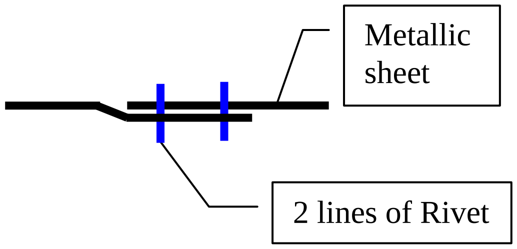


Figure 5, Riveted, Reference solution

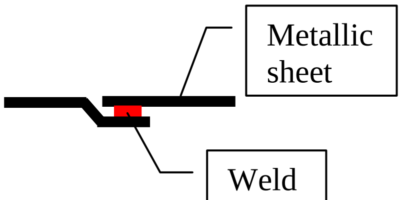


Figure 6, Welded solution « overlap mode »

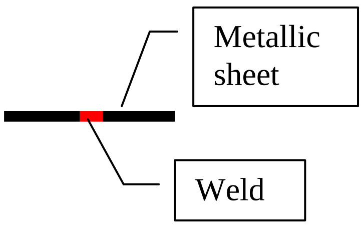


Figure 7, Welded solution « butt join mode »

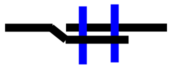
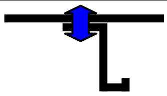
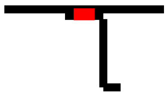
Name of junction	Symbol	Comments
Reference (Riveted),		2 lines of rivets Skin to skin junction
Reference (Riveted),		Stringer to skin junction
Overlap		1 weld line Skin to skin junction
Butt join		Weight saving Skin to skin junction
Overlap		Stringer to skin junction

Figure 8, FSW main assembly configurations

Figure 9, Shell, typical riveted technology

Moreover, helicopter parts are not well suited for automated riveting, due to their complexity and geometry.
FSW will allow to remove all the rivets as well as overlapping, and can be automated, because the operations to carry out are very simple. It only requires scrubbing, positioning, holding and assembling.
The withdrawal of rivets and overlapping will reduce weight, and the automation of the process will reduce costs.

Designing parts assembled with FSW cannot be reduced to the bare replacement of rivets with FSW. This approach is too simplistic, and rules out optimal efficiency. All new technologies must be accompanied by a new design process. For example, FSW allows for butt and lap joins. Butt joins are much more effective, but not possible with rivets.

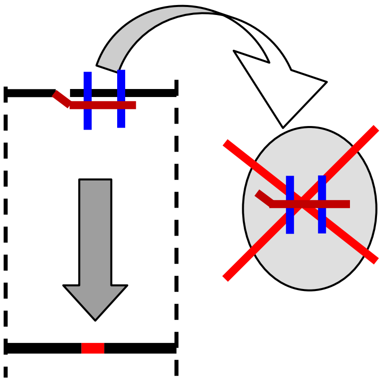


Figure 10, Illustration of weight and cost saving, when replacing a riveted attachment with a butt join.

The figure 10 shows that FSW assembled parts have simpler designs. It also illustrates the removal of rivets, and the weight gain.

1.6. Industrial Quality

In the same way as the design the industrial process must also be rethought in order to be consistent with the specific requirements, particularly on elementary parts, remaining cost efficient.
In addition we have to catch the opportunities offered by the robot and to build a fully automated cell. It must complete a global robotized manufacturing phase, including the welding phase but also the pre and post phases, as cutting and cleaning of elementary parts and on-line NDT record or cutting on the assembled part.
Moreover this kind of cell allows the integration of a fully numerical chain from design (CATIA) to the part manufacturing and control. It secures the quality and conformity level of the part.

Such a cell will also secure and optimize the basic savings brought by the technology and widely compensates the specific efforts and over cost necessary for tooling (performance of the clamping) and on elementary parts (accuracy).

A main factor to keep the savings in serial life is the quality insurance approach.
Due to the simple mechanical nature of the process, it is a robust and repeatable joining method. Out of the external parameters, there are only a few parameters influencing the weld quality and these are mostly NC controllable.
Based on the five main quality drivers (mean, environment, method, labour, material), the robustness of this process results from the control of 4 main domains:

- The joining process.
- The elementary parts manufacturing process.
- The tooling.
- The documentation related to the technology processing.

The general approach is summarized below.

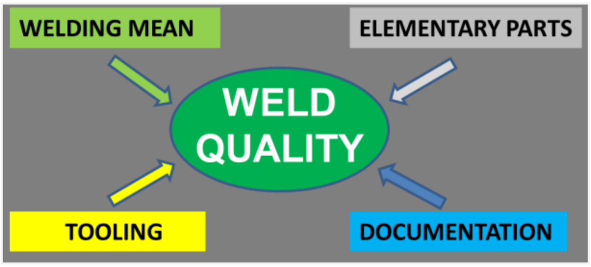


Figure 11, the 4 FSW quality drivers

Based on the analysis of the quality drivers (see above), the knowledge of the non-conformities origins, and the design of the CNC based FSW equipment, the process quality is managed through:

- An active FSW process monitoring (Forge and weld path self-control and rotation and welding speeds on-line monitoring).
- A specification on the tooling design, manufacturing and in-service control.
- A specification on the elementary parts manufacturing and preparation prior to welding.
- Adequate inspection plan.

Once upstream quality plan is deployed, the manufacturing process is then controlled by a safe processing window and an on-line control process system.

The on-line control process system aims allows to visualize during the welding, the main process parameters (rpm, welding speed, vertical down force and the weld path) to control:

- the parameters stability and conformity.
- the gap between command and feedback values.
- any variation inside and outside the process window.

A typical Screen shot of robot monitoring system is shown fig12, which allows the operator to detect deviation out of the process window.

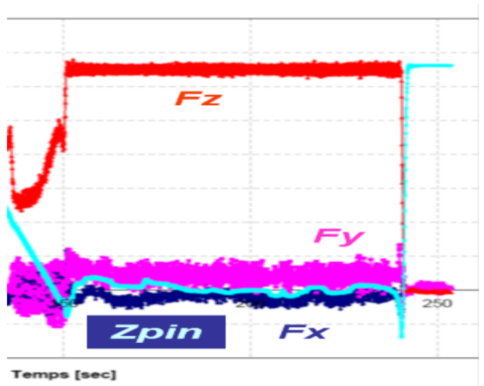


Figure 12, Process Parameters, on line monitoring

2. INTERMEDIATE STRUCTURE. DEMONSTRATOR "Super Puma"

2.1. Why the industry is looking into FSW?

Implementing FSW instead of riveting on intermediate structure as several aims:

- Cost, lead time and weight savings.
- Water tightness.
- Aesthetic improvement.
- Corrosion sensibility reduction.

Figure 13, Location of the intermediate structure

Dimension of Super Puma intermediate structure are H*l*L = 1,87*1,69*1,95 meters.

2.2. Main Function and Design

The main function of the intermediate structure is to transmit the loads introduced by the tail rotor installed on the tail boom to the cabin.
The intermediate structure also conveys the loads of the main landing gear.
The skin is stiffened by:
Longitudinal stiffeners (stringers, spars) obtained by folding or extrusion. Transversal stiffeners (bulkhead where the loads are introduced, shape frames regularly distributed).

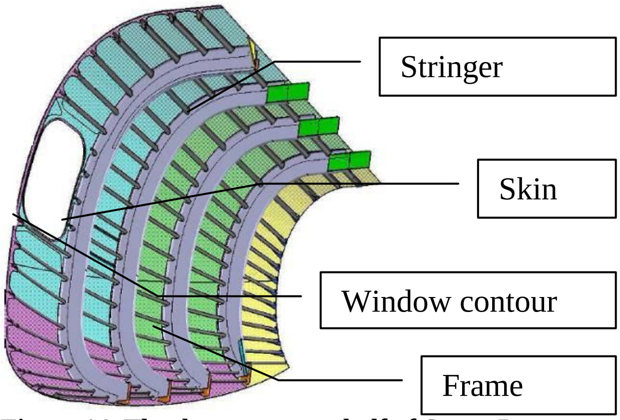


Figure 14, The demonstrator, half of Super Puma intermediate structure

The meshing is optimized to:

- Transfer bending, torsion and shearing loads.
- Avoid skin buckling.

The longitudinal stiffeners are continuous since they transfer normal loads coming from airframe bending solicitations.
The skin transfers, shearing, tension, compression and torsional stress all along the airframe.
The skin has to be calculated to the limit loads.

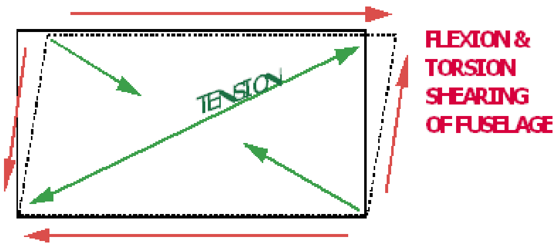


Figure 15, Schematic Skins Stresses

2.3. Detailed definition:

The half intermediate structure is a lateral stiffened panel with double curvature.

It is composed of four stretched 2024 aluminum skins (each developable), twenty stringers, a contour window reinforcement, a fishplate and four secondary frames.

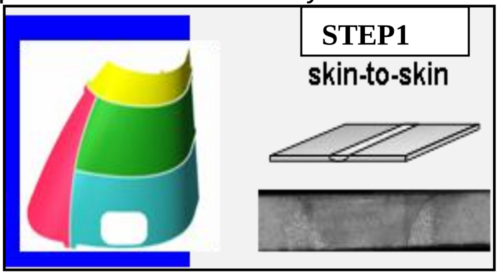


Figure 16, Intermediate structure design. Butt joint assembly.

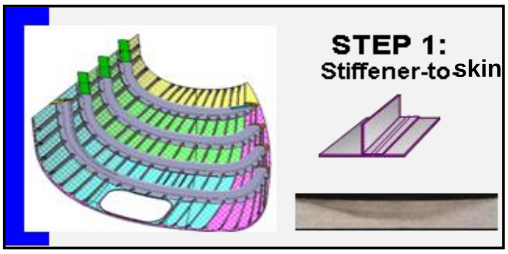


Figure 17, Intermediate structure design. Overlap joining

2.4. Sample and qualification test

The intermediate structure addresses tensile strength (static and fatigue) for the butt skin-to-skin join and shearing and compression for the stringer-to-skin connection.

Tensile specimens have been machined from flat welded coupons whereas shearing tests have been conducted on flat technological specimens with 3 welded stringers. Results include two materials selection, the 2024 T3 bare baseline and the 6056 T78 improved corrosion resistance alloy. The two-rivet row connection is also presented for comparison.
Figure 18 provides the tensile results in static (ultimate strength) and figure 19 in fatigue S-N (life time). FSW butt join exhibits significant savings. In static and in fatigue, the strengths are more than doubled for the 2024 T3 baseline. For the 6056 T78 configuration, savings on static strength is lower than that of the 2024 T3, which is mainly due to the strength reduction of the parent metal but in fatigue, saving is evident.

The corrosion behavior depends on the material and the temper used for welding. In the case of the 2024 T3, the FSW connection has similar sensitivity than the parent metal, whereas for the 6056 T78, the FS weld to consider as 6056 on T4 temper remains insensitive to corrosion. This allows using the same corrosion protection of the parent metal in both cases.

Intermediate structure test Matrix:

Junction	Static	Fatigue	Material
Reference	Tension Shearing	Tension Shearing	2024 T3 6056 T78
	Shearing Compression		2024 T3 6056 T78
	Tension Shearing	Tension Shearing	2024 T3 6056 T78
	Shearing Compression		2024 T3 6056 T78

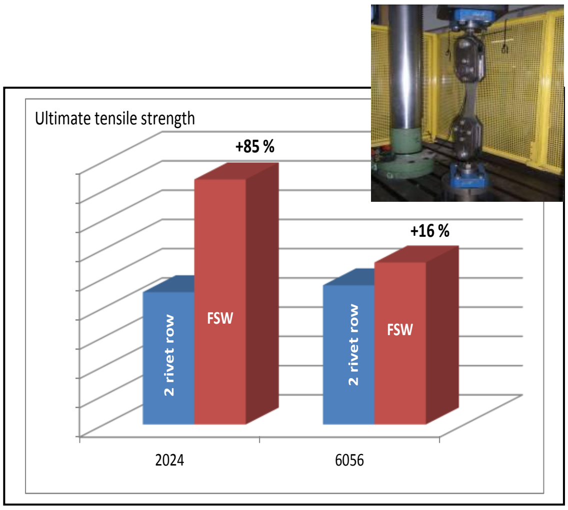


Figure 18, tensile result in Static and fatigue S-N

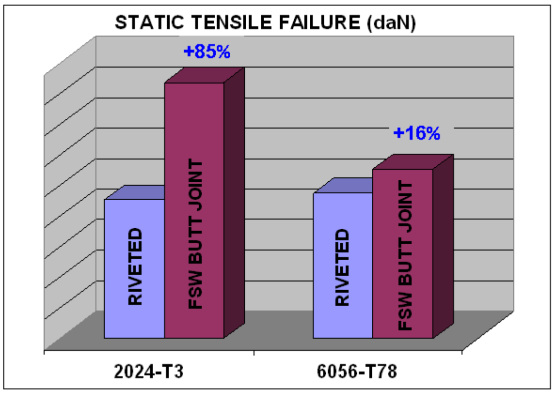


Figure 19, Static and fatigue S-N tensile tests

Figure 20 to 22 shows static test results of articulated frame shearing.

FSW technology is 8% more efficient in permanent wrinkling; a -13% drop is noted when using 6056-T78 material.

FSW is as effective as riveted technology on failure behaviour, when using 2024-T3. A -13% drop is noted when using 6056-T78. This is due to the lower ultimate strength of the 6056-T78 material.

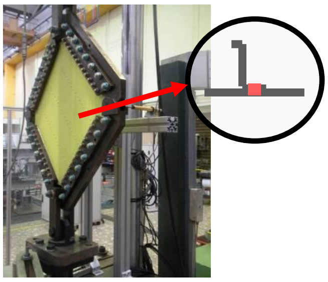


Figure 20, Shearing test installation

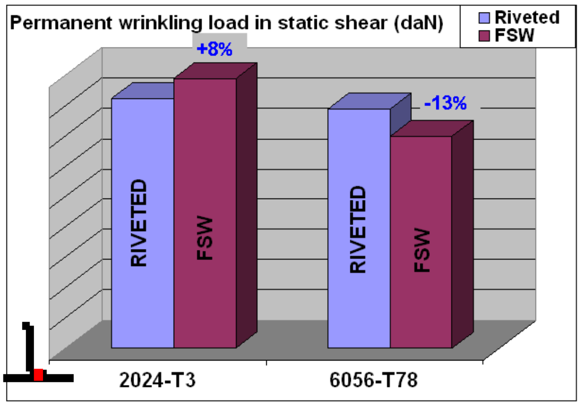


Figure 21, Static Shear, permanent wrinkling Load

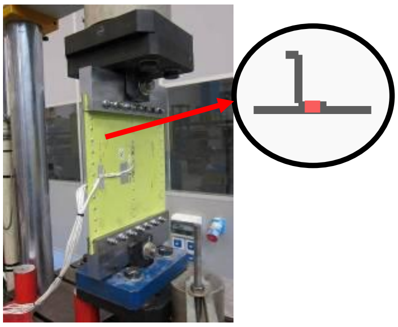


Figure 22, compression test installation

Figure 23 shows comparative results of static compression testing of a stiffened plate. FSW technology is slightly more efficient than riveted technology: +3% when using 2024-T3 material, and +13% when using 6056-T78 material.

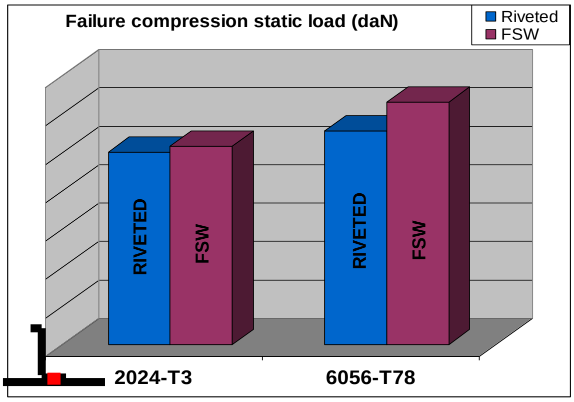


Figure 23: Static compression.

2.5. Industrial constrains and key factors.

The main challenges are:

- To weld on a bi curvature part with dimensions requiring use of the near full envelop of the robot.
- To manage the gap (accuracy of the elementary parts) for butt joint welding in a bi curvature configuration.
- To manage the accuracy, elasticity and deflection of the robot in its full envelop in term of position and angles.

The key figures related to the intermediate Structure are:

- 39 stiffeners with an average length of 1,6 m each.
- 90 m of welding path.
- Welding speed of 0,5 m/mn.

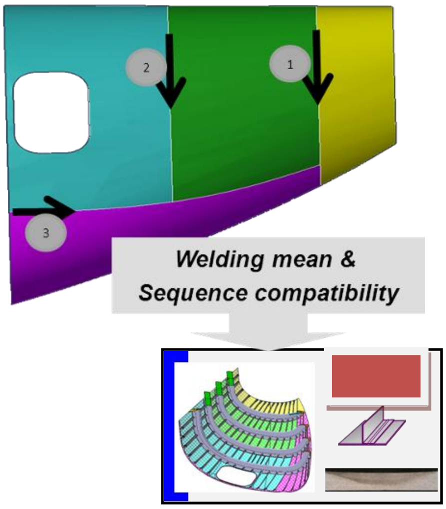


Figure 24, intermediate Structure demonstrator, welding sequences.

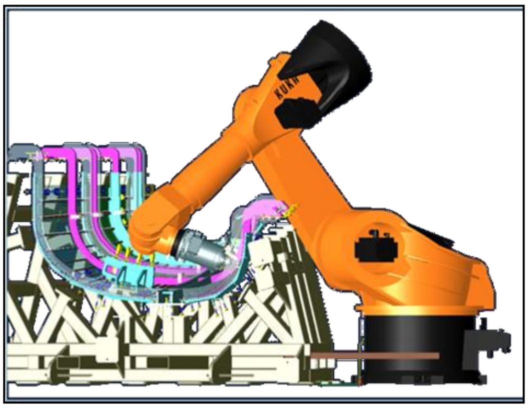


Figure 25, intermediate structure, accessibility simulation.

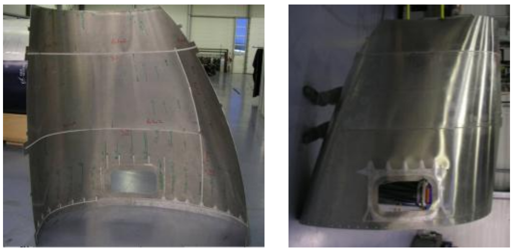


Figure 26, intermediate structure, butt join welding skin

The 90 m of welding have to be compared to the 5000 rivets in the riveted solution.

On this basis, considering only the assembling time (without the preparation and manipulation time, clearly different and impacting the welded solution) the figures are:

- Riveted = 83 h
- Welded = 3 h

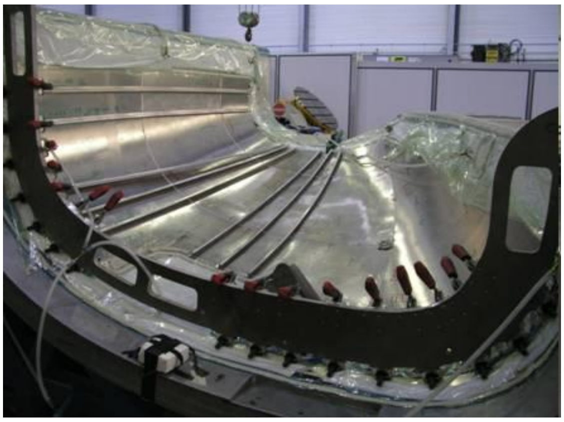


Figure 27, intermediate structure, Stringers welding.

2.6. Aesthetic

Figure 26 is showing internal and external welding skin. The weld is only visible inside the part that corresponds to the shoulder side. On the opposite side to the shoulder, weld is only detectable due to color aspect change.

2.7. Savings

In a global assessment the savings are as follow:

	Riveting technology	FSW technology	Variation
Weight in Kg	100	96	-6%
RC in K€	100	79	-21%
NRC in K€	100	120<	20%<

Figure 28, Intermediate structure, FSW technology benefit.

In order to reach these savings, attention should be given to the tooling.

Three axes have to be highlighted:

- The dependence on and influence of the part design.
- The integration of the process requirements.
- The tooling concept.

The part design shall integrate the strategy by sub-assemblies leaded by the tooling strategy, which should:

- solve accessibilities and overall dimensions issues.
- define welding directions.

- avoid weld in radius toe.
- take into account clamping constraints.
- include the positioning additives to master the parts position.

The process parameters and type of welding (butt joint, overlap, 3 layers, direct or by transparence…) are an integral part of the tooling specification.
The down force associated with the diameter of the welding pin (mainly the shoulder) and the penetration are sizing parameters.
The clamping requirements also are critical tooling specifications.

The tooling concepts are the result of the above mentioned constraints.
The main principles are:
- Framework stability under static and dynamic stress

Figure 29, Intermediate structure, tooling overview.

- Clamping of parts to be welded as close as possible to the welding axis. Usually the clamping function is the result of associating mechanical clamping and vacuum suction. Clamping should be effective on the both sides of the weld.

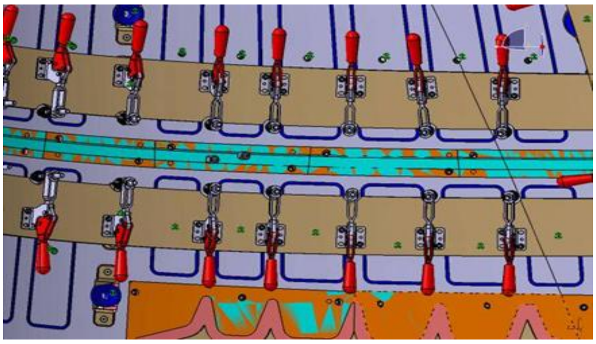


Figure 30, Mechanical and Vacuum Clamping details.

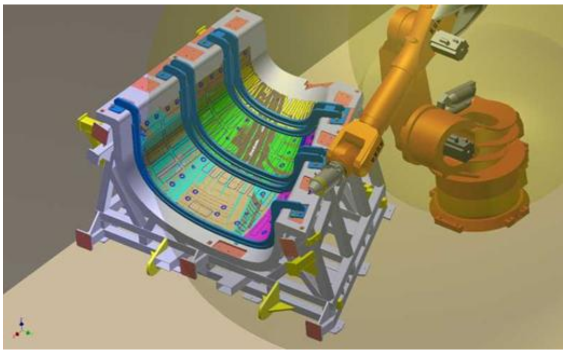


Figure 31, Mechanical and vacuum Clamping System.

- Existence of a steel backing bar under the welds (thermal and stress resistance) with a good surface condition, at least for butt join welding (Ra 0,4).

The tooling must also allow robot indexation for off line welding programming.

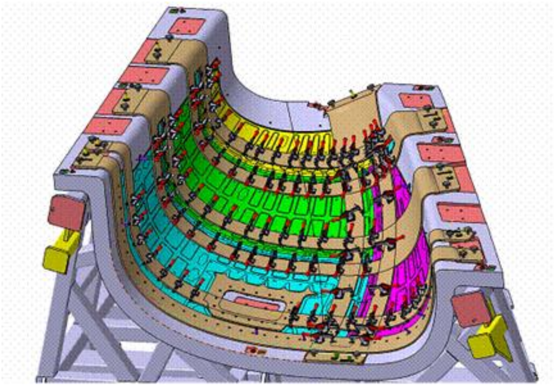


Figure 32, complementary mechanical clamping System.

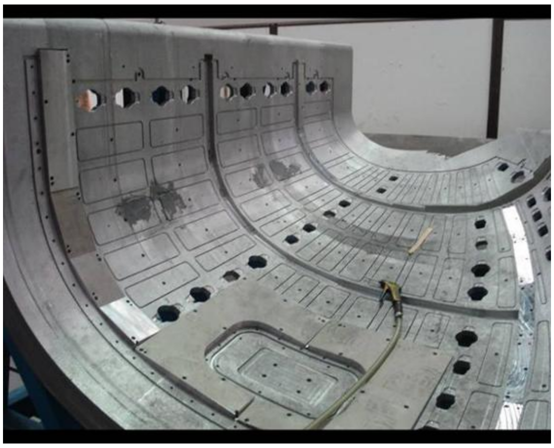


Figure 33; Tooling mattress

2.8. Conclusion on intermediate structure

We reached the TRL6 on stiffened skins for Super Puma intermediate structures.
The accuracy of elementary parts is the most technical challenging aspect and the management of the robot is the most industrial challenging one.

3. “SUB FLOOR BEAM DEMONSTRATOR.

3.1. Why industry is looking on FSW for Beam manufacturing:

Industrial drivers for the FSW implementation on beam are mainly the cost, lead time and weight saving.
The corrosion behavior improvement is also a key factor
But on this kind of part the robustness and stability aspects bring a decisive advantage for the level and repeatability of the quality of the assembled part.

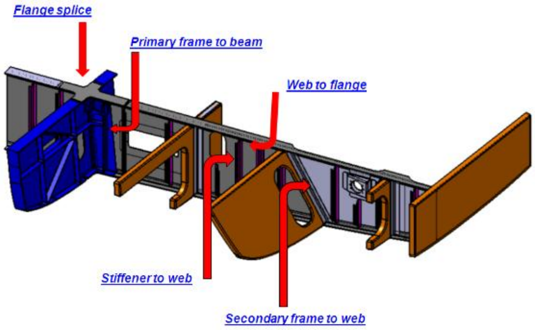


Figure 34, Beam welding joins.

3.2. Function of Beam of a Sub-Floor group.

It is the main part of the Sub floor Group. It supports the entire cockpit and loads introduced by the nose landing gear.

The general loading is:

- Static shearing and compression.
- Dynamic Compression (Crash).
- Fuel Pressure.

This general loading introduces on the beam element the following loads:

- In the flange, Tension, compression, general and local bucking
- In the web, Shearing (stability, permanent wrinkling and failure), static and dynamic compression (crash).

	Traction	Compression	Sharing	transversal Bending
Complete Beam		Crash		
Junction web/flange	Junction web / flange static + fatigue	Junction web / flange static + fatigue	Junction web / flange static + fatigue	
web			Static	Static
Flange	Static Fatigue	Static Fatigue		

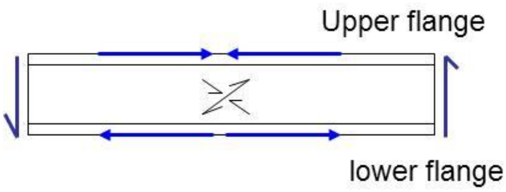
Figure 35, Beam component and interface loading.

Its geometrical aspects are as follow:

- Interface with Nose Landing Gear and introduction of related loads.
- Interface with floor and introduction of related loads.
- Interface with skins and introduction of related loads.
- Interface with frames and transfer of loads.
- Close fuel compartment and withstand fuel pressure.
- Interface with flight controls, harnesses, fuel cell, ECS routings, equipment: holes with reinforcements, brackets, supports.
- In case of crash, absorb energy with limited loads, limit accelerations transferred to the occupants and the structure.

3.3. Design reference for demonstration

The aim of the demonstrator was to validate capability to design and produce a complete sub-assembly of a beam with two machined flanges and a web composed by sheet aluminum 2024T3 with stringers in 2024T3 aluminum alloy.



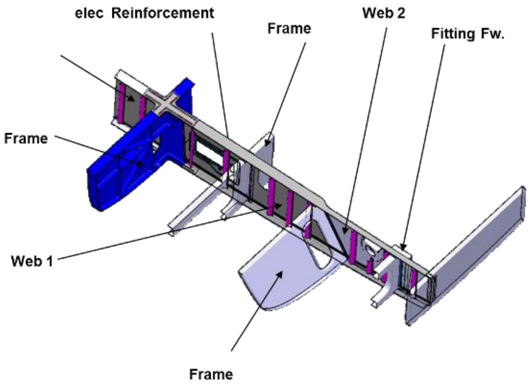


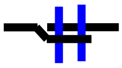
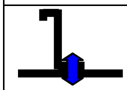
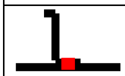
Figure 36, Beam demonstrator design.

3.4. Sample and qualification test

We reach the TRL6 on stiffened skins for Super Puma intermediate structure.
The accuracy of elementary parts is the most technical challenging aspect and the management of robot trajectory is the most industrial one.
The beam addresses shearing and compression for the stiffened web and bending and crash tests for the global welded beam.
Shearing and compression tests are common to the Super Puma stiffened skin application. Beam bending inducing shearing in the FSW joint between web and flange, the butt FSW joint connection between flange and web have been characterized on elementary shearing specimens according to ISO 20505 standard. The different material associations (web and flange) have been investigated and this campaign aimed to provide the weld allowable in shearing.
For each material configuration, the performances analyzed are the joint efficiency and the mean shearing strength (Figure 37). Due the initial temper of the alloys, FSW leads to generate, in the welded nugget: the aged T6 temper of 2024 for the similar 2024 T3 welded configuration, the naturally aged T4/T3 of the 6056 and 2050 for the dissimilar material configurations. Thus the weld performances result from the respective material evolution. More especially for the case of the dissimilar material, the lower properties are mainly due to the natural aging generated by the welding.

Then the behavior in bending (static and fatigue) has been investigated through technological specimens implementing both the welded flange-to-web and the stringer-to-web connections.

<u>Beam Demonstrator Test Matrix</u>

Junction	Static	Fatigue	Material
Reference 	Shearing Crash		2024 T3 6056 T78 2050 T8
	Crash		2024 T3 6056 T78
	Shearing Crash	Shearing	2024 T3 6056 T78 2050 T8
	Crash		2024 T3 6056 T78

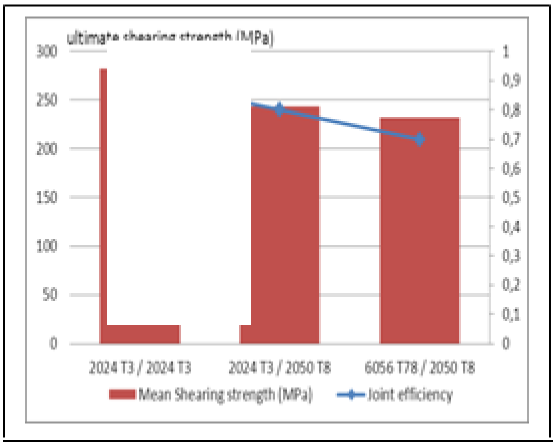


Figure 37 Shearing Strength

Figure 39 provides bending-shear static failure test results on representative technological specimen of lower beam structure element prototype.
These results allow comparing performances between riveted technology and FSW for web-flange connection.

In material association Web-flange 2024-2024, FSW technology shows better strength (+25%) than riveted technology.

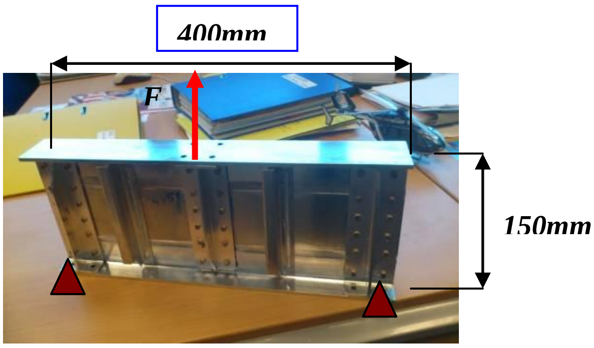


Figure 38, Bending-Shear test sample.

In material association Web-flange 2024-2050 FSW technology shows better strength (+32%) than riveted technology.

In material association Web-flange 6056-2050, FSW technology shows better strength (+25%) than riveted technology.

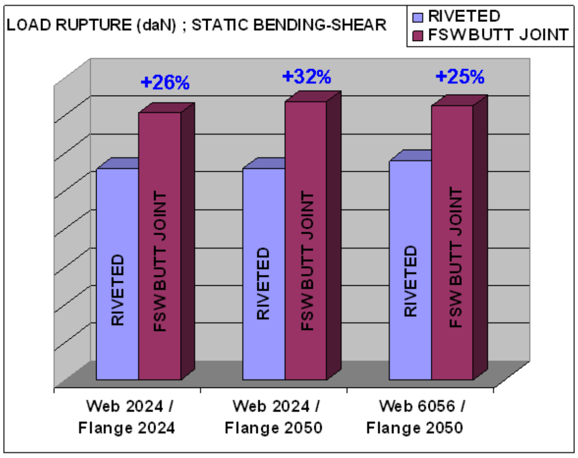


Figure 39 Static Bending Shear performances

Figure 41 provide Crash tests results on technological specimens, FSW technology vs riveted joining. FSW technology crash behaviour compared riveted technology (reference), of a stiffened thin metal sheet.
The technological specimen is representative of the lower beam structure element prototype.
Crash landing required conditions:
Impact on structure (landing gear extended and/or retracted; Vz = 8m/s, 3/3 sustained.
Each design is evaluated according to 3 main criteria:
Criterion 2: Average acceleration
Criterion 3: Maximum acceleration
Criterion 4: Allowed energy in KJ/m

In butt join connection between the flange and web, the crash behavior is equivalent to the riveted technology, with 2024-T3.
In lap join connection between the flange and web, the crash behavior is equivalent to the riveted technology in 2024-T3, except for a higher level in term of maximum acceleration.

Figure 40 Crash installation

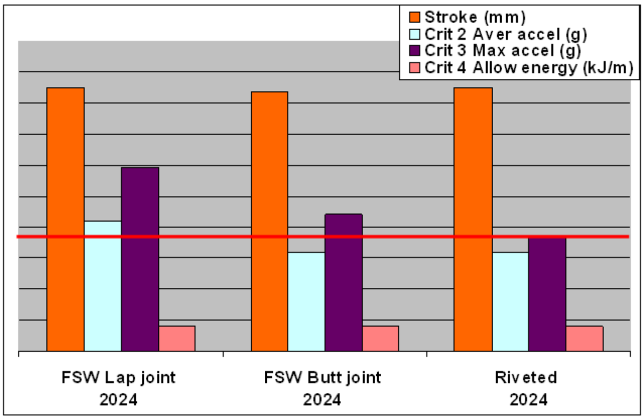


Figure 41, Crash Test Performances- Average & Max acceleration

3.1. Industrial constrains and key factors.

The main challenges are:

- To master dimensions accuracy.
- To avoid distortion (welding sequences).
- Welding of dissimilar thicknesses.
- To manage the space available for the welding head (accessibility and tooling strategy + tool holder).

Figure 42, Beam welding sequences.

3.2. Savings

Based on the same approach than for the intermediate structure, the savings are the followings:

	Riveting technology	FSW technology	Variation
Weight in Kg	100	92,5	-7,5%
RC in K€	100	77	-23%
NRC in K€	100	120<	20%<

Figure 43, Beam demonstrator, FSW technology benefit.

The tooling topic has the same sensitivity and is based on the same principle than for the intermediate structure.

Figure 44, Dissimilar thickness web joining.

Figure 45, Beam to frame joining.

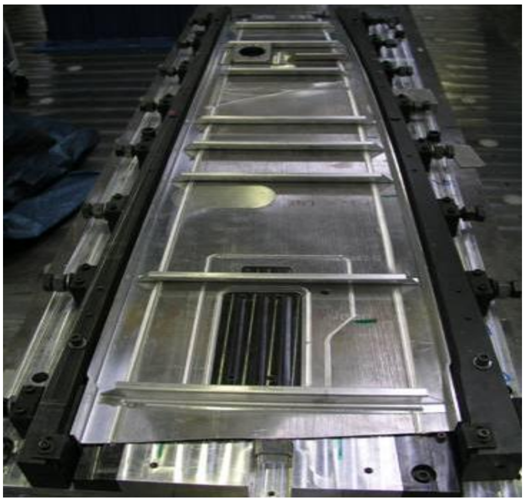


Figure 46, Beam tooling overview.

3.3. Conclusion on sub floor beam

We reached the TRL6 on sub floor Beams application.
The design of the beam to optimize material quantity and welding effector access are the most technical challenging aspects. Parts sizes are only limited by the robot's capacity (complete sub floor).

3.4. FSW technology certification.

FAA as already certified the FSW technology on fixed wing aircraft.
For EASA Certification, EC introduce the FSW technology has a new "Fabrication Method CS 29 § 605".
EASA therefore requires consideration of the following issues.

Issue addressed	H/C consideration
Process control	Yes
Weld performance & Process stability	Yes
Processing changes	Yes
Fatigue & damage tolerance	Yes
Weld run in/out	Yes
Kissing bond	Yes
Ageing effects	Yes
Corrosion	Yes
Bending loads/shear	Yes
Lighting strike	Yes
Continued Airworthiness	Yes
Repair techniques	Yes

3.5. Is the FSW technology reparable?

Yes it is but we consider 2 questions, the first one is, can we repair the FSW during the manufacturing phase, the second is, can we repair the FSW in service.

During the manufacturing phase it is easy to repair parts or components with FSW process. Overaging and performances induced by the repair welding shall be documented. Depending of the criticity of the damage, the reparation is established with a dedicated drawing (quality management).

In services, for support capability, the next step will confirm the management of repair using the current SRM and the fact that FSW is not requiring new technics.

3.6. The future of the FSW technology

The application prospects are numerous, and guided by the FSW major assets associated with the assembled materials performances.

The FSW technology provides in priority cost reduction ranging from -5% to -35%, coming from the process automation and reduction of raw material costs. The automated process brings a repetitive and certified level of quality.

The range of aluminium alloys that can be assembled allows design optimization and generates performance gains in weight (up to -10%) and fatigue resistance (up to +60%).

When used for crash resistance applications, FSW offers equal or greater performances than riveted assemblies. Electric conductivity of aluminium alloys assembled with FSW is better than riveted assemblies; moreover it is not corrosion sensitive when the process parameters and the initial temper prior to welding are judiciously selected.

FSW assemblies are watertight as well.

All the advantages of FSW can be applied to the main components of a helicopter's structure, such as frames, beams and skins. Better yet, it allows reflexion on redesigning and consideration on the manufacturing of more complex subsets, such as the bottom structure, integrating beams, lower parts of frames and skins, or the entire mechanical floor.

4. CONCLUSION

As a conclusion, the robotic FSW technology implemented on enhanced performance materials achieves remarkable technical and economical results. On the full scale demonstration the objectives of 21% cost reduction and 6% weight savings, compared to a conventional metallic riveted design, have been reached on beams and skins. Higher levels of savings can be be expected by full tailored design and the use of new welding tools leading to welding velocity increase.

5. REFERENCES

Patent : FR N°09 01427 – Méthode de soudage par friction entre pièces métalliques, procurant un contrôle de la tempértaure de soudage à partir d'éléments thermiquement conducteurs »

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6. SYMBOLS and ABBREVATIONS

CNC	Controlled Numerical Command
ECS	Environmental Control System
FS	Friction Stir
FSW	Friction Stir Welding
ISO	International Standard Organisation
NC	Numerical Command
NDT	Non Destructive Test
NRC	Non Recurring Cost
Ra	Roughness
RC	Recuing Cost
R&T	Research and Development
S-N	Stress, Number of cycle
SRM	Standard Repair Manual
TRL	Technology Readiness Level
Vz	Vertical Speed