X-ray investigation of complex composite aeronautical parts

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Abstract
The presence of light structures, motivated by economical interest, is widely observed in aeronautics. Indeed, by reducing the total weight, less engine power is required to take off and longer travelling distances can be reached. Composite materials based on organic matrices, especially those in carbon fibres and epoxy resin exhibit good mechanical properties and offer light weight. These materials, issued from a large variety of processes, are specificaly designed for implementation in integrated structures. The increasing complexity of shapes makes sometimes the control by conventional tools impossible. The development of new investigation techniques is therefore a crucial goal. X-ray examination presents an alternative method, that becomes very attractive when combinated with digital radiography. New promising approaches such as tomography are explored. Results obtained with typical complex parts are presented and discussed.
Keywords: CFRP composites, structures assembling, titanium pins, stiffener, digital tomography, 3D reconstruction.

1. Introduction

Composite materials, especially Carbon Fibre Reinforced Plastic (CFRP), are largely implemented in aeronautic structures and tend to replace partly metallic fuselages or wing panels in the future.
CFRP technology is of great interest for several reasons: First, mechanical properties match the aeronautic specifications or can be made compatible to specific requirements by modifying the manufacturing processes. Second, to make a part that exhibits definite functionalities, CFRP processes are equivalent to metallic processes in term of implementation and cost. A CFRP process based on Resin Transfer Molding (RTM) can produce a complex and specific part in one shot. The main interest of using CFRP composites is essentially based on the weight reduction (density CFRP composite: 1.6 vs Aluminum: 2.7). A light weight commercial aircraft saves gas and consequently reaches larger travelling distances. The next transporters Boeing 787 and Airbus A350 XWB aim to be made of at least 50% carbon composite. This challenging concept requires from the designers to innovate, develop and control new manufacturing processes.
As described earlier, CFRP processes can be simpler to implement and allow designing and producing parts that exhibit increasing levels of complexity. Introduced for the A380 aircraft, large panels with thicknesses up to 50mm were developed. Contoured shaped parts such as simple or double curvature panels and corners are usually implemented. More recently RTM parts assembled by pins or stitching in dry preforms are developed and implemented. This consequently increases the level of difficulty for the NDT controls. To be validated and approved for the flight acceptance, each part of a plane must be controllable and finally controlled.
NDT controls of composite aeronautical parts are commonly performed by ultrasonic. When the parts exhibit a complex geometry or a strong ultrasonic attenuation, ultrasonic controls are sometimes impossible. Therefore, alternative NDE such as X-ray presents a great interest for the inspection of these complex materials. To illustrate this purpose,

we present two NDE investigations of assembled T-shaped CFRP composite parts that are dedicated to the optimization of the manufacturing process and the tests monitoring in R&D environment.

2. Context and description of the parts

Fuselage or wing panels are commonly made of metallic parts. These parts are usually constituted of a skin (panel) with frames and stiffeners to strengthen the overall structure. As seen on the figure 1, the skin is generally welded or riveted on the frame or stiffener. Although these processes are approved and very well controlled, they are time consuming because they require preparation of the surfaces, manipulation and assembling of parts.

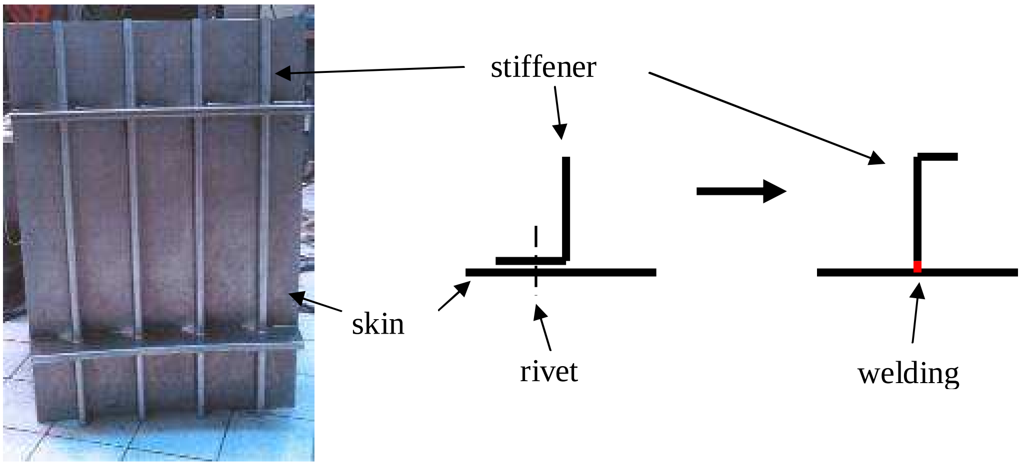

Figure 1: Metallic structure with riveted or welded stiffener.

One solution consists in integrating directly the stiffeners on the panel using a CFRP technology based on the RTM process.
Also based on a RTM process, another method consists in assembling the stiffener with the skin by putting carbon or titanium pins to ensure the cohesion (figure 2).

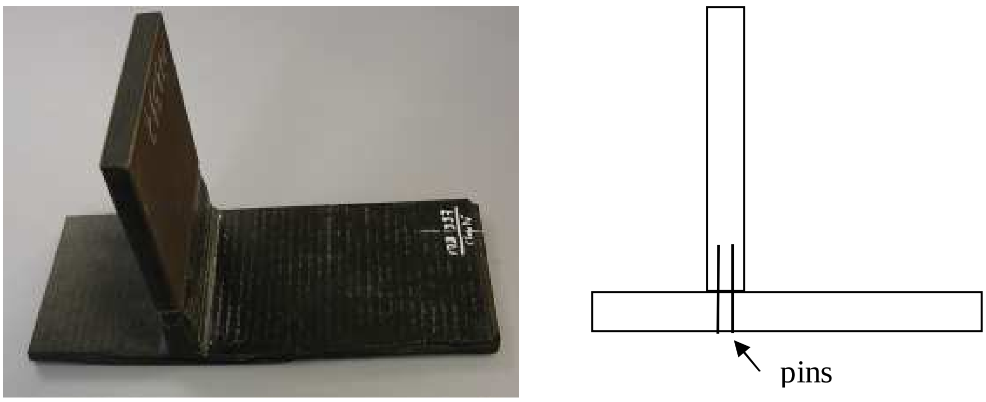

Figure 2: T-shaped CFRP composite assembled with pins.

A technique derived from the previous-one consists in sewing the two parts with a carbon wire. Whatever the method used, the resulting part has a T-shaped profile that requires some NDT control.

The first part of the paper presents some results dedicated to the optimization of manufacturing process. The results inform about the position and alignment of the pins. Some approaches of inspection are investigated with the equipments available in our laboratory.
A second part presents some results obtained for tests monitoring after mechanical constraints. NDT inspection is a helpful tool for observation of mechanical behaviour. It provides feedback to the Design Office to model more accurately and predict the behaviour law of the complex part.
Because ultrasonic inspection is not adapted to these parts, X-ray technology is preferably chosen since it offers numerous advantages such as real time imaging, large thickness inspection and is very attractive when combined with digital radiography and tomography.

3. Description of the X-ray equipment

The source is an adjusted voltage X-ray bi-focus tube comet MXR 160kV/0.4-3mm. The detection system is composed of a brightness amplifier TH 49426 QX from Thales and a CCD camera MX12P 1024x1024 from Adimex. The 3D reconstruction software is DigiCT from Digisens. A scheme of the X-ray tomograph is presented on figure 3.

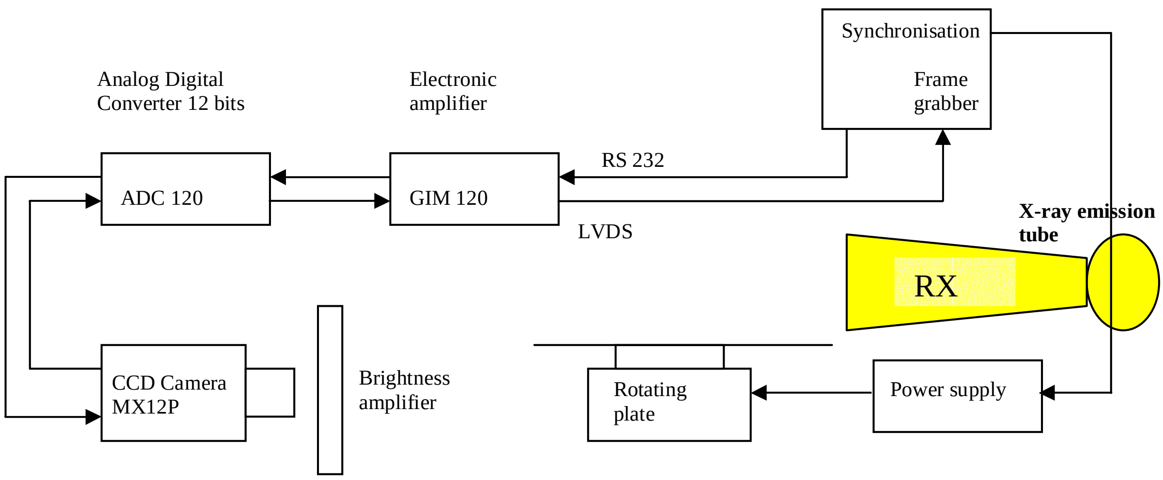

Figure 3: Scheme of the X-ray tomograph.

4. Optimization of the manufacturing process

As shown on figure 4, the assembling of the two CFRP parts is obtained by inserting the pins with a specific trajectory. Pins are introduced along a line with a regular step ΔX (inter-nail distance). Then the device is shifted by ΔY (inter-line distance).

The NDT control aims to check if the sequence has been correctly performed. Checking points are the pins arrangement, the pins orientation and the penetration depth.

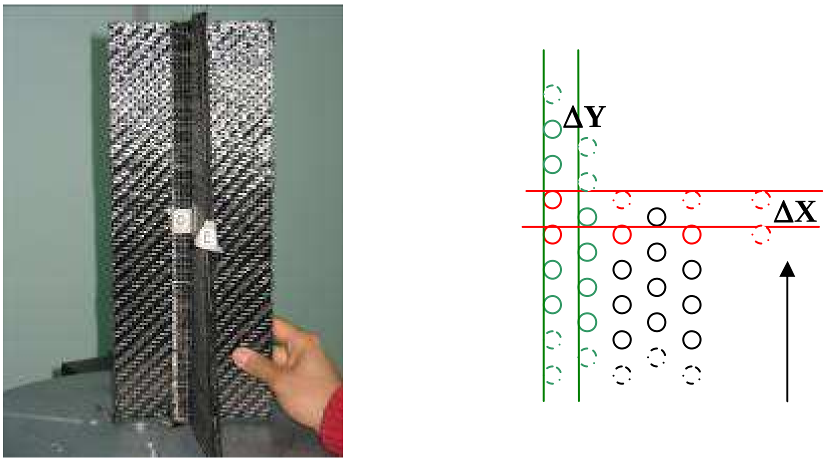

Figure 4: View of a T-shape CFRP preform and nailing sequence.

Digital X-ray radioscopy is a powerful tool since a real-time image can be monitored and the display parameters can be adjusted to improve the image quality. This method is an alternative to the film. A brightness amplifier is irradiated by X-rays and re-emits photons towards a CCD camera. Compared to classical film the gray-scale image is inversed. Indeed, the higher the attenuation, the darker the image. The image quality depends basically of the pins composition (atomic number, density) and the CFRP composition. As seen on figure 5, a nicely contrasted image is obtained with titanium pins. These pins are easily detected due to a larger X-ray attenuation in titanium compared to CFRP. The image informs about the general quality of the pining process and reveals some missing pins, some extra-adding pins, deformation or deviation of pins, etc…

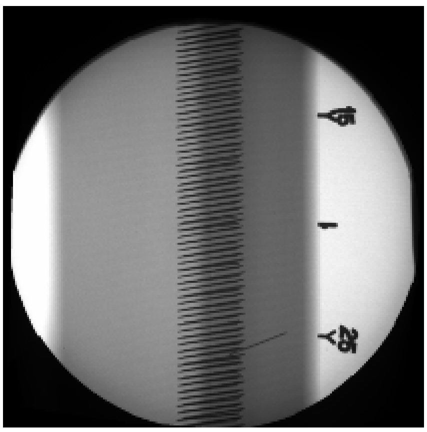

Figure 5: Digital X-ray radioscopy showing the alignment of titanium nails in the CFRP part.

When digital radioscopy is associated with a 2D or 3D reconstruction software, it is possible to perform a tomography of the complex part. This is a very powerful tool because the internal composition of the part can be visualised in 3D environment, which gives a comfortable representation of pins in space (figure 6). Tomography is performed

by capturing a large quantity of digital radiographies taken at different angles of view. The part is put on a rotation motor and 720 images are captured every 0.5 degrees. A special algorithm computes the 720 images to build the 3D object.
The rendering depends greatly of the native image contrast.

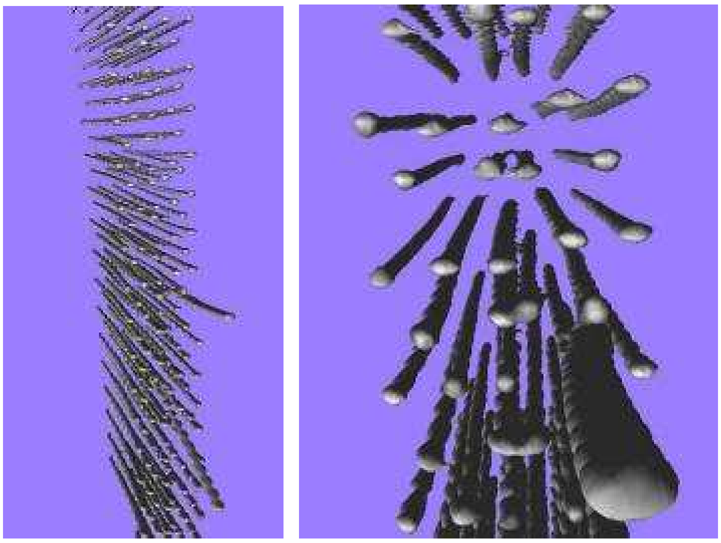

Figure 6: 3D reconstruction of titanium nails. CFRP composite is virtually removed.

From the 3D data, one can obtain a 2D representation by selecting a specific cut in the volume (orientation and depth). The figure 7 presents two 2D-cuts showing the stitching sequence and nails alignment.

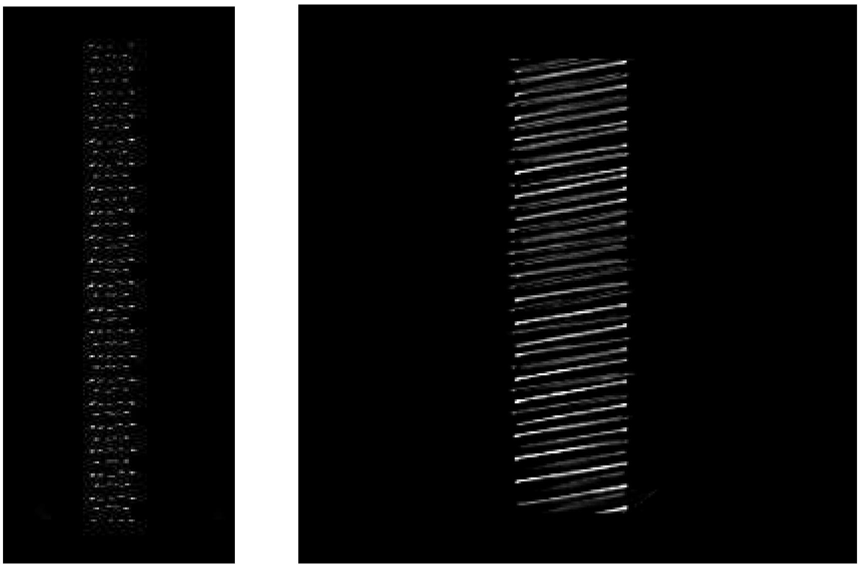

Figure 7: Observation of stitching sequence and nails alignment.

5. Test monitoring after mechanical constraints

Advanced CFRP materials exhibit mechanical behaviour laws that are difficult to predict. Therefore, modeling tools are developed to simulate these laws. Mechanical

properties are evaluated under static or dynamic constraints tests. To be validated, the modeling is continuously adjusted and corrected after rigourous practical tests campaigns.
In the context of all-CFRP fuselage designing, a new process has been approached which consist in sewing a carbon wire instead of putting a pin. Like a classic sewing machine, the carbon wire is inserted from the base plate into the stiffener web using a special switch.
A part assembled by this sewing technique has been injected and polymerised with RTM process. Then to evaluate the strength is the cohesion, the part was tested under mechanical traction. As described in the figure 8, this was performed by pulling out the stiffener from the base plate.

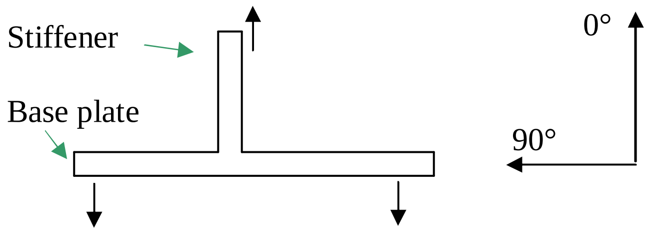

Figure 8: Mechanical constraint to pull-out the stiffener from the base plate.

After this mechanical test, NDE is used to monitor the induced defects associated to broken wires. A simple investigation by X-ray is obviously not sufficient to observe the defects resulting from the wires extraction. Attenuation of the carbon wires is likely the same as the surrounding material. To evidence the defects, a liquid containing heavy metal (ZnI_2) was used to enhance the contrast between defects and carbon material. This method improves greatly the contrast of the resulting image. Of course, this method reveals only the internal defects that are emerging to the material surface.
Radioscopy and tomography are helpful to visualize the internal defects along defined plans of cut.

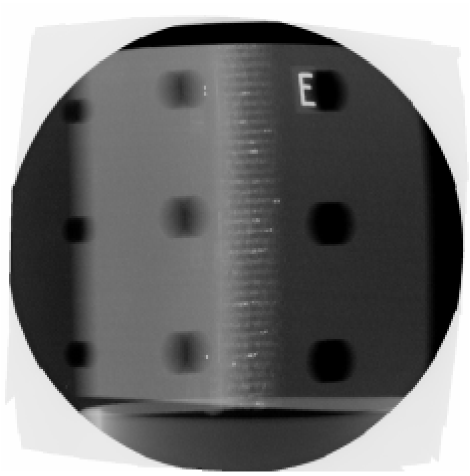

Figure 9: Digital radioscopy of a T-sewed CFRP composite showing defects after mechanical constraints.

First, a simple radioscopy makes possible the observation of the missing wires that were cut or shifted during the traction test (figure 9). The darkening liquid agent fills up the volume that was initially occupied by the wires. Because the thickness of the part is large along the 0°-90° axes, the X-ray energy should be increased to visualize the defects along these directions. But this high amount of energy contributes to scattering effects that make impossible the observation. Then, to circumvent this phenomenon, a tomography of the part is performed. Furthermore, tomography makes observable the cracks located in the base plate or in the stiffener and oriented perpendicular to the plan (figure 10). By capturing a large quantity of shots on the same part, the information of a defect is greatly increased. The pulled out wires are also detected.

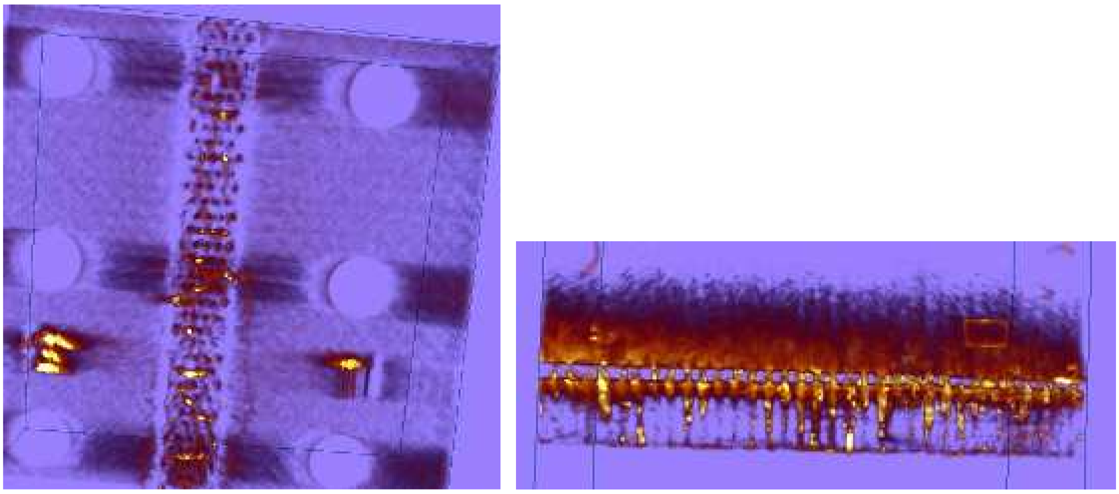

Figure 10: 3D view of stiffener and base plate showing cracks and wire defects. Yellow corresponds to strong attenuation.

By viewing a 2D representation, one obtains information just located in one slice.
In the figure 11, black areas correspond to no emerging defect, and white areas to emerging defects. Defects associated to problems of impregnation are also identified and made detectable just because of the high quantity of images acquisition in tomography.

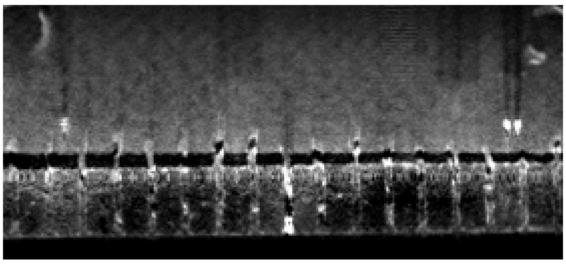

Figure 11: 2D view along the sewing sequence in the stiffener and base plate. White areas correspond to presence of darkening agent.

With 2D vision, the contents of the image correspond only to the slice defined by the user. The slice can be oriented and its depth can be positioned through the thickness. This powerfull tool informs about the accurate position of the defect inside the material. This is not offered by classic radiography where the information is simultaneously projected on the same image.

With 3D vision, the reconstruction of the information in a 3D environment is of great interest. The user can appreciate a volumic repartition of the defects in space. This visualizing tool is very helpful since it informs directly about the uniformity of the sewing sequence, the exact position of the wires break and finally the position of part weaknesses. In return, these observations are taken into account to correct the modeling and improve the sewing process.

6. Conclusion

Driven by economical interest, aeronautic market tends to implement CFRP composites structures for the next generation of commercial planes. The reliability of the CFRP parts depends greatly of the making process, but also of the control process.

We presented two processes under investigation to assemble and solidify two CFRP parts: the nailing and sewing. It is reported some difficulties for NDT tools to control and detect carbon nails or carbon wires in the CFRP parts. This is obviously caused by the nature of the implant which has almost the same attenuation as the part. It is shown that digital radiography combined with tomography reconstruction could provide a good representation of titanium nails in 3D space. Tomography was also helpful to find the defects that appeared after a mechanical traction. The inspection was made possible after the impregnation of a darkening liquid agent.

This study reveales some difficulties associated to the inspection of specific T assembled parts. Some improvements should be obtained by increasing the quality of equipment control, such as the X-ray source stability. Some modification in the making process could also improve the controlability, such as implanting darkening liquid agent with the carbon pins. This could be done assuming the darkening agent doesn’t interact pollute the CFRP composite.

The inspection of the future CFRP structures requires the development of performing tools to detect faster (improved reconstruction algorithm) with a better resolution. Dual energy X-ray concept is under study and should discriminate the epoxy resin from carbon fibre in complex shape parts. X-ray associated to tomography is a powerful NDT tool.