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Computed Radiography and Microtomography of Riveted Lap Joints of Glare™ Subjected to Constant Amplitude Loading (CAL) Fatigue

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Abstract

Riveted lap joints made of two sheets of Glare™ are known to develop cracks at the faying surfaces of aluminum sheets when subjected to cyclic axial constant amplitude loading (CAL).

The purpose of this work was to conduct high-resolution digital radiographic inspections of cracks generated by the CAL in the aeronautical grade Glare™ riveted hybrid composite lap joints and to show that misinterpretations of crack position by computed radiography (CR) of one projection can be solved by computed microtomography (µCT).

Glare™ joints with two aligned rivets were studied after a number of CAL fatigue cycles. Cracks have propagated from the rivet holes towards the lateral boundaries of the test specimen in the inner aluminum layers.

High definition CR showed a similar quality and details of conventional X-ray radiography using (nondestructive technique) NDT film. However, when multiple cracks are detected, it is quite difficult to determine from which aluminum plate layer they have been propagated, because depth resolution is impossible with just one radiographic projection. In this case, by using computed microtomography this drawback has been overcome so that details of multiple fracture patterns are revealed and the ambiguity is solved, proving to be a more elucidative methodology towards inspecting assembled components and complex shaped materials and structures.

Keywords: Computed Radiography, Computed microtomography, Fiber-Metal Laminate, Fatigue Crack Propagation, Riveted Lap Joints

1. Introduction

Advances in the aerospace industry have led scientists and engineers to develop materials whose properties must combine exceptional mechanical performance and low weight, features often very hard to achieve in a component built from a single material. In order to overcome this ever-increasing challenge, composite materials have been developed to use the best characteristics of each of its individual components. One such composite material is Glare™.

Conceived at the University of Delft, in the Netherlands, Glare™ is a hybrid fiber-metal laminate built up from two 0.5 mm thick 2024-T3 aluminum layers, interspersed with and bonded to four layers of high strength glass fibers thermoset epoxy resin, oriented at 0°/90°/90°/0°, resulting in a 1.6 mm thick plate in the case of Glare-5 grade. Due to its high mechanical properties (property/density), Glare™ has been widely used in the aerospace industry in several applications such as in some upper fuselage panels of the Airbus A380 airliner[3].

Since some engineering designs lead to riveting Glare™ plaques together, it is mandatory to ensure the integrity of the final assembly, especially around the rivet holes, by some nondestructive technique able show the fatigue initiation and/or its development throughout the components. Studies concerning riveted lap joints of Glare™ subjected to CAL[3,5] clearly show that under low-to-medium stresses (i.e., below 65 MPa), typical of those imposed to civil aircrafts during normal service conditions, cracks propagate along faying (i.e., no visible) surfaces by vast extents before emerging to the external surface of the joints, so that they remain undetectable by visual inspection for long time.

Eddy current and conventional radiography has shown promising results, and studies have been carried to improve both quality and reliability of the inspections[3,4]. Also, when using medium and low resolution computed radiographies with portable sources of X-rays[3], it was extremely difficult to detect the cracks. Moreover, both techniques produce images that cannot assure in what aluminum sheet a crack has initiated. This kind of ambiguity may have a negative impact on maintenance costs and time.

Computed radiography technique has already been used to address several types of non destructive inspections, with very good results in image quality and, most importantly, in safety and environmental issues[3,4]. On the other hand, computed microtomography has been used mostly for symmetric specimens of relatively reduced dimensions, in spite of its unquestionable quality in terms of resolution, detailing and data interpretation possibilities.

2. Experimental procedures

The riveted test specimen used in this work is one already employed by Tarpani et al.[3,4,5] in their study on radiographic techniques to detect fatigue cracks in single lap joints of Glare™. The joint consisted of two Glare-5 sheets held together by a row of two rivets aligned with the loading direction (Figure 1), which was fatigued until crack propagation is established.

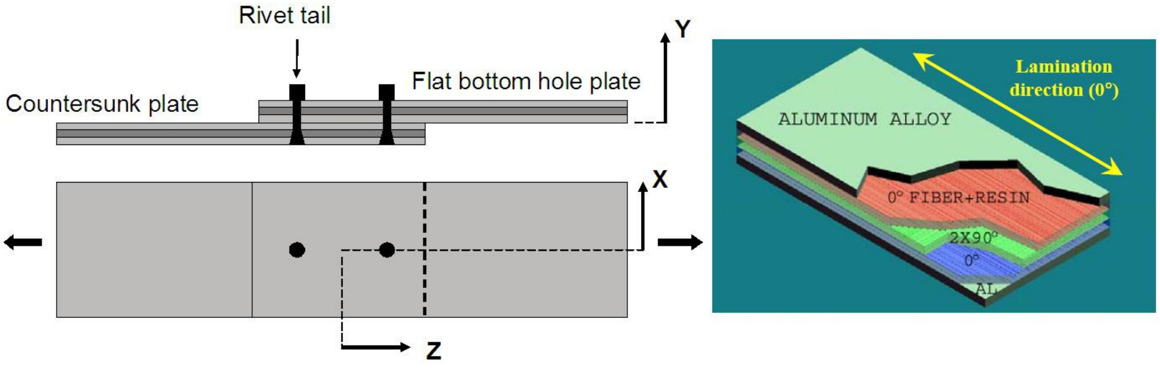

Figure 1 – Test specimen schematics: direction of cyclic loading and the riveting pattern and geometry. The X, Y and Z arrows represent directions for the tomography. Also shown is a typical Glare™ sheet.

Previous studies[3,4,5] reveal that the prevailing failure mechanism is basically a function of the applied stress level. The prevalent failure mode varies from rivet fracture by pure shearing under relatively high stresses, to fretting developed at the faying surfaces of Glare™ sheets under reduced applied stresses, with mixed mechanisms occurring under intermediate cyclic stresses.

The number of applied cycles to the test specimen was 1,929,990,000, with maximum gross peak stress of 49MPa and maximum peak load of 3.5kN. The test specimen was periodically inspected and, although visually intact, cracks were found at the faying surfaces of the aluminum sheets by conventional (film) radiography (Figure 2).

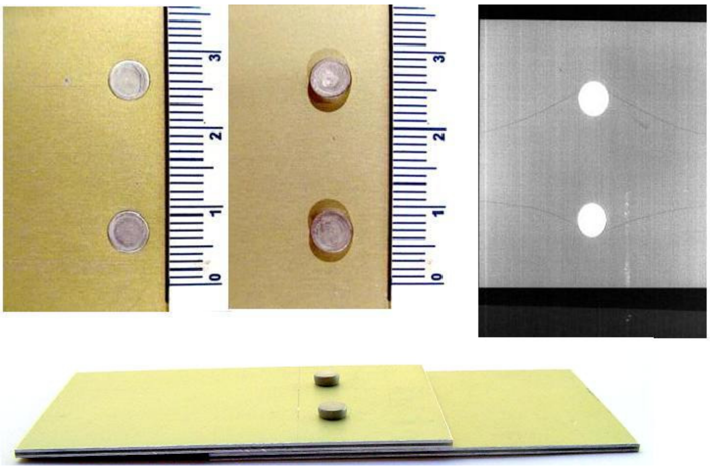

Figure 2 - Test specimen photography and conventional radiography[3] . From left to right: countersunk rivet heads, bottom rivet heads, radiography and test specimen full image. Those were taken after more than 1,000,000 cycles of CAL. Scale in centimeters.

In the present work, computed radiography (CR) and micro tomography (µCT) were used to reveal cracks which have propagated in the inner aluminum sheets of joints with the geometry shown in Figure 1. Both experiments were carried at BAM – Federal Institute for Materials Research and Testing in Berlin, Germany.

The CR tests were conducted using a 320 kV X-ray source and a source to detector distance of 1200 mm. Two types of CR systems have been used, a standard CR system with 130 µm basic spatial resolution (FujiFilm ST-VI IPs and DynamiX XG-1 scanner) and a high definition CR system with 40 µm basic spatial resolution (Duerr HD-IP and HD-CR35NDT scanner) The CR images were processed by ISee v1.7.3-demo software, developed by BAM.

In order to achieve the best resolution possible, two images of the lap joint were taken using IP of different resolutions, as stated in Table 1.

Table 1 - Experimental procedures settings for the CR

Experiment	Imaging Plate	X-ray voltage (kV)	Current (mA)	Exposure time (s)	pixel size
CR1	HDCR-35 Duerr	60	4	120	21 µm
CR2	ST-VI FujiFilm	60	3	120	100 µm

The µCT source was a microfocus X-ray of 225 kV and a flat panel detector XRD 1620 with CsI scintillator, 200 µm pixel size and 2048 x 2048 pixels. The reconstructed projections were treated via CT Image Viewer, trial edition, developed by Bilgi interface, GmbH. Images were treated solely by tolls provided by the programs described.

3. Results and discussions

3.1 Computed Radiography

Upon inspecting the Glare™ joint, three fames were recorded for each experiment according to the settings described at Table 1. Frames were identified by a number at the upper left corner of each image. Images were taken of the XZ plane (see Figure 1), with the rivet heads up.

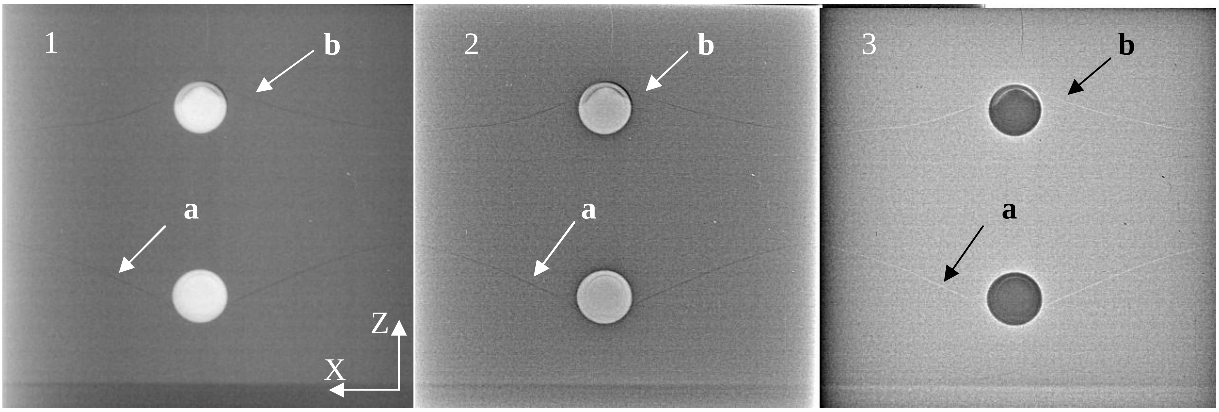

Figure 3- CR1 radiographies

Figure 3 shows the results for experiment CR1. Frame 1 represents the radiography as recorded, with little image manipulation, mainly in gray levels. A subtle change in contrast can be seen near and around the upper rivet head (**b**), which represents a discontinuity of the material in the rivet head itself. The crack, on the other hand, is barely visible. A Fourier Transform high pass filtering was performed at frame 2 to enhance details. Cracks (arrows **a** and **b**) have better contrast against the image, as well as the rivet head damage. In frame 3 a negative image was created in order to give a different view of the cracks.

The experiment CR2 has its frames shown at Figure 4. The same features described for CR1 can be seen. Nevertheless, as a penalty for lower resolution, a little granulation can be seen at the frames. Again, Frame 1 has the untreated image, at Frame two a Fourier transform was performed and Frame 3 has a negative image of the latter.

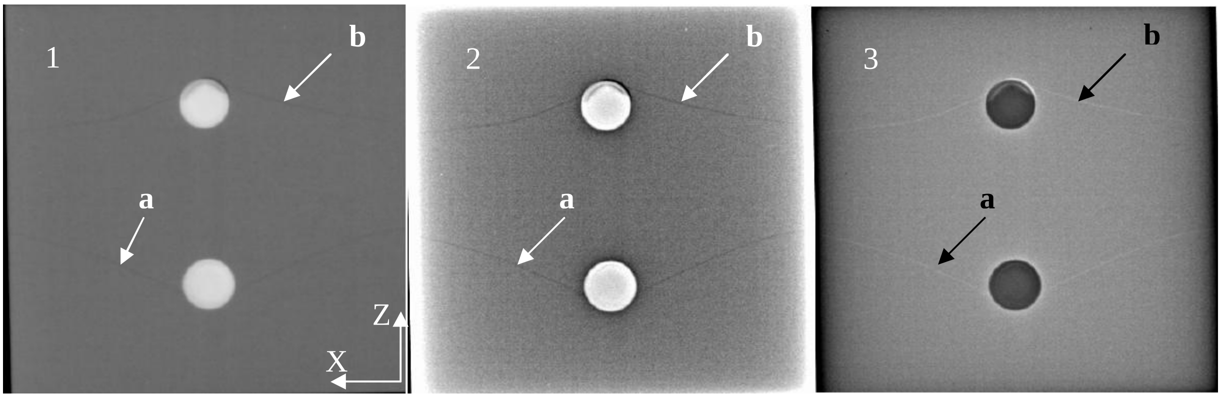

Figure 4 - CR2 radiographies

Comparing the two experiments above, it is clear that even using different CR systems with different basic spatial resolutions, it is still possible to detect these cracks with very good contrast. However, the cracking pattern cannot be solved in terms of which aluminum sheet contains each crack. This is caused by the loss of depth resolution if a 3 dimensional object is projected on the image plane as in standard radiographic inspection.

3.2 Computed Microtomography

Referring to Figure 1, the first tomographic inspection was carried along the Y axis, from the rivet tail to the countersunk head end. The next two figures are upside down with respect of those shown in the CR experiment (note axis orientation).

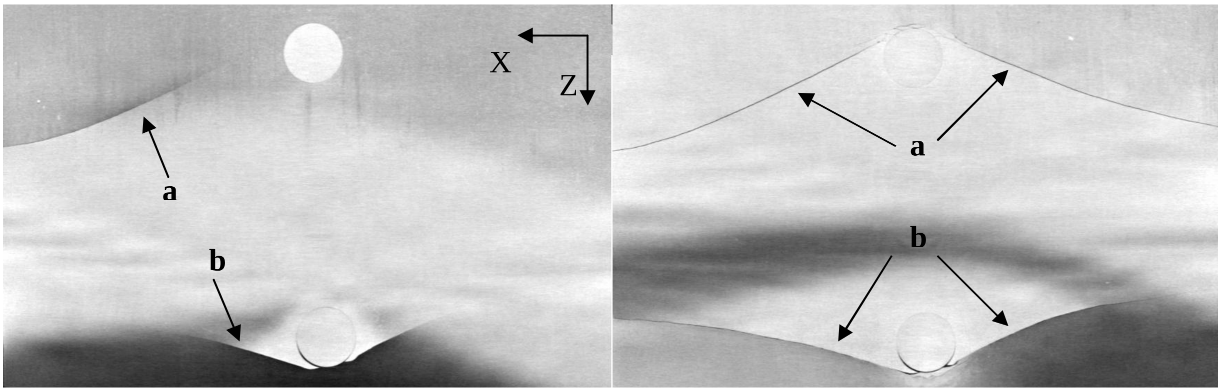

Figure 5 – First µCT sequence along Y axis (XZ plane cuts)

Figure 5 reveals the same cracks as shown by CR, but details are much more visible. It is important now to start trying to figure out in what aluminum sheet each crack has propagated. As the left hand side image of Figure 5 suggests, a slight misalignment of the Glare™ joint with respect of the table where it was placed may have occurred. The arrow **a** indicates an upper crack that is not completely visible, while the crack pointed by arrow **b** is well defined. This is sufficient for one to suspect that the cracks do not belong to the same plate. Moving on in the tomography, the right hand side image now shows the upper and lower cracks fully propagated. Also noticeable are differences in gray intensity before and after the crack limits. This effect can be caused by small displacements between the two portions of the cracked plate. It is also possible to see that the region above the upper rivet has suffered additional damage.

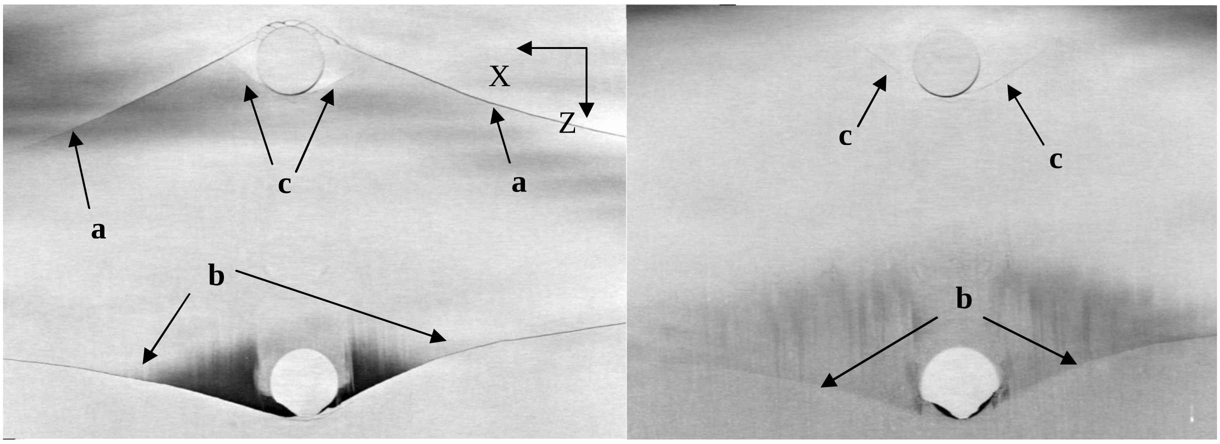

Figure 6 - Second µCT sequence along Y axis (XZ plane cuts)

The tomography has continued through Y axis, as seen by Figure 6. The left hand side image now reveals the cracks around the rivets, just like shown by CR, but an additional small crack around the upper rivet can be seen (arrow **c**), with an orientation that is reverse to that expected to happen in this kind of joint[3]. Also noticeable is a seriously damaged region above the upper rivet, created due to the fatigue process. The right hand side frame of Figure 6 shows the small crack and a slight difference in contrast at the lower end of the picture. Both figures clearly show the failed countersunk head of the lower rivet, which cannot be seen with this quality in the CR images.

It has become clear that the cracking mechanism of the Glare™ riveted join here analyzed is not trivial. There are multiple cracks propagating in reverse directions around the same rivet head, aluminum sheets misalignments and localized damages near a rivet head. It is not possible to determine in what plate a specific crack is just by inspecting the figures shown until now.

One of the most powerful tools of the µCT is that images are recorded of several planes throughout the entire specimen and along three axes. Figure 7 shows a sequence of images taken from XZ planes of the lap joint along the Y direction (refer to Figure 1). The arrows **a**, **b** and **c** refer to the same cracks discussed above. It becomes clear now that crack **a** belongs to the inner aluminum sheet of the flat bottom hole plate, while cracks **b** and **c** belong to the inner sheet of the countersunk plate.

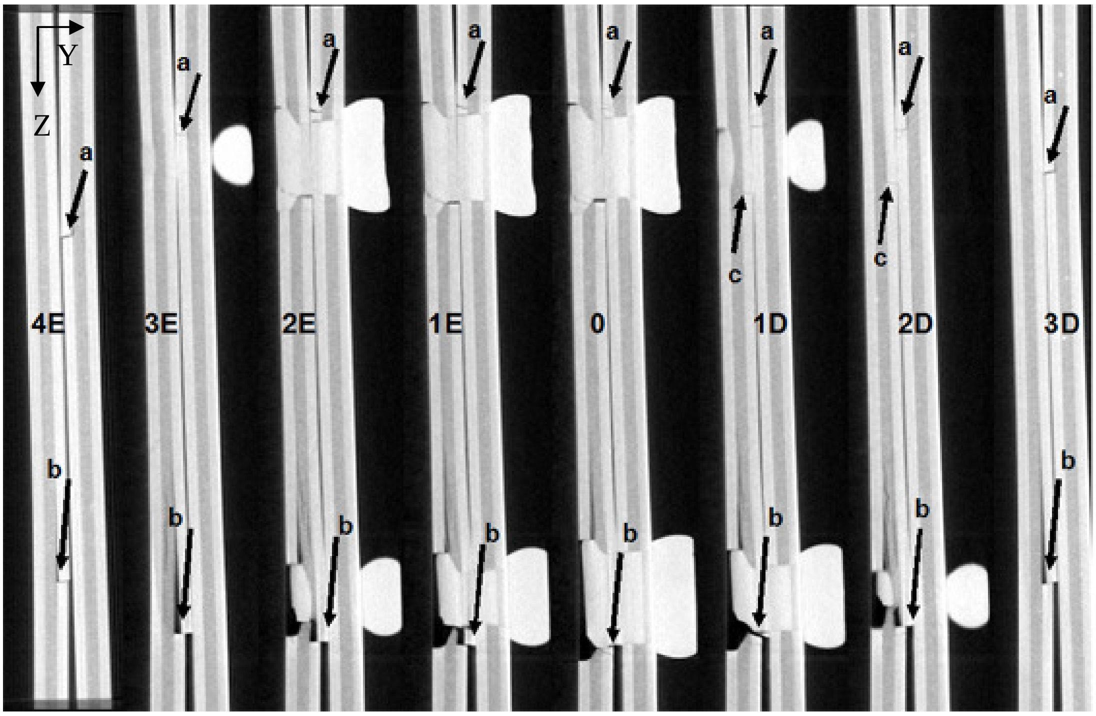

Figure 7 - µCT images of the riveted joint along the X axis (YZ plane cuts)

Also noticeable is the failure of the countersunk head of the rivet at the lower part of image below, with serious loss of mass. The other countersunk rivet head have also been cracked, but did not separate from the body.

The fatigue process caused the fiber glass bonding to fail. It is possible to see separation between the aluminum sheets and the core as well as failure throughout the fiber glass layers themselves. Separation occurs until considerable distances form the cracks are reached to the direction of the center of the riveted lap, suggesting great loss in mechanical performance of the plate.

The misalignment mentioned when analyzing Figure 6 is confirmed throughout Figure 7, especially where the countersunk rivet have failed and lost part of its head.

In order to have a better understanding of the damaged suffered by the joint near the upper rivet head, images of the XY plane (Z direction) are presented in Figure 8, showing only cuts of this area. The cracks **a** and **c** are marked and it can be noticed again that the latter belongs to the countersunk plate while the former is in the flat bottom plate.

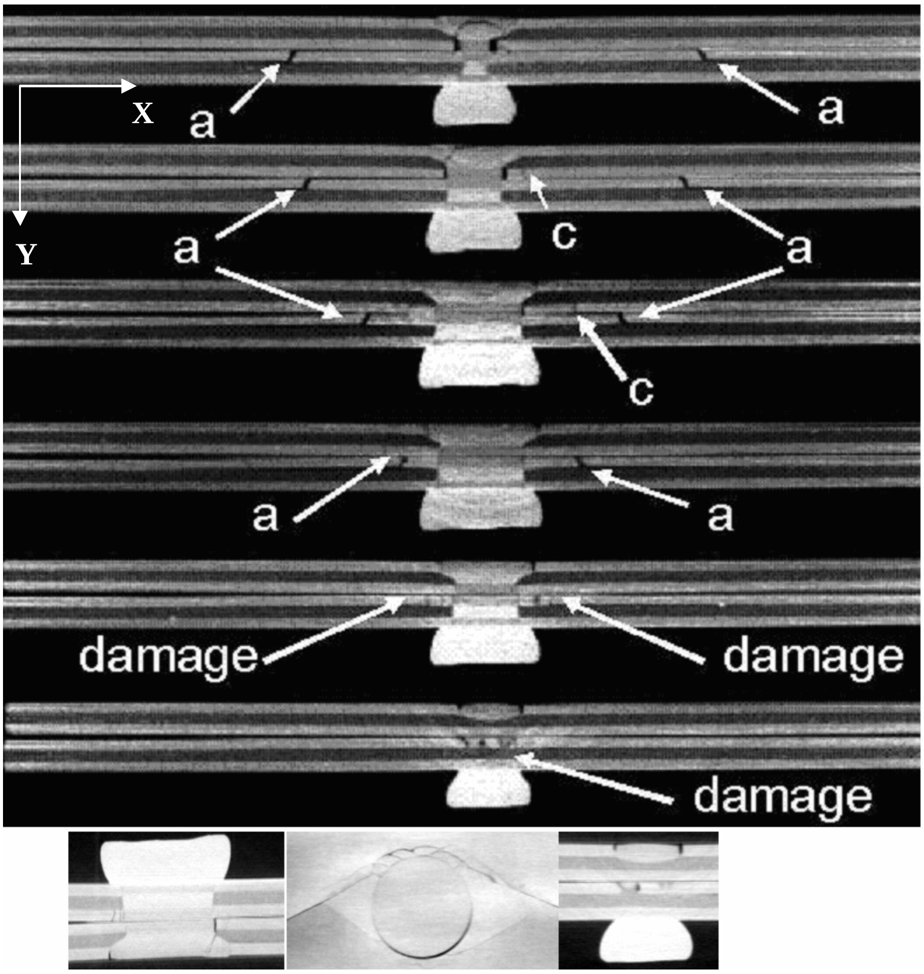

Figure 8 - µCT images of the riveted joint along the Z axis (XY plane cuts). Below is an insert showing three axes images of the region with serious damage around the rivet head

The damaged area is visible in Figure 8 and it is also possible to see that small cracks have occurred around the rivet head (insert), in the flat bottom aluminum sheet.

4. Conclusions

Results from the CR experiments using CR systems according to EN 14784 show that the technique is very well suited for preliminary inspections. Image quality, resolution and exposure time have shown little effect on crack detection.

By analyzing the CR and µCT images, some preliminary conclusions can be made:

a. By CR projection technique alone it is not possible to define in what plate each crack is;
b. CR did not show the small crack (arrow ***c*** at Figures 6 to 8);
c. Damage in the plate, above rivet head (e.g. Figure 6), was not visible in the CR images. The aluminum mass of the rivet head may have formed a barrier that caused the X-ray to be absorbed and, consequently, denying the damage to be shown;

d. CR shows that one of the rivet heads is broken and the other may have developed some cracking, although not clearly shown. This is confirmed by the µCT (e.g. Figure 7, 1E and 2E images);
e. µCT can show defects inside the fiber glass core, but CR cannot.
f. The µCT has a much better resolution, as it works layer by layer and information is not as much superimposed as in conventional CR; but there are limitations by the size of the samples due the requirement of rotation of 360°.
g. Details can be easily resolved even without the need of filtering. This has a great impact on work load and worker expertise reduction, software costs and time expended in image interpretation;
h. All aspects of a determined damage can be studied, allowing the technique to be used as an auxiliary or complementary method for fatigue and fracture mechanics studies, in terms of crack propagation and geometry.

By comparing the two techniques, it is clear that the use of CR for single projection radiography in nondestructive testing (NDT) of Glare™ joints leaves some doubts about the location of a specific crack, which could only be pointed by inspecting the µCT images.

It has become clear that µCT has enormous potential in the NDT field. The reliability levels achieved with such a technique are outstandingly high, maybe enough to justify its use by the aerospace industry in some applications in substitution for conventional radiography or even more complex maintenance interventions.

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