NONDESTRUCTIVE INSPECTION OF FATIGUED RIVETED LAP JOINTS OF HYBRID FIBER-METAL LAMINATE GLARE™

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Abstract. *X-ray radiography and eddy current methods were employed to detect and delineate fatigue cracks in riveted single shear lap joints of fiber-metal laminate Glare-5 devised to modern commercial airframe structures. Conventional film-based x-ray radiography produced higher quality images than computed-digital modality. Low-frequency eddy current technique relied strongly on the operator skills and previous calibration procedures to generate acceptable results.*

***Keywords**: Fatigue, fiber-metal laminate, nondestructive inspection, riveted lap joint.*

1. OBJECTIVE

This prospective work aimed at evaluating the ability of two nondestructive inspection techniques, namely X-ray radiography and eddy current, to detect and delineate internal fatigue cracks in riveted lap joints of hybrid fiber-metal laminate (FML) Glare™, a constructional material which has been employed in primary and secondary structures of modern civil aircrafts (e.g., B787, A350, A380).

2. INTRODUCTION

Aircrafts are the fastest, safest and most efficient way to transport passengers and pay-load. The development of lighter and stronger materials has significantly increased and improved such area of mobility industry by extending service lifespan and ensuring better performance of structures and components. This evolution is expected to be reflected directly on the operational cost reduction, particularly those related to fleet maintenance, more specifically related to periodical nondestructive inspection, failure analysis and prevention.

Glare is an interply hybrid fiber-metal laminate composite conceived at the University of Delft – The Netherlands, built up from thin aeronautical-grade aluminum alloy sheets interspersed with and bonded to layers of high-strength glass fibers reinforcing a thermoset epoxy resin [1,2]. This material has already caught the attention of the national scientific community [3].

Glare presents extremely high fatigue crack growth resistance combined with other very attractive properties to the aeronautical industry, such as low density, high impact, corrosion and flame resistance [4]. The superior endurance to fatigue crack propagation of Glare relies in the so-called crack bridging mechanism, by which glass-fibers, even partially fractured, debonded and pullout from the epoxy matrix, still withstand a considerable parcel of the applied load acting in the structural component, so that crack driving force is substantially reduced and cracks progress preferentially on the adjacent aluminum layers (Figure 1).

Thanks to its high specific properties (property/density ratio) an extraordinary potential of Glare in aeronautical industry has been forecast. Indeed, this material has been extensively employed in primary and secondary aircraft parts (e.g., fuselage of Airbus 380 in Figure 2, as well as this airplane's fin's leading edge), thus replacing traditional aeronautical-grade aluminum alloys, especially the 2024-T3.

Since riveting Glare sheets is unavoidable in such circumstances, a big challenge now is to ensure the structural integrity of the resulting lap joints so that in-flight safety of these new aircrafts can be warranted.

Previous fatigue results in riveted lap joints of Glare [5] have shown that the prevalent failure mechanism depends upon the applied stress level, ranging from rivet fracture by pure shearing, under relatively high stresses, to fretting developed at the faying surfaces of Glare sheets, under reduced stresses typically developed in commercial aircrafts during in-service conditions. Mixed-mode mechanisms were identified at intermediate cyclic stress levels. An essential fracture feature in riveted lap joints of Glare subjected to fatigue at low and intermediate stresses is that cracks nucleate and develop almost exclusively at faying surfaces of the hybrid plates, thus preventing their detection by purely visual inspection techniques [5]. More sophisticated nondestructive methods than visual need, therefore, be assessed and adapted to inspection programmes of this recently introduced class of engineered materials.

The main nondestructive methods routinely used in periodical inspections of aircrafts include, besides the visual one, dye penetrant, magnetic particles, X-ray, eddy current and ultrasonics [6,7]. Amongst them, the most suitable to the purposes of this research project are X-ray radiography and eddy current, basically due to the constructional specificities of the hybrid laminate Glare as well as to typical fatigue cracking patterns developed in riveted lap joints [8-13]. More specifically for mechanical joints of Glare, it has been found that fatigue cracking onsets almost invariably at the edge of rivet holes and propagates internally across the lap joint, perpendicularly to the axial loading direction [5].

This fracture process does not involve large delaminations in Glare, justifying the limited usefulness of ultrasonics in this task. By virtue of the insulation nature of epoxy resin in Glare, magnetic particles also finds restricted, if any, application as well. Dye penetrant would only be useful for cracks emerging to external surfaces of the joint, but, as emphasized earlier, this stage is likely only when the ultimate catastrophic failure of the component is approached.

(a) (b)

Figure 1. (a) Crack bridging concept, extensively explored in hybrid FML. (b) Crack bridging in a fatigue experiment with Glare at EESC-USP.

Figure 2. Airbus A380 aircraft: the upper Glare-made fuselage is in blue.

Computed radiography (CR) has been accepted as an advantageous technique over conventional film (CF) radiography by virtue of its following characteristics: wider dynamic range (more “forgiving” approach), higher sensitiveness to radiation, lower radiation dose required, shorter exposure times and a reduced safety area. Proclaimed environmental advantages of CR are that no darkroom or chemicals are needed. Furthermore, it has been emphasized that scanning an imaging plate can take one minute only, which means significant time savings, higher productivity, and the guarantee of a more effective workflow. The lightweight, somewhat inexpensive, and reusable nature of the imaging plates render CR as an attractive solution for fieldwork, low-volume manufacturing and high dose applications as well [14].

By its turn, eddy current has been widely employed as a powerful nondestructive inspection tool in aeronautical industry [15]. Amongst numerous applications of this technique in this field of activity, the following ones can be highlighted: surface and subsurface crack detection, borehole internal cracking indication, electrical conductivity measurement, thickness measurement of non-ferrous materials, non-conductive coatings and protective layers, and estimative of weight loss by corrosion mechanisms. Since it has been successfully employed in structural integrity assessment programmes, notably in riveted lap joints of conventional monolithic Al-alloys, the present study seems to be a good opportunity to put it at proof in detecting defects in mechanical joints of concurrent hybrid laminate Glare.

3. MATERIAL AND TEST SPECIMENS

Glare-5 2/1 plaques have been used in this study. A schematic of this high-impact resistant material is shown in Figure 3. It is formed by outer 0.5 mm-thick layers of 2024-T3 sandwiching four unidirectional fiber glass-epoxy composite tapes disposed according to 0°/90°/90°/0° architecture, resulting in 1.6 mm full-thickness laminates.

Two aeronautical-grade Al-alloy rivets were used to assemble each specimen, according to two different configurations, namely, with the fasteners aligned (i.e., vertically disposed) and non-aligned (i.e., horizontally arranged) to the axial loading direction, as seen in Figure 4a. Figure 4b specifies all the constructive elements of a Glare riveted single shear lap joint.

4. EXPERIMENTAL

Riveted Glare specimens were submitted to axial cyclic stresses under constant amplitude load (CAL) conditions in order to derive stress-life (S-N) curves. A multi-purpose servo-hydraulic MTS™ testing machine with maximum full-scale of 250 kN was utilized in this task.

Maximum applied gross (remote) stress during fatigue tests were selected according to previous monotonic tensile tests conducted with identical lap joints. Load ratio (R) was set in +0.1 and a sinusoidal wavelength signal was applied at a frequency of 10 Hz in order to prevent, respectively, bending moment and heating build-up in the riveted specimens tested at ambient temperature.

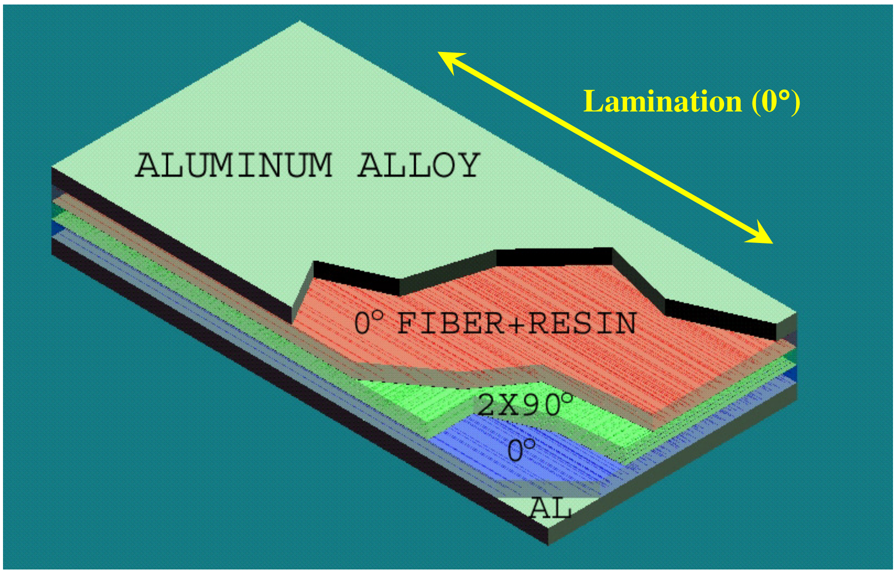
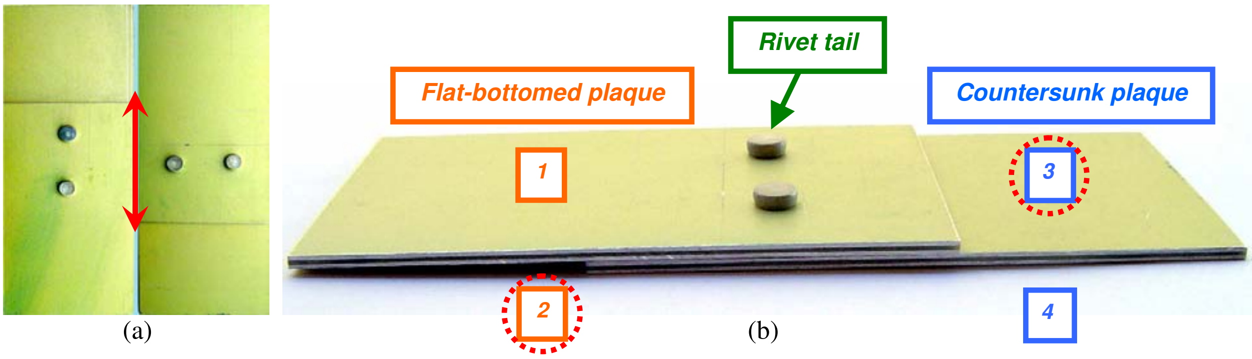


Figure 3. Glare-5 2/1 laminate exhibiting a centrally symmetrical array $2/(0/90)_S$.



(a) (b)

Figure 4. (a) Two specimen geometries tested in this study (the axial loading direction imposed during fatigue testing is indicated by a red arrow) (b) Test specimen with horizontal rivets and nomenclature utilized for the joint's elements.

Failure criteria adopted originally to stop the fatigue tests were either the complete specimen rupture or the application of 1 million fatigue cycles, which first occurred. However, several tests conducted under sufficiently low stresses were carried out until much higher number of applied cycles, since although internal cracking had already been created and spread, applied loads were not high enough to lead the specimen to full fracture.

Periodically, along the fatigue testing, riveted specimens were retired from the testing machine and submitted to nondestructive characterization via X-ray radiography techniques (conventional or film-based CF, and digital on computerized mode CR by using imaging plates - IP) and low-frequency eddy current, aiming at detecting crack-type discontinuities created during previous applied mechanical loading.

The entire nondestructive surveying process, including radioactive sources and equipment selection, process variables, normative procedures and reference patterns, along with image managing, editing and interpretation, was completely under control of companies and universities owning the X-ray equipments. That is to say, each participant of the round-robin programme accomplished its task in a completely independent way, with no interference from the moderator (JRT).

Basically, such strategy intended to avoid breaking up any commercial or industrial proprietary protocols, as well as to prevent any influences and pressures that could end up in any kind of tendencies, bias, impairments, and prejudices on behalf and/or against any project participant. Since the experimental programme is still running, utilized equipments and followed procedures will be omitted at this stage of the project.

5. RESULTS AND DISCUSSION

Figure 5 presents S-N curve results obtained for the two types of riveted joint specimens previously illustrated in Figure 4. By comparing the S-N curves, one can conclude that vertical riveted joints are more fatigue resistant than horizontal ones [5]. Shortly, higher stress concentration and bending moment in horizontal (non-aligned) testpieces were responsible for this behavior.

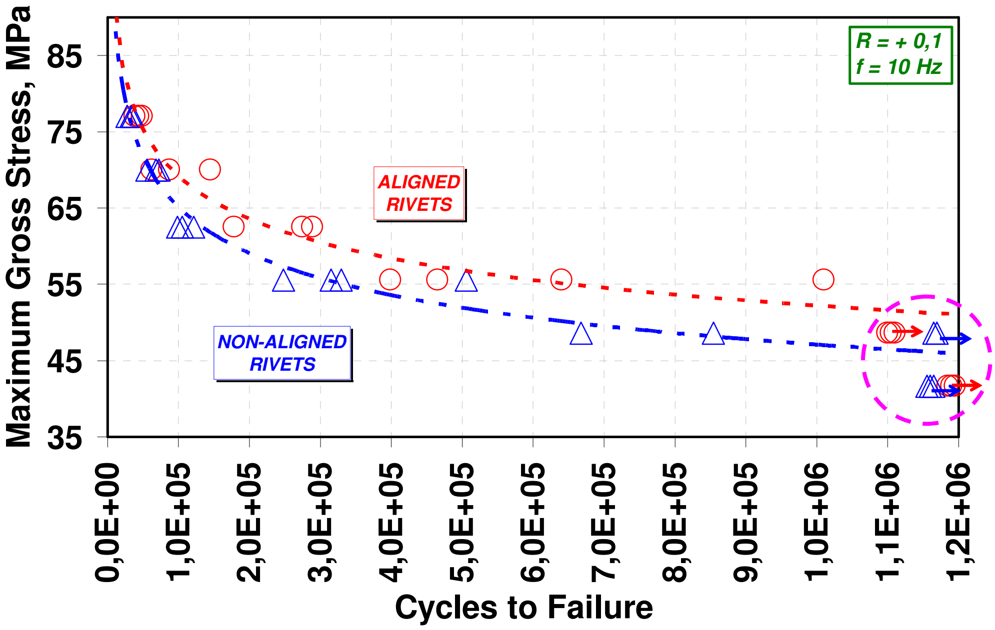


Figure 5. S-N curves of Glare joints with rivets assembled vertically (red) and horizontally (blue).

Table 1 provides some data referring to the four riveted specimens evaluated in this study. It lists the peak load of the constant amplitude loading (CAL) cycle, the corresponding maximum attained stress and the total number of applied cycles. These test specimens correspond to some of the data points plotted in Figure 5, which are indicated by the magenta circle.

Table 1. Test conditions of four riveted lap joints submitted to CAL fatigue testing and periodically inspected by X-ray radiography and eddy current techniques.

Riveted Test-Piece (RTP) identification	Peak load (kN)	Peak stress (MPa)	Total number of applied cycles (N)
19 (non-aligned rivets)	3.0	42	2.297.900
29 (aligned rivets)	3.0	42	7.724.352

111 (non-aligned)	3.5	49	1.169.000
211 (aligned)	3.5	49	1.929.990

Figure 6 exhibits conventional film (CF) X-ray images of the testpieces listed in Table 1. They correspond to, respectively, positive and negative (reverse) imaging modes. The internal cracking patterns developed in both joint geometries are clearly delineated, allowing their complete and unambiguous visualization.

In the vertical rivets array (Figs. 6b-b’,d-d’), a pair of cracks emanates from each rivet hole, but the employed X-ray technique does not permit identifying in which of the faying surfaces (2 and/or 3, according to the sketch in Fig. 4b) these couples of cracks nucleate and propagate.

Post-mortem failure analysis of similar specimens [4,5] showed, however, that the crack pairs develop at opposing Glare sheets [16].

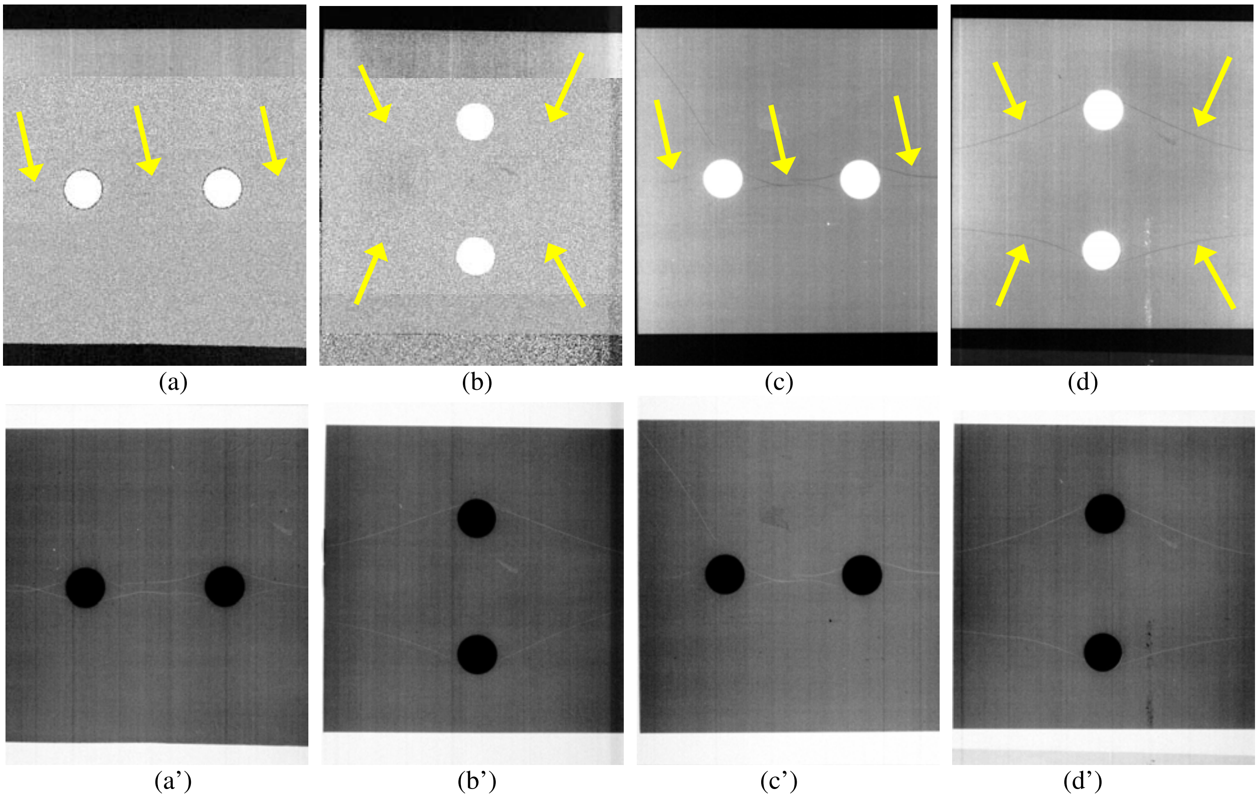


Figure 6. Positive and negative modes of conventional film X-ray images of four riveted specimens listed in Table 1: (a,a’) RTP 19; (b,b’) RTP 29; (c,c’) RTP 111; (d,d’) RTP 211. Detected cracks are arrowed in yellow.

Figures 7 and 8 present digital radiographies, via indirect method, obtained by two participants of this project for specimens RTP 111 and 211 (previously showed in Figures 6c-c’ and 6d-d’, respectively). Images were obtained by sensitizing storage phosphor-based imaging plates (IP) and reading out them in scanners: (i) one originally destined to odontological application and adapted for industrial use (Figure 7), and (ii) another specifically designed for industrial environment (Figure 8). Four distinct image modalities are supplied for each fatigued test specimen, which are described on the figure’s caption. While the industrial equipment is partially successful in unveiling internal cracks (Figure 8), if compared to images provided by film-based radiography in Figure 6, the adapted commercial equipment completely failed in performing such task (Figure 7).

It is worth of mention that images supplied in Figures 6 and 7 were obtained with incident X-ray beam orthogonal (90°) to the main plane of the specimen, whereas in those images provided in Figure 8 a 45° tilted radiation beam was applied. According to the equipment operator, this procedure enabled signal intensification, so that cracks not detected by means of the conventional 90° procedure could now be indicated. This finding has been empirically determined, and it may be related to the typical slant (45°) fracture surface (mixed mode I/III) developed in thin Al-alloy sheets subject to tensile loads [17]. Despite the better imaging results obtained by adopting an angular X-ray beam, it is possible to verify in Figure 8, however, a range of artificially created effects which are characteristic of image intensification procedures, and may have been heightened due to the tilted X-ray incident angle to the joint plane, as utilized by the operator aimed at “enlarging” the cracks to the passage of the ionizing radiation beam. To some extent, the uneven distribution of cracks along the joint thickness, as well as the joint-to-imaging plate distance, can contribute additionally to the observed nuances. Since imaging plates (IP) utilized in this study has a maximum resolution of 50 microns, against 12 microns of class I and II conventional films, one can blame this difference as the main responsible for the outstanding images discrepancies between filmless and traditional radiography methodologies.

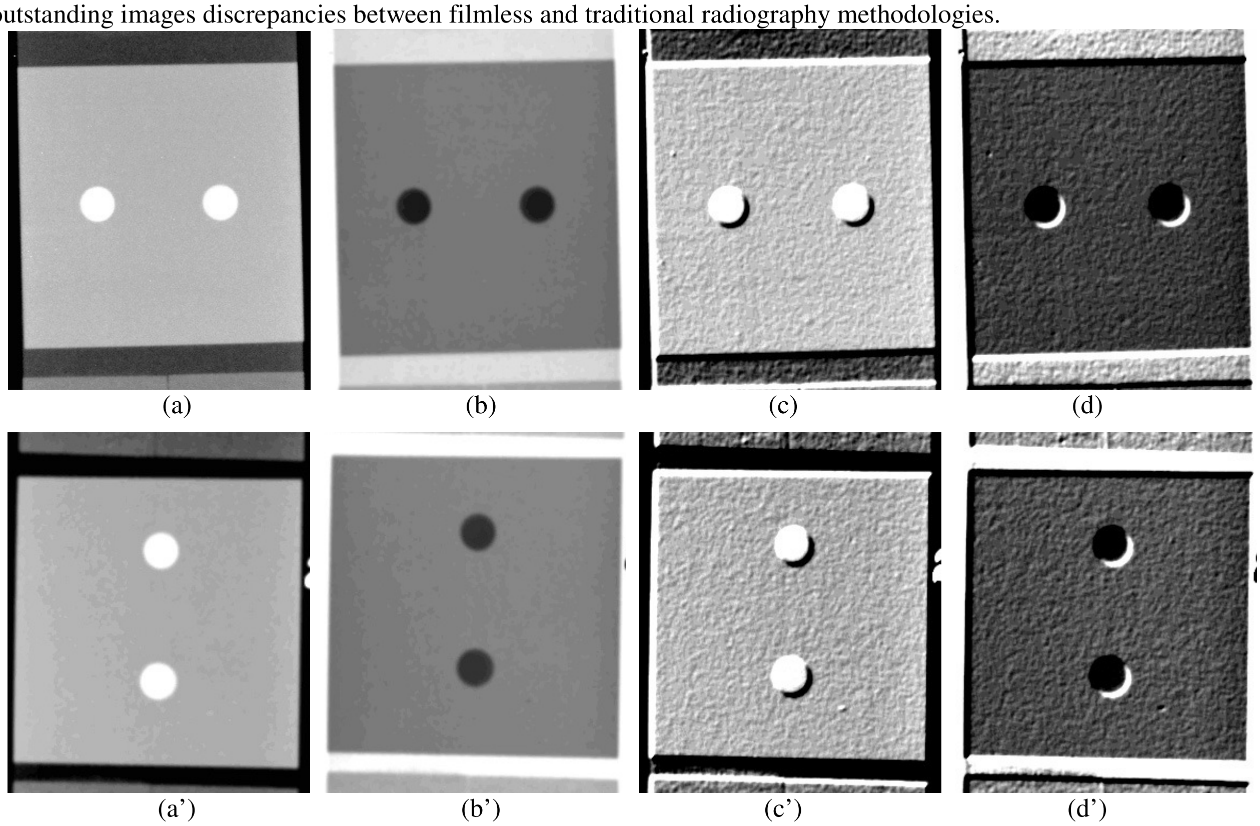


Figure 7. IP-digital radiography images (equipment originally destined to odontological application) of RTPs 111 (non-aligned rivets) and 211 (aligned rivets): (a) Standard image; (b) Corresponding reverse tone; (c) Embossed image; (d) Corresponding reversed tone.

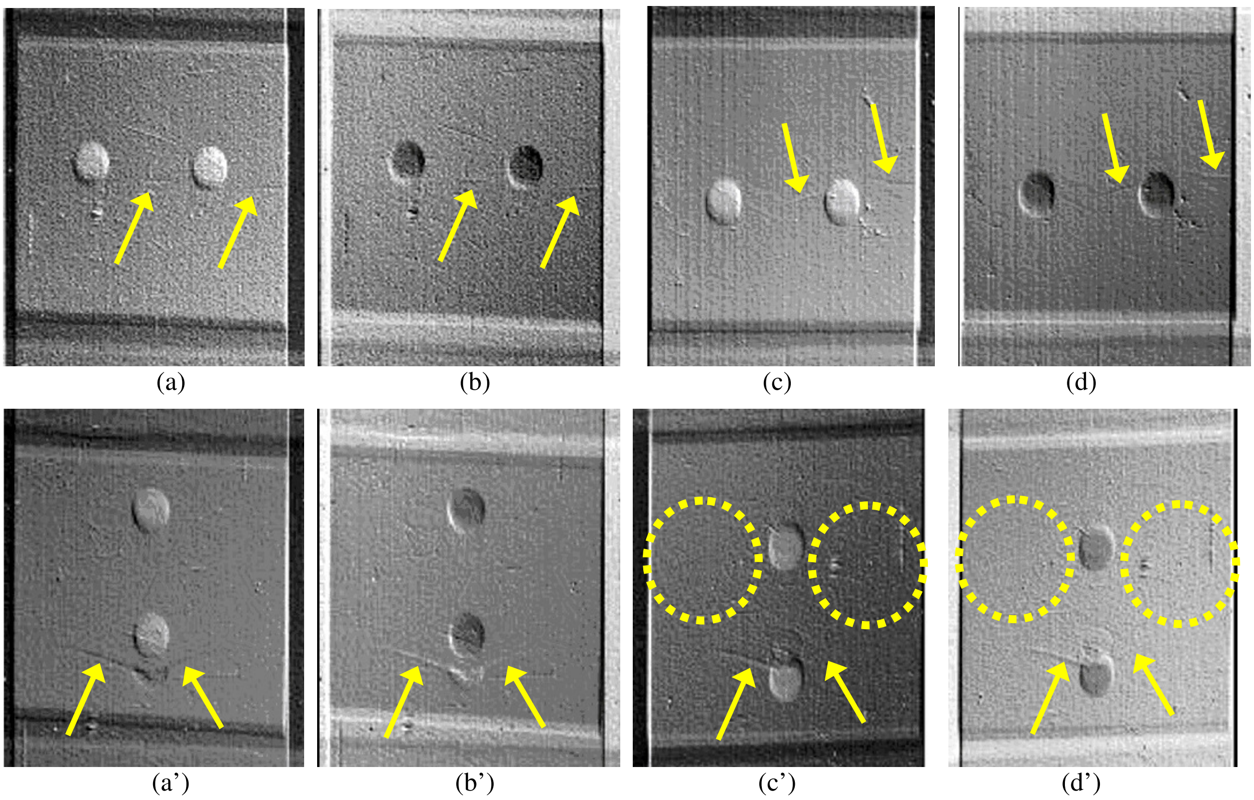


Figure 8. IP-digital radiography images (industrial equipment) of RTPs 111 (non-aligned rivets) and 211 (aligned rivets): (a) Emboss Filter; (b) Corresponding reverse tone (a&b refer to a 45° incident X-ray beam); (c) Emboss Filter;

(d) Corresponding reverse tone (c&d refer to a 45° X-ray beam). Areas delimitated by dotted yellow circles still demand a more comprehensive analysis in order to certify that cracks have been indicated by radiography.

Regarding eddy current testing, it is worth to mention that it relied strongly and equally on the equipment accuracy and the operator's skill as well. Unlike modern fully automated equipments and probes yielding real time outputs, the outdated device utilized in this study demanded manual scanning of the test-specimens as well as visual and somewhat subjective interpretation of signals displayed on the equipment screen.

Eddy current technique performance was evaluated in two conditions, with and without previous calibration by using riveted Glare specimen halves containing only visible cracks.

Figure 9 presents some results without previous calibration. By comparing them to the radiographies provided in Figure 6, one can conclude that all internal cracks in the horizontal joints are indicated. However, for vertical joints most cracks were missed.

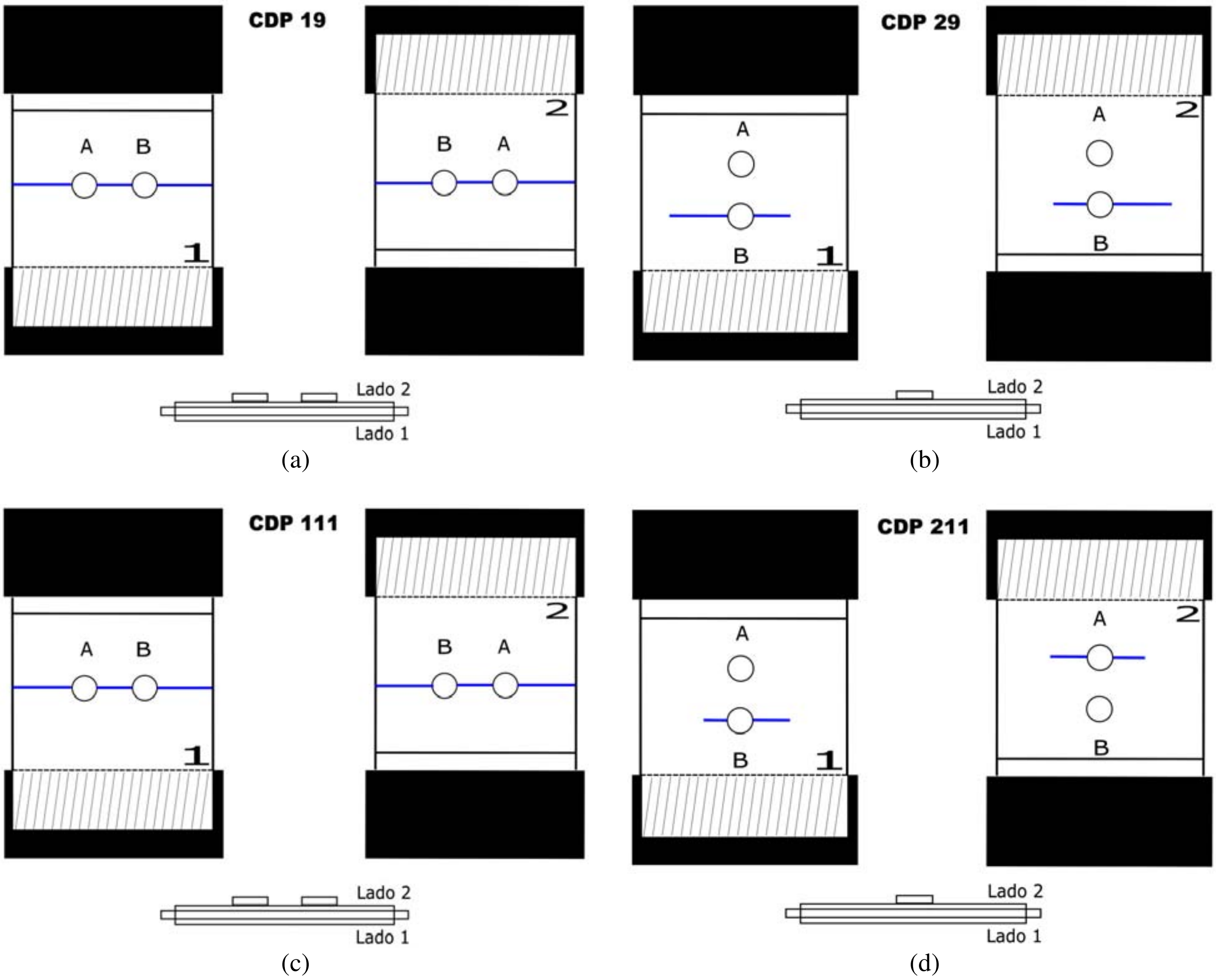


Figure 9. Schematic results of eddy current testing, with no prior calibration, considering both the front (1) and backside (2) of riveted test specimens: (a) RTP 19; (b) RTP 29; (c) RTP 111; (d) RTP 211.

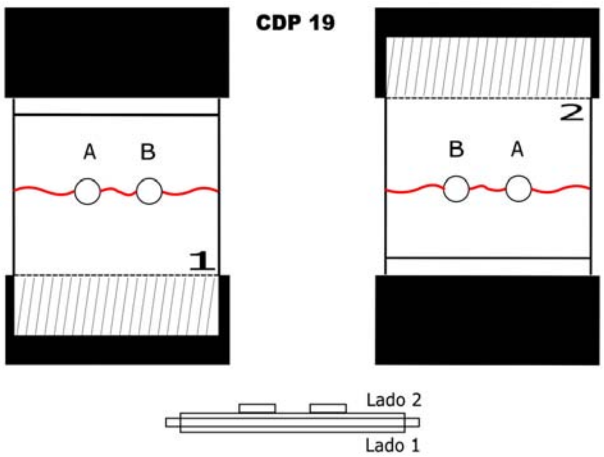
Figure 10 shows eddy current results after calibration. When confronted to Figure 9, it is possible to infer that previous equipment calibration is vital to achieve acceptable cracking estimations. However, true cracking pattern and fatigue crack distribution at the faying surfaces (metallic layers 2 and 3, respectively) will only be reliably warranted after complete disassembling of the testpiece, when in-loco visual inspection is possible.

It should be mentioned that low-frequency eddy current technique enabled to locate the exact position of fatigue cracks developed internally to the lap joints. In other words, this nondestructive method made possible to determine if cracks nucleate and propagate at the faying surfaces of the straight-shank and/or the countersunk plaques of Glare (metallic layers 3 and 2, respectively, according to the reference established in Figure 4). Recall that this information is virtually impossible to be obtained via radiography, unless its tomography modality is employed. This constitutes a significant advantage of eddy current technique over conventional radiography, as long as the former technique can lead to considerable time and material consumption savings during maintenance and repair of riveted Glare joints when only one of the Glare sheets has been damaged.

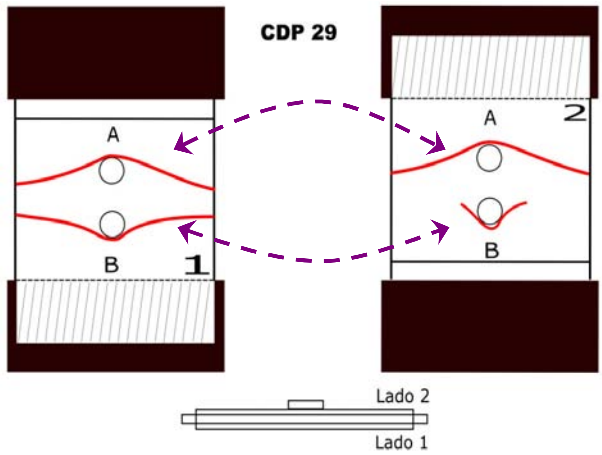
In spite of this eddy current's advantage, the technique is not able, however, to measure crack length and crack path precisely, when compared to radiography. Since the former technique relies in a magnetic probe scanning the specimen surface, its accuracy in regard to those basic crack features (length and trajectory) is inversely proportional to the probe diameter (6 mm in this study), as long as the crack-type discontinuity is immediately identified once the probe area/perimeter overlaps it. This also implies that eddy current cannot distinguish two very close propagating cracks located at the same faying surface and separated by a distance not exceeding the probe diameter. It seems to be the cases (a) and (c) in Figures 9 and 10, respectively, which correspond to horizontal rivets array, as it can be inferred from corresponding radiographies in Figure 6.

In Figures 10(b,d), however, there appears to exist a perfect compatibility between cracks detected during eddy current testing and those observed in the radiography images supplied in Figure 6. Nonetheless, it is not still possible to certify that identical cracking patterns (which are unlikely according to previous failure analysis accomplished in fully fractured riveted Glare joints [18]) occurred in both faying surfaces of vertical joints, as Figures 10(b,d) suggest (see cracks pointed out by dashed purple arrows) and are not proved false by corresponding radiographies in Figure 6. Therefore, in order to establish accurately the real cracking patterns developed in the test specimens analyzed, it is mandatory to disassemble them and conduct a detailed visual inspection.

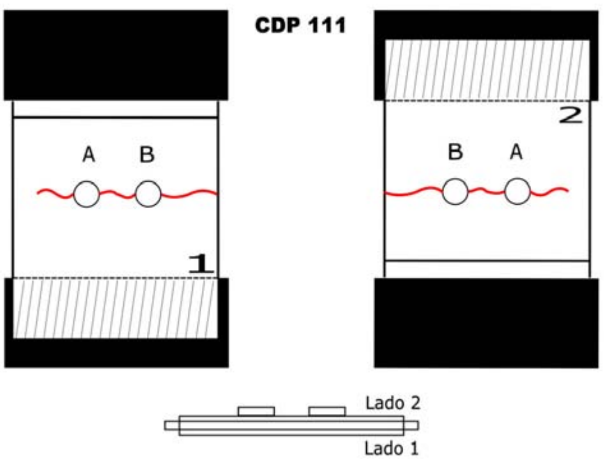
A big challenge now for the nondestructive methods presently assessed would be identifying incipient cracks, transiting from nucleation to propagation stages, therefore only fractions of millimeter long and very shorter than those shown here. Currently, some tests focusing on this issue are underway, whether in homogeneous riveted joints of Glare as well as in mixed rivet joints of Glare and Al 2024-T3 alloy.



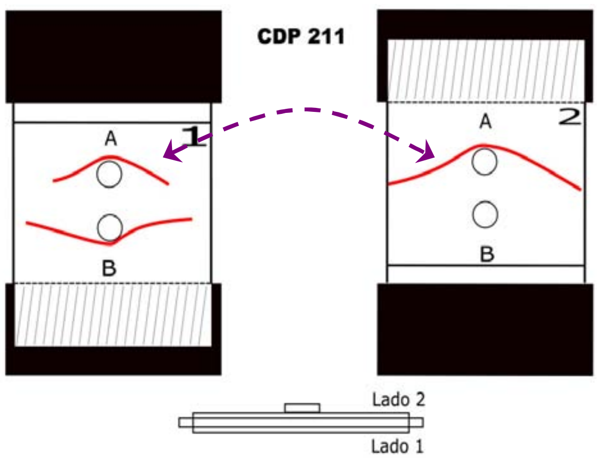
(a)



(b)



(c)



(d)

Figure 10. Post-calibration eddy current testing results considering both front (1) and backside (2) of riveted test specimens: (a) RTP 19; (b) RTP 29; (c) RTP 111; (d) RTP 211.

6. MAIN CONCLUSIONS

Experimental results obtained from this prospective round-robin study permitted to conclude that:

1. Vertical riveted joints of Glare are more fatigue resistant than horizontal ones by virtue of higher bending and net stresses (i.e., stress concentration) developed in the latter riveted array;
2. Conventional or analogical x-ray radiography produces pretty higher resolution images than digital (filmless) modality;
3. Industrial equipment of digital radiography is potentially applicable to inspect riveted Glare joints, while adapted commercial systems are probably not suitable for this task;
4. Eddy current might be satisfactory to ensure structural integrity of riveted single shear lap joints of Glare as long as prior and proper equipment calibration is conducted;
5. Eddy current can identify the faying surfaces of Glare sheets in which cracks initiate and grow;
6. Eddy current's drawbacks in regard to radiography are not measuring precisely crack length and its trajectory, and not distinguishing relatively close cracks in a given metal layer of the hybrid laminate.

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8. RESPONSIBILITY NOTICE

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