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National Aerospace Laboratory NLR

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In-service inspection of Glare fuselage structures

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Abstract

This paper describes a first investigation into the suitability of current non-destructive inspection (NDI) methods for the in-service inspection of Glare fuselage structures. The NDI methods comprise the eddy current technique for the detection of sub-surface cracks at fastener rows, and the Fokker Bondtester (resonance-impedance method) and ultrasonic technique for the local detection of delaminations or debonding.
It is shown that the NDI methods described are suitable for the detection of significant defects. The detection of sub-surface cracks greatly depends on the depth of interest: for example at a depth of 3 mm, cracks larger than 4 mm are readily detectable, but at a depth larger than 6 mm cracks are no longer reliably detectable. Both the Fokker Bondtester and ultrasonic inspection can detect delaminations or debonding to a degree of accuracy: the Fokker Bondtester is preferred for relatively thin structures (up to 5 mm) and ultrasonic inspection is preferred for thicker structures. The detectable delamination size is in the order of the probe diameter.
The results primarily represent measurements with Glare specimens with artificial defects. In addition, specimens with real defects were inspected. First results of an ongoing investigation indicate that the results described in this paper are representative for those specimens.

Introduction

Glare (GLAss-fibre REinforced aluminium laminate) is a hybrid material consisting of thin aluminium sheets bonded together by glass-fibre reinforced adhesive layers (Fig. 1). It is a member of the family of Fibre Metal Laminates (FML) and was developed at the Delft University of Technology. The material is an attractive option for application in aircraft fuselage structures due to its relatively low density, high corrosion and fire resistance, and its excellent fatigue, impact and damage tolerance characteristics (Ref. 1).

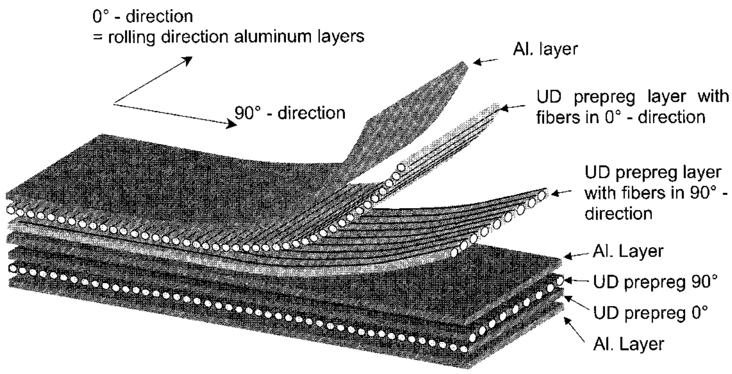


Fig. 1 Schematic of a Glare laminate with 3/2 lay-up: three aluminium layers and two intermediate prepreg layers with glass fibres in the 0º- and 90º direction

During the in-service use of Glare structures, defects can be caused by ground handling and maintenance, and by severe operating conditions and environmental factors such as fatigue, impact, corrosion, moisture ingress, overheating and lightning strike. These factors can result in defects such as surface damage (dents, cracks and discoloration), fatigue cracks in the aluminium sheets, and delaminations or debonding in the adhesive bond lines. The defects will occur at impact locations or start at structural details such as stiffener radii, thickness steps, splices and rivet locations.

Glare fuselage structures do not require an extensive NDI programme for in-service inspection due to their excellent fatigue, impact and damage tolerance characteristics. The following guidelines can be given:

- Visual inspection as the principal method during C/D-checks: zonal surveillance or detailed visual inspection of specific or critical areas such as lap joints and cutouts (doors, windows).
- More advanced NDI methods during D-checks for local inspection purposes: primary methods will be eddy current sliding probe inspection or MOI (Magneto-Optic/Eddy Current Imager) inspection of lap joints and butt joints.
- In case of suspected damage (e.g. FOD, lightning strike) and for repair purposes: detailed visual inspection, eddy current inspection for sub-surface cracks, Fokker Bondtester and/or ultrasonic inspection for delaminations or debonding.

Primary NDI items will be the detection of sub-surface cracks at fastener rows, and the local detection of delaminations or debonding. Global inspection of large surface areas for delamination or debonding is not foreseen.

This paper will describe an investigation into the suitability of the eddy current technique for the inspection of fastener rows, and the Fokker Bondtester and ultrasonic technique for the local detection of delaminations or debonding. In the investigation use is made of Glare test specimens with artificial and real defects.
The investigation was performed within the framework of the GTO (Glare Technology Development), a research programme supported by the Dutch Ministry of Economic Affairs through the Netherlands Agency for Aerospace Programmes NIVR. This research programme aims at the technology readiness of Glare and is controlled by the Fibre Metal Laminates Centre of Competence (FMLC) in Delft; contributing partners are the Delft University of Technology, Fokker Aerostructures and the NLR.

Glare test specimens

Most experiments were performed with two Glare 4B-0.4 specimens with artificial defects: a test panel with flat-bottomed holes and a lap joint specimen with electric discharge machined (EDM) notches. The denotation 4B-0.4 implies a lay-up with layers of aluminium alloy 2024-T3 of a thickness 0.4 mm per layer, and glass fibre layers consisting of three unidirectional prepreg layers with a thickness of 0.125 mm per layer (the middle prepreg layer with the glass fibres oriented in the aluminium rolling direction, the two outer prepreg layers with the glass fibres oriented in the transverse rolling direction). The Glare 4B type represents a typical material for fuselage structures (Glare types with two and four glass fibre layers also exist).

The *test panel with flat-bottomed holes* is a Glare 4B-32/31-0.4 laminate, hence comprising 32 aluminium layers and 31 glass fibre layers of a total thickness of about 25 mm, see figure 2. The material configuration 32/31 represents the thickest sections in fuselage structures (door and window surrounding structure). 31 Flat-bottomed holes of diameter 50 mm had been machined to different depths into the specimen, each hole being one single aluminium layer deeper than the last.

Fig.2 The Fokker Bondtester Model 90 and the Glare 4B-32/31-0.4 test panel with flat-bottomed holes

The *lap joint specimen with EDM notches* consists of two Glare 4B-5/4-0.4 sheets riveted together. The rivets are aluminium rivets of type 2017A, placed in holes of diameter 5.7 mm. The rivet hole pitch is 28 mm.
42 EDM notches of different sizes had been machined in individual aluminium layers of the specimen, see figure 3. The notches represent fatigue cracks initiated in the rivet holes. The notch size ranges from a minimum of 2 mm to 4, 6, 8, 11 mm up to a maximum of a rivet hole-to-hole notch of about 22.5 mm. The notch width is about 0.2 mm. Most notches are single-sided relative to the rivet hole; in a number of layers also 4/4, 6/6 and 8/8 double-sided notches relative to the rivet hole had been machined.
All notches had been machined along the rivet centreline. This is representative for practical applications where the riveting force during manufacturing is average. Another situation can occur when the riveting force is relatively high. In that case, as for conventional aluminium alloy structures, the fatigue cracks no longer initiate in the rivet hole itself, but outside the hole. Then the cracks first grow in tangential direction around the hole and radial to the next rivet hole only later in the fatigue life. This has a beneficial effect on both the fatigue and residual strength behaviour of the joint (Ref. 2). However, a high riveting force is not usual because of difficulties with implementation and implications for the certification. Further, analytical calculations are conservatively based on radial cracks.

Besides the two specimens with artificial defects a range of other Glare specimens with real defects were used in the investigation.

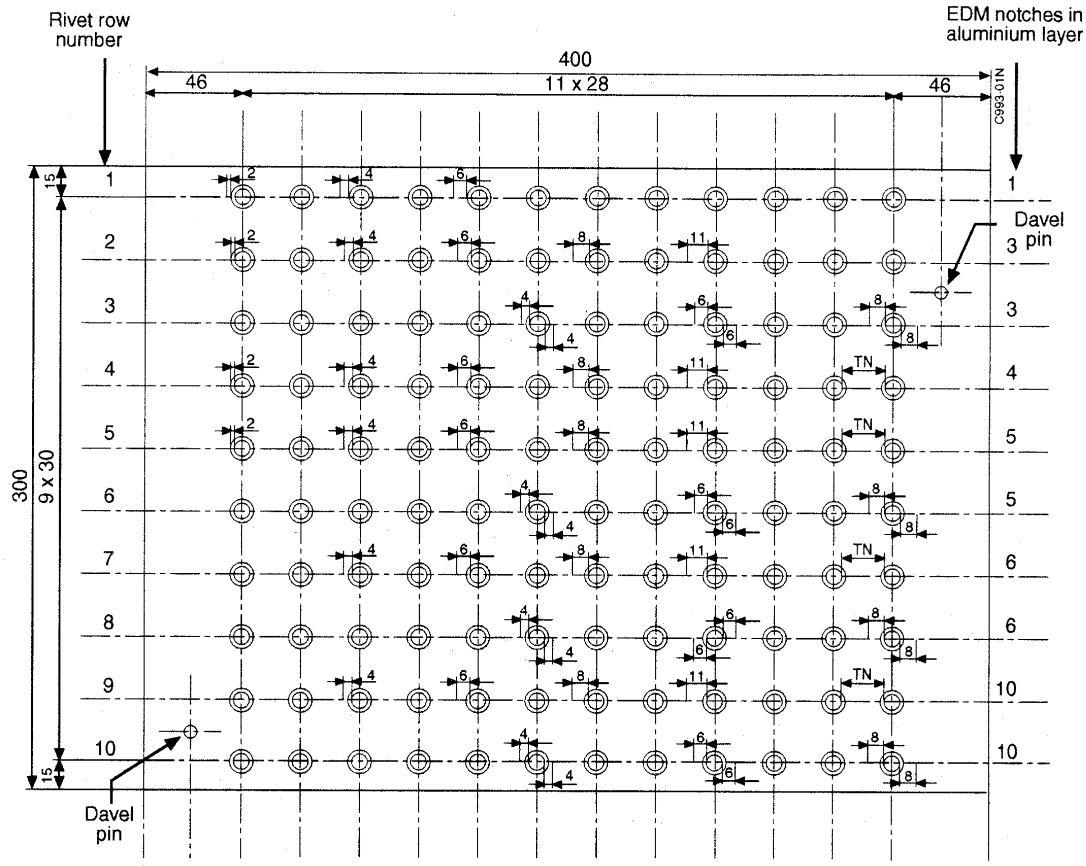


Fig. 3 Schematic diagram of the Glare 4B-5/4-0.4 lap joint specimen with EDM notches

Inspection for sub-surface cracks at fastener rows

During the in-service use of Glare fuselage structures, fatigue cracks can initiate and grow in the aluminium sheets, predominantly at the fastener rows of the joints (lap joints, butt joints). Because the maximum stress occurs in the faying aluminium layers due to secondary bending, the cracks will initiate first at the mating surface (layer 1), see figure 4. Cracks will initiate in the next aluminium layer (layer 2) only considerably later in the fatigue life due to the lower stress level (Ref. 2). For the detection of these sub-surface cracks the low-frequency eddy current technique is the most appropriate NDI technique.

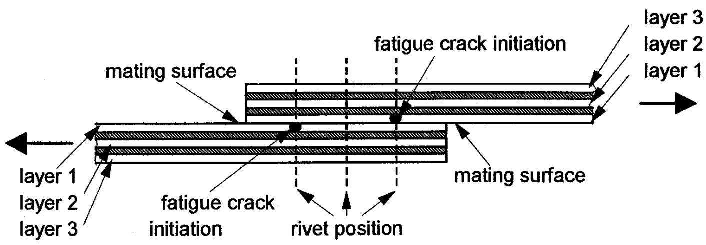


Fig. 4 Cross-section of a Glare 3/2 riveted lap joint with the first crack initiation locations (Fig. 4.6 from Ref. 2)

Reference 3 describes an investigation into the suitability of the eddy current technique for the detection of surface or sub-surface cracks at fastener rows. For this purpose, both the test panel with flat-bottomed holes and the lap joint specimen with notches were used.
The eddy current measurements were carried out with a Nortec-19e^{II} dual-frequency instrument, frequency range 100 Hz to 6 MHz, and a range of eddy current probes (sliding probes and surface probes).

The *test panel with flat-bottomed holes* was used to determine the penetration depth, as function of the test frequency, in Glare 4B-0.4 laminate for a variety of sliding and surface probes. The penetration depth was determined by observing the eddy current response of a material discontinuity at varying depth; the penetration depth was herewith defined as the material depth for which the response of the discontinuity has a signal-to-noise ratio equal to or larger than two. For the material discontinuity two methods were evaluated: the FBH method (response of the edge of a flat-bottomed hole at varying depth) and the EDM method (response of an EDM through-notch in a single sheet of aluminium alloy 2024-T3 inserted in a flat-bottomed hole at varying depth).
The results showed that the sliding probes have in general larger penetration depths than the surface probes. The maximum value obtained for the penetration depth was 18-19 aluminium layers (14-15 mm) for a sliding probe (Nortec SPO-2181) at a frequency of 200-500 Hz, using the FBH method. For practical use, however, the EDM method is of more relevance. With this method the maximum performance obtained was 12-13 aluminium layers (9-10 mm) for sliding probe Nortec SPO-2181 at a frequency of 500-900 Hz and 10 aluminium layers (about 7.5 mm) for surface probe Nortec SR/100Hz-20kHz/.62 at a frequency of 500-700 Hz.
An example of the inspection results is given in figure 5, with the optimum performance of the surface probes (Nortec SR/100Hz-20kHz/.62 probe). It is emphasised that such figures only indicate the maximum penetration depth attainable, although they can be useful for selecting a suitable test frequency for a typical inspection configuration in practice.

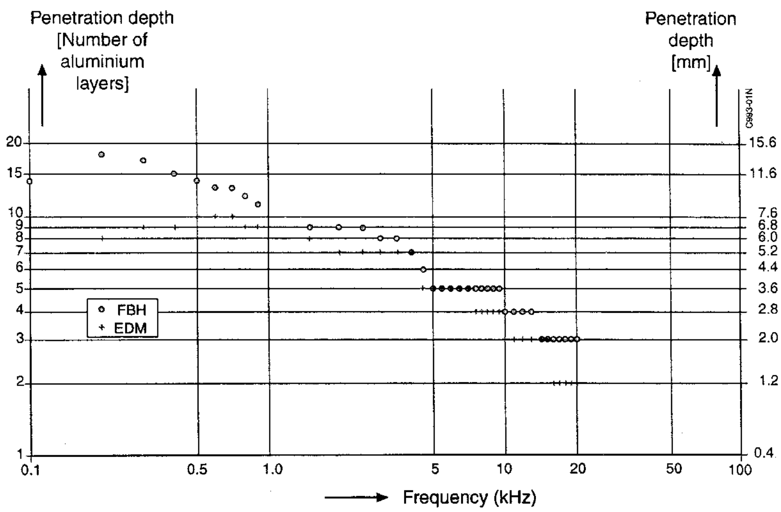
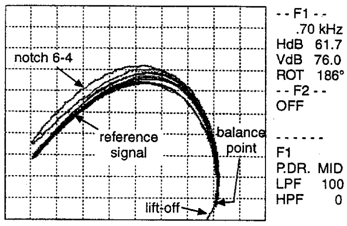
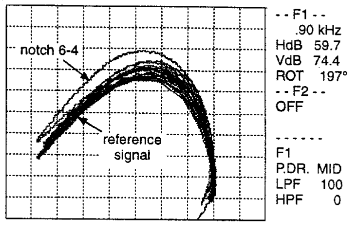


Fig. 5 Eddy current penetration depth in Glare 4B-0.4 laminate as function of the test frequency. Optimum performance of the surface probes

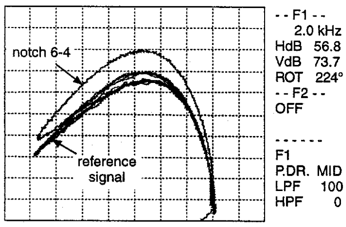
Based on the results of the penetration depth estimation, a selection of two sliding and three surface probes was made for the inspection of the *lap joint specimen with EDM* *notches*. The selected sliding probes were employed for all notches by sliding them over all rivet locations; the surface probes were only employed for the rivet hole-to-hole notches in the specimen by scanning them between the rivets concerned. All probes were evaluated for their complete frequency range.



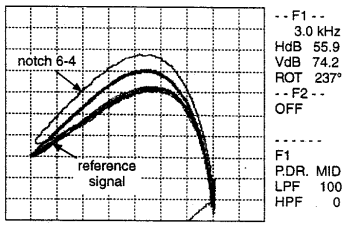
a Frequency 0.7 kHz
Notch 6-4 not detectable (-)



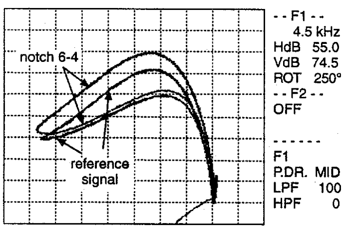
b Frequency 0.9 kHz
Defect indication (~)



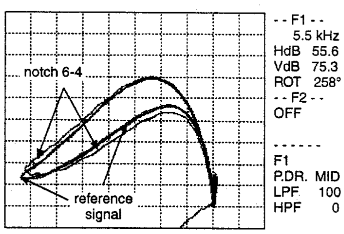
c Frequency 2.0 kHz
Notch 6-4 detectable (+)



d Frequency 3.0 kHz
Defect indication (~)



e Frequency 4.5 kHz
Defect indication (~)



f Frequency 5.5 kHz
Notch 6-4 not detectable (-)

Fig. 6 Determination of the optimum eddy current test frequency (about 2 kHz) for the sliding probe inspection of notch 6-4 (length 4 mm, at a depth of 6 Al layers) in the Glare 4B-0.4 lap joint specimen

The sliding probe response of notch-free rivet locations provides a reference signal against which the responses of the rivet locations with notches were compared. A scatter band can be observed in this reference signal due to the variability in the eddy current response for different rivet locations. A notch was considered detectable when the response of that rivet location exhibits a significant deviation (set at 1 screen division) when compared with the reference signal. This procedure is illustrated in figure 6 which gives an example of the determination of the optimum test frequency (in this case about 2 kHz) for the sliding probe (Nortec SPO-2181) inspection of notch 6-4 (notch with length 4 mm at a depth of 6 Al layers) in the Glare lap joint specimen.
For the surface probes, defect detection was judged by observing the signal-to-noise ratio (S/N) of the eddy current responses on the impedance plane of the instrument. For reliable defect detection an S/N ratio equal to or larger than 3 was maintained.

The inspection results showed that the eddy current technique could detect EDM notches in Glare 4B-0.4 material to a certain degree.
Sliding probes can be employed for the fast inspection of fastener rows for surface and sub-surface cracks starting from the rivet holes, by scanning them over the rivet centreline. It has been shown that surface notches with a length ≥ 2 mm are detectable (optimum frequency in the range of 30 – 35 kHz). The detection of sub-surface notches greatly depends on the depth of interest:

- At a depth of 3 to 4 mm (Al layer no. 5), single-sided notches with a length ≥ 2 mm and double-sided notches with a length ≥ 4/4 mm (optimum frequency in the range of 2.5 – 4.5 kHz).
- At a depth of 5 to 6 mm (Al layer no. 8), single-sided notches with a length ≥ 6 mm and double-sided notches with a length ≥ 8/8 mm (optimum frequency about 1 kHz).
- Notches at a depth ≥ 6 mm (Al layer no. ≥ 9) are no longer reliably detectable.

Surface probes can be employed for the detection of surface and sub-surface cracks, for general laminate structures or for lap joints by scanning the probes between the rivets concerned. It has been shown that sub-surface rivet hole-to-hole notches at a depth up to 5 mm (Al layer no. 7) are detectable (optimum frequency in the range of 1 – 3 kHz). Notches at a depth ≥ 5 mm (Al layer no. ≥ 8) are not reliably detectable anymore.

Local inspection for delaminations or debonding

Delaminations or debonding can occur during the in-service use of Glare fuselage structures. They can initiate for example at impact locations and at the run-outs of doublers and bonded stringers (often starting at crack locations). Global inspection of the complete fuselage structure is not foreseen, but local inspection for delaminations or debonding could be necessary (e.g. after visual indication of suspect areas, or for repair purposes).
Reference 4 describes an investigation into the suitability of the Fokker Bondtester (resonance-impedance method) and the ultrasonic technique for the local detection of delaminations or debonding. For this purpose, both the test panel with flat-bottomed holes and specimens with real delaminations were used.

Fokker Bondtester inspection

The resonance-impedance measurements were carried out with the Fokker Bondtester, model 90, see figure 2. This instrument displays both the resonance frequency shift (A-scale) and the impedance amplitude (B-scale), in graphical and numerical way. Eight different Bondtester crystals were used, with diameter varying between 0.25 and 1.5 inch (6 – 38 mm). Calibration of inspection was generally performed with the crystal in air (A-value 0, B-value 100).

The test panel with flat-bottomed holes, representing delaminations or debonding, was used for an evaluation of the different Bondtester crystals. For each crystal the A- and B-values for each hole were measured and drawn versus each other in a graph. Independent measurements were carried out to check the reproducibility of inspection. Typical graphs are given in figure 7 and 8 for the smallest crystal (1414, diameter 0.25 inch) and a large crystal (5410, diameter 1.25 inch), respectively.

The results showed that there is a good reproducibility of inspection, for both the Bondtester A- and B-values. Combination of the A- and B- values enables the determination of the depth of delaminations or debonding but this capability is dependent on the probe type. It was shown that crystal 1414 (0.25 inch diameter) is the best small crystal and can measure accurately up to the first 7 layers (about 6 mm), and that crystal 5410 (1.25 inch diameter) is the best large crystal and can differentiate between at least 32 layers (about 25 mm), but with an accuracy of 2 to 3 aluminium layers. The detectable flaw size is in the order of the crystal diameter.

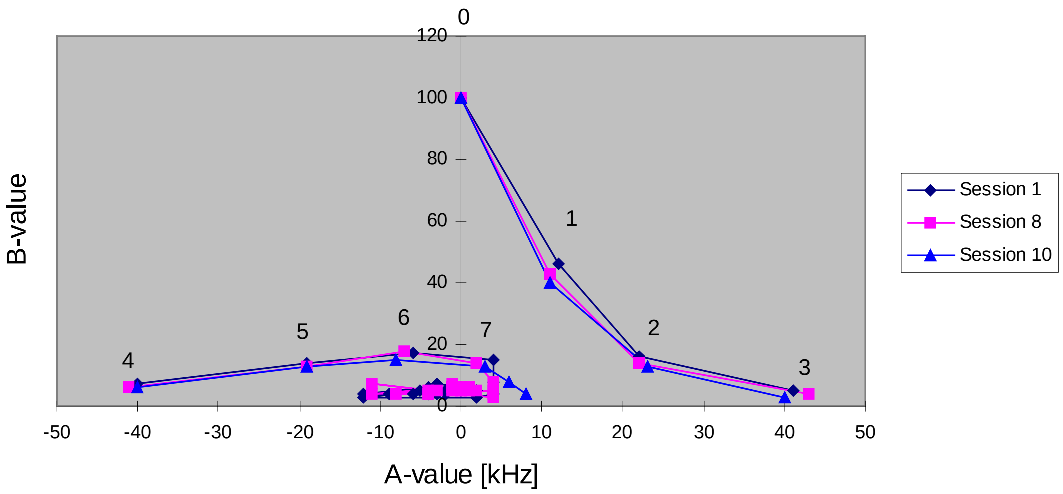


Fig. 7 Fokker Bondtester A/B values for the flat-bottomed holes in the Glare 4B-32/31-0.4 panel. Three independent measurements with crystal 1414 (diameter 0.25 inch). The numericals indicate the depth in aluminium layers

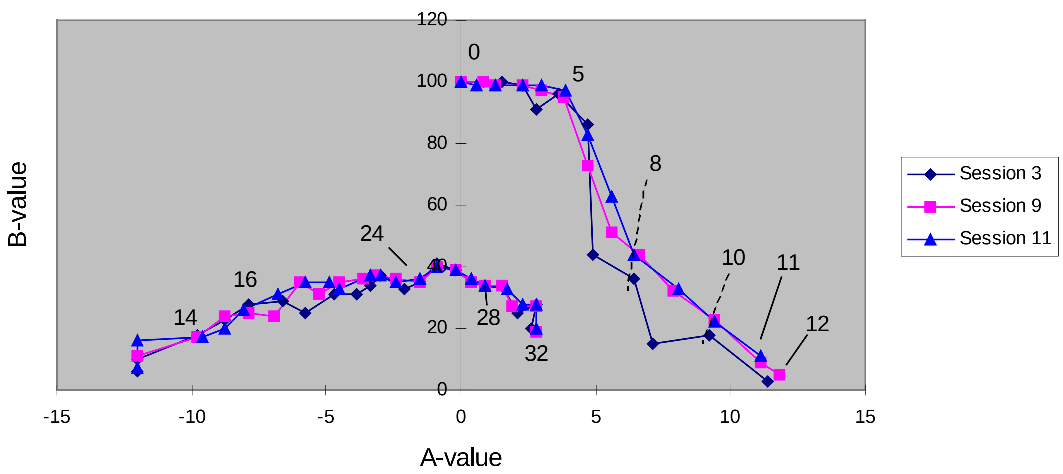


Fig. 8 Fokker Bondtester A/B values for the flat-bottomed holes in the Glare 4B-32/31-0.4 panel. Three independent measurements with crystal 5410 (diameter 1.25 inch). The numericals indicate the depth in aluminium layers

Ultrasonic inspection

Ultrasonic inspection was performed with the Staveley Sonic-138 flaw scope operating in the pulse-echo method. A range of ultrasonic transducers was used for standard thickness measurements, with test frequencies varying between 1 and 25 MHz. To improve the near-surface resolution for flaws located near the material front surface a delay-line was used for some transducers. Calibration of inspection was performed on Glare laminates of known thickness.

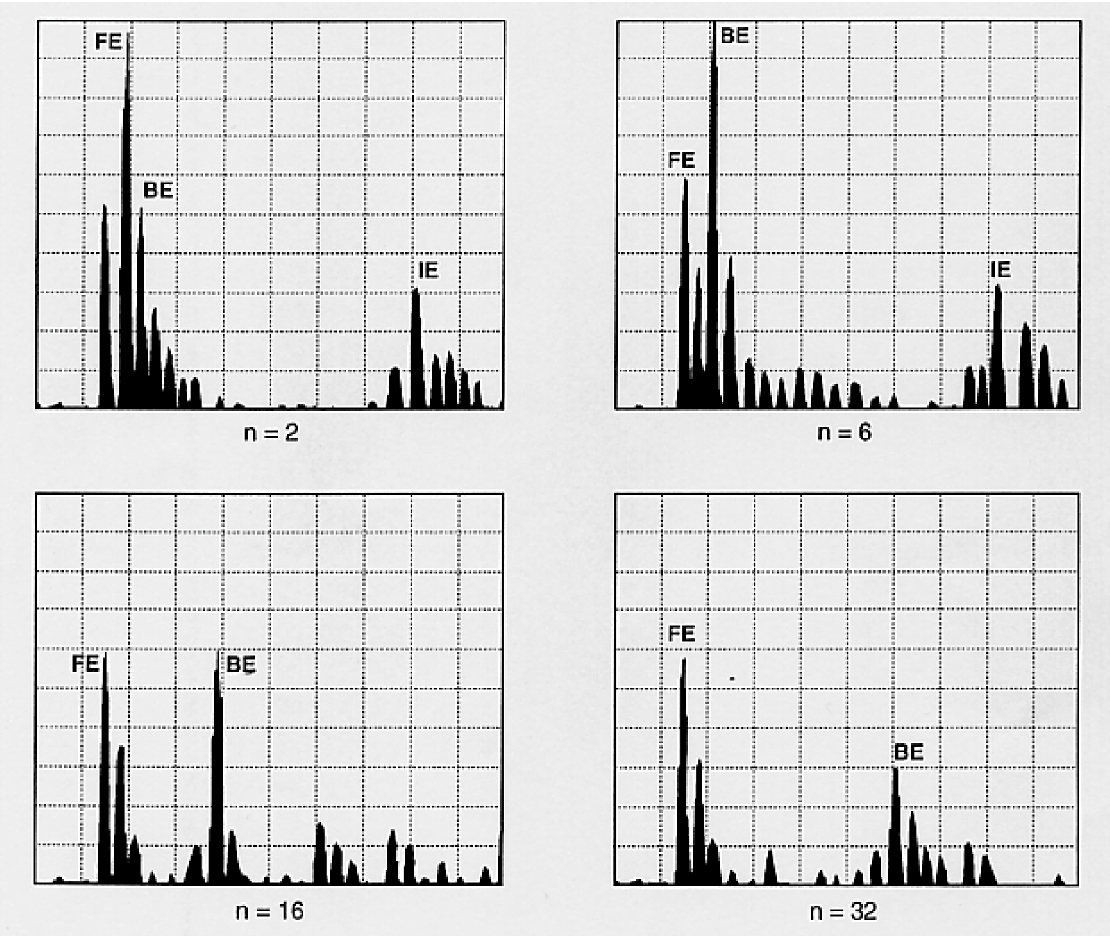


Fig. 9 Ultrasonic pulse-echo responses for a Glare 4B-0.4 test panel with n layers (FE: front echo of the test panel, BE: back echo of the test panel, IE: internal echo in the transducer/delay line)

The test panel with flat-bottomed holes (Fig. 2) was used for an evaluation of the different ultrasonic transducers. The results showed that most transducers proved not useful because of complicated interference patterns of the ultrasonic signal (due to the layered structure) yielding no distinctive “backwall echo”. Only one transducer, a Harisonic HGR-6207-1 (frequency 1 MHz, diameter 1 inch) with delay-line (diameter 1 inch, length 1 inch) yielded useful signals without this disturbing interference, see figure 9. For Glare material with more than 3 aluminium layers the transducer even shows an excellent performance by accurately determining the depth of the flat-bottomed holes up to 32 aluminium layers (with an accuracy of 1 layer), see figure 10. The detectable flaw size is in the order of the transducer diameter.

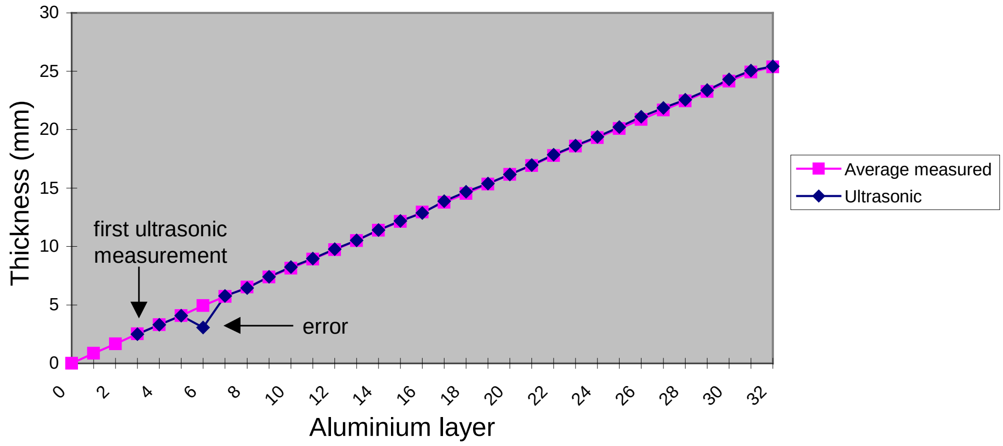


Fig. 10 Ultrasonic depth measurements for the flat-bottomed holes in the Glare 4B-32/31-0.4 panel. Comparison with actual values (average measured)

Concluding remarks

It has been shown that the NDI methods described are suitable for the detection of significant defects in Glare material. The detection of sub-surface cracks greatly depends on the depth of interest: for example at a depth of 3 mm, cracks larger than 4 mm are well detectable, but at a depth larger than 6 mm cracks are no longer reliably detectable. Both the Fokker Bondtester and ultrasonic inspection can detect delaminations or debonding to a degree of accuracy: the Fokker Bondtester is preferred for relatively thin structures (up to 5 mm) and ultrasonic inspection is preferred for thicker structures. The detectable flaw size is in the order of the crystal diameter.

The results described represent measurements with Glare 4B-0.4 specimens with artificial defects. In addition, specimens of other Glare grade and specimens with real defects (fatigue cracks, delaminations) were inspected. First results of an ongoing investigation indicate that the results described in this paper are representative for those specimens.
For specimens with fatigue cracks at fastener rows the main parameter seems the riveting force: as long as this force is average the cracks initiate radial in the holes and then the EDM notches are representative. On the other hand, when the riveting force is relatively high the cracks initiate outside the holes, grow tangentially around the holes and are then less detectable with eddy current equipment. However, in a later phase of the fatigue life the cracks grow radial to the next hole and become readily detectable again.
For specimens with real delaminations, first results show that a delamination can be represented well by a flat-bottomed hole. Different Glare grade specimens will result in slightly different A/B values for the Fokker Bondtester but will exhibit comparable defect detection capability. Comparable results are expected for ultrasonic inspection.

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