Inspection of Carbon Fibre – Titanium – Carbon Fibre Stepped-Lap Joint

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Abstract

The optimal combined use of composites and metallic material is essential for the performance of modern tactical aircrafts. At the same time, the resulting structures include complex metal-to-composite joints that may develop failures during use. The inspection of such structures is often highly demanding.

The present paper discusses the complex inspection of stepped-lap joint between carbon fibre wing panel and titanium attachment of tactical aircraft. The joint has been found to be susceptible to disbonding both in the outer and inner titanium to carbon fibre interfaces. Due to the multi-material multi-layer structure, the inspection is particularly demanding, especially for the inner interface.

It is shown, that successful inspection can be developed by careful analysis of the ultrasonic signal. In particular, by taking advantage of the following phenomena:

1. Phase shift happens in the ultrasound signal when sound goes from lower acoustic impedance material to higher acoustic material (i.e. from carbon fibre to titanium).
2. Disbond on first interface will damp the response from the second interface and back wall.
3. Disbond on one bond line will increase the response amplitude from that bond line.

Consequently, sound waves encountering the joint on the outer interface will result in phase change at the interface, that can be detected on the RF signal. A disbond prohibits this phase change and thus can be detected by noting the absence of this phase change. Defects bigger than 4 mm can be detected using this method

Disbond on the outer surface will also prohibit sound from traveling to the inner surface. Therefore, the disbond on outer surface can also be detected by noting a decreased amplitude in the inner-interface echo. The disbond on the inner surface will, likewise, prohibit sound from going through the interface and thus increase reflection from that interface. Hence, the disbond on the inner surface can be detected by noting an increase in the amplitude of the inner-interface echo. Thus disbonds on both inner and outer surfaces can be detected by monitoring possible decrease or increase in the inner surface echo indicating disbond in the outer or inner surface, respectively. To separate these effects from numerous other echoes resulting from various effects in the multilayer structure, a representative reference sample is required. Such sample can be prepared using flat bottom holes drilled from the back surface into each step on step-lap-joint.
1. Introduction

Complex metal-to-composite joints are common in modern tactical aircrafts and may develop failures during extended use. Especially, the multi material joints may be develop disbonding during in-service loads. These may, if unchecked, lead to failure of the structure. Consequently, the joints are periodically inspected to confirm safe operation of the aircrafts. Due to the complex geometry and multiple materials, the inspection of these joints is often highly demanding.

The present paper concerns the complex inspection of stepped-lap joint between carbon fibre (CF) wing panel and titanium (Ti) attachment of tactical aircraft. The joint has been found to be susceptible to disbonding both in the outer and inner titanium to carbon fibre interfaces. Due to the multi-material multi-layer structure, the inspection is particularly demanding, especially for the inner interface. The lap joint location is shown in Figure 1. The inner surface is inaccessible during inspection and thus both the inner and outer side steps needs to be inspected with single sided access from the outer side.

![Figure 1. The geometry and the location of the stepped-lap joint of a tactical aircraft. Titanium and carbon fibre structures are joined with stepped-lap joint with 6 steps to form strong joint. (Adapted from [2]).](image)

Mueller et al. [2] report recent disbond in stepped-lap joint, that had developed into delamination fatigue crack. The disbond was found in ultrasonic inspection using C-scan
images from “Mobile Automated Ultrasonic Scanner” (MAUS) system. 10 MHz transducers were used to inspect the thin composite steps near the titanium root and 5 MHz transducers to reach the joint through thicker carbon fibre layer near the tip of the joint. The system is automated inspection set-up developed for the wing skin inspection and is widely used for detecting disbonds in such stepped-lap joints. However, the system has limited capability to detect inner side disbonds in joints.

In addition to ultrasonic scanning, various other methods have been used to inspect composites and the composite-metal joint structures in wing structures ranging from electric methods [3] to thermography and vibration methods [4]. Delaminations carbon fiber and impact damage are readily detected by many of these methods. However, for the composite-metal joint structures, ultrasonic scanning is typically used.

2. Materials and methods

Phased array ultrasonic inspection was performed on stepped-lap joint shown in Figure 2. Inspection was carried out with Olympus Omniscan MX phased array system using 32 and 64 element, 5 MHz normal probe (Olympus 5L64-NW1). Two calibration samples were used. Calibration sample A (Figure 3) was produced by glue-bonding AS4 carbon fibre plates and Al-7075 aluminium plates with 2 mm steps using FM300-2 glue. The aluminium plate contained 4, 6 and 12 mm diameter through holes that simulate disbonds. Aluminium was used instead of titanium due to easier production. Both have significantly different acoustic impedance compared to air and carbon fibre and thus will provide essentially similar ultrasonic response for present purposes. Calibration sample B was manufactured with representative stepped lap joint including outer and inner side joints. Artificial defects were manufactured from the inner surface to depths representing both inner and outer side disbonds for outer side scanning, Figure 4. Phased array inspection set-up was created to detect both inner side and outer side disbonds with one (outer) sided access.

Figure 2. Schematic structure of the stepped-lap joint in question. (Adapted from [2].)
Figure 3. Calibration sample A with stepped wedge aluminium plate glued to carbon fibre. The aluminium plate has 4, 6 and 12 mm diameter holes to simulate disbonds of the outer side joint.

Figure 4. Calibration sample B with stepped wedge aluminium plate bonded to carbon fibre. The sample has machined areas simulating both outer side and inner side disbonds (for one sided access).

3. Phased array ultrasonic inspection of stepped-lap joint with single sided access

In the present paper, a method is developed to inspect the stepped-lap joint using phased array ultrasonic inspection. In particular, the method can detect disbonds on the outer side and on the inner side. Due to the single-sided access, complex material geometry and multi material construction, the inspection is exceedingly challenging. Consequently, reliable detection requires the combined use of several ultrasonic effects in concert. In addition, the inspection signal is riddled with high attenuation, multiple echoes and resonance-effects, which make the signal interpretation difficult and necessitates calibration sample with all possible flaw locations represented.

The inspection is performed in two different parts, outer and inner side disbonding, in order to improve the detectability of flaws in the structure. The outer side is easier to
access and its inspection significantly easier to perform. Thus, it is addressed first. To inspect for inner side disbonds, the sound must travel through outer side joint to reach the inner surface and back to the probe. Therefore, successful outer side inspection and intact outer side joint are required to inspect the inner side.

### 3.1 Outer side disbond

Ultrasonic signal from outer surface will meet the CF-Ti interface and cause partial reflection due to differing acoustic impedance of the two materials. In case of a disbond, the amplitude of the reflected signal is almost unchanged. Nevertheless, disbond can be detected by phase shift.

When ultrasound travels from lower acoustic impedance to higher acoustic impedance (as is the case in the CF-Ti interface), the reflected signal exhibits a phase shift [1]. If the joint contains a disbond, the reflection is, the result of CF-air interface and the phase shift is prevented. Thus, the presence of a phase shift can be taken as an indication of the joint’s good condition. On the contrary, the absence of phase shift of the outer side joint echo indicates disbond. The phase shift is difficult to detect from isolated A-scan signals. However, using phased array probe in RF-signal arrangement, the adjacent S-image show colour change and the phase shift can be detected. In addition, the front wall echo (also exhibiting a phase shift due to transmission from transducer to CF) can be made visible to allow additional comparison. In the inner side joint (Ti-CF interface) phase shift does not occur and thus this technique is only applicable to outer side joint. The process is illustrated in Figure 5. Tests indicate, that disbonds corresponding to 6 mm diameter can be detected using phase shift (Figure 6).

Disbond in the outer side joint will also prevent sound transmission at the joint and thus decrease or suppress echoes from inner-side joint and inner surface. Therefore, an outer side disbond can also be detected by following the inner side joint echo and/or inner surface echo.

![Figure 5. Outer side disbond detected by monitoring phase shift at disbond location. The phase shift can be detected by comparing adjacent A-scans in phased array S-image and by comparing the phase of the outer joint echo to the outer-surface echo. The disbond also suppresses echoes from inner joint surface.](image)
Disbond in the outer side joint will prevent sound transmission and thus prevent inner side joint inspection. Thus, intact outer side joint is precondition of successful inner side joint inspection and the outer side joint may need to be repaired before inner side joint can be inspected.

Inner side interface does not cause phase shift and thus this cannot be used to detect disbonds on the inner side joint. A disbond in the inner side joint reduces or prevents transmission through the joint. This results in suppression of inner surface echo (i.e. back wall echo) and it is seen as decrease in back wall echo amplitude.

For first three steps, the back wall echo comes before the multiples of the outer side joint echo due to the relative thicknesses of the Ti and CF layers (Figure 7). From the fourth step onwards, the multiples of the inner side joint echo mix with the back-wall echo making the detection of the inner wall echo unreliable. Consequently, the amplification of the inner side joint echo and its multiples is the most prominent indication of inner side disbond.

**3.2 Inner side disbond**

Figure 6. Detection of 12 mm and 6 mm outer side disbond using phase shift
Figure 7. Echoes at the second step structure. The back-wall echo comes before the inner side bond echo multiples and thus is easily discerned using calibration sample.

If the thickness of the Ti-layer is multiple of wavelength, the inner side joint echo and its multiples are also amplified. Since the Ti layer decreased in stepwise fashion, such resonance amplification is likely to occur at some steps. Unfortunately, this resonance amplification is similar and can be confused with the amplification caused by inner side joint disbond. Consequently, a full calibration sample containing simulated defects for each step and joint-interface is required to reliably discern disbond effects from naturally occurring amplitude changes due to the complex joint structure.

3.3 Summary of the method

Using phased array ultrasonic inspection, an outer side disbond can be detected by following the inner side joint signal. Outer side disbond is indicated by decrease in inner side joint signal caused by reduced transmission due to disbond. The outer side disbond can be confirmed by absence of phase shift, or by monitoring the inner side bond echo. This is illustrated in Figure 8.

Inner side disbond can be detected by following the inner side joint echo. Disbond at the inner side joint is indicated by increase in inner sided bond echo amplitude and, more prominently, its multiples. This is illustrated in Figure 9. This evaluation was done with TomoView software after the data had been collected. With Tomoview program cross section can be taken of any area of C-scan and A-scan of any point of the inspected area afterwards. The place and the width of the gate can also be modified afterwards and this updates whole C-image.
Decrease in inner side joint echo indicates outer side disbond

Figure 8. Outer side disbond detected by decrease in inner side joint echo amplitude.

Increase in inner side joint echo and its multiples indicated an inner side disbond

Figure 9. Inner side disbond is detected by increase in inner side joint echo amplitude and its multiples.

All of these techniques rely on comparing data from the flawed location and adjacent unflawed regions and representative calibration sample to identify expected changes in the correct echoes within the complex ultrasonic signal.

3. Conclusions

Disbonds in the outer side joint of the stepped-lap joint can be detected by monitoring inner bond line echo amplitude, as outlined in this paper. The inner side disbonds on three
first steps can be seen on backwall echo pattern, but from the 4th step on can not be reliably detected by some of current systems due to the complex signal patterns. The inner side disbonds are indicated most prominently by increase of signal amplitude in inner side interface echo and its multiples. This can be detected, but requires correct identification of these echoes in the complex signal image. This requires both representative calibration sample and analysis of the full wave form signal, as presented in this paper.

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