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Biagini, D.; Pascoe, J.A.; Alderliesten, R.C.

Publication date
2023

Document Version
Final published version

Published in
Proceedings of the 31st symposium of ICAF - the International Committee on Aeronautical Fatigue and Structural Integrity

COMPRESSION AFTER IMPACT FATIGUE DAMAGE GROWTH IN CFRP – WHAT DOES NO-GROWTH REALLY MEAN?

Davide Biagini*[1] , John-Alan Pascoe[1], René Alderliesten [1]

[1] *D.Biagini-1@tudelft.nl
Aerospace Structures & Materials Department, Faculty of Aerospace Engineering
Delft University of Technology,
Kluyverweg 1, 2629 HS Delft
The Netherlands

Abstract: Impacts on carbon fiber reinforced composites (CFRP) can produce a complex internal damage comprising multiple delaminations, which is hard to detect from visual inspection. This situation is known as barely visible impact damage (BVID). Considering that every airplane faces several impacts during its operational life, and that the majority of exposed surfaces in new generation aircraft is made of CFRP, there is a high chance that some aircraft will be flying with unnoticed impact damage. For this reason, BVID damage tolerance must be taken into account in design. The FAA and EASA dictate a no-growth design philosophy for BVID. Although multiple delaminations are present, BVID fatigue growth is usually assessed by measuring only the projected delaminated area with ultrasound inspections. This is done to simplify the damage description and because of the limitations in ultrasound inspection methodologies. In the present work, we show two cases of delamination propagation that are neglected following this procedure. Our experimental monitoring of delamination propagation with different ultrasound techniques shows a) growth inside the impact cone and b) faster growth of shorter delamination. The conclusion is that the projected area description is insufficient, since a no-growth in the projected area does not necessarily correspond to a no-growth in the actual damage.

Keywords: BVID, Damage Tolerance, Delamination, Fatigue, Ultrasound-scan

INTRODUCTION

Over the last decades, carbon fibre reinforced plastics (CFRP) became extremely popular in the aerospace sector to the point that it is nowadays hard to find new aircraft designs using no CFRP structures. CFRP mainly owe this success to their advantageous specific in plane properties compared to their metal counterparts. Their tolerance to out of plane dynamic loading (like impacts) however, still represents a limiting factor.

Impacts on CFRP can produce an internal damage comprising of matrix cracks, multiple delaminations and possibly fibre fracture, together with a small impact dent which is hard to detect by visual inspection [1]. This situation is commonly known as barely visible impact damage (BVID). Regardless of its low

detectability, BVID is capable of reducing the compressive static strength [2]. In addition to that, BVID is known to propagate under the effect of cyclic fatigue loading, resulting in premature failure of the components [3], [4], [5].
BVID is generated by low velocity impact (LVI), characterized by relatively low impact energy [6]. Different sources of LVI can be found in service like foreign object damage and hail, or during maintenance actions like in the case of tool drops. Arguably every airplane will face impacts of various severities during its operational life and there is a high chance that the same aircraft will be flying with unnoticed impact damage for a certain number of flights. For this reason, BVID fatigue propagation is always taken into account when designing CFRP structures exposed to impacts.
The Federal Aviation Administration (FAA)'s advisory circular 20-107B [7] and the European Union Aviation Safety Agency (EASA)'s acceptable means of compliance (AMC) 20-29 [8] dictate a no-growth design philosophy for BVID. This is usually implemented by means of extensive fatigue testing campaigns. During these tests, the damage state is commonly assessed by applying ultrasound monitoring at different stages of fatigue life. Ultrasound scan is selected as preferential inspection technique since it allows to perform in loco inspections, and it gives a clear picture of the delaminated area, which has traditionally been linked to the residual compressive strength [9]. Applying the no-growth design philosophy then, means defining a limit load for the structure that will produce no observable growth of BVID in fatigue, evaluated using ultrasound inspection.
It must be considered that, like every inspection technique, ultrasound scan provides a partial representation of damage and has limitations. Ultrasound inspection can be performed in through-transmission or in a pulse-echo fashion.
In through-transmission scan, we measure the attenuation of the ultrasonic signal that has passed through the thickness of the laminate. If a free surface is encountered by the signal, reflection happens and larger attenuation is measured by the receiver.
In echo-pulse scan instead, we measure the echo returned when the sound wave encounters the damage and is reflected. The additional advantage of this technique is that, by using the time of flight of the ultrasonic pulse, it is possible to locate the position in depth of the defect/damage. This information is missing in through-transmission mode. The limitation of echo pulse instead, is the impossibility to inspect precisely areas with high local radius of curvature, due to the echo produced by the front surface. For this reason it is difficult to inspect the area below the impact dent.
Both techniques work using the physical principle of ultrasound getting reflected when a free surface is encountered. This means that they are fit to detect damage perpendicular to the traveling velocity of the ultrasonic pulse. Since the inspection is in most cases performed perpendicular to composite panels, delamination are easily detected, while intralaminar matrix cracks and fiber failures are not visible.
The first delamination encountered by the ultrasonic pulse causes a strong reflection and makes it difficult to see a second reflection. This means that a delamination positioned below larger ones is in most cases not visible using ultrasounds. This phenomenon is commonly referred as shadowing effect [10]. Considering that impact damage is composed by multiple delaminations located in different interfaces, only some of them will be visible.
In the current implementation of the no growth philosophy, the projection of the total impact delamination area is usually considered as the metric to define growth or no-growth. This is done due to the limitations in ultrasound, but also to adopt an inspection procedure that is easier for the operators. This procedure however, neglects the potential growth of shadowed delamination [11], and a possible growth in the central area located below the impact dent. Considering that our observation neglects some parts of the damage, to what extent does a no-growth in the detected damage correspond to a no-growth in the real damage?
The present work shows two experimental cases of delamination growth not considered by the commonly adopted procedure. Fatigue compression after impact (CAI) tests were conducted on a quasi-isotropic layup of CFRP. The fatigue damage propagation was monitored using through thickness attenuation scan and echo-pulse C-scan leading to two main outcomes:

- Through thickness attenuation scan results, previously presented at the ECF23 conference [12], show growth inside the impact non delaminated cone before the onset of growth in the external projected area.

- Echo-pulse scan result show growth of short delaminations before the onset of growth of overall projected area.

In light of these results, we then discuss the use of projected delaminated area as metric to quantify damage growth in CAI fatigue test.

METHODOLOGY

Materials and manufacturing

Toray M30SC Deltapreg DT120-200-36 UD carbon fibre/epoxy prepreg was laid-up in a $[-45, 0, 45, 90]_{4,S}$ laminate for the CAI fatigue tests. A curing cycle at 120 °C maximum temperature and 6 bar maximum pressure was conducted in an autoclave, following the procedure suggested by the manufacturer. Following that, CAI specimens were cut in dimensions 150x100x5.15 mm as indicated in the ASTM D7136 standard.

LVI test

Impact testing was conducted using a drop-weight tower according to ASTM D7136. The support fixture has a cut-out of 125 ± 1 mm in the length direction and 75 ± 1 mm in the width direction (Fig1.a). To obtain single impacts, the impact tower was equipped with a catcher triggered by optical sensors. A hemi-spherical impactor with a diameter of 16 mm and a mass of 4.8 kg was used. A target impact energy of 34 J was used in all the impacts. This condition can be classified as low velocity impact (LVI).

Fatigue test

To estimate the static CAI strength, 3 specimens were tested following the ASTM D7137 standard for static CAI tests [13]. Next, since there is no standard for fatigue CAI, testing was conducted using the same setup as for the static CAI tests (Fig.1.b). Two series of two specimens were loaded in compression - compression under force control at different load levels. A frequency of 3 Hz was used to avoid specimen self-heating. The crosshead displacement and the applied force were recorded using a 100 kN load-cell on an MTS hydraulic testing machine. The test was periodically stopped to allow the ultrasound inspections.

Ultrasound inspection

To evaluate delamination size, two different ultrasound systems were used: **system 1** is a through thickness attenuation scan immersed in a water tank (Fig.2.a) and **system 2** is echo pulse Dolphicam 2 system (Fig.2.b). In system 1, a probe of 8 MHz was used to emit ultrasound towards the receiver placed at 100 mm distance. Scanning speed was set to 100 mm/s and a definition of 1 mm was achieved. In system 2 a scanning probe of 5 MHz was used.

We decided to perform the analysis using through thickness attenuation (system 1) in order to avoid the reflection effects form the top surface of the specimen, especially in the dent region, and to be able to capture delamination growth below the impact dent area. We used the echo pulse scan (system 2) instead to be able to detect delamination position in depth.

Inspection using through thickness scan was performed in a water tank located close to the test location (Fig.2.a). The procedure of removing, scanning and repositioning the specimens took on average 10 minutes. Inspection using an echo-pulse system was performed directly in loco without removing the specimen from the fixture (Fig.2.b).

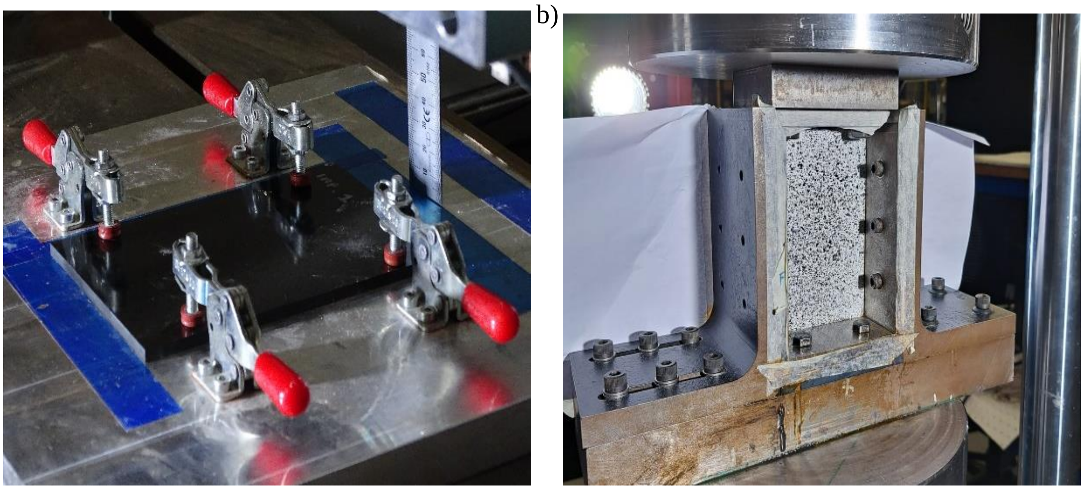

Figure 1: a) Impact test fixture and b) CAI fatigue test fixture.

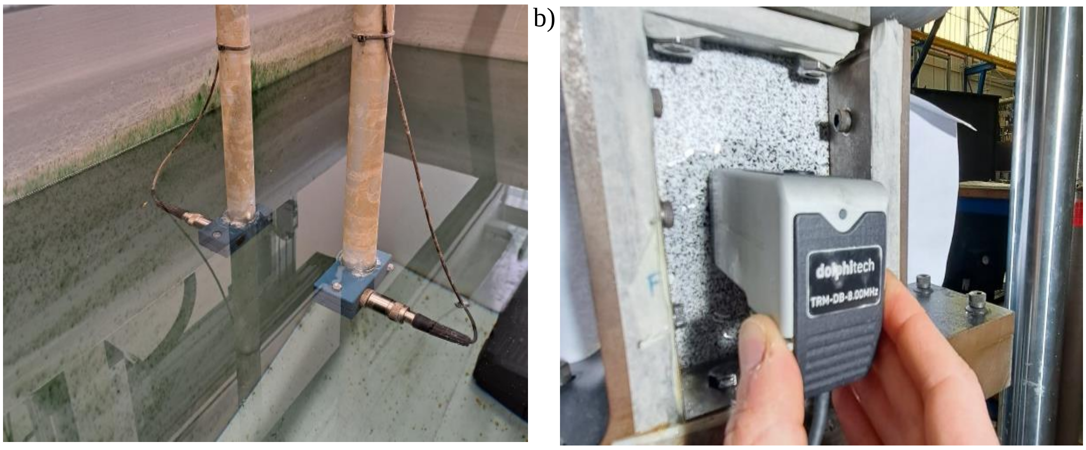

Figure 2: a) Through thickness ultrasonic scan system immersed in water tank and b) Echo pulse ultrasonic scan inspected in loco.

RESULTS AND DISCUSSIONS

<u>Impact damage</u>

The low velocity impact tests resulted in an impact dent of < 0.3 mm depth, which falls in the BVID category. As can be seen from the three dimensional reconstruction of impact damage, created with Dolphicam 2 system (Fig.3.a), the impact damage structure comprises multiple delaminations located in different interfaces. As reported by previous literature, delaminations tend to grow in every interface, bounded by the orientations of the upper and lower plies. Considering this, if the mismatch angle between consecutive plies is kept constant at 45 degrees through the laminate's layup, the delamination envelope will appear like a spiral composed of triangular shapes, all characterized by the same 45 degrees angle. This feature was documented in previous literature [10][14] and can be clearly observed in the 3D reconstruction of delamination in Fig.3.a obtained with echo pulse ultrasonic scan.

Fig.3.b shows instead a through thickness scan of BVID. A central area with less attenuation can be observed, indicating that no delamination was formed during the impact in the area below the impact dent. The presence of this feature was observed by other authors in the literature both in LVI test [15], and quasi static indentation [16]. This non delaminated area can be attributed to the out of plane

compression originating in the contact between the impactor and the composite plate, which reduces the mode II strain energy release rate and acts as inhibitor to the delamination propagation.
It is important to notice here that, while the non-delaminated region is clearly visible from a through thickness scan, it is hard to detect this feature using an echo pulse system. This because of the strong echo generated by the surface of the impact dent. The impact contact area, being permanently deformed in the out of plane direction, appears to be at the same depth as the first interfaces of the non-deformed regions of the laminate. For this reason, to the authors' interpretation of the results, in the echo pulse scan the impact dent area appears in red colours (Fig.3.a), like it does in more external regions if a delamination is present within the first mm of depth.

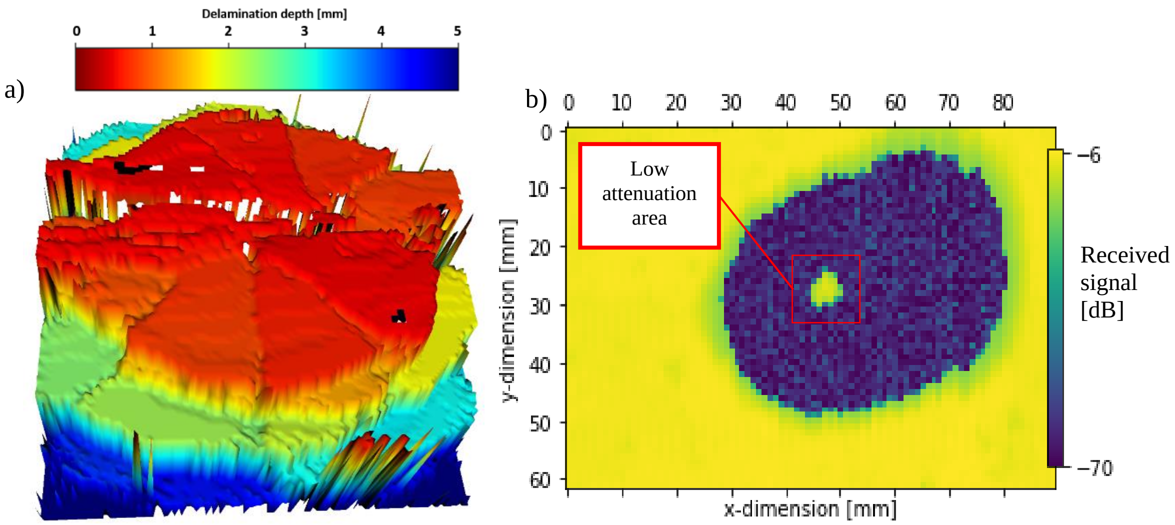

Figure 3: BVID reconstructed using a) echo pulse Dolphicam2 system, showing the 'spiral shape' delamination envelope and b) through thickness attenuation scan showing evidence of the non-delaminated area below the impact dent.

Fatigue test

Two series of two specimen were tested in fatigue after impact:
Series 1: two specimens were tested in fatigue and growth was monitored using periodic through thickness scan inspection. *Specimen 1* was tested at maximum compression stress 65% of CAI strength producing a fatigue life of 180,000 cycles. *Specimen 2* was tested at maximum compression stress 85% of CAI strength producing a fatigue life of 2,500 cycles.
Series 2: two specimens were tested in fatigue and growth was monitored using periodic echo pulse scan inspection. *Specimen 1* was initially tested at maximum compression stress 65% of CAI strength but produced no growth after 101,000 cycles, hence the load was increased to 75% of CAI strength. At the new load level the specimen failed after 94,000 cycles. *Specimen 2* was tested at maximum compression stress 80% of CAI strength producing a fatigue life of 5,600 cycles.
Some common trends were observed in the fatigue damage propagation and failure of the four specimens. In *series 1 – specimen 1*, no growth was captured with the through thickness scan. This because failure happened after 2,600 cycles and only three inspections were performed at 10, 100 and 1,000 cycles. In all the remaining specimens, a macroscopic and relatively fast delamination growth happened in the perpendicular to loading direction, proceeding from impact damage towards the lateral edges of the specimen (Fig.5 and Fig.6). This observation is consistent with several tests in literature [17] [18].
In all specimens final failure was characterized by unstable delamination propagation in multiple interfaces and fiber kinking. The fractured specimen appears very similar to static CAI tests previously conducted by the authors [13], showing a final fracture that runs in the centre of the specimen, perpendicular to the loading direction (Fig.4).

Figure 4: Failed specimen after CAI fatigue test.

In the following two sections we show two specific cases of delamination growth that we observed in our test. The goal is to question the largely adopted practice of considering the projected delaminated area as metric for fatigue growth of impact generated delaminations.

Fatigue growth below the impact dent

The first observation presented is the growth monitored in specimen 1 of series 1. In this case we used through thickness attenuation scan to evaluate growth below the impact contact point. As explained in previous sections, there is an area below the impact point, where little or no delamination is present. Because of the impact dent curvature reflection, it was difficult to evaluate this area using the echo-pulse system. For that reason we adopted through thickness transmission scan. The results clearly show how the delamination propagation firstly happened in the central area, and only after that, a single delamination started growing towards the lateral edges (Fig.5). If only the outer projected external area is taken into account, this growth in the central area is *not* considered.

It is important to consider this phenomenon, since growth in the non-delaminated central cone may have serious implications in terms of residual strength of the laminate, as hypothesized by Bull et al. [15].

At the starting point of Fig.5, if a central non delaminated area is present, the laminate is forced to deform locally in two half buckle shapes. Delamination growth in the central area may join two half delaminations into a single larger one. This would result into a single buckle, a sudden increase in the strain energy release rates at the external edges of delaminations and a reduction of the buckling load.

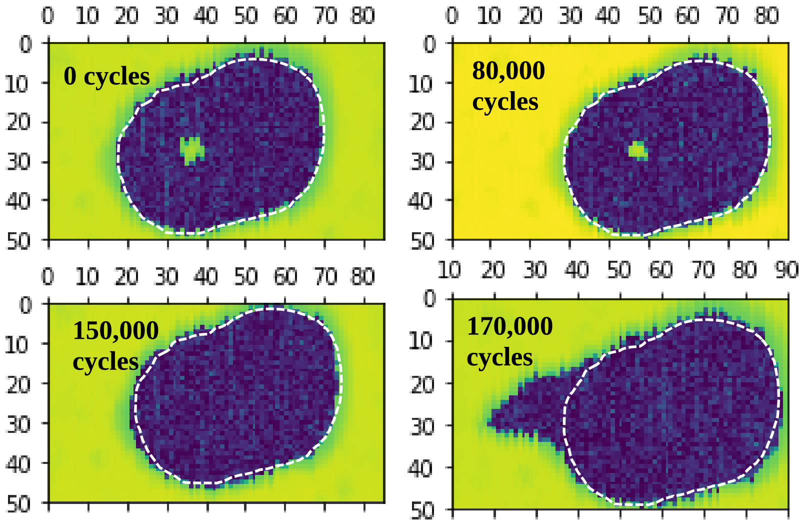

Figure 5: Delamination monitoring in fatigue using through thickness attenuation [12]

Fatigue growth of short delamination

The second observation presented is the growth observed in specimen 2 of series 2 (Fig.5). A short delamination, located in the first interfaces close to impact surface, started growing in the transverse direction. It is interesting to notice that all this growth phase took place inside the projected delamination area, hence would not have been captured by only considering the projected area as metric to describe growth.

As shown in Fig.3, BVID is composed of multiple delaminations located in different interfaces. Short delaminations will most likely be present also in the shadowed area. Based on this observation we cannot exclude that the faster growth of short delamination can happen in certain cases, without being noticed. Pascoe [11] hypothesised that the no growth observed in certain tests could be a misconception generated by the limit in the observation we can perform using ultrasound inspections. The present observation (Fig. 6) supports that hypothesis.

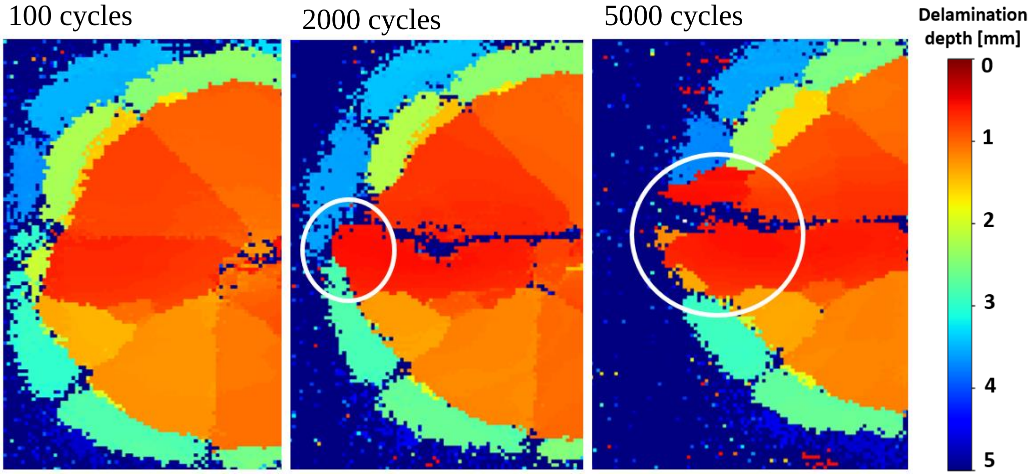

Figure 6: Delamination monitoring in fatigue using echo-pulse system.

CONCLUSIONS

A series of low velocity impact tests and compression after impact fatigue tests were conducted. During the fatigue tests delamination growth was monitored using two different ultrasound based techniques: through thickness transmission scan and echo pulse scan.

Through thickness transmission scan showed fatigue growth in the impact cone region, where no delamination was present at the post-impacted condition. This growth happened before the onset of outwards growth of delamination outside of the projected impact damage areal contour.

Echo pulse scan showed the growth of short delaminations taking place, again, before the onset of growth of delamination outside of the projected impact damage areal contour.

These results show that the two techniques provide complementary information to describe CAI fatigue growth, since the first phenomenon could not be captured using an echo pulse scan, while the second phenomenon can’t be observed via simple through thickness transmission scan.

Furthermore, these results clearly show that projected delaminated area is not a good metric to describe fatigue propagation in CAI tests, since by doing that, we are missing a large part of delamination growth. From a more general perspective these results show the necessity to carefully consider the concept of ‘no-growth’ in the current damage tolerant design methodologies. Applying the no-growth design philosophy usually comes down to verifying the no-growth performance via testing. To quantify the damage growth in tests, NDI techniques are usually adopted. If we do that, we are not applying an absolute ‘no-growth’ requirement. This because each inspection technique is limited and there is always a risk of missing some growth scenarios, as shown in the present work. This means that components that are certified following the ‘no-growth’ design philosophy, can still present damage growth in service that is not observable with the current inspection methods. At present, it is not clear what the consequences of such damage growth would be, and whether it invalidates the 'no-growth' design philosophy. For this reason, future research should target specifically the damage modes that are hard to detect with C-scan and other NDI methods, like intralaminar matrix cracking or shadowed delamination, to study their influence on the structural integrity of the aircraft. The key finding of this work is that no change of the projected delamination area does not necessarily correspond no growth of damage. Therefore, a more sophisticated damage metric is needed, that can more fully capture the complexity of the problem.

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