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Slow-growth damage tolerance for fatigue after impact in FRP composites: Why current research won't get us there

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ABSTRACT

Using the slow-growth certification approach for damage tolerance of composite aircraft structures has the potential to reduce their weight. Applying this approach requires that damage growth is slow, stable, and predictable. However, currently available methods do not allow for sufficiently accurate predictions, due to knowledge gaps related to damage characterisation, prediction of damage growth, and prediction of final failure.

This article highlights these knowledge gaps, discusses the limitations of the current state of the art and research approaches, and identifies possible ways forward.

1. Introduction

Composites structures used in service will inevitably sustain damage. In 2006, the German airline Lufthansa reported nearly 1800 damage events to composite aircraft parts [1], and the use of composite materials in operational aircraft has only grown since then. Thus, structural integrity requires designing composite aircraft structures to have sufficient residual strength even when they are damaged.

The problem of damage is further exacerbated by damage in composite materials being difficult to detect. Damage mechanisms such as matrix cracking and delamination occur entirely inside the material and therefore are not detectable with the naked eye. Some damage mechanisms are visible from the surface, e.g. a dent or fibre failures produced by an impact, but typically the largest damage will be produced on the interior of the structure (see e.g. images in Ref. [1]), where it is hidden from view. So even this visible damage is not easily detectable without a targeted inspection. Until structural health monitoring (SHM) systems become widely available, detection of damage in composite aerostructures therefore requires scheduled inspections with specialised equipment. For economic reasons, the interval between such inspections can be on the order of several months or years. Thus, an aircraft may perform hundreds or thousands of flights with an undetected damage present in its structure, making an understanding of the fatigue behaviour of a damaged structure critical to ensuring structural integrity.

As the issues mentioned above can already be foreseen in the design phase, the certification requirements prescribe that designers take them into consideration. One possible strategy is to design the structure such that a damage will not grow at all under fatigue loading. Such a 'no growth' philosophy is currently the predominant approach, but it requires keeping the stresses in the structure very low, and therefore imposes a weight penalty. Experience from metal structures suggests that weight could be saved if a 'slow growth' philosophy is followed instead. In a slow growth philosophy, damages are allowed to grow under fatigue loading (allowing for higher stresses in the structure), and structural integrity is ensured by mandating an inspection schedule that will find and repair any damages before they can grow to a critical size. This inspection schedule has to be defined as the aircraft is being developed, and therefore requires the ability to accurately predict the growth of any damage in the structure.

While there is good reason to believe that following the slow-growth approach could be beneficial for composite structures, it is not possible with the current state of knowledge. To apply the slow-growth approach, it has to be shown that damage growth is "slow, stable, and predictable" [2]. There is experimental evidence that damage growth in composites is slow and stable in many cases [3], but accurately predicting damage growth remains very difficult.

This paper will discuss the knowledge gaps that currently prevent prediction of damage growth in composites. Three main areas can be identified in which knowledge is lacking, which are:

1. How to characterise damage in composite structures.
2. How to define and predict damage growth.
3. How to predict the residual strength of a structure with a given damage state.

The paper will discuss each of these points in turn, including highlighting limitations of current research practice which hinder applying

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the findings to actual structures. Where possible the paper will identify potentially fruitful approaches for addressing these issues. In terms of scope, the paper will mainly deal with compression after impact (CAI). This is traditionally considered to be the most severe case for the residual strength of a composite. However, it is important to realise that damage in composites can also be caused by e.g. stress concentrations or manufacturing flaws [4,5]. Furthermore, while compression–compression fatigue cycles are generally identified as the critical load case [6] based on unidirectional in-plane loading experiments, real structures typically face multi-axial loading, also including flexural or out of plane components. Furthermore, tension–tension fatigue after impact can also result in damage growth [7].

Before discussing the knowledge gaps in more detail, some additional context will be given on the certification requirements for composite aerostructures.

2. Certification and damage tolerance

The need to design composite aerostructures for residual strength is codified in Federal Aviation Regulation (FAR)/Certification Specification (CS) 25.571. Here FAR refers to the regulations set by the US Federal Aviation Administration (FAA) and CS to the regulations set by the European Union Aviation Safety Agency (EASA). Thanks to intensive harmonisation efforts, these regulations are almost identical. FAR/CS 25.571 requires designers to show that “catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage will be avoided throughout the operational life of the airplane” [8].

How to show this damage tolerance for composite structures is specified in more detail in guidance material, published by the FAA as Advisory Circular (AC) 20-107B [9] and by EASA as Acceptable Means of Compliance (AMC) 20-29 [2]. These documents refer to two load levels: design limit load (DLL) and ultimate load (UL). Design limit load is the highest load that is expected to occur during the lifetime of an aircraft. Ultimate load is design limit load multiplied by a safety factor of 1.5. The regulations require a structure to be designed with sufficient strength to sustain ultimate load when undamaged. As illustrated in Fig. 1, damage is allowed to reduce the residual strength of the structure to a level that is below ultimate load, but it has to remain above limit load. The structural integrity risk caused by the damage is then indicated by the product of the strength reduction below ultimate load, and the time until the damage is detected and repaired (the shaded areas in Fig. 1). The regulations allow for larger damages to result in larger reductions of residual strength, because they are easier to detect and therefore will be repaired sooner, making the risk equivalent to that of a smaller damage repaired later. If a damage is not reliably detectable with either the naked eye, or by non-destructive inspection techniques, then the residual strength of the damaged structure is required to remain above ultimate load for the entire lifetime of the structure. Two certification concepts for dealing with damage are defined in the guidance documents.

The first concept is called ‘no growth’ and is illustrated in the left panel of Fig. 1. In this concept, after the damage is inflicted it is not allowed to grow any further, and thus the residual strength remains constant. Inspection procedures and schedules have to be defined to ensure that the structural integrity risk is acceptably small, by keeping the time until the damage is detected and repaired within acceptable limits. The requirement that damage does not grow means that the structural load levels have to be kept below the fatigue threshold of the *damaged* structure. This requires high knockdown factors compared to the undamaged strength of the material and thereby can impose a significant weight penalty on the structure.

The second certification concept is the ‘slow growth’ concept, illustrated in the right panel of Fig. 1. In this concept the damage is allowed to grow under the influence of fatigue loading and environment, and thus also the residual strength is allowed to degrade, as long as the damage is found and repaired before the residual strength becomes lower than the limit load. The length of time between damage becoming detectable and the residual strength becoming lower than the limit load is known as the inspection window. Typically inspections are required to be scheduled such that three inspections will take place within this inspection window. Of course, scheduling inspections in such a way is only possible if the size of the inspection window can be accurately determined. This is the source of the requirement that the damage growth is ‘slow, stable and predictable’ before the slow growth concept can be applied. Damage needs to be slow and stable in order to have a meaningful inspection window, and it needs to be predictable so designers can calculate what inspection schedule will place enough inspections in the inspection window.

A slow growth damage tolerance analysis then requires the following steps:

1. **Determine an initial damage**. An initial damage should always be assumed, based on knowledge of possible sources of damage. This could be based on a ‘natural’ material flaw or manufacturing defect, a damage inflicted during the first use cycle, or the detection limit for an inspection technique (effectively assuming that any larger damage would be found during that inspection).
2. **Determine the damage growth**. The growth over time of the assumed initial damage should be predicted, based on the loads and environment expected during use of the structure. Time here is expressed in terms that are relevant to the fatigue process, i.e. in terms of load cycles or usage.
3. **Determine the critical damage state**. The aim of the slow growth design philosophy is to ensure that the residual strength remains above limit load at all times. Thus, the damage state which would cause the residual strength to become equal to the limit load should be established. This is the critical damage state; any further growth will cause the residual strength to become too low. Damage should be found and repaired before it reaches this state.
4. **Determine the inspection window**. Based on the prediction from step 2, it can be determined at what point in time the damage will become detectable by a given inspection technique. It can also be determined at which point in time the damage will reach the critical size. From these two time-points the inspection window can be determined, and a suitable inspection schedule can be established.

The process described above was initially developed for metal structures [10]. In metals the damage can straightforwardly be characterised by a crack length. The crack growth can be characterised by a plot of crack length versus time (expressed in number of load cycles) and the critical damage state can be characterised by a critical crack length. For composite materials, such characterisations are less straightforward. Furthermore, the understanding of damage growth and how to define the critical damage size or state is also limited. The next section will start by discussing the issues with characterising the damage state.

3. Damage characterisation

Impact damage in composites is a complex process, involving various different damage mechanisms [11,12] that can occur either sequentially or simultaneously and that can interact with each other. At the smallest scale there is fracture of fibres and debonding between the fibres and the matrix. Intralaminar cracks can form in the matrix under the influence of shear or tension — depending on the location in the laminate. Delaminations can occur at each interface in which there is a change of fibre orientation. At the macro scale, under compressive loading, the loss of stiffness due to this damage can lead to local sublaminate buckling, or even global buckling.

Characterising impact damage in composite materials therefore requires somehow quantifying this complex damage state and its effect on material and structural properties such as stiffness and (residual)

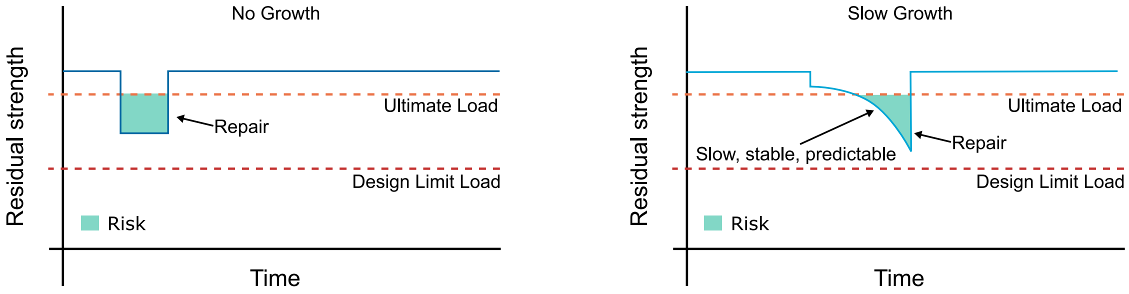

Fig. 1. Schematic illustration of certification concepts for damage to composite aircraft structures.

strength. However, the different damage types and their extent can be difficult to detect, especially without causing further damage to the structure.

Micrographic observation (e.g. as shown by Yasaee et al. [13]) is perhaps the most reliable in terms of being able to detect the presence of each damage type, but it is limited by only being possible on a single cross-sectional plane – only capturing a 2D slice of a 3D damage configuration – and requiring cutting of the specimen to be observed.

Another technique that is capable of detecting matrix cracking and fibre failures, as well as delamination, is X-ray (micro-) computed tomography (CT), as e.g. demonstrated by Schilling et al. [14] and Bull et al. [15]. While microCT is a very powerful technique, not many research groups have access to the necessary equipment. The limited scan volume also means that microCT is not a practical inspection technique for operational structures.

The most popular technology for detecting damage during impact and fatigue after impact experiments is ultrasonic C-scan. There are two possible modes of operation for this technique. Through-transmission C-scanning measures the attenuation of a signal that has travelled through the thickness of the specimen. High attenuation is an indication of the presence of one or more delaminations at that location, but it cannot be determined at which depth in the laminate the delaminations are located. Pulse-echo scanning, as the name suggests, relies on receiving echoes from sound waves emitted onto the specimen. In an undamaged specimen, only the top and bottom surfaces of the specimen – being the interfaces between the laminate and the surrounding medium – will reflect a signal. If there are delaminations present in the material, then these will reflect an additional signal, which can be identified in post-processing. By measuring the time-of-flight of the signal, the depth at which the damage is located can be determined.

While ultrasound C-scan equipment is widely available and relatively straightforward to use, the main disadvantage is that it can only be used to detect delaminations. Matrix cracks and fibre fractures are typically too small or have the wrong orientation to show up on the scan. This has led researchers to adopt the practice of characterising impact damage in terms of delamination size, expressed in terms of either width or projected area. There is clearly a correlation between delamination size and residual strength. However, it is important to realise that the focus on delamination size as the sole descriptive parameter is driven by the capabilities of available inspection technology, rather than by the physics of the failure processes.

Does it matter that damage is characterised purely in terms of delaminations? In the case of quasi-static compression after impact, it can be argued that the strength is not affected by the presence of matrix cracks. Sun and Hallett [16] have shown numerically that matrix cracks play an important role in the formation of delaminations during the impact, but do not seem to have much effect on the subsequent compression after impact strength. This supports the idea that matrix cracks do not need to be considered when characterising impact damage. However, an opposite conclusion follows from the numerical modelling of McQuien et al. [17]. They found that including some initial matrix cracks (created during the impact) in their model, but blocking matrix crack growth during post-impact loading resulted in an 11% increase of strength. They also found that if both the impact dent and the matrix cracks were excluded from the model, then the strength was increased by 48%. McQuien et al. note this suggests the matrix cracks play an important role in facilitating the buckling, which would mean their presence and extent should be characterised. The investigations of Sun and Hallet and McQuien et al. were limited to quasi-static loading. Further research is needed to investigate whether their conclusions also hold under fatigue loading, and whether e.g. the potential interaction between matrix cracks and delamination growth is important in fatigue.

Fibre failure is typically also not characterised, again at least in part due to the difficulty of detecting it non-destructively. Another reason is that compression after impact studies tend to focus on the barely visible impact damage (BVID) scenario. In this scenario the impact energy is kept low, such that the dent formed on the impacted face is ‘barely visible’. Because the impact energy is low, these impacts often do not produce fibre fracture. However, it should be realised that at higher impact energies fibre fracture may occur, which can affect the stress distribution in the laminate, as well as the laminate strength and stiffness and buckling behaviour [7,18]. If this is not distinguished in the damage characterisation, the laminate behaviour cannot be correctly predicted.

Even if one considers it acceptable to characterise impact damage purely in terms of the delaminations, there are still two important limitations of ultrasound C-scan to consider: (1) shadowing and (2) projection and data reduction, which are illustrated in Fig. 2.

Shadowing is illustrated in Fig. 2(a). It refers to the phenomenon that during C-scanning delaminations closer to the surface of the specimen will interact with the sound waves first. That means that much less acoustic energy will reach any delaminations deeper in the specimen. As a consequence, it is usually only possible to get information from the one or two delaminations closest to the specimen surface, and any delaminations located below these first delaminations are hidden from view in the scan. Shadowing is clearly an issue during pulse-echo scanning, but is also a problem for through-transmission scans. If the delaminations near the top surface attenuate the signal strongly enough, it becomes impossible to determine if the signal has passed through any subsequent delaminations before exiting the laminate and reaching the detector.

The issues of projection and data reduction are illustrated in Fig. 2(b). It is known from experimental evidence [11,13,15,20] that during an impact, delaminations are created at the interface of every ply at which there is a change of fibre orientation. However, if an ultrasound C-scan is done in through-transmission mode, then the only information that is obtained is the amount of signal attenuation along each path through the thickness. It is not possible to retrieve where along the path the signal was attenuated. This makes it impossible to determine whether damage indications in two different positions on the specimen are from the same delamination, or are from two delaminations in different interfaces. In short, a through-transmission C-scan will project the 3D delamination state in the specimen down to a 2D representation. Even if a pulse-echo C-scan is used, the delamination extent is often still only described in terms of the total projected area, or even reduced to the delamination width (see Fig. 2(b)).

(a) Delamination shadowing in pulse-echo mode (b) Projection and data reduction

Fig. 2. Issues in quantifying damage severity based on ultrasonic C-scan information [19].

The convenience of such forms of data reduction is clear. What is less clear is whether such data reduction is physically justified. Researchers such as Guild et al. [21], Sun and Hallet [16], and Nettles and Scharber [22] have reported strong correlations between reduced parameters, such as projected area or delamination width, and compression after impact strength. However, it should be noted that such correlations are usually found within single test series, where the impact boundary conditions, lay-up, and specimen geometry are kept constant. In such a case one can imagine that the delamination state scales with the impact energy, and a single number suffices to characterise the entire 3D delamination state. However, it should be questioned whether such a correlation is generalisable to other geometries, lay-ups, or impact boundary conditions. In other words, if compression after impact strength is related to e.g. projected delamination area or width based on standard test coupons, it is not clear if this relationship will hold for full-scale structures. Furthermore, even if a projected delamination area is sufficient to characterise the residual strength, it seems likely that two different damage configurations which happen to have the same projected area, could have quite different evolutions under fatigue loading, possibly meaning a more detailed damage description is required to correctly model fatigue than what is needed to predict the residual strength.

For a slow growth analysis, the pressing question is: how to correctly represent the initial damage? Is a fully detailed description of the 3D damage state needed, including also representing matrix cracking and fibre failures? Then either a microCT scan or a high-fidelity impact simulation (see e.g. [16,17]) may be needed. Ideally however, the damage would be represented by a reduced set of parameters, e.g. representing the delaminations as circles or ellipses. For quasi-static strength, Baluch et al. [23] have been successful with this approach, reconstructing a simplified representation of damage from C-scan data and then predicting the compression after impact strength numerically.

However, for the moment it remains unclear whether such an approach could also be successful in fatigue. In part this is because it is not fully understood which properties or aspects of damage are important. Do matrix cracks play a role in fatigue? Are all delaminations important, or only those close to the surface, as suggested by Baluch et al. [23]? Or does it depend on the load level, as suggested by Melin and Schön [24]? Do the fibre orientations of the plies adjacent to a delamination matter, with e.g. delaminations adjacent to 0-degree fibres being more important?

It is possible to create engineering models which empirically relate residual strength and fatigue life to damage size and thereby set acceptable damage limits. However these models need to be backed up by large test programmes. The results of these tests are specific to the lay-up and geometry tested and require setting conservative damage limits. Therefore it would be beneficial to better investigate which fatigue and failure processes play a role during fatigue after impact. The aim of such investigations should be to establish what the minimum information is that is required to correctly characterise damage in a composite laminate, so that its subsequent fatigue behaviour can be correctly modelled. One promising approach is for example that followed by McQuien et al. [17], who investigated the effect on quasi-static compression after impact strength of ‘switching off’ different damage modes in their numerical model. They also investigated the effect of creating damage patterns based on information that can be obtained from inspection techniques realistically available in the field, e.g. ultrasonic C-scan and tap testing, rather than X-ray CT. This was found to result in conservative predictions.

An understanding of which damage modes do or do not need to be accurately captured for a prediction model could be used to reduce the amount of testing required for certification of new composite structures. It can also be used to derive requirements for non-destructive inspection and structural health monitoring equipment.

4. Damage growth

The issues mentioned above also form an important hindrance to the investigation of damage growth under fatigue loading. Without suitable inspection techniques, it is difficult to be certain what is happening in the specimen during the fatigue loading. Researchers typically have to rely on interrupting the fatigue test at set intervals and then performing a C-scan (see e.g. Xu et al. [25]), and then have to contend with the limitations of C-scanning as discussed in the previous section.

Furthermore, it was also discussed above that it is not yet clear how to correctly characterise damage in a composite laminate. This forms an issue when investigating damage growth, because the question immediately becomes what, exactly, do we mean by damage growth? Is it the growth of delaminations? If so, all of them or only some? Is it growth of matrix cracks? Or is it the creation of new matrix cracks, while the existing ones remain stationary? This section will follow literature in talking mainly about delamination growth; however the reader should keep in mind that other damage processes may also play a role in fatigue after impact behaviour, and that the correct definition of damage growth remains an open issue.

When it comes to characterising delamination growth, researchers tend to adopt some form of the Paris equation, which empirically relates the delamination growth rate $\mathrm{d}a/\mathrm{d}N$ to the strain energy release rate G:

$$da/dN = CG_{max}^{n} \quad \text{or} \quad da/dN = C\Delta G^{n} \tag{1}$$

where G_{max} is the strain energy release rate at maximum load, ΔG is the strain energy release rate range, and C and n are empirical values found by curve fitting. This equation was originally introduced for metals in terms of the stress intensity factor [26], and later rewritten in terms of the strain energy release rate for use in delamination growth prediction [27]. Various variations on this basic formulation have been proposed to capture effects of parameters such as the R-ratio (the ratio of minimum to maximum load) or the opening mode mixity. Recently Jones and Kinloch [28,29] have used the Hartman–Schijve equation, which extends the original Paris equation, to capture various sources of experimental scatter and produce worst case growth rate curves that can be used for design. Nevertheless, all methods based on the Paris equation are ultimately empirical correlations [30,31]. A derivation of the Paris equation from physical first principles has so far not been presented in the literature. This lack of physical understanding limits use of these equations to cases where sufficient experimental data is available to produce good curve fits. A better understanding of the underlying physics could likely significantly reduce the amount of testing required to be able to predict fatigue delamination growth under a variety of test conditions.

4.1. Experimental observation of damage growth under fatigue after impact

As reviewed by Davies and Irving [6], most fatigue after impact (FAI) research has focused on stress/strain-life approaches. In these approaches the fatigue life is related to the applied stress or strain, in terms of either amplitude or maximum applied stress or strain. As the fatigue life will depend on the initial damage, a large test programme is required to ensure the effect of different damage sizes can be captured. Furthermore, consistently reproducing the same impact damage is not trivial, as impact tests themselves tend to have scatter in the damage size for a given energy. This scatter in initial damage can then amplify the scatter in the fatigue data.

Uda et al. [32] have presented evidence that S-N curves for different impact damage sizes can be collapsed by normalising the applied stress amplitude by the compression after impact strength. This of course does require that the correct compression after impact strength is known for the given damage. However, it does offer the possibility of predicting the fatigue behaviour based on data gathered for only one impact condition. Further research is required to understand whether this is indeed possible, and if the obtained S-N curves can indeed be generalised beyond the specific test coupons used to generate them.

A more fundamental issue with S-N curves is that while they can be used to predict the number of cycles to failure starting from a certain initial condition, they cannot be used to predict the actual damage evolution. Therefore, S-N curves cannot be used to analyse the effect of damages that do not match the initial condition for which the curve was generated. Performing a damage tolerance analysis as required for certification then means either creating S-N curves for many possible damage states, or using a method based on predicting the actual damage growth.

Various researchers have investigated delamination growth under constant amplitude loading, including Davies and Irving [6], Chen et al. [33], Xu et al. [25], Isa et al. [34], and Ogsawara et al. [35], while Mitrovic et al. [36] and Clark and van Blaricum [37] have performed variable amplitude fatigue tests. Due to the issues discussed in Section 3, the researchers were only able to measure the delamination growth, and reported the results in terms of projected delamination area or delamination width.

The behaviour reported by the researchers is not consistent, as highlighted by Davies and Irving [6]. Isa et al. [34], Ogasawara et al. [35] and Xu et al. [25] reported a long period in which no or very little growth occurred, followed by rapid growth near the end of the life. The period of no or slow growth is sometimes preceded by a short period of rapid growth at the start of the test, as illustrated in Fig. 3. In contrast Chen et al. [33] and Mitrovic et al. [36] reported seeing continuous growth throughout the fatigue life.

One clue to what may be happening is offered by the recent results of Tuo et al. [38]. They performed fatigue after impact tests at four different load levels and quantified the amount of damage in the specimen by measuring the stiffness degradation. For the two lower load levels the damage followed a fast–slow–fast pattern, with a plateau region of almost no growth during a large part of the test. For the two higher load levels on the other hand there was no plateau region, but instead a continuous growth behaviour was seen. This suggests that different damage mechanisms are activated at different load levels. This hypothesis is also supported by the results of Djabali et al. [39], who monitored acoustic emissions generated during bending fatigue tests. They noticed that different clusters of signals were received at different load levels, again suggesting the activation of different mechanisms at different load levels.

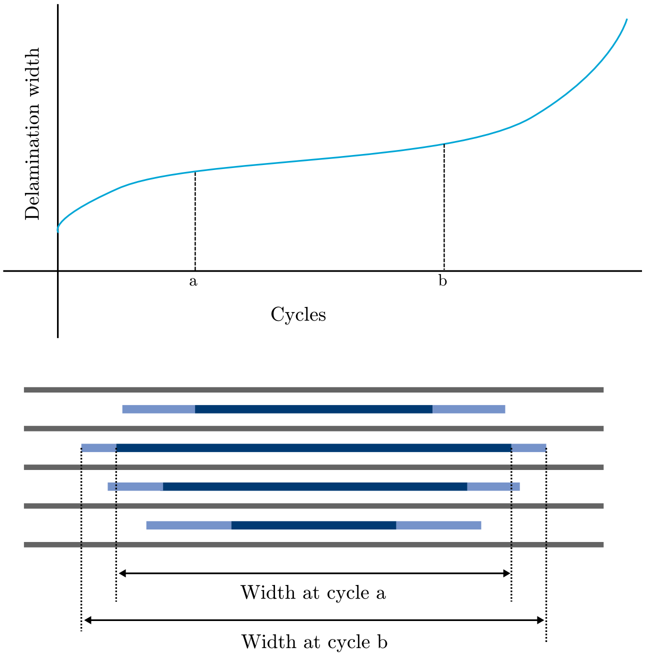

Fig. 3. Typical fatigue delamination growth behaviour as reported in literature and a schematic illustration of how undetected delamination growth could present the illusion of a plateau region [19].

Another point to be kept in mind is the limitation of inspection techniques, as discussed in Section 3. Delaminations close to the surface shadow lower lying delaminations, meaning growth of the lower lying delaminations can go undetected, as illustrated in Fig. 3. Furthermore, the use of projected area as a damage measure can make it seem that no damage growth is occurring, when in fact there may be delamination growth in multiple interfaces, just not extending beyond a certain outer envelope. Additionally, even if no delaminations are growing, it is possible there is growth of other kinds of damage, such as matrix cracks, which is not detected by the chosen inspection method.

As discussed above, for better or worse, studies of damage growth in fatigue after impact have focused mainly on delamination growth. To better understand delamination growth, researchers make heavy use of standardised approaches. Although formal standards for fatigue delamination growth testing are still under development [40–42], a number of test geometries have *de facto* been adopted as standards by the research community. These standard geometries are usually based on quasi-static test standards and include the double cantilever beam (DCB) for mode I, the end notch flexure (ENF) for mode II and the mixed-mode bending (MMB) for mixed mode testing.

While these tests have proven their worth, it is important to realise that there are many aspects of laminates used in operational structures that are not captured by such set-ups. These include the ply orientation jump, planar delamination growth, the presence of multiple delaminations, and fluctuating mode-mixity.

4.2. Ply orientation jump

The standard test specimens make use of unidirectional lay-ups, in which the fibre direction on either side of the delaminating interface is the same. Usually a 0//0 interface is studied, but in some cases also a 45//45 or 90//90 interface is examined. In operational structures on the other hand, typically laminates are multidirectional, and thus one finds many interfaces where there is a jump of fibre orientation across the interface. In fact, in the case of impact one typically only finds delaminations at such interfaces, while interfaces between plies with the same fibre orientation do not delaminate.

Blondeau et al. [43] have reviewed delamination growth in multidirectional interfaces under quasi-static loading. They noted that contradictory results have been found. Some researchers have reported that the fracture toughness was affected by the change in fibre orientation, while others found no effect. Investigation of fatigue delamination growth in multidirectional interfaces has so far been very limited. Banks-Sills et al. [44] have reported results for fatigue delamination growth in a multidirectional interface, but did not compare them to fatigue delamination growth in a unidirectional interface.

Having a multidirectional interface can affect the local mode-mix at the crack tip, as analysed by Davidson et al. [45,46]. Furthermore, multidirectionality at the interface may also affect the occurrence of fibre bridging. Multidirectionality will also affect the delamination front and the crack path, as the fibres on at least one side of the interface will not be parallel to the delamination growth direction, unlike in the case of the standard unidirectional specimens. The combination of all these effects is likely to affect the delamination growth rate for a given external loading. Therefore more research on fatigue delamination growth in multidirectional interfaces is crucial to understanding if and how standardised tests can be related to delamination growth in operational structures.

4.3. Planar delamination growth

In the standard delamination growth specimens there is one delamination and the delamination front is more or less straight across the width of the specimen.[1] Thus, the delamination can be adequately characterised by a scalar delamination length. Growth of this delamination is also a one-dimensional process, so can again be characterised by a scalar value.

In contrast, in the case of an impact, the delaminations will be planar, that is, two dimensional. Furthermore, delamination evolution may also be a two dimensional process, and therefore needs to be characterised by a vector field, with the direction and magnitude of the delamination growth vectors varying along the delamination front.

The two dimensional shape of the crack also means that the mode-mix will change along the delamination front, and that in certain areas the mode III opening component, – which is not often studied – could become non-negligible. The continuous change of mode-mix means reliable mixed-mode delamination growth models are needed, and this remains a challenging issue. Recently, Amaral et al. [47], Daneshjoo et al. [48] and den Ouden [49] have suggested that a solution could be to characterise the crack driving force in terms of the strain energy density (SED), rather than by the commonly used strain energy release rate (SERR). The initial results are promising under quasi-static loading, but further work is needed to investigate these ideas for fatigue.

Investigation of planar delamination growth requires suitable experimental and numerical tools. As mentioned, the standard delamination growth specimen geometries are only suited for one dimensional growth. Thus new test set-ups are needed for planar growth. Such set-ups have recently been proposed by Camselle-Molares et al. [50] and den Ouden [49], but further standardisation work is necessary. In terms of numerical tools, Carreras et al. [51] and Amiri-Rad et al. [52] have presented different numerical approaches that are capable of dealing with two-dimensional delamination growth, and look to be promising for further development.

4.4. Multiple delaminations

An impact will typically form delaminations in each interface at which a jump in ply orientation occurs. If there is no ply blocking, that means that for example in a cross-ply or quasi-isotropic laminate, there will be a delamination at each interface in the laminate. Each delamination will affect the local stress state, as well as the constraint of adjacent plies against sub-laminate buckling. In other words, the delaminations will interact with each other (see e.g. [18]), and understanding these interactions is required to correctly predict delamination growth under fatigue loading. Correctly predicting these interactions likely requires high-fidelity numerical models with small mesh sizes. If crack propagation is included, that will drive up the computational cost even further, making such models very expensive to run and limiting the specimen size, number of different lay-ups, and number of damage scenarios that can be studied.

A computationally cheaper strategy could be to map the crack driving force distribution of different delamination configurations, without including crack propagation in the model. Predictions can then be generated by using more simple (analytical) models to predict how the damage will evolve from one mapped state to another. Such an approach proved useful in the analysis of a double lap adhesive bond, where there were interactions between four disbonds growing simultaneously [53]. Artificial intelligence or machine learning techniques could potentially be used to further refine the map of the crack driving force for different damage configurations. Such a map can also provide qualitative understanding, which could be used to justify selection of worst case damage scenarios, preventing unnecessary analyses and certification tests.

Although the standard test geometries are designed to contain only a single delamination, the occurrence of secondary delaminations in adjacent plies is sometimes reported, e.g. by Goutianos and Sørensen under quasi-static loading [54] and by Khudiakova et al. in fatigue [55]. Further study of such cases can form a starting point for better understanding of how to account for the interaction between multiple delaminations.

4.5. Fluctuating mode-mixity

The majority of fatigue after impact tests focus on compression–compression loading, which is usually considered to be the most severe case. Experimentally it also avoids issues with test rig grip design, and with slack in the test set-up when the load is close to zero. However, it should be noted that if an impact damage is subjected to tension–compression loading, then the mode-mixity will change during the load cycle. During the tensile part of the cycle, the delaminations will typically only be loaded in mode II. During the compressive part of the cycle, sublaminate buckling may add an additional mode I component, thus causing the mode-mixity to fluctuate during the load cycle. Even in pure compression–compression loading this change of mode-mixity can occur, if buckling only starts at higher load levels. In contrast, the standard mixed-mode test set-up, the MMB, has a mode-mixity that is fixed throughout the load cycle, and thus currently available data does not provide much insight into the consequences of the mode-mix fluctuation.

A related issue is that the standard mode II test set-ups usually only apply shear in one direction (the R-ratio is always positive) and therefore there is very little data on the effect of reversed shear on mode II crack growth. Some studies are available [56–59], but they focused on obtaining empirical prediction models, rather than on understanding the mechanisms, so further work is needed in order to be able to generalise the results.

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[1] To be precise, there is usually a small curvature, with the delamination length being slightly shorter at the edges of the specimen and slightly longer in the middle. Typically, the effect of this curvature is considered to be negligible.

5. Final failure

In order to be able to correctly determine the length of the inspection window, one needs to be able to predict at what point in time the residual strength of the structure will degrade below the acceptable level, which in aviation is typically the design limit load. The damage state at which the residual strength equals the design limit load is known as the critical damage state. In metal structures this can be characterised by the critical crack length, which is a single value. However, due to the complex damage inside a composite laminate, multiple different damage configurations could all produce the same residual strength, making the critical damage state more difficult to define.

Complicating the determination of the critical damage state is the difficulty of correctly predicting the residual strength of a laminate for a given damage configuration. For aircraft structures, these predictions still rely heavily on empirical correlations generated for specific components. As discussed in Section 3, damage detected in service is difficult to characterise in full detail. Furthermore, it is well known that both the impact damage and the residual strength are sensitive to the impact scenario and boundary conditions. Therefore it is difficult to correlate damage detected in service to compression after impact tests conducted during development and certification. As a consequence, acceptable damage limits are set conservatively, leading to parts being repaired or replaced when this may not actually be necessary.

A first step to better prediction of compression after impact strength would be to clarify what is the critical damage mode that leads to final failure under quasi-static loading. On this point there is currently no consensus. Sun and Hallet [16] and Bull et al. [15,60] focus on propagation of delaminations, with Bull et al. emphasising the role of delamination growth into the undamaged cone beneath the impact location. On the other hand, Nettles and Scharber [22] conducted a series of compression after impact tests on laminates with the same fibres (IM7) but different epoxy resin systems, with different mode I and II fracture toughnesses. They found that the damage size for a given impact energy depended on the fracture toughness. However, the compression after impact strength at a given damage size did not depend on the fracture toughness. From this Nettles and Scharber concluded that the critical damage mode initiating failure was compressive fibre failure (by kinking) due to stress concentrations at the edge of the delamination.

These conflicting views can be reconciled by the work of Yang and Li [61,62]. They conducted numerical simulations, which suggest that fibre failure and delamination propagation are in fact competing mechanisms. Which of these mechanisms leads to final failure depends on the delamination configuration, i.e. the number of delaminations, their size, and where they are located through the thickness of the laminate. The implication of this is that damage tolerance analyses need to consider both unstable delamination propagation and fibre kinking as possible failure modes. Which one is critical likely depends on the specific initial damage and damage evolution in the case being analysed.

It should also be mentioned here that the failure mode seen during a test depends on the boundary conditions. For example, the standard ASTM compression after impact test [63] is specifically designed to prevent global buckling from occurring in the specimen. While this is justified given the objectives of the test standard, it does need to be checked whether the failure modes seen during a particular test actually match the failure modes that will occur in an operational structure.

Sun and Hallet [16] have shown that high fidelity models are capable of generating accurate predictions of compression after impact strength. The downside of these models is that they are very computationally expensive. This limits their current application to relatively small geometries, such as the 150 × 100 mm ASTM standard [63] compression after impact coupon. Additionally, the results generated by the model are specific to the distinct geometry, lay-up, and impact scenario being studied. Therefore, using these models for structural design, where many different lay-ups need to be evaluated, is impractical.

For a damage tolerance analysis there are two possible approaches for determining when the critical damage state has been reached. The first is to predict the damage evolution and for regular increments in that evolution predict what is the residual strength for that damage state. The damage evolution analysis is then halted when the residual strength becomes too low. The second approach is to start from the desired residual strength and reverse engineer what would be the critical damage state that produces that residual strength. Then the damage evolution prediction is run to find how long it will take the damage to evolve to the critical state.

Predicting the residual strength as the damage grows could in principle be done with high-fidelity numerical models, but their computational cost prohibits this in practice. Analytical models can potentially offer a cheaper solution. Wang et al. [64] have developed a model that is capable of accurate prediction in the case of a single elliptical delamination, which might be suitable, if it can be extended to deal with multiple non-elliptical delaminations. Esrail and Kasspoglu [65] presented an analytical model that can analyse the effect of damage in multiple plies or interfaces, as long as it can be represented by elliptical inclusions. It produced accurate estimates of compression after impact strength for some lay-ups but was less accurate for others. Esrail and Kasspoglu suggested that including modelling of sub-laminate bucking and the subsequent stress redistribution could improve the accuracy of the model, but this has not yet been done. Another option is to use equivalent hole models such as suggested by Soutis and Curtis [66], Puhui et al. [67], and Edgren et al. [68]. The challenge here is how to select the equivalent hole size. Additionally, equivalent hole models assume that the laminate fails due to fibre kinking as a result of stress concentrations. It is not clear how accurate they are in cases where delamination propagation is the critical failure mode.

The reverse engineering approach is very common for metals, where it is relatively straightforward to determine a critical crack length if the material fracture toughness and desired residual strength are known. For composites, such an approach is currently hindered by a lack of understanding of the critical failure mechanisms, making it difficult to efficiently reverse engineer what damage configuration would result in a specific residual strength value. Additionally, as pointed out above, it is likely that there is no unique critical damage state, but rather a set of different damage states that would all produce the same residual strength. These considerations mean that *a priori* determination of the critical damage state is likely not the best approach to performing a damage tolerance analysis.

In summary, in order to effectively perform slow growth damage tolerance analyses, more understanding of the failure mechanisms governing the quasi-static residual strength is required. Furthermore, there is a need for either a fast and accurate way of evaluating the residual strength for a given damage configuration, or for a convenient way to find the set of critical damage states for a given residual strength.

6. Conclusions

Composite structures are currently certified for damage tolerance using a no growth concept. A slow growth approach could potentially save weight, without sacrificing safety. Such a certification approach is already allowed in principle by the guidance material published by the FAA and EASA. However, it requires designers to show that damage growth will be slow, stable, and predictable. The requirement for damage to be predictable is the main barrier to adoption of a slow growth approach, as reliable prediction methods are currently not available.

This paper highlighted the knowledge gaps that currently prevent accurate prediction of damage growth. These gaps exist in three main areas:

1. **Damage characterisation** It is unclear how to characterise damage effectively, as it is not clear which damage features actually govern the damage propagation or residual strength. It is also not known whether some damage mechanisms (e.g. matrix cracking) can be neglected or not in a damage tolerance analysis. Characterisation of damage in current research practice tends to be driven by the capability of available non-destructive inspection techniques, rather than an understanding of critical damage mechanisms driving requirements on inspection methods. Non-destructive inspection techniques that are suitable for operational settings have known limitations, but it is not clear to what extent these limitations hamper accurate prediction of the effect of defects detected using these techniques.
2. **Damage propagation** As it is unclear how to characterise damage, it is also unclear how best to define damage propagation. Studies into damage propagation under fatigue loading tend to only focus on delamination growth, neglecting the potential effect of interactions between delaminations and matrix cracks. Delamination propagation studies rely on standard test specimens, which are not representative of operational composite structures in many ways, including the number of delaminations, 1D vs 2D delamination growth, fibre orientation adjacent to the delamination, and mode-mixity during the load cycle.
3. **Final failure** There is no consensus on which damage mechanism leads to final failure. It seems that fibre kinking and unstable delamination growth may be competing failure mechanisms, with the critical mechanism depending on the damage configuration. Quasi-static compression after impact strength can be accurately predicted with high fidelity numerical models. However these models are computationally expensive, and the results are only applicable to the specific case analysed. Faster prediction methods are required to support slow-growth damage tolerance analysis.

Potential approaches for addressing the identified knowledge gaps were highlighted. To develop the knowledge and understanding necessary for slow-growth damage tolerance analysis, it is important for researchers to keep in mind the limitations of non-destructive inspection techniques. They should be aware of the possibility of damage propagating without being detected. There should also be more investigation of how to generalise results from test coupons, so that predictions can also be made for structures that have lay-ups, geometries, and boundary conditions that do not match the test coupons, and which furthermore may have been subjected to different damage scenarios (e.g. different impactor radius, mass, or velocity). There is also a need to develop methods that are fast and computationally cheap enough to be used in design or maintenance contexts.

Filling the identified knowledge gaps will help industry by reducing the conservatism needed in damage tolerance analyses, hopefully allowing for lighter structures and more permissive damage limits. It can also help to reduce the reliance on empirical models, cutting down the need for costly testing. Scientifically, it will deepen our understanding of fatigue driven damage growth in composites, moving us beyond empirical correlations towards understanding of the underlying physical mechanisms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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