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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

Impact damage in CFRP structures is currently managed using the 'no-growth' concept, meaning that damage is not allowed to grow under fatigue loading. This requires that stresses in the material are kept below the fatigue limit, imposing a significant weight penalty. A 'slow-growth' concept would allow more efficient structural designs, but several knowledge gaps need to be addressed before this is possible. These gaps exist in three main areas: (1) damage characterisation, (2) fatigue driven delamination growth after impact, and (3) final failure of impacted laminates. The paper highlights open questions and the shortcomings of current research in addressing them, and suggests avenues for future research.

Keywords: Damage management; Compression after impact; Damage tolerance

1. Introduction

Aircraft used in service sustain damage on a regular basis (Sauer, 2009). This means that aircraft structures must not just be designed to have sufficient strength when undamaged, but also to have sufficient residual strength in the presence of damage. Composite structures face the additional challenge that strength degradation tends to be caused by damage (e.g. delamination) that is not visually detectable from the outside of the structure. This means scheduled inspections are required to detect the damage, raising the question of what happens in the time between a damage being created and an inspection detecting it.

Roughly, we can say there are two possibilities: either the damage grows due to fatigue loading, or it does not. According to published regulatory guidance material (Federal Aviation Administration, 2010; European Aviation Safety Agency, 2010) both scenarios are in principle acceptable. Slow damage growth can be allowed, on the conditions

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that (i) the residual strength does not decrease below limit load and (ii) the growth is "slow, stable, and predictable" (European Aviation Safety Agency, 2010).

Applying the slow growth concept allows higher loads in the structure, and therefore has weight benefits. However, showing that damage growth is slow, stable, and predictable is difficult. Consequently, in current practice composite structures are designed and certified according to a 'no-growth' philosophy. In this philosophy loads have to be kept below the fatigue threshold, even in the presence of damage, which imposes a weight penalty. While there is experimental evidence for damage growth being slow and stable in many cases (Molent and Haddad, 2020), accurately predicting it remains difficult. There are large knowledge gaps in three different areas which need to be addressed. These areas are: (1) characterisation of damage, (2) prediction of damage growth under fatigue loading, and (3) prediction of final failure.

This paper will highlight the open questions preventing adoption of slow growth damage management for fatigue after impact in composites and discuss why current research practices may not be helpful in addressing them. It will also offer some perspectives for alternative research approaches to better address these knowledge gaps.

2. A note on the scope of the paper

Many discussions on damage growth in composites focus on the compression after impact (CAI) case, due to its perceived severity. In order to limit its scope, this paper will share that focus. However, it should be remembered that delaminations in composite laminates are not only initiated by impacts, but also by e.g. stress concentrations or manufacturing flaws (see e.g. Saunders et al. (1993); Mueller et al. (2016)). Compression-compression loading is generally identified as the critical fatigue load case (Davies and Irving, 2015), based on laboratory tests of specimens loaded unidirectionally with in-plane loading. However, real aircraft structures typically face multi-axial loading, including flexural components in addition to in-plane loads. Although this paper, to limit its size, will also focus on in-plane compression-compression loading, it should be borne in mind that this is only one facet of a larger problem.

3. Damage Characterisation

In order to design a structure using a slow-growth approach, suitable inspection intervals need to be established. This requires specifying an initial damage, predicting how it will evolve under fatigue loading and when it will have grown large enough to cause final failure. During manufacturing or service, damage is usually detected through a non-destructive inspection (NDI) technique. The severity of this damage then needs to be determined and compared to acceptance criteria to decide on further actions. Again this requires characterisation of the damage.

In metal structures, damage is typically characterised in terms of the crack length, as fatigue damage can be assumed to take the form of a single crack growing from some initial flaw. In the case of composite structures however, the damage is much more complex. Impact damage can result in matrix cracks, delaminations, and fibre failure, all of which can potentially grow under fatigue loading, and all of which may interact. Unfortunately, common NDI techniques such as ultrasonic scanning can only detect delaminations, and not matrix cracks or fibre failure. Matrix cracking and fibre failure can be detected in a lab setting using microCT (see e.g. Schilling et al. (2005)), but this technique is not feasible for operational aircraft structures.

The first question this raises is, does it matter? In the case of quasi-static compression after impact (CAI) loading it is usually argued that the matrix cracks do not affect the residual strength; a claim for which there is some numerical evidence (Sun and Hallett, 2018). However, propagation of matrix cracks, and their interaction with delaminations, may prove to be more significant in fatigue, in which case it may in fact be necessary to detect their presence in order to make meaningful predictions.

Fibre failure as a damage mode has received less attention, because CAI studies tend to focus on the barely visible impact damage (BVID) scenario, in which the impact energy is often too low to create fibre failure. Nevertheless, it is important to realise that fibre failure will reduce the laminate's strength, and there is some evidence that the occurence of fibre failure can limit the validity of empirical correlations between delamination size and residual strength. Furthermore, laminate modifications to improve CAI strength such as interleaving and Z-pinning may become less effective in impact scenarios where fibre failure occurs (Pascoe et al., 2019).

(a) Delamination shadowing

(b) Data reduction

Fig. 1: Issues in quantifying damage severity based on ultrasonic C-scan information.

Even when only considering delaminations, it is important to be aware of the limitations of NDI techniques in both lab and operational settings. Typically, ultrasonic techniques are used, where damage is detected based on either the attenuation or reflection of ultrasonic waves by the delaminations. When relying on reflection, one runs into the issue of shadowing: delaminations closer to the surface of the laminate will block the sound waves from reaching deeper delaminations, meaning that those delaminations cannot be detected (Figure 1a). When using through-transmission (attenuation) based scanning, the scan will project all delaminations onto the same plane. Thus the actual 3D configuration of the delaminations is lost, and only a 2D projection can be retrieved, which hides the fact that delaminations in different interfaces have different orientations and sizes.

This leads to the issue of data reduction in describing the delamination configuration. As mentioned above, the actual delamination configuration after impact is a complex 3D state, with delaminations in many different interfaces, each with their own orientation, shape, and size. However, researchers tend to quantify the delamination state by only a single number, e.g. the projected area, or the delamination width or length (Figure 1b). Despite this data reduction, researchers have reported strong correlations between CAI strength and damage measures such as project area or damage width, see e.g. Nettles and Scharber (2018). Note however, that these correlations are established within a single test series, where typically the impact energy is varied, but the impact boundary conditions and laminate lay-up and thickness are kept constant. In such a situation one can imagine that there are strong correlations between the different delaminations within a laminate, such that a single parameter can suffice to describe them all. However it does not follow that the correlation between different delaminations will remain the same if the impact boundary conditions or laminate lay-up are changed. Thus it's unclear if correlations between reduced parameters (e.g. projected area or delamination width) and CAI strength, established by standardised coupon testing, can be generalised to hold for other lay-ups or full-scale structures. This makes it very difficult to establish acceptance criteria for damage detected in service that are not overly conservative.

In short, it is not clear which information is actually needed in order to correctly characterise the severity of any damage. Is it indeed the projected area, or the width of of the largest delamination that is critical? Or do the depth of a delamination, or which plies are adjacent to it also matter? What about the presence of other delaminations in the laminate? This lack of clarity as to which information is needed follows directly from a lack of understanding of the fundamental damage and failure mechanisms. Thus, developing a better understanding of these mechanisms has to be the first step. Once the critical parameters have been identified, capability requirements for NDI techniques can be defined, to ensure the necessary information can also be collected in practice. Furthermore, identifying the critical parameters will also help identify what features of damage evolution under fatigue loading need to be represented by damage growth prediction models.

4. Fatigue delamination growth

In order to manage damage according to a slow growth concept, an accurate prediction of the damage growth under fatigue loading is crucial. However, research in this area is rather limited. Most fatigue after impact (FAI) research has focussed on S-N approaches, where fatigue life is related to the applied stress amplitude (Davies and Irving, 2015). Of course, the problem is that the S-N curve obtained will be specific to the initial damage size, which means that S-N curves need to be obtained for different initial impact scenarios, requiring a large test programme. There is evidence that normalising the applied stress amplitude by the CAI strength can collapse S-N curves for different impact energies, with other conditions remaining identical (Uda et al., 2009). This suggests it may be possible to extrapolate behaviour from an S-N curve generated for a single impact scenario. Further research is necessary to understand to what extent such generalisations are possible. In any case however, because S-N curves only provide the number of cycles to failure, starting from a specific initial condition, they cannot be used to carry out effect of defect analyses.

Some work has been done to monitor the growth of delaminations under constant amplitude FAI loading (Davies and Irving, 2015; Chen et al., 2002; Xu et al., 2017), and Mitrovic et al. (1999) have studied variable amplitude. Unfortunately, these works have been hindered by many of the issues described in Section 3. Rather than monitoring the evolution of individual delaminations, researchers were only able to measure projected damage areas. Davies and Irving (2015) highlight that the reported fatigue behaviour is not consistent. Some researchers report a long period in which no growth occurs, e.g. Isa et al. (2011); Ogasawara et al. (2013) and Xu et al. (2017), whereas others report continuous growth (Chen et al., 2002; Mitrovic et al., 1999) with the projected area or delamination width evolving as schematically shown in Figure 2. There appears to be a short period of initial growth, followed by a long plateau period in which very little growth appears to occur. This plateau continues until there is a sudden acceleration, with sustained rapid delamination growth until the specimen fails shortly afterwards. For authors who report no initial growth there is a similar plateau region, in this case completely horizontal, followed by a period of (very) fast growth.

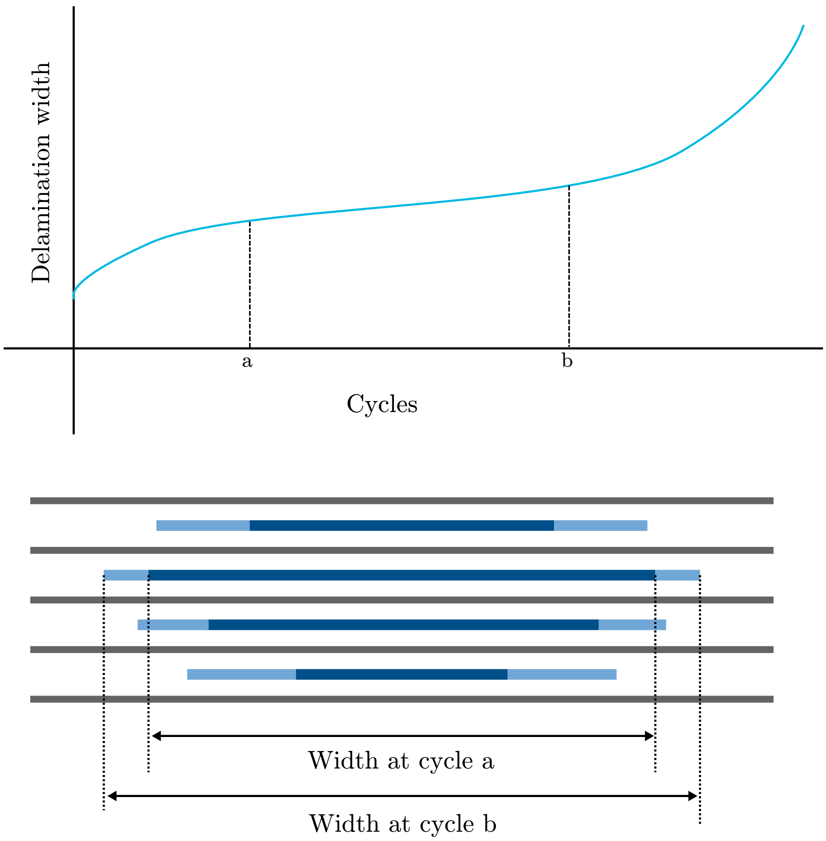

Fig. 2: Typical fatigue delamination growth behaviour as reported in literature and a schematic illustration of how undetected delamination growth could present the illusion of a plateau region.

The obvious questions here are why is there such a plateau region, and why do the delaminations suddenly accelerate? It is important to realise that the delamination width only provides a measure for the largest delamination. It is very likely that the different delaminations present after an impact will all grow at different rates, as it has been shown that the different delaminations face different crack driving forces, based on their size and depth in the laminate (Melin et al., 2002; Zhang et al., 2012). As illustrated in Figure 2, it is possible that the largest delamination grows slowly, while other delaminations grow much faster. If one is only measuring the width of the projected damage area, this would give the illusion of a plateau region in which not much growth is happening, when actually there is a much larger amount of delamination growth. The sudden acceleration could then be triggered by the hidden delaminations reaching a particular configuration where they also trigger growth of more visible delaminations. This hypothesis needs to be experimentally tested. One piece of evidence which is already available is the work of Xu et al. (2017), who found that the acceleration of the delamination growth corresponded to a change in the buckling mode of the specimen. Another hypothesis is that the sudden acceleration near the end of the fatigue life is triggered by saturation of a damage mode (e.g. matrix cracks) which is not detectable by ultrasonic scanning.

When attempting to model fatigue delamination growth, it should be noted that this phenomenon is typically studied using standard specimens (e.g. double cantilever beam (DCB), mixed-mode bending (MMB)) that differ from actual structures (and standard CAI specimens) in a number of important respects:

- **Ply orientation jump** In standard delamination growth, the fibre angle on either side of the delaminating interface is the same. Usually delamination of a 0//0 interface is studied, although in rare cases a 45//45 or 90//90 interface may be examined. In impacted specimens on the other hand, one typically only finds delaminations at interfaces where there is a fibre angle mismatch, e.g. at a 0//45 or 45//90 interface. Blondeau et al. (2019) have provided an overview of research on fracture toughness of multi-direction interfaces, showing that some researchers found an effect of fibre offset angle on fracture toughness, while others didn't. Investigation of fatigue delamination growth in a multidirectional interface has been done (Banks-Sills et al., 2019), but comparisons with a unidirectional interface could not be found.
- **Linear vs planar delamination growth** In standard delamination growth specimens, the growth is one dimensional, and can be adequately characterised by the delamination length. In the case of FAI however, the delamination might grow in two dimensions. This also could mean that the mode-mix changes along the delamination front, and that the little studied mode III crack growth behaviour could also be relevant. The potential change of mode-mix along the crack front raises the question of whether the strain energy release rate (SERR) is the best similitude parameter to characterise the crack driving force, or whether a different parameter such as the strain energy density (SED) is more appropriate (Amaral et al., 2018; Daneshjoo et al., 2019; den Ouden, 2020). Set-ups to investigate planar growth behaviour (Cameselle-Molares et al., 2018; den Ouden, 2020), and numerical techniques capable of dealing with two dimensional growth (Carreras et al., 2019; Amiri-Rad et al., 2017) have been proposed, but need further development.
- **Presence of multiple delaminations** In the standard specimens there is only a single delamination, whereas an impact will generate a delamination at each interface in the laminate where the fibre orientation changes. These delaminations will interact with each other by changing the local stress fields, as well as the constraint against (local / sub-laminate) buckling. Correctly predicting the effects of these interactions will likely require high-fidelity numerical modelling. If crack propagation is included in these models, the computational expense will be very high, limiting the number of damage scenarios that can be studied. A computationally cheaper strategy could be to focus on understanding the crack driving force distribution for different delamination configurations, without including crack propagation in the model. Such a strategy can provide qualitative insight and general predictions for how certain scenarios will evolve (Pascoe et al., 2013a). This understanding can help validate the selection of worst case scenarios to investigate with higher fidelity models. Being able to justify which damage configurations constitute the worst case can avoid unnecessary analyses or testing during certification of a structure.

Looking broader than just FAI, it is important to highlight that prediction of fatigue driven delamination in composites in general relies on empirical correlations, rather than an understanding of the physics of delamination growth (Pascoe et al., 2013b; Alderliesten et al., 2018), limiting their applicability to cases where sufficient experimental data is available. Current numerical techniques under development for modelling of FAI tend to incorporate existing fatigue delamination growth criteria, and so suffer from the same short-comings. While numerically capable of representing two-dimensional growth, the underlying physical theory is lacking. There is a clear need for more experimental data showing what physically happens in the material during FAI, especially at the level of individual delaminations. Even qualitative descriptions of how damage evolves under fatigue loading are currently very limited.

5. Final failure

Prediction of quasi-static CAI strength has received quite a lot of attention over the past decades. Nevertheless, for actual structural components, prediction of residual strength still relies heavily on empirical correlations generated for specific components. The difficulties of characterising in-service damage (see Section 3), as well as the known sensitivity of impact damage to impact and boundary conditions, mean that it is currently not possible to predict residual strength of a component based on generic coupon tests. Furthermore, damage detected in service can often not be correlated to CAI testing conducted during structural development, leading to perhaps overly conservative repair and replacement decisions.

Complicating this matter is the fact that there is as yet no consensus as to the critical damage mode that leads to final failure under quasi-static compressive load. Sun and Hallett (2018) and Bull et al. (2018) point to the importance of unstable delamination, and the role of delamination growth into the undamaged cone. On the other hand, Nettles and Scharber (2018) present a series of experiments where for a given damage size, the CAI strength does not depend on fracture toughness, implying that delamination does not trigger final failure. Instead, Nettles and Scharber suggest that it is fibre failure, due to stress concentrations around the delaminations, which causes final collapse of the specimen. Uniting these views, Yang (2016) conducted numerical simulations which indicate that delamination and fibre failure may in fact be competing mechanisms. Which of these damage modes is critical depends on the lay-up and delamination configuration.

In order to settle this debate, future research should place emphasis on understanding the physical mechanisms, rather than predicting the residual strength of a specific configuration. It should be realised that an ability to predict, especially when limited to specific cases, does not necessarily imply an understanding of the physical behaviour of the problem. Given the many variables that play a role in CAI failure of a laminate, there is a pressing need to develop this understanding of the physical behaviour, so that general rules governing the behaviour can be identified. It would already be a significant step if we could confidently define worst case scenarios, based on physical rules governing CAI failure. Finding such rules requires research dedicated to better understanding the physical mechanisms, rather than predicting residual strength for a particular case.

Recently, high fidelity models have been reported in the literature, which are capable of achieving accurate predictions of CAI strength (Sun and Hallett, 2018). However, these models are computationally expensive, even for the relatively small (150 x 100 mm) ASTM standard CAI coupon, and the results are applicable only for one impact scenario, on one specimen geometry, with one specific lay-up. While these models can help us understand the physical mechanisms, using them for design purposes, to evaluate many different lay-ups, is impractical. Similarly the computational cost is too high to use these models to evaluate the severity of damage detected in-service. Recently Wang et al. (2020) published an analytical model which showed good results for the case of a single elliptical delamination. This approach may be suitable for rapid evaluation of in-service damage detection, but will need to be extended to multiple delaminations of arbitrary shapes first.

There is also the question of how to correctly incorporate damage detected in service into any models, taking into account the issues discussed in Section 3. One way of basing the damage on NDI indications has been suggested by Baluch et al. (2019). More often, high fidelity models first model a specific impact scenario, to generate a more detailed damage description than is possible to obtain by NDI. While studying a known impact is valuable for research and design purposes, it should be remembered that in service the impact scenario will typically be unknown, and the NDI damage detection needs to be the starting point of the analysis.

Another point to highlight regarding final failure is that a slow-growth analysis may have different needs when it comes to residual strength. Traditionally, a certain damage configuration is taken as an input, and researchers predict the residual strength for that particular damage. This approach is useful if a desired critical damage size is selected, e.g. to obtain a desired inspection interval. Then the length of the inspection interval and the residual strength can be traded against each other.

However, in other cases, e.g. if unexpected damage is detected in serivce, the known design limit load (DLL) sets the residual strength requirement. The question then is, up to what size can the damage be allowed to grow, such that the residual strength does not decrease below DLL? In other words, the question then is not what is the critical load for a given damage, but rather, what is the critical damage size for a given load? Note that due to the complexity of damage in an impacted laminate, and the possibility of interaction between different damage modes, 'critical damage size' in this context should be understood as referring to a certain delamination envelope, or a set of critical damage configurations, rather than a single length or area measure.

6. Conclusion

Switching to a slow-growth damage management concept for CFRP structures with impact damage could offer weight benefits. However, before this is possible, knowledge gaps need to be addressed in three areas.

1. **Damage Characterisation** A better understanding is needed of how to quantify the severity of impact damage. Which damage features do and don't need to be described? What level of data reduction is appropriate? Which damage modes do we need to be able to detect? What NDI capabilities are needed, and how to deal with known shortcomings?
2. **Fatigue driven delamination growth** There is very limited information available on how impact damage evolves under fatigue loading. Experimental data providing a 'narrative' of how this damage evolves would already be a helpful first step. New experimental methods are also required, because current test methods such as DCB and MMB do not investigate effects such as multi-directional interfaces, 2D growth, and the presence of multiple delaminations. Furthermore, current delamination prediction models rely on empirical correlations, rather than an underlying physical theory.
3. **Final failure** The cause of final failure is still being debated. There may be competing failure modes, with the critical mode being dependent on the specific laminate and damage configuration under investigation. Research should aim to the failure mechanisms and generate broadly applicable rules, rather than predicting residual strength in particular cases. Furthermore, there is a need to predict the critical damage size for a given maximum stress, in order to determine the maximum size to which damage can be allowed to grow.

Addressing the questions posed above will require new research directions. Some suggestions for this were given in the preceding text. In general it can be said that the focus needs to be on improving our scientific understanding of damage mechanisms, rather than on predictions of the behaviour of specific laminates or engineering structures. This will deepen our understanding of fracture and fatigue in composite materials, having benefits not only for fatigue after impact, but for understanding failure and damage tolerance in composite materials more generally.

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