TOWARDS UNDERSTANDING RESIDUAL STRENGTH AND DAMAGE EVOLUTION IN DAMAGED COMPOSITE LAMINATES

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Abstract: Fibre reinforced polymer composites have found increasing use in aircraft structures. This means that fleet managers need damage assessment tools for such materials, in order to decide on appropriate sustainment strategies. Developing such tools is hindered by the difficulty of generalising from lab tests to predict the behaviour of full-scale structures. A more focussed research effort is needed to address the knowledge gaps that prevent such generalisations. This paper highlights the limitations of current non-destructive inspection techniques, and how this can lead to misinterpretation of experimental results. Furthermore, it discusses differences between coupons and full-scale structures caused by 1D vs 2D delamination growth and the effects of lay-up. New test methods to deal with these issues are discussed and some preliminary results are presented. Finally, the paper discusses the prediction of residual strength and the difficulties of determining a suitable end-point for damage propagation analyses. While the residual strength in the presence of a given damage can be accurately modelled for small components, if sufficiently computational resources are available, further development is needed to develop tools that can be implemented for sustainment of operational aircraft.

Keywords: CFRP, Damage Tolerance, Delamination, Fatigue, NDT

INTRODUCTION

The use of fibre reinforced composites for high-strength, low-weight, structures, such as in use in aerospace, is by now well established. The structures of the A350 and Boeing 787, which are reaching their first decade of service, contain just over 50% by weight of composite materials. In the military world, the F-35's structure is about 35% composite [1]. For modern helicopters, such as the NH-90, the fraction of composite materials can even exceed 90% [2].

These composite structures have generally been designed using the 'no-growth' concept, as explained in the Federal Aviation Administration (FAA)'s advisory circular 20-107B [3] and the European Union Aviation Safety Agency (EASA)'s acceptable means of compliance (AMC) 20-29 [4]. This means that the structures have been designed to be free from fatigue issues, even in the case of barely visible

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damage, e.g. caused by manufacturing defects or impact damage. Achieving this design concept is aided by the large knock-down factors on design allowables, which are currently applied to account for manufacturing defects and environmental effects, and to ensure sufficient quasi-static residual strength. As a consequence, MIL-HDBK-17-1F advised: *``It is important to note that, for the majority of current aircraft composite structure, fatigue capability does not become a limiting factor if all static strength concerns have been thoroughly and successfully addressed. Exceptions to this are high-cycle components such as those found in helicopter dynamic systems''.* Note that the MIL-HDBK is not stating that composite materials do not fatigue. Rather, the implication is that the safety factors used to ensure sufficient static strength are so high, that stress and strain levels in the structure are low enough to prevent fatigue from occurring due to the normal loading expected during the operational life of the aircraft. As reported by Vassilopoulos in his very comprehensive review [5], the first investigations of fatigue in composite materials were concurrent with their development in the 1940s and 50s and fatigue of composites has remained an active field of research ever since.

Molent and Haddad [6] note that a 'slow growth' design approach could potentially lead to weight savings, but could also provide more flexible fleet management options if damage is found in service. Such a slow-growth approach is allowed by the regulatory guidance in AC 20-107B / AMC 20-29, but only if the damage growth can be shown to be 'slow, stable, and predictable'. Molent and Haddad [6] provide a review suggesting that 'slow' and 'stable' can be achieved in many cases, but prediction of the damage is not yet possible. It should also be noted that while Molent and Haddad provide examples of slow and stable damage growth, other researchers have presented examples of apparently sudden acceleration of damage growth under fatigue loading (e.g. Chen et al. [7], Tuo et al. [8], Xu et al.[9]).

Notwithstanding the no-growth design concept, growth of damage from manufacturing defects can be induced in the lab [10] and has also been found in operational aircraft under certain conditions [11]. Therefore, from a sustainment point of view, if a damage is found on an aircraft, tools are needed to evaluate the consequences of this damage. In particular two issues are relevant: (1) what is the residual strength of the structure, and (2) will the damage grow under the influence of fatigue loading?

At the moment, the residual strength and fatigue behaviour of damaged composite laminates is mainly substantiated by tests, conducted during development and certification of the aircraft structure. As a consequence, if damage is detected in service, its severity can only be judged by comparing it to these tests, which may not exactly reproduce the damage location and or boundary conditions. This makes it difficult to evaluate the severity of damages that do not exactly match the scenarios investigated during development. As a result, when evaluating damage, conservative damage limits are employed and parts and even entire aircraft are potentially retired prematurely.

To support sustainment of aircraft, better tools are needed to enable evaluation of the severity of damage and to predict its evolution. This has not gone unnoticed by the research community, who have dedicated considerable effort to the investigation of both residual strength and of fatigue of composites. While these efforts have produced valuable insights, the limitations of the experimental designs make it difficult to generalise the results of these efforts to full-scale structures. Therefore, we argue that rather than continue with traditional experimental designs, new research directions are needed to bridge the gaps between typical test coupons and full-scale structures. In this paper we will highlight the most important knowledge gaps, and suggest ways of addressing them.

LIMITATIONS OF DAMAGE DETECTION TECHNIQUES

The first step to evaluating the severity of damage and its possible evolution is to understand the damage mechanisms involved, which we will review in this section, along with some of the available techniques to detect this damage both in the lab and in service.

Damage mechanisms in composite materials

A fibre reinforced polymer composite consists of fibres and a matrix material. In a very general sense, we can therefore identify three kinds of damage: damage to the fibres, damage to the matrix, and damage to the fibre-matrix interface. While these damage modes can occur in isolation, typically they interact, and one kind of damage can trigger another kind.

Instead of categorising damage by which constituent is being damaged, we can also categorise damage by the plane in which it occurs, such as when we distinguish between delaminations and transverse matrix cracks, which are both combinations of matrix damage and fibre-matrix interface damage, as illustrated by Figure 1.

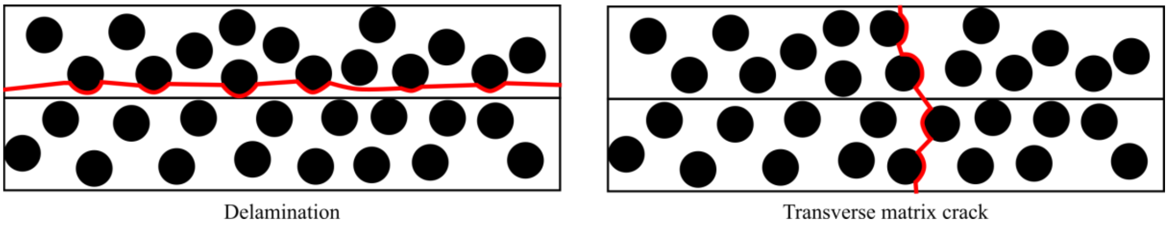


Figure 1: Schematic illustration of delamination and transverse matrix cracking as combined damage modes.

Characteristic of composite materials is that a damaged composite can contain many different physical damages. Thus 'damage growth' in a composite can refer to the physical extension of a particular crack or delamination, but also to the creation of new cracks or other damages in the material, or in other words, to an increase of damage density.

Damage detection techniques

A variety of techniques are available to detect damage, some of which are more applicable to a lab environment, and some of which are also available in operational settings.

Micrographic cross-sections can provide very detailed pictures of damage. When performed carefully, this technique can be used to identify matrix cracking and delaminations, but with the downside that it is inherently destructive. This makes it applicable for lab research, but not to assess damage in service. Even during lab experiments, the necessity to cut the specimen means it cannot be employed to track damage evolution. One could try to track damage evolution by using multiple specimens and e.g. section one specimen after 50% of the fatigue life, the next after 60%, and so on. However, the amount of scatter typically seen in fatigue experiments makes such a comparison across specimens difficult. What is 50% of life for one specimen could already be 60% for the other. Furthermore, it is often unclear which cutting plane would offer the best view of the damage, especially if the damage propagates in multiple directions, as is e.g. the case for planar delaminations.

Micro computed tomography X-ray (Micro CT) can solve many of the drawbacks of cross-sectioning. It is in principle non-destructive, (as long as the specimen will fit inside the scan chamber), and with sufficiently high-resolution equipment is even able to identify fibre breaks [12]. However, this equipment is not widely available, and for the foreseeable future will also be limited to lab applications. To the best of the authors' knowledge, this technology has not yet been used to study damage evolution during fatigue. This would be a challenging experiment to conduct, requiring the use of interrupted testing, but could potentially provide valuable insights.

Ultrasonic scanning (also known as C-scan) is by far the most commonly used technique for damage detection, at least in research settings. It is a non-destructive technology, that can be employed both in the lab and in the field. However, this technology also has significant limitations, which need to be understood in order to avoid being misled by the results. The underlying principle of ultrasonic scanning is to detect the interaction between ultrasonic waves and damage in the composite materials. We can distinguish between two modes of operation: through-transmission and pulse-echo.

In through-transmission scanning, one measures the attenuation of an ultrasonic signal that has passed through the thickness of the laminate. The downside of this mode is that it does not provide information on the depth of any damage, and therefore does not allow one to distinguish between damages located at different interfaces.

In pulse-echo scanning, one detects the echo returned when the sound wave encounters the damage. By measuring the time between emission of the signal and detection of the echo, the depth of the damage can be determined. However, damages located at a shallower depth in the laminate can shadow deeper delaminations, preventing building up a full picture of the damage configuration. A more detailed comparison between the two ultrasonic scanning modes and their limitations is provided elsewhere in these proceedings [13].

A limitation of both types of ultrasonic scanning is that they typically are only sensitive to damage modes that have a large damage area perpendicular to the travel direction of the soundwaves. I.e., this technology is suitable for detecting delaminations, but is not well suited for detecting matrix cracks or fibre breaks. Thus, when relying solely on ultrasonic scanning to inspect a specimen, it is important to keep in mind that undetected damage mechanisms may also play a role in the degradation of the specimen. Recently, Morokov et al. [14] demonstrated that a variant of ultrasonic scanning, called ‘acoustic microscopy’ is potentially capable of detecting matrix cracking, and can also avoid damage shadowing. At the moment, this technology is not yet widely available, but it could provide interesting insights in future.

A different kind of acoustic technique is **acoustic emission.** This is a passive technique in which sensors are used to detect ultrasonic signals emitted when damage mechanisms occur. A downside of this technique is that a signal is only emitted when the damage occurs, and thus it cannot be used to inspect a structure after the fact. Nevertheless, many researchers are investigating the potential of acoustic emission for structural health monitoring systems. In a research setting, the value of acoustic emission is that proper analysis of the signals can allow one to distinguish between different damage modes and thereby identify at which point during an experiment which modes are active [15]–[17]. When combined with other techniques, e.g. ultrasonic scanning to monitor the growth of delaminations, acoustic emission can provide valuable insight into the activity of otherwise undetectable damage modes.

In addition to acoustic techniques, there are optical techniques, such as **shearography** and **digital image correlation**, which detect differences in surface strain above damaged areas of the laminate. Another popular technique is **thermography,** which detects damage through differences in the thermal response of different areas of a laminate. All three techniques have in common with through-transmission ultrasound that they can only provide a 2D projected damage area, and cannot distinguish between damage in different interfaces of the laminate.

In summary, there are a variety of inspection techniques available, but they all have limitations, especially those that are applicable for use in service. Many techniques are only capable of detecting delaminations, and even then the full 3D configuration of the damage may not be captured. It is important to keep these limitations in mind when trying to come up with a suitable measure to quantify the damage severity, and to avoid being misled by experimental results. As new non-destructive methods are being developed [18], it is important to ensure an understanding of the underlying physics is used to set requirements for what damage needs to be detected and with what resolution, rather than letting the limitations of the available methods be implicitly ‘baked in’ to our damage models.

QUANTIFYING DAMAGE

In order to discuss damage growth, or to easily express the severity of a particular damage, it is desirable to be able to quantify it. In metal structures, damage is usually quantified in terms of the crack length. This is a relatively unambiguous measure (at least in the case of a single, through-thickness, crack in a plate-like structure) that has a clear correlation to both residual strength and the crack growth rate.

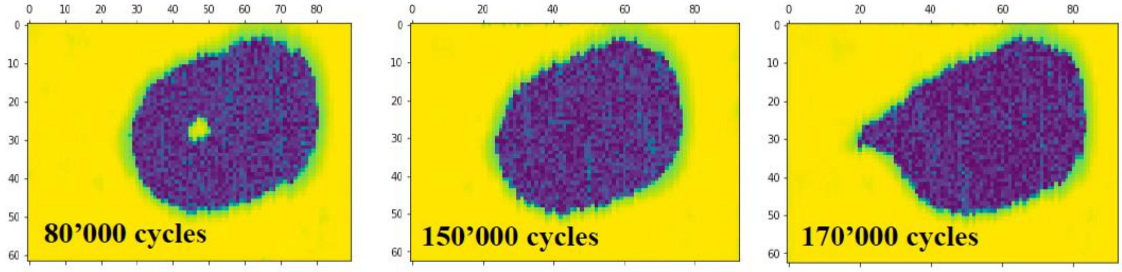
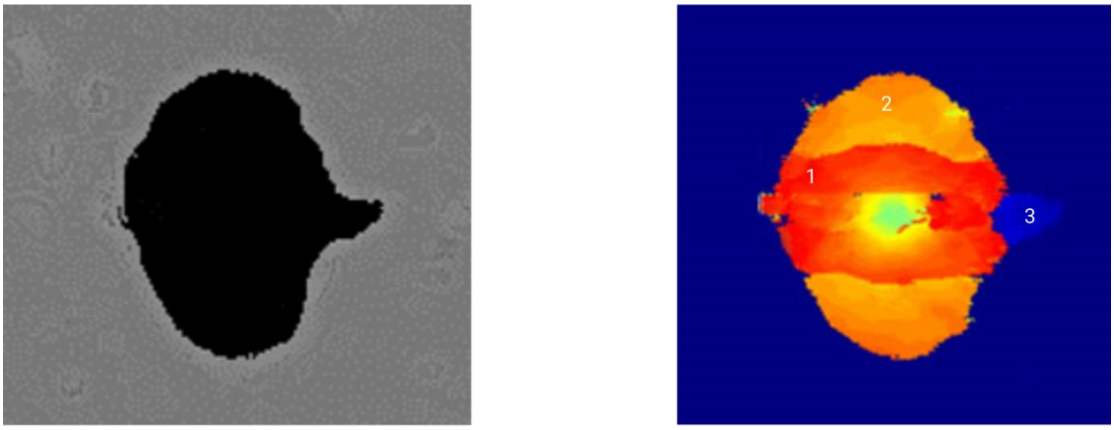


Figure 2: Delamination growth during a fatigue after impact test monitored with through-transmission ultrasound. Reproduced from [53]

For composites, as mentioned, many researchers have relied on ultrasonic scanning to monitor damage size after impact or during fatigue tests. This led to the use of geometric properties of the delamination to quantify the damage. Popular choices are to either use the projected damage area, or the delamination width. However, as we will illustrate, both choices are problematic.

Figure 2 shows the growth of a delamination during a fatigue after impact test. In the leftmost panel it can be seen that initially the specimen contained a non-delaminated cone in the centre of the damaged area (a typical feature of impact damage in composites). As more fatigue cycles were applied, the delamination growth was first inwards, closing this non-delaminated area, as visible in the centre panel. Only after this did damage grow outside of the initial damage envelope. In this case, if the width of the delamination had been taken as a damage parameter, it would have seemed as if no growth had occurred for the first 150,000 cycles of fatigue loading, when actually delaminations were already growing.



Through-transmission

Pulse-echo

Figure 3: Comparison of through-transmission vs pulse echo view of the same damage. The colours in the right panel correspond to different depths in the laminate.

One might instead suggest that the delamination area could be an appropriate measure, as long as one correctly subtracts the non-delaminated area in the centre of the damage zone. However, in that case one should realise that Figure 2 does not show only a single delamination. As illustrated in Figure 3, a single area of attenuation in a through-transmission scan can correspond to damage located at different interfaces. In the case of Figure 3, at least three different delaminated interfaces can be identified. Since these are delaminations with different shapes, and located in the interfaces between different plies, using the combined projected area as the damage metric seems inappropriate.

In quasi-static compression after impact testing a correlation has often been found between the projected damage area and the residual strength. However, in these cases it should be noted that the impacts were produced with the same boundary conditions, just varying the impact energy. This means different damage features likely scale with the energy in a similar way, and there is a correlation between the projected area and the more detailed damage configuration. If the boundary conditions would be

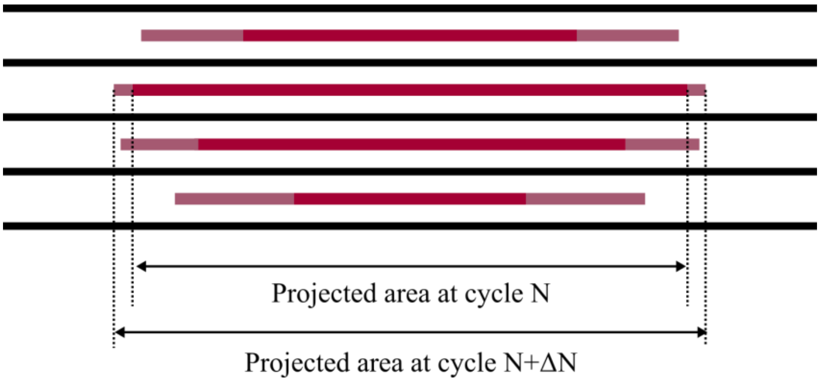


Figure 5: Illustration of damage shadowing resulting in projected area not capturing the amount of damage growth correctly

changed, the same impact energy could result in a different damage configuration. Then, the damage features would not correlate to the projected area in the same way. Consequently, we cannot assume that the relationship between projected area and residual strength will be the same if the boundary conditions of the impact event are changed.

Another issue with the use of projected area as damage metric is illustrated by Figure 4. Due to shadowing of damage, it is possible that smaller delaminations could grow by a significant amount without changing the overall damage envelope. In that case there would be no change to the projected area, while significant delamination growth was in fact occurring. This could be a partial explanation for the apparent plateau often reported in fatigue damage propagation experiments, as illustrated in Figure 5. Of course if the plateau is truly horizontal, it also needs to be explained why the largest delaminations don’t grow at all, resulting in the projected area remaining constant. For this, further investigation is needed to understand the crack driving forces during the fatigue cycle.

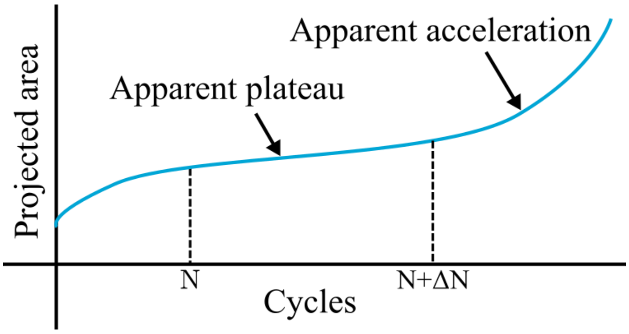


Figure 4: Typical progression of projected delamination area during a fatigue experiment.

Figure 5 shows another often reported feature, which is that at some point in the fatigue life the growth of the projected area accelerates. One possibility is that this simply represents a change from shadowed growth, to growth outside the original delamination envelope. Another possibility is that the delamination growth is accelerated by the accumulation of a different damage mode, e.g. matrix cracking or fibre fracture, reaching a critical threshold. Figure 5 only shows the progression of the delamination area, while other damage mechanisms are likely also active during the test. Relying only on ultrasonic scanning can therefore be misleading, as it means that some of the damage modes are invisible. Future research should thus work to identify which other mechanisms are active during a fatigue test, and how this activity evolves over the fatigue life.

The preceding discussion has shown the potential pitfalls of trying to quantify damage in a composite laminate with a single parameter. However, although a more complex description would do more justice to the physical complexity of the problem, it would also be more difficult for engineers to work with in practice. Therefore it should be investigated how detailed a damage description needs to be, or whether simplifying assumptions can be used to reduce the complexity of the problem, without sacrificing (too much) predictive capability, as suggested by Baluch et al. [19]. Justifying such simplifications of course first requires a good understanding of the underlying physical mechanisms and their sensitivity to the damage configuration.

PLANAR DELAMINATION GROWTH

Despite extensive work by bodies such as the European Structural Integrity Society (ESIS) and ASTM International [20], [21] there is still no standard for experimental measurement of fatigue driven delamination growth. Nevertheless, a de facto standard approach has been adopted in the literature, with most researchers making use of the same specimen geometries, based on published standards for quasi-static delamination growth resistance. Examples include the double cantilever beam (DCB) specimen (defined by ASTM D5528 or ISO 15024:2023) and the mixed mode bending (MMB) specimen (defined by ASTM D6671).

What these methods have in common is that they are designed to allow delamination growth to be studied in isolation, without interactions with transverse matrix cracking. Furthermore, in these specimens the delamination front is treated as being straight (or at least, constant) across the specimen width. This reduces the delamination growth to a one dimensional problem, with only the delamination length being sufficient to characterise the delamination.

However, in real structures delaminations typically have a planar shape, and can grow in two dimensions, as illustrated in Figure 2 and Figure 3. Such a delamination growth brings with it many issues that are not covered by the one dimensional tests. For example, for a planar specimen the mode mixity will most likely vary around the circumference of the delamination. The fibre orientation with respect to the delamination front will similarly vary around the circumference. Furthermore, the delamination growth is not necessarily uniform (see Figure 2, although note that this image likely shows a composite of delaminations in multiple interfaces) and so cannot be easily captured by a single scalar. Fully capturing planar delamination growth most likely would require the use of a vector field distributed around the entire delamination front.

Because the fibre orientation is not uniform around the circumference of the delamination, delamination migration will tend to occur during planar delamination growth. An example of this can be seen in the right panel of Figure 3. This figure shows an ultrasonic scan of a composite panel with a circular PTFE insert that was subjected to out-of-plane loading. Due to this loading a delamination grew from the insert. Where the delamination growth direction was parallel to the adjacent fibre direction, the delamination remained in the same interface as the insert (the area labelled ‘1’ in Figure 3). However, in the region where the delamination growth direction was perpendicular to the fibre direction, the delamination first migrated to an adjacent interface, where it could then grow parallel to the fibres (area ‘2’ in Figure 3). This migration behaviour is in accordance with what has been previously reported by Canturri et al. [22], but still remains challenging to deal with in prediction models.

It should be noted here that delamination migration is often regarded as an undesired artefact of a test, which is to be eliminated by proper experimental design. This is true if the objective of the test is to specifically characterise e.g. the interface fracture toughness. However, from the data that is available so far, it would seem likely that migration is something that will occur naturally in full scale structures. Therefore, we should seek to understand it and be able to predict its occurrence, not simply eliminate it from our tests. Some researchers have developed experimental set-ups specifically for investigating, such as Canturri et al. [22] and Pernice et al. [23]. Further research along such lines is needed, as it seems unlikely that we will be able to correctly predict the delamination growth behaviour in a full-scale structure, based purely on coupon testing in which delamination migration does not occur. To add to the preceding discussion on damage quantification, delamination migration is another reason why using a single parameter to quantify the delamination severity is likely not enough.

To study planar delamination, new experimental methods are being developed, in which the delamination actually grows in two dimensions. Recently, such set-ups have been proposed by Cameselle-Molares et al. [24] and by den Ouden [25], [26]. Results from a further development of den Ouden's set-up are presented elsewhere in these proceedings [27]. The aforementioned set-ups all apply out-of-plane loading to grow the delamination. For in-plane loading, the set-up used for compression after impact testing in ASTM D7137 can be modified to be used in fatigue.

Compared to the beamlike specimens used for one dimensional delamination growth testing, these set-ups have the challenge that the delamination size cannot be monitored from the side of the specimen. Possible solutions include the use of translucent specimens (possible when using glass-fibre based composites, but not for carbon fibres), the use of indirect methods such as digital image correlation to monitor delamination growth, or interrupting tests to perform ultrasonic scans.

The results of these planar delamination growth experiments can then be used to develop and validate predictive models. Planar delamination growth specimens typically require more material than the beamlike specimens used for one dimensional growth. Therefore, it would be interesting to examine to what extent planar delamination growth can be predicted based solely on parameters derived from experiments on beamlike specimens.

EFFECT OF LAY-UP

Composite structures usually make use of multi-directional laminates. This adds an additional challenge for the prediction of damage propagation (whether under quasi-static or fatigue loading), because the lay-up will affect which damage modes occur, if and how damage modes interact, and how damage modes will propagate. For example, the preferred direction of delamination growth, and whether it will migrate, is determined by the fibre orientation adjacent to the fibre interface [22].

Many researchers have developed models to predict the fatigue life of a composite laminate. Typically, these models need to be initialised with material parameters determined by fatigue testing of coupons. What is usually seen is that these models can then produce accurate predictions for validation cases where the lay-up matches that of the coupons used to generate the initiation data. However, the accuracy is much lower when the validation case makes use of a different lay-up. An illustrative example is the comparative study performed by the US Airforce Research Laboratory (AFRL) [28], which compared seven different models. Overall, the average error for the blind prediction of residual strength and stiffness was 42%.

To properly account of the effect of lay-up on the fatigue life, the effect of fibre orientation on different damage modes needs to be understood. However, the standard test set-ups used for fatigue delamination growth all make use of unidirectional lay-ups, with the same fibre orientation (nearly always 0^0) on either side of the delaminating interface. The effect of fibre orientation on quasi-static delamination has received a decent amount of attention; see for example the review in the introduction of Ref. [29], as well as recent works by Pichler et al. [30] and Mollenhauer et al. [31]. The effect of fibre orientation on fatigue driven delamination growth has been reported in Refs. [32]–[39]. While these works present data on individual interfaces other than 0//0, a systematic comparison of different interfaces is lacking, let alone a model that can account for the fibre orientation. A step in this direction has been provided by van der Panne [40], [41] who investigated seven different interfaces. A summary of the results for the 0//0, 0//45, and 0//90 interfaces is shown in Figure 6.

The results match what has previously been found for quasi-static delamination growth [29]. In quasi-static growth, the initiation toughness is hardly affected by the fibre orientation, as it mainly depends on the matrix properties. However, as the delamination grows, the propagation toughness or R-curve behaviour does depend on the fibre orientation. This is because different fibre orientations allow for different toughening mechanisms such as progressive [30] or even oscillatory [31] migration behaviour. Similarly, as shown in Figure 6, van der Panne found that for short pre-crack lengths, where there is not

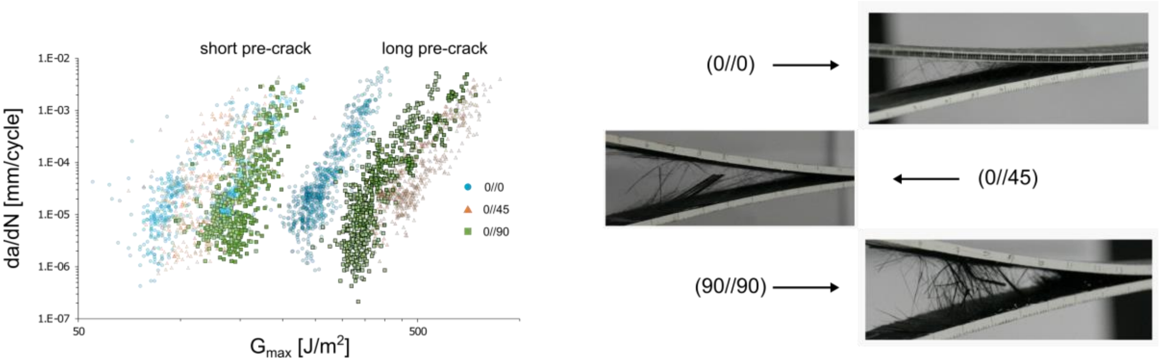


Figure 6: Fatigue delamination growth rates for different interfaces. The Paris curves (crack growth rate versus maximum strain energy release rate) are shown on the left, while the different fibre bridging behaviours are shown on the right. Data from Ref. [36]

much fibre bridging, the effect of fibre orientation on the Paris curves is relatively limited. On the other hand, for long pre-crack lengths, the effect is much larger, and the fibre bridging and/or delamination migration behaviour is qualitatively quite different, as shown in the photographs in Figure 6. For the 0//90 and 90/90 interfaces, the same oscillatory migration was observed as was reported by Mollenhauer et al. [31] for the quasi-static case.

The initial reaction here might be to dismiss the delamination migration as a test artefact and therefore declare the results invalid. Indeed, it is true that the occurrence of migration means that it is not entirely clear how the data should be properly analysed, and the graphs in Figure 6 should not be interpreted as representing any kind of material property. Nevertheless, it seems clear that delamination migration should also be expected to occur in multidirectional laminates in full-scale structures. While one approach could be to simply rely on the 0//0 interface properties (where there is no delamination migration) as a ‘worst-case’ curve, a more accurate approach would be to seek to properly understand delamination migration, and develop the capability to accurately predict its occurrence and effect on delamination growth, e.g. by building on work such as that of Mollenhauer et al. [42] and Pernice et al. [23]. Given the large shift in the delamination growth curves shown in Figure 6, it seems that toughening mechanisms such as fibre bridging and delamination migration could give substantial benefit in terms of service life, as for example proposed by McGugan et al. [43]. Of course, taking credit for such benefits requires that these effects are reliable and predictable.

RESIDUAL STRENGTH

The prediction of residual strength is important both in order to evaluate the quasi-static strength reduction caused by a detected damage, and in order to be able to determine the end-point of a slow growth damage tolerance analysis. High fidelity finite element models are capable of producing accurate predictions of residual strength and quasi-static damage propagation [19], [44], [45]. However, in experimentally validating these models, damage is typically created by a known impact scenario, which can itself be modelled. If damage is detected in service, the limitations of the inspection technologies make it challenging to create a matching damage representation in the finite element model. Baluch et al. [19] have proposed a method for this, which relies on the assumption that matrix cracking and the impact dent shape do not affect the residual strength. Baluch et al. were able to obtain accurate predictions of compression after impact strength with these assumptions. However, McQuien et al. [45] using a different modelling approach, found that the impact dent and matrix cracking had a large impact on the residual strength. Further investigation is needed to determine the limits of applicability of the Baluch et al. method.

Another limitation of the high-fidelity models is their high computational cost. This means that they can mainly be used for small components (e.g. flat material coupons) rather than for full scale structures. Furthermore, while they can be employed to predict the residual strength for a given damage configuration, they cannot be used to investigate the inverse problem, i.e. to determine which damage configuration would result in a specific residual strength, as this would require many analyses. This inverse problem needs to be solved when conducting a damage tolerance analysis, as in such an analysis it is crucial to determine at what point in time (given the predicted damage propagation) the residual strength will drop below design limit load. Adding to the complexity of the problem is the fact that many different possible damage configurations could result in the same residual strength.

In traditional metal structures it is possible to define a certain critical crack length, at which the residual strength equals a certain value (e.g. design limit load). By analogy it would be desirable to be able to define a (set of) critical damage state(s) for a composite laminate, but this is hindered both by the analysis challenges discussed in this section, and by the question of how to correctly characterise damage, as discussed previously.

A simplified method of predicting residual strength is to make use of an equivalent hole model [46]–[48]. The challenge here is to determine what is the appropriate equivalent hole to use for a given damage, especially if the location of the damage detected in service does not match with available test data. Additionally, it should be noted that equivalent hole models take fibre kinking, due to stress concentrations around the damage, as the critical failure mode. This is supported by some experimental evidence [49], but other researchers point to unstable delamination growth as the critical failure mode [50], [51]. Yang and Li have suggested that these failure modes are actually in competition, with the critical failure mode depending on the damage configuration [52]. A recent study by the present authors attempted to investigate this question experimentally, using analysis of acoustic emissions. Unfortunately, it was found that so many signals were received simultaneously close to the failure load, that it was not possible to clearly distinguish different damage modes. Interestingly, for the material and lay-up investigated, a sudden increase of signals attributed to fibre-matrix disbonding was noted at around 80% of the final failure load [15]. More work is needed to understand how general this observation is, and how it fits into the overall failure process.

Further investigation is clearly needed to understand residual strength and final failure of composite laminates. For application in sustainment of aircraft, what is particularly needed is a computationally cheap method of evaluating the residual strength, as well as clear definition of critical damage states, which can be used as an end point for damage tolerance analyses.

SUMMARY AND CONCLUSIONS

Most operational composite aerostructures have been designed according to the no-growth design philosophy, substantiated with full scale testing. This limits the sustainment options when damage is detected in service. Evaluating the residual strength is difficult when the damage does not match the test data generated during certification, and tools to predict damage evolution under fatigue loading are limited, especially tools suitable for full-scale structures.

This paper highlighted that while extensive research is being conducted on fatigue of composite laminates, the limitations of the research design limit how much of the results can be applied to full-scale structures. New research methods and research directions are needed to address this gap. In particular the following issues were highlighted:

- Non-destructive testing (NDT) techniques have limitations that often prevent giving a full picture of the damage present in a composite laminate, especially if only ultrasonic C-scanning is used. Damage modelling should be based on an understanding of all the physical damage mechanisms involved, not just the ones detectable by the available NDT techniques.
- The use of projected delamination area, or delamination width, to quantify damage is not appropriate. Understanding damage growth as purely the propagation of delaminations is too limited. More sophisticated damage descriptors are needed.

- Existing studies of fatigue driven delamination propagation rely on beamlike specimens, which produce one dimensional delamination growth. More studies are needed that investigate two dimensional delamination growth. Some experimental set-ups for this have recently been proposed.
- Changes in lay-up affect the initiation, propagation, and interaction of damage mechanisms. There is a need to develop models that can properly capture these effects. This would allow coupon test data to be generalized to cover arbitrary laminates, rather than having to rely on the coupons having exactly the same laminate as the full scale structure.
- Residual strength can be accurately predicted, if a sufficiently detailed damage description is available. However, obtaining such a damage description in practice is challenging due to limitations of available NDT technology. Furthermore, the computational cost of the models needed to predict residual strength is high, limiting their applicability for use in operational conditions. Additionally, these models cannot be used to establish critical damage states that can be used as end-points for damage tolerance analyses.

Addressing the knowledge gaps discussed in this paper would help close the gap between academic research and industry practice and provide fleet managers with more robust information for their sustainment strategies.

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