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Fatigue in fibre metal laminates: The interplay between fatigue in metals and fatigue in composites

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Abstract
With the introduction of fibre metal laminates (FMLs) as a (fatigue) damage tolerant material concept in aeronautics, an interesting field emerged where fatigue damage interaction plays a dominant role. The hybrid concept effectively demands evaluating fatigue damage growth based on fracture phenomena typical for both metals and fibre-reinforced composites that continuously interact with each other. This paper explains current understanding of the fatigue fracture phenomena in FMLs, and it demonstrates how this interaction limits the criticality of both the metallic and composite fracture phenomena. In addition, it explains how the laminated hybrid configuration can be further exploited scientifically to unravel the physics of the individual fatigue fracture phenomena.

KEYWORDS
crack growth, damage interaction, delamination, fatigue, fibre metal laminates, fracture mechanics

1 | INTRODUCTION

The concept of fibre metal laminates (FMLs) has been successfully developed to a mature structural material technology, as demonstrated with the large-scale application of GLARE, comprising aluminium layers and glass fibre epoxy layers, on the Airbus A380 fuselage and empennage-leading edges. This hybrid concept originates in the early attempts to improve the damage tolerance characteristics of metallic materials subjected to fatigue loading.[1] First, adhesive bonding of thin aluminium layers was developed based on the observation of improved fatigue resistance and fracture toughness compared with a monolithic plate with similar thickness.[2] The addition of fibre layers to the bondline formed the second step towards the FML concept development.

Although the initial objective with FMLs was to improve fatigue damage growth resistance, other characteristics were soon identified underlying the excellent damage tolerance characteristics of FMLs. Among these characteristics are the high impact resistance and impact tolerance, corrosion resistance, and burn-through resistance.[3-5]

With the FMLs developed for the Airbus A380, ie, GLARE, an excellent balance had been obtained between the contribution of aluminium and that of glass fibre-reinforced polymers. However, soon, people realized that depending on the application, different optimal solutions can be developed, specifically tailoring the combination of properties and performance characteristics of the hybrid laminate. Such optimization obviously requires thorough understanding of the phenomena, which has

led to numerous studies aiming at fully understanding in particular the fatigue fracture phenomena.[6] Initially, these studies were very basic and empirical,[7-10] but the current state of art is described by in-depth understanding formulated in analytical theories based on fracture mechanics principles.[11-15]

Now, the FML concept has reached its maturity and technology readiness level through large-scale aeronautical applications; it seems time to question the scientific relevance of this hybrid technology. For example, one could question whether the development of FMLs has pushed the frontiers of scientific knowledge in the field of fatigue or whether this hybrid concept can contribute in any way to our scientific understanding of fatigue in engineering materials.

To address these questions, this paper explains current understanding of the fatigue fracture phenomena in FMLs, and it demonstrates how the interaction of phenomena limits the criticality of both the metallic and composite fracture phenomena despite initial prejudices. In that respect, it will be explained how the scientific knowledge on fatigue damage growth in metals and composites has been utilized in describing the process in FMLs and how that can be applied within an engineering context. In particular, the principle of superposition, equivalent to the physical superposition of layers in laminate lay-up, is presented as key enabler for developing the methodology. The last part of this paper explains how the laminated hybrid configuration can be further exploited scientifically to unravel the physics of the individual fatigue fracture phenomena.

2 | SUPERIMPOSING LAYERS REQUIRES SUPERPOSITION PRINCIPLES

What past research on fatigue damage growth in FMLs has taught is that the physical superposition of layers, ie, laminating metallic plies with fibre-reinforced polymer layers, requires a methodology that effectively constitutes a similar superposition in its basic principle. For example, instead of describing the observed crack growth in FMLs using a stress intensity factor (SIF) $K_{applied}$ (assuming the laminate to be homogenous as material),[7,8] the crack tip SIF is described by

$$K_{tip} = K_{farfield} - K_{bridging}, \qquad (1)$$

in which $K_{farfield}$ represents the standard SIF for a crack in the metal layers and $K_{bridging}$ describes the reduction of that SIF imposed by intact bridging fibres.[14] Now, when additional stiffening elements, like stringers or

frames, are added to create a stiffened panel, the principle is further extended to

$$K_{tip} = K_{farfield} - K_{bridging} \pm \sum K_{stiffeners}, \qquad (2)$$

where the summation indicates treating all stiffeners individually, while the "±" indicates whether the stringer is intact or broken. An intact stringer increases the bridging, hence "−," while a broken stringer increases the crack tip SIF, calculated with "+."[16-18]

Here, the crack is the typical metal fatigue fracture phenomenon, while the typical composite fracture phenomenon observed is ply delamination. The metal crack length a is straightforwardly accounted for through

$$K_{tip} = \beta S \sqrt{\pi a}, \qquad (3)$$

while the delamination areas are implicitly accounted for in Equations 1 and 2 when calculating $K_{bridging}$ and $K_{stiffeners}$. Note that in the case stiffeners are bonded to the FML panel, the phenomenon is commonly referred to as adhesive disbonding or disbond growth rather than delamination.[19-21] In the case stiffeners are riveted to the FML panel, then the $K_{stiffeners}$ term can be evaluated through a methodology originally proposed by Vlieger[22,23] and later adapted by others.[24,25]

3 | SUPERIMPOSING MATERIALS SUPERIMPOSES CRITICISM AND PREJUDICE

What has become evident in the development of FMLs for aeronautical applications is that the combination of two distinctively different materials into a single structural material concept invites two communities to express concerns and criticism. On the one hand, this is considered advantageous, because in the development process, it forces to look outside often limited scope when addressing potential issues. However, when both communities adhere too strict to rules and standardized approaches in their respective fields that appear to hinder the development and application rather than improve it.

Take, for example, the case where under the damage tolerant design regulations, it is mandatory to repair fatigue cracks in metallic structures once detected. Residual tensile stresses present after curing in the aluminium layers of GLARE, together with the stiffness mismatch between aluminium and glass/epoxy layers, increase the mean and amplitude of the actual stress cycle of the metal layer and thus reduce the fatigue crack initiation life. The fact that cracks occur earlier in FMLs than in monolithic aluminium[26] has often been brought up in the metals community as showstopper to reject the hybrid concept.
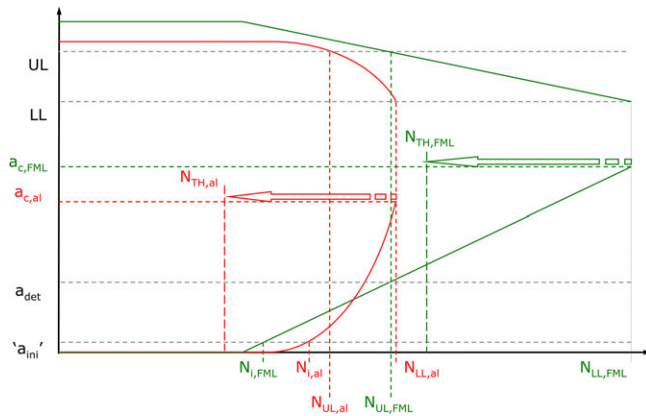
FIGURE 1 Illustration of determining the inspection threshold based on fatigue life evaluation for monolithic aluminium and fibre metal laminate (FML) (not to scale); UL and LL are ultimate load and limit load, respectively[27] [Colour figure can be viewed at wileyonlinelibrary.com]

The fact that this initiation life relates in its definition to a crack length[27] of 1 mm, which is too small for detection in practical conditions, was mostly ignored. Here, it did not require much experimental substantiation to demonstrate that despite the reduced lifetime until initiation, the lifetime until detectable crack length in FMLs is longer,[27] see Figure 1. After a fatigue crack has initiated, fibre bridging retards the growth rate, substantially increasing the lifetime to longer cracks compared with monolithic metals.

A similar example can be given that originates in the composites community. Since Marissen[11] described fatigue damage growth mechanisms in FMLs, it is understood that along with the fatigue cracks in the metal layers, delaminations occur at the interface with the fibre layers. In literature on fatigue damage in composites,

delaminations are listed as the most important and detrimental damage mechanism. One rather prefers transverse matrix cracking or splitting over delaminations. Hence, the fact that along with cracks in metallic layers, delaminations occur in FMLs was generally seen as bad and detrimental.

What the research on fatigue damage growth in FMLs has revealed, however, is that these delaminations distribute the high stresses over a larger area, allowing the bridging fibres to remain intact and contribute to crack bridging. Very tough epoxies with high delamination resistance resulted in premature fibre failure, see Figure 2, reducing the fatigue life to what was commonly observed for metals. So despite counterintuitive, these delaminations in FMLs should be considered advantageous.

In fact, one may qualitatively compare the function of delaminations in FML fatigue damages to what, for example, matrix splitting does at the notch root of a composite structure; it tends to distribute the severity of stresses over a larger area and thus reducing potential damage.

4 | SUPERIMPOSING ADVANTAGES IMPLIES REDUCING DISADVANTAGES

FMLs have been presented as the hybrid concept combining the best of both worlds.[30] For example, the ductility of metals combined with the fatigue insensitivity of composites provided the excellent damage tolerance characteristics of FMLs. Hence, historically, FMLs have been considered as the concept in which composite plies
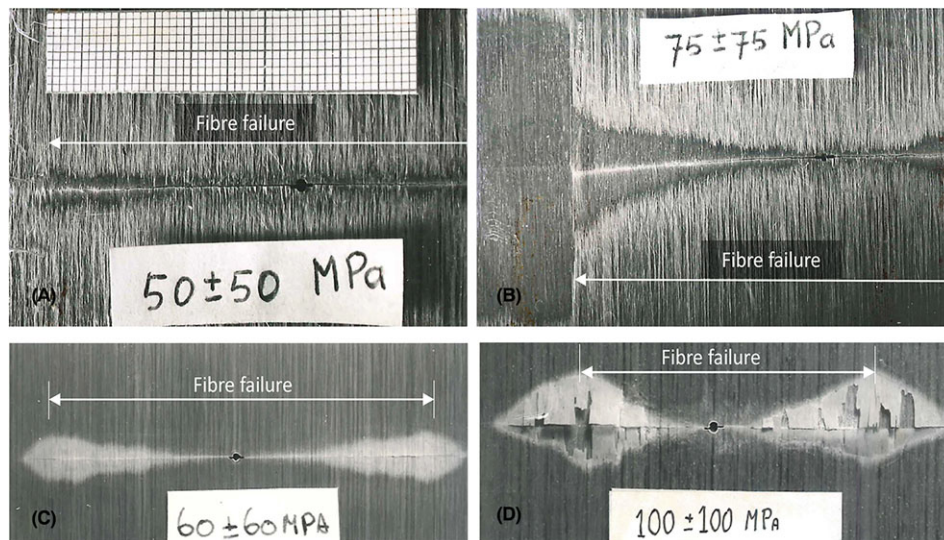

FIGURE 2 Image of delamination shapes in aramid fibre-reinforced aluminium laminate (ARALL) containing evidence of fibre failure[28,29] [Colour figure can be viewed at wileyonlinelibrary.com]

improve the performance of metals, ie, fibre-reinforced composites as reinforcement of metals. However, with the development of major primary aeronautical and space composite structures, one may reverse that perspective and consider the hybrid concept of FMLs as the reinforcement of composites by the addition of metallic constituents. Rather than adding, for example, composite plies in multiple directions (0°, 90°, ±45°), one may insert few isotropic metal plies without the need of increasing the laminate thickness substantially. This thickness increase can be limited further by replacing specific composite plies by metallic layers.[31,32] The isotropy of the metal layers improves to the through-thickness characteristics improving the manufacturing tolerances for mechanically fastening. The combination with the ductility of metallic layers substantially improves the bearing strength required for joining panels.[33]

Another disadvantage of fibre-reinforced composites is impact damage detectability. Take the impact damage tolerance of layered composites.[34] The impact introduces delaminations in a laminate that mostly responds linear elastic. Hence, the presence of delaminations is not or barely visible in composites after impact. Beyond certain impact energies, residual dents may be visible to aid inspection, but at lower impact energies, these dents may not be observed, while delaminations can occur (referred to as nonvisible damage). Non-destructive inspection techniques are then needed if one aims to quantify the damage state. Here, FMLs have the benefit of ductile metal layers at the outside that leave a residual dent after impact. Experimental studies have demonstrated that delaminations within the laminate are constraint by the dent size.[33] Hence, no additional inspection technique is required to quantify the damage state, because if no dent is visible, then no damage (or delamination) is to be considered within the FML. The ductile layers effectively act as sensor to aid visual inspections. In addition, the plastic deformation together with the local residual stresses introduced significantly retards the propagation of cracks created under impact.

5 | SCIENTIFIC EXPLOITATION OF THE HYBRID CONCEPT TO UNRAVEL THE PHYSICS

What has not received a lot of attention until today is that the hybrid laminate lay-up of FMLs provides an excellent test bed to scientifically investigate metallic or composite fatigue fracture phenomena. The combination of both constituents and the ability to tune the laminate properties in its lay-up allow to investigate the physical aspects of fatigue damage growth.

5.1 | No-growth concepts

Take, for example, the "no-growth" concepts adopted in composites engineering.[35] Because the assessment and evaluation methodologies for fatigue and fracture in fibre-reinforced composites have not reached the required level of maturity, no-growth concepts are adopted in engineering practice that are validated with (full scale) tests. Instead of the common practice for metallic structures, to assume the existence of initial flaws and predict the growth of these, composites engineering tends to define allowable stress levels such that any in-service (impact) damage does not propagate. Scientifically, the question here remains whether the selected allowable stresses create a stress condition below a fatigue limit or below a damage growth threshold?

For fatigue in metallic structures, it is known that under certain conditions cracks may nucleate at a notch root but subsequently retard.[36] Such condition remains below the fatigue limit of an S-N curve, because the S-N curve and its lower asymptote both relate to failure. Similarly, no growth could imply that damage that has been formed still grows but that the growth is limited such that it does not reveal apparent and obvious macroscopic growth within the tested lifetime.

This mechanism can be illustrated with a specific case for FMLs. Take the interlaminar ply drop-off within an FML, as illustrated in Figure 3. This case was experimentally evaluated by Hooijmeijer[37,38] who applied 180 000 cycles at an equivalent fatigue stress spectrum, to report observing no macroscopic growth. For the engineering application at the time this "no growth" was sufficient.

Scientifically, one could study this case further though. With the quasistatic delamination growth evaluated in Vries et al,[39] see Figure 4, and the fatigue delamination resistance for the particular interface characterized in Alderliesten et al,[40] one could predict for the given configuration and test load cases in Hooijmeijer[37] what the
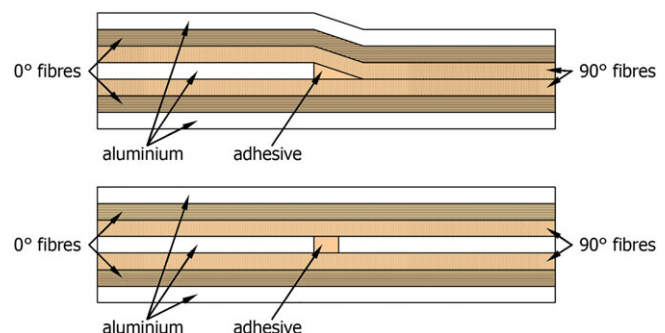

FIGURE 3 Doubler run-out configurations in fibre metal laminates (FMLs); single run-out (above) and internal splice (bottom)[37,38] [Colour figure can be viewed at wileyonlinelibrary.com]
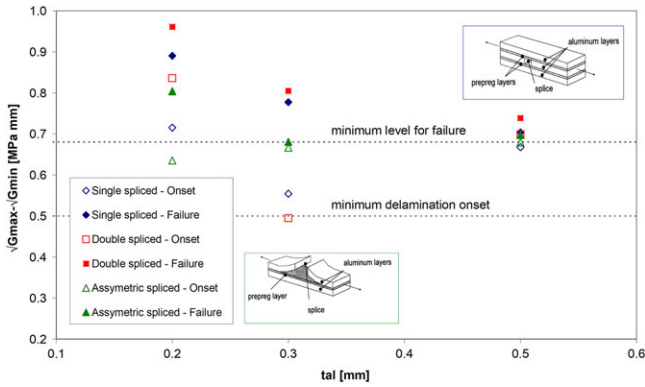
FIGURE 4 Energy release rate calculated from the experiments reported in Vries et al[39] for delamination onset and final failure[38] [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Crack growth rates recorded in Daandels[41] plotted against the effective stress intensity factor range calculated with the empirical model[42] [Colour figure can be viewed at wileyonlinelibrary.com]
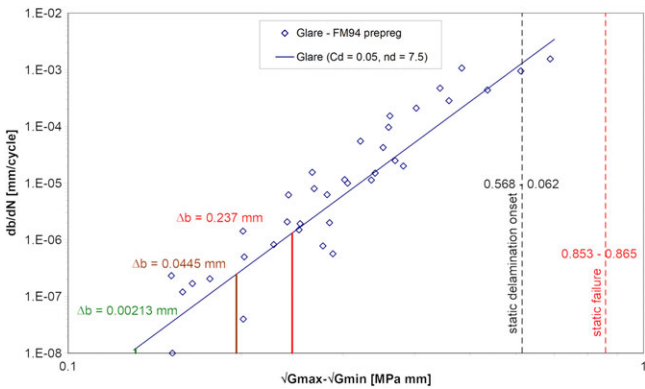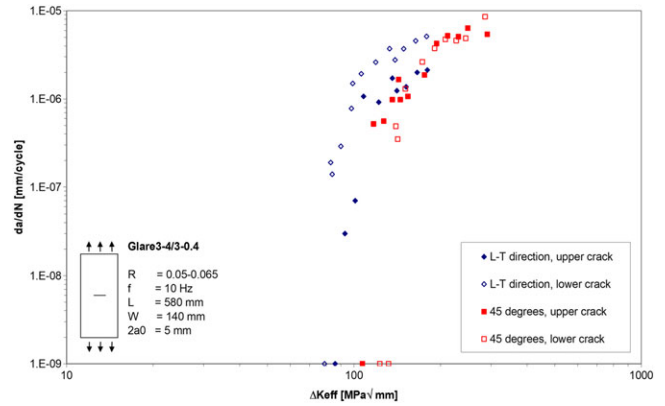

FIGURE 5 Comparison between the crack growth rates predicted for the cases tested in Hooijmeijer[37] with the delamination resistance curve for the interface determined in Alderliesten et al[40] [Colour figure can be viewed at wileyonlinelibrary.com]

corresponding delamination growth rate and total delamination increment would be. This correlation was presented in Alderliesten[38] and is illustrated here in Figure 5; the total accumulated crack increment that is to be expected in the tests by Hooijmeijer is less than a quarter millimetre. This explains the observation of no apparent macroscopic crack growth. It also illustrates how a better characterized damage resistance could allow the prediction of limited growth, instead of assuming "no growth."

5.2 | Fatigue threshold

Another example, possibly connected to the previous one, relates to the physical interpretation of fatigue threshold. Following the observation of a threshold when plotting the crack growth rate da/dN against ΔK in studies on fatigue crack growth in metals, attention was given to

whether composite fatigue delamination resistance curves exhibit such threshold as well. This appears not always to be obvious.

Similarly, fatigue threshold was studied initially for FMLs,[41] see, for example, Figure 6, until it was understood that the interplay between a threshold in crack growth and the apparent absence of threshold in delamination growth yield different slow crack growth characteristics compared with monolithic metals.[43] Hence, despite that crack growth in FMLs is described using, for example, Equation 1, a threshold SIF is not considered, simply because the continuation of delamination growth eventually will raise the K_{tip} above the threshold resulting in further crack growth.

Physically, the fatigue threshold may constitute a minimum amount of strain energy required in the crack tip vicinity to impose a crack increment, analogue to exceeding static friction in moving a box over a floor. This threshold energy can be experimentally assessed, when testing multiple FML lay-ups (each with their distinct residual curing stresses in the metal layers), while determining with, for example, acoustic emissions the metal crack onset level. Such study may reveal that the reason why threshold levels appear to be stress ratio dependent is because threshold is expressed as $\Delta K_{threshold}$ rather than $K_{threshold}$, which implies different values for different stress ratios (as $K_{threshold}$ may remain approximately constant).[44]

5.3 | Uniaxial loading or biaxial loading?

A third case in which the concept of FMLs could be exploited to study fatigue crack growth in metals relates

to crack growth under the uniaxial versus biaxial loading. Originally, the Westergaard stress distribution in the crack tip vicinity was developed for a biaxial load condition as occurs in a pressure vessel.[45] Adopting these stress field equations for an uniaxially loaded specimen therefore required the modification with a transverse monotonic stress component, often referred to as the T-stress.[46,47] With the orthotropic characteristics of FMLs, one may impose different levels of biaxiality in the metal layers of the laminate, simply by altering the lay-up. The mean stress levels of the effective stress cycles in both material constituents may be further tuned with changing the residual curing stresses through altering the curing temperatures.[48] This concept of imposing biaxial loading through material orthotropy has been subject of a former investigation,[49] in which biaxiality in loading was induced through a special lay-up utilizing a layer with extremely high stiffness in the transverse direction, see Figure 7. Constraining transverse contraction, while loading in the axial direction effectively imposes a transverse load component. One should consider that, though at a smaller scale, this is also the case in standard FML lay-ups comprising fibre-reinforced polymer layers in transverse or off-axis directions. Hence, the stress field in the crack tip vicinity can be modified and altered to further study the contribution of biaxiality or off-axis load conditions on the crack growth behaviour.

5.4 | Physics of finite width corrections

A fourth example relates to the application of geometry correction factors in the equations for SIFs. In several studies on fatigue damage growth in FMLs,[14,15] it was
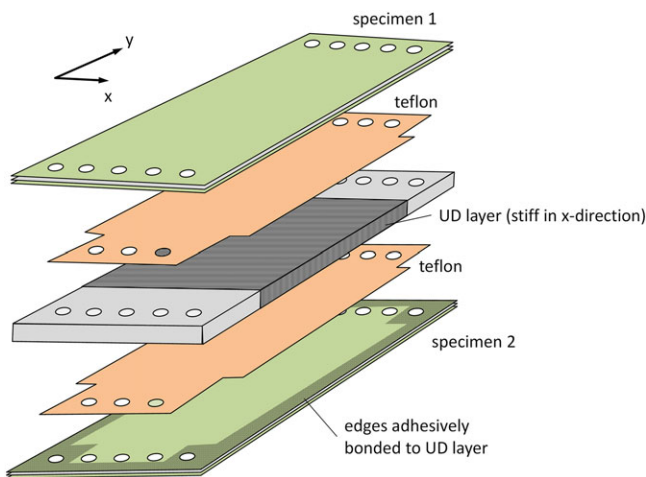

FIGURE 7 Illustration of biaxially loaded specimens; axial machine load applied in y-direction with stiff unidirectional (UD) layer adding load to the specimens in x-direction[49] [Colour figure can be viewed at wileyonlinelibrary.com]

observed that the application of the finite width correction factor β in the expression for $K_{farfield}$ in Equation 1, ie,

$$K_{farfield} = \beta S_{metal}\sqrt{\pi a}, \tag{4}$$

resulted in overly conservative predictions, while excluding the correction made the prediction slightly unconservative. A physical explanation could not be given for this observation. More recently, however, when discussing proper similitude to describe fatigue damage growth in agreement with the physics of the process,[50,51] re-evaluation of this observation provided a physical explanation. The difference between finite and infinite for which β corrects physically requires an energy correction. For a linear elastic panel without a crack, the applied work for a constant load P is described by (assuming for simplicity that the P-δ curve runs through the origin)

$$W_0 = \frac{1}{2}P\delta_0. \tag{5}$$

When the crack grows, the panel compliance increases yielding larger displacements under the application of load P, hence

$$W_a = \frac{1}{2}P\delta_a, \tag{6}$$

and

$$\beta = \frac{W_a}{W_0}. \tag{7}$$

For $2a \rightarrow W$, the compliance increase yields $\beta \rightarrow \infty$, which is in agreement with all finite width correction factors. However, because of the presence of intact bridging fibres, the compliance increase of FML panels is substantially limited to the elongation of only the fibre layers under the load P. This means that β in Equation 7 is not
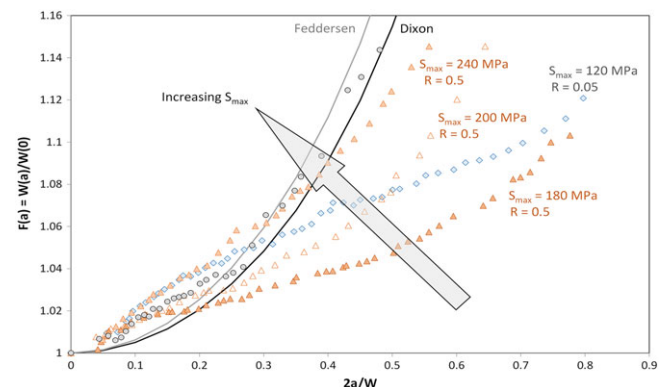

FIGURE 8 Illustration of the finite width correction factors $F(a/W) = \beta$ for cross-ply Glare3 laminates tested at different fatigue stress levels[54] [Colour figure can be viewed at wileyonlinelibrary.com]

equal to standard finite width corrections factors[33,52-57] and effectively depends on the laminate lay-up and the size of the fatigue delaminations,[54] see Figure 8.

Hence, the physical meaning of the finite width correction can be studied in detail through testing FML lay-ups at various fatigue-loading conditions. The latter can be varied in the applied fatigue load spectra but can also be tuned with the magnitude of residual curing stress through modifying the curing temperature and cure cycle.

In that respect, one may learn that the standard finite width corrections may all become incorrect, once an ambient temperature cycle occurs while fatigue testing a monolithic metallic specimen containing a centre crack. Depending on the magnitude of the temperature variation, the corrections may be inaccurate by several percent.[58]

6 | CONCLUSIONS

With all the past research on fatigue damage growth in FMLs, the fracture mechanisms and their interplay are rather well understood. The damage tolerance potential, however, is not yet fully exploited, illustrated by most efforts to develop only fibre-reinforced composites, which do not have proven to have more potential. Academically, the concept of FMLs could be further exploited to develop scientific test methods and procedures to better understand the physics of fatigue fracture in both metals and composites. This has been illustrated in this paper through four examples.

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