Evolution of FML Fatigue & Damage Tolerance Assessment: Moving from Damage Tolerant Metal to Hybrid Composite

René Alderliesten, Calvin D. Rans, Rinze Benedictus
Faculty of Aerospace Engineering, Delft University of Technology
Kluyverweg 1
2629 HS Delft

ABSTRACT
This paper provides an overview of the evolution of methodologies to assess fatigue and damage tolerance of hybrid laminated structures. The transition from metallic methodologies towards full hybrid methodologies is evaluated and discussed. The transition is illustrated with the assessment of fatigue initiation and damage growth in FMLs. In addition, the importance of structural details for reliable assessment is explained and the necessity to explore the design freedom with the composite FML concept is highlighted.

1. INTRODUCTION

In the past decades, the Fibre Metal Laminate (FML) material concept has been developed with success for aeronautical applications. Although originally aiming for lower wing skin panels with FMLs containing aramid fibers (Arall), the concept has been brought to a technology readiness level for fuselage skin applications with FMLs containing glass fibers (Glare). Today, the interest for FML wing concepts seems to be rising again for both civil and military transport aircraft.

In the literature, both scientific and applied research have been published on the FML technology. Based on these publications, it can be illustrated how the assessment methodologies evolve from metallic towards hybrid concepts. In addition, it also has been observed that lack of interaction between science and application seems to contribute to misperceptions on the hybrid technology at both sides. These misperceptions do not only play a role in the development of FML concepts, but also in the related fatigue and damage tolerance assessment methodologies.

This paper provides a brief overview of the evolution of assessment methodologies for FMLs, starting from metallic methods towards hybrid methods. The presented methodologies will be discussed in context of lower wing skin applications.

2. HISTORY OF FML DEVELOPMENT

The history of the development of FMLs has been described in detail by Vlot [1] and Vogelesang [2]. Originating from the poor man’s solution to build up aluminum structures using bonding technology, rather than using expensive milling equipment, the major driver in the development
The first patented FML concept combined aramid fibers with aluminum sheet materials, initially developed for a F27 wing skin application. This concept has been thoroughly investigated especially with respect to its fatigue characteristics [3]. Further studying the concept for wing load spectra, however, revealed poor fatigue resistance as result of fiber failure induced during compressive load cycles. Subsequent development led to the FML based on glass fibers, Glare [4].

In the development of Glare, additional beneficial properties were identified that supported its application to primary fuselages structures; high impact resistance and tolerance, high burn through resistance which could potentially increase evacuation time (safety aspect), and improved corrosion resistance (durability aspect) as result of its layered structure.

As a consequence, not only were structural applications which benefited from the improved fatigue performance studied, such as wing and fuselage panels, but other applications that could benefit from the impact and fire resistance were also studied, such as (bulk) cargo floors and liners, flap skins, and unpressurized bulkheads. Aside from large component fatigue tests or exposure tests, several applications made it on to aircraft to investigate the in-service performance of the hybrid concept. Examples are the Fokker F-50 lower wing tank cover, several cargo floors and liners and the C-130 flap skins. Only a few applications were developed to sufficiently technology readiness to be implemented in the production of aircraft structures, such as the C-17 cargo doors and the A380 fuselage sections.

Although the amount of successful applications seems limited, the experience generated with all these studies and design exercises has proven to be indispensable. Knowing the design drivers, the design constraints, the manufacturing aspects including required tolerances, certification related aspects, etc., for a specific application enables the optimization of the FML design for that particular application. This seems to be the key insight that the development of the FML technology provided; FML should not be tailored or optimized on a material level, but on the structural level.

3. EVOLUTION OF FATIGUE ASSESSMENT

3.1 Fatigue initiation life towards fatigue crack growth life

The history of FML technology development, described in [1], significantly influenced the perception of the assessment methodologies for fatigue. Starting with adhesively bonding metallic structures, the assessment of fatigue was considered initially similar to monolithic metals. This has led to a twisted view of the fatigue assessment of FMLs.
Several concepts come into play when performing the fatigue and damage tolerance assessment of a metallic structure. The fatigue characteristics of metallic materials are often characterized by a crack initiation phase followed by a crack propagation phase. The overall fatigue life is the sum of the time periods for both crack initiation and propagation (typically expressed in number of load cycles or flights). For metals, the overall fatigue life is dominated by the initiation phase. The damage tolerance characteristics of a structure can be expressed by the inspection threshold (time before first required inspection, $N_{\text{threshold}}$) and inspection interval (time between subsequent inspections, $N_{\text{inspection}}$). Determination of the inspection threshold is related to the overall fatigue life analysis [ref] up to failure. In given structures, failure occurs when cracks reach critical lengths that can be determined with proper residual strength analyses (typically based on limit load, LL, carrying capability). Determination of the inspection interval is dependant on the portion of fatigue life in which the crack is detectable, and thus related to crack propagation.

The damage tolerance approach used to determine the inspection threshold and inspection interval can be illustrated as it is in Figure 1 for a typical metallic structure. This figure illustrates some of the common outcomes for a damage tolerant assessment for a metallic structure. Due to the relatively short fatigue propagation life for metals:

- $N_{\text{threshold}}$ (based on the overall fatigue life) tends to occur well before crack initiation
- $N_{\text{inspection}}$ is small relative to the overall component life

The implication of these two characteristics for metals has twisted the perception of damage tolerant structures. Since $N_{\text{inspection}}$ is short and $N_{\text{threshold}}$ occurs before crack initiation, then an inspector is forced to try and detect very small cracks near the detection threshold limits. As a result, there tends to be a lot of focus on the occurrence of small cracks at the limits of non-destructive inspection detection limits, and thus emphasis on crack initiation life.

![Figure 1. Illustration of a damage tolerance evaluation for a metallic structure](image-url)
If one considers the fatigue performance of FMLs, the situation changes. FMLs are known to have a superior fatigue performance compared to monolithic metals; however, that increase in fatigue performance is derived entirely from an improvement in crack growth performance. In fact, for the most prevalent FML in application, Glare (GLAss Reinforced aluminum), crack initiation occurs earlier compared to similarly stressed monolithic aluminum structures due to the stiffness mismatch between the glass fibre and aluminum layers. This has led to a lot of concerns about FMLs as early crack initiation, based upon the above described experience with metals, would indicate a shorter $N_{\text{threshold}}$ and many costly inspections.

One must be careful, however, in blindly applying their experience with metals to FMLs. If we reexamine the illustration of the damage tolerance approach for metals and superimpose on it the case for FMLs (Figure 2), a very different behaviour can be observed. Due to the dominance of the fatigue life of an FML by crack propagation:

- $N_{\text{threshold}}$ occurs well into the crack propagation phase of the fatigue life
- $N_{\text{inspection}}$ is large relative to the component life

![Figure 2. Illustration of the relative damage tolerance assessments of a metallic and FML structure](image)
These characteristics also have implications to the treatment of FMLs. Despite having a shorter crack initiation life, the \( N_{\text{inspection}} \) can still be larger for FMLs compared to metals. Also, since \( N_{\text{threshold}} \) occurs well into the crack propagation phase of an FML, it is no longer necessary to try to detect very small cracks. As a result, less expensive NDI techniques can be used (even visual detection in some cases). And finally, since \( N_{\text{inspection}} \) is larger, inspections also can be performed less frequently, thus saving even more on maintenance costs.

The relative difference in crack initiation and growth lives for metals and FMLs has also led to some other misunderstandings. Some academic studies report investigating fatigue performance in FMLs by fatigue testing coupons until failure [10,11,12]. This life then incorporates the initiation and crack growth phase to a damage level that causes failure in a small specimen. This type of information may be considered originating from a safe-life design philosophy initially adopted for metallic structures after the Second World War. However, especially because of its crack growth characteristics, the failure life of a small FML coupon is by no means relevant for large structural components, designed according to the damage tolerant design philosophy to sustain large fatigue or accidental damages.

### 3.2 From material towards laminated structure

Another illustrative example of the historical influence on the assessment methodology development is the approach to predict the fatigue crack growth behavior of FMLs. For metallic materials, the crack growth resistance is often described in \( da/dN \) versus \( \Delta K \) curves that on double-log scale result in approximately linear curves, described by exponential relations such as the Paris relation. Initially, the logic step for FMLs then seems to follow a similar approach, describing the stress intensity factor \( K \) for the laminate as bulk material.

Results of that approach are illustrated in Figure 3, where the exponential trend for monolithic aluminum is compared with the curves obtained for FMLs with different starter notch lengths and fiber orientations. The general observation is that without empirical corrections it is not possible to come to a generic FML description, because there is no single relationship describing the crack growth resistance of these materials.

To some extent this aspect is related to a thorough understanding of the nature of fatigue damages in FMLs. In fact, it may even be argued that the perception of fatigue damage in general is highly influenced by the fact that fatigue damage has been discovered for monolithic metals first. Fatigue is often related to crack growth; a damage mechanism that does not manifest in a similar manner in fiber reinforced composite structures. This has contributed to the misperception that composites do not suffer from fatigue [14], but it also seems to contribute to how fatigue is approached in FMLs.

Indeed, due to the visibility of the outer metal layers in an FML, fatigue damage in an FML is most visible in the form of cracks in the metal layers. However, in conjunction with the formation of cracks in the metal layers of an FML is the formation of delamination (a composite damage) between the damaged metal and intact composite layers surrounding the crack. The bridging interaction between the cracked metal and intact fiber layers which is so critical to the slow crack growth performance of FMLs is highly dependent on that delamination. Thus, it is
impossible to fully characterize the fatigue behavior of FMLs by crack length alone, and limiting ones view to crack length alone may produce unexpected results.

Figure 3. Illustration of the da/dN versus ΔK relationship for FMLs based on the assumption of homogeneous material: influence of notch length (left) and fiber orientation (right) [13]

An example is provided by Wilson [15] who compared the crack growth in FMLs containing 2024-T3 sheets and with 2524-T3 sheets. The latter is an alloy with higher crack growth resistance; however, the comparison of the fatigue damage in the two FMLs based on equal crack length alone indicated that the FML containing the more fatigue resistant alloy had larger fatigue damage (due to delamination). This seeming contradiction can be explained considering the fracture mechanisms in the panels. However, this case illustrates that treating FMLs as bulk material, it will be less straightforward to explain why material with more crack resistance results in larger (delamination) damage sizes based on the visible crack lengths. Only understanding the fracture mechanics, i.e. crack growth in the metal layers and delamination growth at the interfaces, enables an explanation for these observations.

3.3 Flat laminated panels towards structural details

It does not require a thorough review to identify that most publications in the literature addressing the fatigue performance of FMLs are related to research on flat panels loaded in cyclic tension. In most cases, the laminates are often utilized with a central starter notch that is either sharp (i.e. saw-cut or pre-crack), or blunt (open hole). The advantage of these experimental studies is that the assessment of the damage is fairly straightforward. The cracks may be assumed to be present in all metallic layers with equal length and observations can be performed on both sides of the samples.

Indeed, from an experimental perspective as well as from an analytical perspective, this configuration is preferred. It eases the understanding of the mechanisms and it enables the
development of relatively simple prediction models that describe the observed crack growth. However, these cases may be interesting to understand the damage resistance of the material structure, but they are often inapplicable to the fatigue cases to be considered for applications.

For example, the fatigue aspects of FML structures are to be considered at the locations where the panel is joined to other panels or laminates. These joints may either consist of mechanical fastened joints, or adhesively bonded joints.

In the first case, the joints consist of aluminum rivets or titanium bolts that also transfer load by bearing and friction, while other secondary load transfer mechanisms can be identified. Here, the flat panels containing an open hole loaded in tension only account for so called by-pass loads, which is only one of the load transfer mechanisms present in mechanically fastened joints, see Figure 4. Both the bearing load and the load transferred by friction add to the mechanisms locally near the hole. Another aspect that differs from the flat panel loaded in tension is that the stress concentration is different for a hole filled with a fastener compared to an open hole. Especially if interference fit fasteners are being applied, the difference may be considerable. A very important difference is the presence of secondary bending in the joint that changes the response of damage initiation and growth compared to the panel uniformly loaded in tension.

In the case of adhesive bonding, the geometry to be considered for the fatigue assessment will be substantially different. The adhesive bond will create thickness steps that induced stress concentrations upon loading. These stress concentrations may either initiate cracks in the
metallic layers underneath the thickness steps, or bondline failure between the two adherent, see Figure 5.

Development of prediction models based on bulk material assumptions will be completely impractical for FML structures. Especially, because the damage considered is no longer uniform through the laminate thickness. Currently, several approaches have been proposed. The first approach considers crack growth in the critical metal layer, i.e. the metal layer containing the largest crack, and predicts its growth based on the occurring cyclic stresses assuming a surface crack [18]. The cracks propagating in subsurface layers are then predicted using empirical relations.

The second approach applies finite element analysis to calculate the stress intensity factors for cracks in each individual layer, and uses these factors in the analytical method to subsequently predict the growth of these cracks [19]. This approach can also be performed fully analytically, using the displacement methodology proposed by Wilson et al. [20]. However, although it will provide an accurate and fast analysis compared to the finite element analysis, it requires thorough understanding of the relations that describe the observed mechanisms.

![Figure 5. Illustration of the different load transfer mechanisms that can be identified in mechanically fastened joints [17]](image)

### 4. EVOLUTION OF FML CONCEPTS

#### 4.1 FML parameters that determine the level of damage tolerance

To optimize the design of FML structures for damage tolerance, it is evident that thorough understanding of the laminated concept is a necessity. Although this may seem a straightforward statement, ideas have been presented in the past that indicate misunderstanding the concept. For
example, Jensen et al. [21] presented recently a study on FMLs made with the VARTM process, which is a well known manufacturing process for fiber reinforced polymer composites. To provide means for the adhesive to flow through the laminate thickness, holes had to be created in the metal layers. Although the process itself may result in laminates with good reproducible manufacturing quality, the damage tolerance characteristics are evidently poor, because of the fatigue critical features introduced in the metal layers of the laminate. Therefore, such manufacturing process could be of interest for certain hybrid applications, but certainly can not be considered for primary aircraft structures because of required damage tolerance.

But even when structural design limits itself to an FML concept using the current state-of-the-art manufacturing process (i.e. lay-up with subsequent vacuum bagging and then curing in an autoclave), misunderstanding may lead to non-optimal design solutions with lower damage tolerance. Therefore, the contribution of the individual FML constituents to the damage tolerance characteristics must be understood in detail.

Concerning the metallic constituents, several parameters can be identified that influence damage tolerance. On the one hand, the thickness of the metallic layers and the total contribution to the laminate (often represented by the Metal Volume Fraction, MVF) are important parameters. On the other hand, the mechanical-, initiation-, crack growth- and fracture toughness properties of the metal have an evident effect on the laminate’s performance. These material properties should not be treated separately from the laminate configuration parameters, such as the thickness and the MVF. The crack growth resistance and the fracture toughness are in general related to the sheet layer thickness. Especially, when thin sheets are considered that have been rolled down to the small thicknesses.

In this perspective it is striking to see that current interest of OEMs for the hybrid technology seems to focus on FMLs containing aluminum layers with relatively large thicknesses. The optimization of the FML concept initially started with seeking the balance between the crack growth in the metal layers and the delamination growth at the interfaces. Vlot [1] explained that this led to the reduction in sheet metal thickness to 0.6 mm, which in the development towards the fuselage applications was further reduced to 0.3-0.4 mm.

Applying the FML concept with metal layer thicknesses exceeding 1 mm, will thus re-introduce the issues initially faced in the early development of the FML concept. Indeed, the application of relatively thick metal layers in the FML CentrAI distorted the balance between crack growth and delamination growth, resulting in extremely large delaminations and ineffective fiber bridging [7]. To counteract this un-balance while keeping the metal layer thickness, additional adhesive is applied at the interface. The additional adhesive in so-called resin rich layers, see Figure 6, increases the delamination resistance as observed in a study performed during the development of Arall [22].

Concerning the composite constituents, several parameters can be identified that are either related to the fibers or to the adhesive system. The Fiber Volume Fraction (FVF) has a significant effect on the fatigue performance of the FML. An increase of the FVF in the composite layers increases the bridging performance of these layers, resulting in slower crack growth in the metal layers. However, there is a maximum fraction that can be obtained; above a certain value the amount of adhesive between the fibers and especially between fibers and metal
layers is insufficient to transfer the shear load. At this fraction, the high amount of fibers, beneficial for bridging, are compensated by the low delamination resistance due to the small resin rich layer. Related to the previous discussion on the metal layer thickness, this implies that that optimal FVF depends to some extent on the metal layer thickness applied.

However, a low FVF, or large resin rich layer thicknesses, imply a high amount of adhesive in the FML that contributes to the total thickness of the system, without contributing to its stiffness or strength. In other words, if the aluminum layers are relatively thick, additional adhesive is needed to compensate for the reduced delamination resistance under fatigue and residual strength. As a consequence, this additional adhesive reduces the static strength and stiffness properties of the FML.

The additional aspect that can be tailored is the adhesive system itself. Based on past experience, the delamination resistance of the different adhesives studied can be significant [23]. However, up until today there is no clear relationship between the mechanical properties of the applied adhesives and the fatigue delamination resistance as observed in fatigue loaded FMLs. In addition, tailoring the adhesive system for delamination resistance requires fundamental understanding of the chemical aspects, not in the least place related to the necessary sizing for the applied fibers.

4.2 FML design freedom

It has already been mentioned earlier, but the FML concept is in the first place a structural concept, rather than a material concept. This means that the FML should be considered as a structure built up from individual elements, or constituents, rather than a material. To fully

Figure 6. Cross sections of the composite plies in Arall (left), Glare (centre) and CentrAl with bondpreg (right)
benefit from the hybrid damage tolerant design concept, a design freedom should be considered equivalent to the one common for composites. This means that local changes to the FML can be made to cope with certain strength- or manufacturing requirements that not necessarily change the base FML configuration.

An example in this case may be interlaminar doublers, see Figure 7. When for reasons of mechanical joining (minimum required bearing strength) a higher MVF is required in a specific area of the structure, this could be achieved not by increasing the FML or aluminum layer thickness in the FML, but by applying additional metal layers in the area where needed. As a consequence, the FML locally may consist of a different laminate configuration with its own strength characteristics, while the base FML remains unaffected.

A similar example has been presented in [23]. In order to reach the minimum required residual strength of the FML Glare in the forward fuselage of the A380, the FML configuration has not been changed in the entire panel, but additional glass fiber straps have been applied interlaminar locally underneath the frames, see Figure 8. This solution is often denoted as ‘Glare improved’.

The application of this design freedom implies that the structure and the related design constraints and requirements have to be identified first, before the appropriate FML can be determined. This is opposite to the design approach applied nowadays, where the FML is designed first, before the actual structure has been determined [7].
5. CONCLUSIONS

This paper presented an overview of the development aspects of FMLs relevant for the fatigue and damage tolerance assessment. Based on the discussion some conclusions can be put forward:

The FML concept is a structural concept that requires a different F&DT approach than currently applied to metallic structures

In the F&DT assessment a distinction must be made between the individual constituents and their contribution to the fracture mechanisms.

To describe the fatigue and fracture behavior of FMLs, the methods for monolithic metallic structures can not be applied directly. However, if the all failure mechanisms are described together, the principle of similitude can be used to describe the initiation and crack growth in the metallic constituents of the FML.

To fully benefit from the F&DT characteristics of FMLs, the FMLs should be designed from a structural perspective, i.e. the structure and related requirements should define the FML, rather than that an FML is ‘designed’ which then has to be tailored to the structure.

6. REFERENCES


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