JOURNAL OF AIRCRAFT
Vol. 45, No. 4, July–August 2008

Fiber/Metal Composite Technology for Future Primary Aircraft Structures

R. C. Alderliesten* and R. Benedictus†
Delft University of Technology, 2629 HS Delft, The Netherlands

DOI: 10.2514/1.33946

This paper discusses the structural and material considerations for fiber/metal composite technology for future primary and secondary aircraft structures. Based on these considerations and the experience obtained so far with fiber/metal laminates in primary aircraft structures, the potential field of further development of fiber/metal composite technology will be explained. It is concluded that a composite technology approach, in which both metals and fibers are combined to form a tailored structural material, can lead to significant weight reduction in future structural applications.

I. Introduction

ITEMS to be considered when developing structural materials for future aircraft structures are mainly related to the durability and damage tolerance requirements by the airworthiness authorities, the structural and manufacturing aspects, and not in the least place, the development, production, and operational/maintenance costs. The latter are usually underestimated in the initial development phase of materials, although it is the most important consideration for an aircraft operator and therefore also for the aircraft manufacturer.

The design drivers for current and future airframes depend on the aircraft type, design life, and flight envelope (following from its mission). This makes the pitfall of being too generic for future applications inevitable when discussing the design drivers and structural aspects for primary aircraft structures. Nevertheless, following the distinction in aircraft type made by the airworthiness regulations and trends visible in current aircraft operation, some general remarks considering the structural and material aspects of future aircraft can be made.

Current trends in aircraft operations are showing an increasing demand for lower operational and maintenance costs. Practically, this translates into aircraft with longer design lives, longer inspection intervals, and shorter inspection downtimes.‡ Despite the effort being put into integrated vehicle health management systems [1–3], the best way to deal with these stringent requirements is to consider these aspects from the early stage on, in the structural design and material selection phase.

Considering these life-cycle costs in the early stages of design requires knowledge of current and future structural materials, as well as detailed knowledge of current and future airframe structures. The type of structure is related to the applied materials and the design philosophy used. In general, three classes of materials can be identified in current airframe designs: metallic materials, fiber reinforced polymers, and fiber/metal composites, to which class fiber metal laminates (FMLs) belong.

Based on extensive experience with FMLs [4,5] and the successful approach taken to obtain technology readiness for some of these laminates for primary aircraft fuselage structures [6], this paper discusses the considerations for the development of next generation fiber/metal composites for future aerospace technology.

II. Structural Considerations

The discussion on structural aspects of primary aircraft structures will be limited to the conventional civil transport aircraft configuration. The reason for this limitation is twofold: It is believed that this configuration will be applied for many decades, and even for alternative configurations, such as blended wings [7–10] and high speed aircraft [11,12], many structural and material aspects discussed for the conventional configuration will remain applicable.

Damage tolerance considerations for structural design comprises various impact damages, environmental aspects, and fatigue related damages. Impact damage types to be considered are hail, bird strike, engine debris, runway debris, gear tire shrapnel, and damages due to ground handling and tooling. Environmental related damages are corrosion damage, temperature, humidity and radiation effects, erosion, and lightning strikes. Fatigue damage is directly related to the operational loads and the structural design. The fatigue evaluation consists of identification of relevant damage scenarios and load spectra.

Figure 1 illustrates with a few examples that the location on the aircraft structure determines to a great extent which load cases and damage scenarios are the relevant design drivers for that particular structure. The load cases are mainly determined by the overall design, whereas the damage scenarios are mainly determined by the location.

This means that the fatigue and damage tolerance evaluation will be different depending on the location of the component and that the structural solutions may also differ. The airworthiness authorities give guidelines for the damage tolerance evaluation on how to comply with the requirements. There are several ways to comply with these requirements.

The first method of compliance is through the use of damage tolerant materials. One can search or develop, for instance, materials with inherently high resistance to impact damages, good durability, and fatigue performance for structural components susceptible to these damage scenarios.

The second method is to incorporate damage tolerant features within the structural design, allowing the use of conventional materials that are insufficient on their own to meet the first method of compliance. This can be achieved, for example, with thicker or sandwich structures. The latter could be designed as an impact resistant outer skin with the main load carrying part being the inner skin.

Presented as Paper 2404 at the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Waikiki, HI, 23–26 April 2007; received 8 August 2007; accepted for publication 5 December 2007.

*Assistant Professor, Aerospace Materials and Structures, Faculty of Aerospace Engineering, Kluyverweg 1.

†Professor, Aerospace Materials and Structures, Faculty of Aerospace Engineering, Kluyverweg 1.

‡Boeing.com/commercial/aeromagazine/articles/qtr_4_06/AERO_Q406.pdf

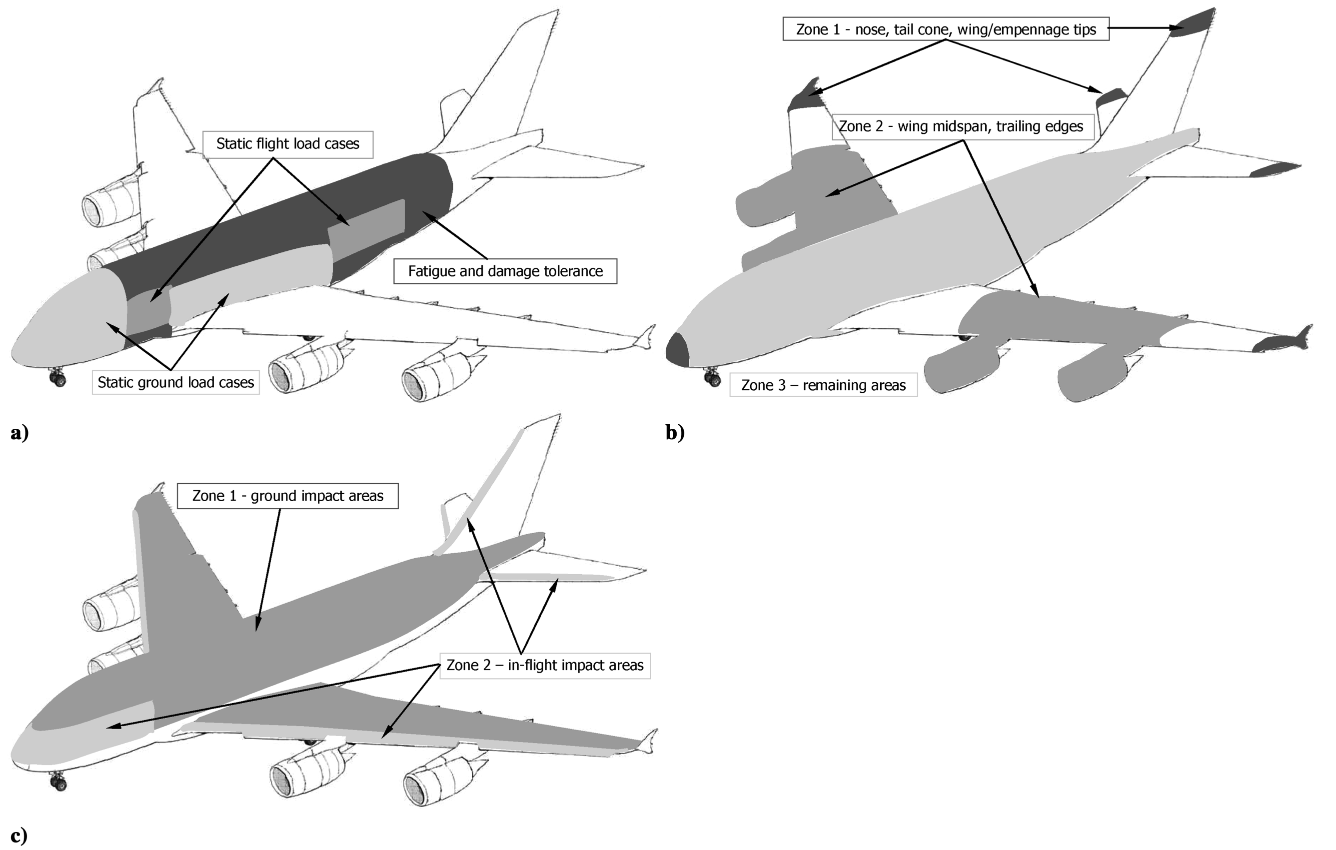

Fig. 1 Different load cases and damage scenarios: a) significant load cases in a fuselage structure, b) damage areas for lightning strike, c) impact damage areas.

The third approach to comply with the damage tolerance requirements is to combine material and structural design to develop the component (or in some cases the skin) as a structural concept, rather than making it from a single material. This approach allows the flexibility of a material system to be tailored for a particular component, leading to an optimal solution. An example of this approach is the development of the fiber metal laminate skin concept, where the fuselage skin is built up of alternating layers of metal- and fiber-reinforced composites providing multiple load paths.

By definition, none of the three approaches is the best for any application, because the selection of material and design of structure is related to manufacturing techniques, as well as operational life considerations, such as maintenance and repairability. After all, no unique (composite or monolithic) material exists that leads to the optimal design when it is applied everywhere in the structure. In general, however, one can state that for meeting the design cost reduction drivers in the aerospace industry, the third method of compliance, whereby material tailoring uses a compositelike approach, offers the greatest potential.

For the application of materials in aircraft structures, one has to be aware of the relationship between material, structure, and manufacturing technique. In practice, this means the selection of materials cannot be discussed without looking at the structure and the potential manufacturing techniques.

A. Damage Tolerance Design Philosophy

The damage tolerance aspects of primary aircraft structures is becoming more and more important, due to the increase in life extension programs [13] for existing aircraft and the tighter design requirements of new aircraft on the design table. Despite the generic definition, there is a large variety in the application of damage tolerant design philosophies as result of the different aircraft types (transport, military, and helicopters). The airworthiness regulations do not describe in detail the way in which aircraft manufacturers should design for and validate structural integrity in the presence of operational structural damage [14]. The method of design, as well as the experimental and numerical substantiation, remains the responsibility of the manufacturer. In addition, the different nature of current (and future) structural materials could increase the variety of approaches and philosophies even further.

Nevertheless, all damage tolerance concepts have to prove that the occurrence of any damage (fatigue initiated, foreign-object induced, etc.) will not impair structural integrity. As a result of the different structural materials available nowadays, the validation of this damage-bearing capability might be affected by the different ways in which damage is initiated and in which damage grows. An example of this is the strong belief among aircraft engineers that carbon-fiber-reinforced composites (which are not metals) do not suffer from fatigue, making fatigue analysis in the structural assessment obsolete [15]. However, the assessment should include structural durability in general, which means the incorporation of damage mechanisms other than those known for the common metallic materials that may initiate and grow under service load spectra.

In the evaluation of materials for structural application and, in particular, in the comparison of structural weight of structures built up from different materials, one has to incorporate all damage scenarios which might occur. Any structural weight analysis that does not include all aspects will, by definition, be unrealistic and unreliable.

B. Inspection and Damage Detection

The ability to detect any type of damage in an aircraft structure is related to the number of inspections (defined in the maintenance program), but also to the type of inspection. The increasing demand by the operators to decrease the number of inspections, as well as the inspection downtime, makes inspection and damage detection an important aspect for structural consideration.

Damage detection is related to the damage type, the material used, and the applied inspection technique. However, these three aspects cannot be dealt with separately, because they are interrelated. The accuracy of the inspection technique and the minimal detectable damage depends on the damage type and the material type, which are also related.

The significance of damage detection can be illustrated with the difference in impact response of metallic materials and fiber-reinforced polymers [16]. Whereas the impact area in metallic materials can be identified by the damage to the material surface (damage forms a visible “dent”), composite materials often fail within the material without evidence at the surface. The nonvisible impact damage can be a concern as it affects the material behavior, although it cannot be identified by visual inspection. To assess this topic in certification, a barely visible impact damage (BVID) threshold is used, which is the minimum damage that still can be detected. However, despite detection, assessment of the full extent of the damage requires more sophisticated nondestructive investigation methods, which is often not the case for metallic structures.

For material considerations, one should therefore address all potential failure mechanisms in the development phase, as well as the corresponding effect on the structural properties. In addition, inspection techniques must be developed to identify the location and magnitude of the damage before a critical level is reached. The latter aspect should take into account the demand for decreased inspection downtime and should be proven on a (complex) structural level and not only on coupon level.

Most techniques reported in the literature detect the presence and magnitude of damage, or in case of in-flight detection techniques, the occurrence of damage, but not the location [17]. Even for relatively simple coupons with riveted or bonded joints or stiffeners, damage localization appears to be a complex exercise.

In-flight inspection and damage detection techniques considered for vehicle health usage monitoring will only reduce operational and maintenance costs if the location and magnitude of the damage can be determined. Detection of damage without sufficient information about the severity will only increase the operational costs. If damage severity can also be assessed, a damage tolerance evaluation can be performed to determine whether the structure should be repaired immediately or whether postponing repair until the next regular inspection is acceptable. This approach, however, requires a modification to the current regulations, which still require repair once damage is detected.

C. Durability Assessment

Many authors have elaborated on assessing fatigue damage in relation to the inspection interval [13,18,19]. Whereas accidental damage and environmental-induced damage can be considered as random events, fatigue damage is to a certain extent related to the usage of the aircraft structure.

As mentioned before, the difference in nature between metallic materials and fiber-reinforced polymers has confused many engineers with respect to assessment of fatigue damage. Fatigue initiation and crack propagation, characteristic for metals, do not occur in a similar way in composite materials. Nevertheless, the assessment should provide a valid proof of the structural integrity throughout the design life, which implies considering not only fatigue, but any type of cumulative or progressive damage occurring as a result of the usage-related load spectra. This includes specific damage types such as delaminations, matrix cracking, fiber failure, etc., characteristic for composite materials [15].

Corrosion aspects should be considered at a structural level rather than a material level. Although it is known that metallic materials may suffer various forms of corrosion, fiber-reinforced polymers are considered to be insensitive to this phenomenon. However, the application of carbon-fiber polymers in a structure might induce galvanic corrosion issues in time in combination with metallic structural parts. Commonly, this aspect is considered in the design, by the application of glass fiber composite layers as a barrier. Nevertheless, one should keep in mind that although this approach slows down corrosion, it does not stop the process.

D. Structural Repair

The repairability aspect discussed here concerns both the ability to repair the structure, by means of patching for instance, as well as the ability to exchange parts at acceptable costs. This aspect should be considered in the early design phase.

As a result of the many life extension programs for existing aircraft, a lot of research is performed on how to design and analyze repairs. However, integration of functionalities (i.e., integration of complex stiffeners with the skin material, using sandwich core material to replace insulation) is often introduced with the application of composite materials in aircraft structures. This trend requires considerations on the repairability of the structure. Separation of functionalities might be necessary in damage sensitive areas in an aircraft structure to increase the repairability or to enable exchange of parts at low costs.

To the same extent, the component size should be evaluated in the design phase. Large components cured or manufactured as a single piece (such as full fuselage barrel sections) might reduce the manufacturing costs, but if the component has to be exchanged, it will lead to high repair costs. Depending on the application, an optimum needs to be determined to reduce overall costs as much as possible.

For each material or structure, repair methods can be determined. However, the complexity or limitation of possible repair methods highly affects the attractiveness of the considered material.

III. Fiber/Metal Composite Technology

The concept of fiber metal laminates has been invented and developed at Delft University of Technology in The Netherlands [4,5]. In close cooperation with industrial partners, the technology readiness of this material concept has been proven by actual full scale applications. For example, the first candidate for aerospace applications, Arall, has been applied as the skin material for the C17 cargo door. The successors, Glare [20–22] and HSS Glare, have been selected as the upper fuselage skin material of the Airbus A380 [23]. Since the introduction of FML technology [24], many researchers all over the world have tried to understand the failure mechanisms of this type of structural material and have sought for alternative FMLs to be developed for various applications [25–27].

Despite all the effort performed so far, the growth of FML applications has been small, limited primarily to the application of a similar Glare variant elsewhere in aerospace (or sometimes even nonaerospace) structures [28]. This might give the impression that FMLs have a limited applicability in aircraft structures and might as well be replaced in the future by new aluminum alloys or carbon-reinforced polymers. However, such a statement would testify to the misunderstanding of the FML concept. Fortunately, many researchers still strive for further improvements as they understand the enormous potential of the concept for primary aircraft structures.

The question that remains is why the next generation of FMLs have not seen the light of application yet, because the time between the first and second generation (Arall and Glare, respectively) was remarkably limited. From the authors’ perspective, a part of the answer to that question can be found in the excellent FML that Glare is, considering the current state of the material technology. Apparently, the researchers that developed Glare [8] provided variants of the FML concept that give superior properties and brought it toward technology readiness for primary structural application. Nevertheless, knowing the effort of many researchers over the world, such an answer alone would certainly be insufficient. The authors believe that a part of the answer should be sought in the lack of sufficient experience in an already limited world of FML engineers. For this reason, this paper tries to outline the road onward to future fiber/metal composite technology based on the extensive amount of experience with FMLs.

Fiber/metal composite technology combines the advantages of metallic materials and fiber-reinforced matrix systems. Metals have a high bearing strength and impact resistance and are easy to repair, whereas full composites have excellent fatigue characteristics and high strength and stiffness. The fatigue and corrosion characteristics of metals and the low bearing strength, impact resistance, and repairability of composites can be overcome by the combination.

Depending on the application and the requirements, the constituents and how they are combined can be varied to obtain the desired material characteristics for that specific application. In addition, the application can be further optimized by designing the structure on a constituent level. This approach is referred to as the smart material approach. An illustration of this approach is the improved FML with additional crack-stopping capabilities within the structure [29]. The combination of constituents and the position and size in the structure determine to a great extent the overall response of the structure.

The FML concept was developed to enhance the fatigue performance of (laminated) aluminum structures. As a consequence, this material concept has been treated as a metal derivative, which in time could be replaced by fiber-reinforced polymer composite material. However, fiber/metal composites do not only enhance specific metallic materials, but also the composite materials. This section discusses the advantages of adding metallic constituents to fiber-reinforced polymer composites.

A. Damage Tolerant Concepts

1. *Quasi-Isotropic Material Behavior*

The opposite of isotropic metallic materials, fiber-reinforced polymers are highly anisotropic due to their nature. The high stiffness and strength values published in the literature for these unidirectional composites (see Fig. 2) are often used to show the superior behavior of these materials compared with their metallic counterparts. However, unidirectional composites have little use in actual structures, where loads are not typically oriented in only one known direction. In-plane biaxial load systems and out-of-plane loads would then lead to premature failure.

To overcome this problem, quasi-isotropic material properties are obtained by applying fiber layers in various orientations. This approach will lower the in-plane stiffness and strength in any direction of the laminate compared to the unidirectional material properties. Furthermore, this approach will only achieve quasi-isotropic material properties in-plane, whereas the out-of-plane material properties often remain significantly lower [30]. Techniques to increase the material properties in the thickness direction with, for example, z-pinning and tufting [31–36], have a negative effect on the in-plane properties of the laminate.

The solution to this problem is provided by fiber metal composites (FMCs): introduction of isotropic metallic layers into the composite results in quasi-isotropic material behavior without the necessity for many additional fiber layers in various orientations. The effect of both approaches on the material properties is illustrated in Fig. 2.

This aspect has been proven by the application of the FML Glare in the upper fuselage of the Airbus A380. The main laminate types being applied are the so-called cross-ply grades Glare3 and Glare4. As a result of the combination with aluminum sheet material, only fibers in 0 and 90 deg are being applied. Following from the most significant load cases, the forward fuselage section contains mainly Glare3 (50% of the fibers in circumferential direction), whereas in most of the rear upper fuselage, Glare4 is applied, which contains 67% of the fibers in circumferential direction.

2. *Growth of (Fatigue) Damage*

The major difference between metallic materials and fiber-reinforced polymers is the material response to load spectra. The initiation and propagation of fatigue cracks in metals induced by notches or other structural stress raisers have been studied by many researchers since the phenomenon of fatigue has been identified [18]. The response of composite materials to load spectra, however, is completely different, which has led to the misunderstanding by many aerospace engineers that composites are not susceptible to fatigue. Throughout the past decades it has become known that composites show a more overall material degradation as a result of many local microcrack-induced delaminations and matrix cracks as result of the cyclic loading [15]. This behavior becomes more evident when maximum allowable strains above 0.3% are being used.

Until today, no clear and generally accepted method or approach has been found to predict the fatigue behavior of composite materials. The variety in possible composite materials (fibers, matrix systems, layups) introduces a large amount of potential responses to cyclic loading, which seem to prohibit a general approach to describe the fatigue behavior. The simplicity of crack lengths being the dominant damage parameter in monolithic metals has confused many researchers in their attempt to determine a method based on a single damage parameter. A single damage parameter does not make any sense for the description of the multiple damage modes in composites.

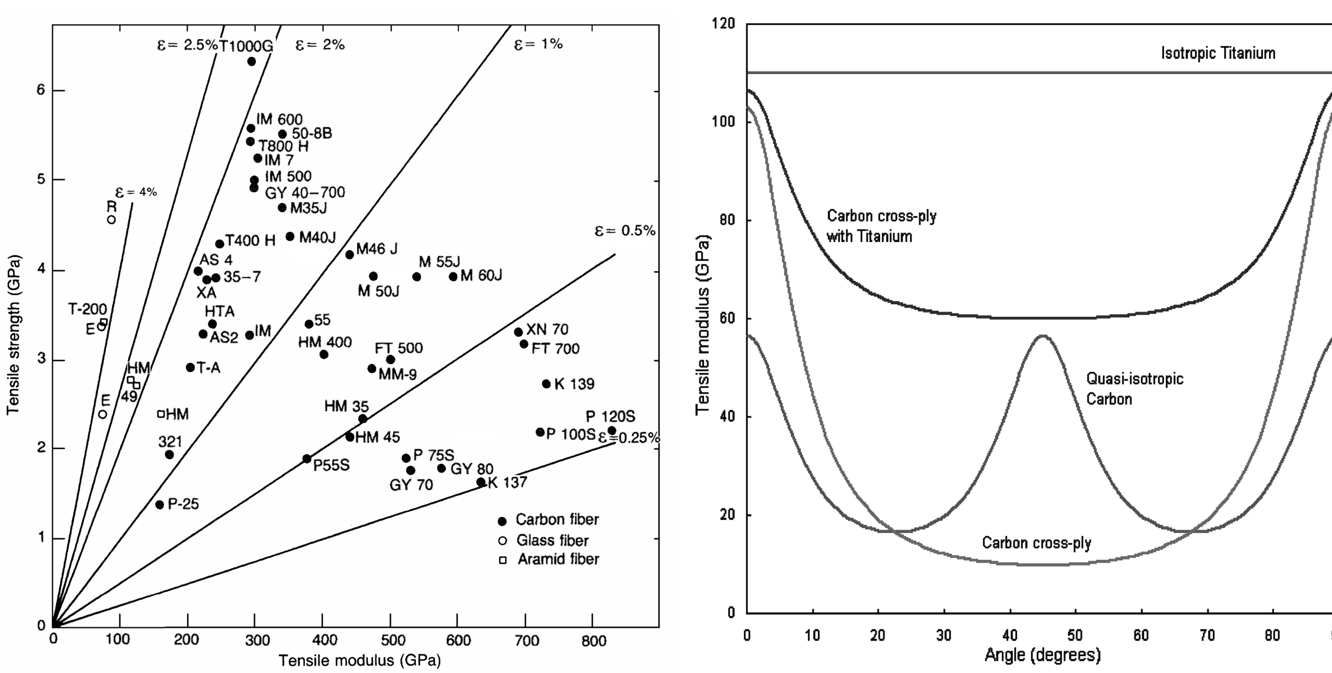

Fig. 2 Fiber strength as function of the modulus for carbon, aramid, and glass fibers (left) [45]; illustration of elastic moduli for cross-ply and quasi-isotropic CFRP and a titanium/carbon FML (right).

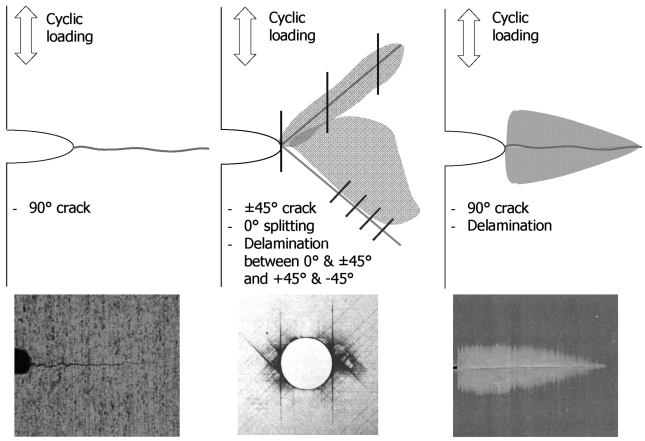

Fig. 3 Fatigue damage modes in metals, fiber-reinforced polymers, and fiber metal laminates.

Although the fatigue response of composite materials is often not the design driver, static properties and especially the small strain to failure associated with composite fatigue damage reduces the allowable stresses significantly. Thus, the designer should be aware that high cyclic stresses in the structure might decrease the structural properties in time. Usually, this aspect is incorporated in the evaluation and design by knockdown factors.

However, due to their overall degradation as a result of microcracking and delamination, repair of this type of damage in the structure is not easy and, for economical reasons, usually not an option. If fatigue damage exceeds the allowable structural degradation due to unanticipated structural usage, components need to be replaced. Metals, however, show more local damage as fatigue cracks initiate and propagate from notches, such as rivet holes. These types of damages can be repaired more easily by patching techniques as compared to composite materials.

The combination of composites and metallic materials in one structural FMC, however, enables an enhancement of the fatigue response of the material, but limits the fatigue damage to the occurrence of fatigue cracks similar to metals. Besides easier (visual) inspection, these fatigue crack damages are also easier to repair [37].

Figure 3 illustrates the most dominant damage modes in monolithic metal, fiber-reinforced polymer composites, and FMCs. In metals, a crack initiates at a stress concentration, whereas in fiber-reinforced polymer composites, various damage modes occur, making damage growth and failure prediction difficult. In FMCs, however, the damage is induced in a similar way as compared to monolithic metals at stress concentrations, with a crack in the metal constituents, with, in addition, delamination at the interfaces. Nevertheless, the overall damage remains limited to cracking in the metallic layers, but at load levels equivalent to quasi-isotropic fiber-reinforced polymer composites. As result of the unique balance between delamination at the interfaces and crack growth in the metal layers, damage initiation, damage growth, and failure can be predicted in a similar fashion to monolithic methods using linear elastic fracture mechanics [38,39].

In fact, it has been proven that the damage growth for fatigue crack growth and residual strength of the overall structure is related to the propagation of cracks and the related delamination growth at the interfaces, which can be described accurately in terms of stress intensities or energy releases. Figure 4 gives an example of the comparison between prediction and experiments for a fatigue crack configuration in the FML Glare. Because the prediction model is similar to the methodology developed for monolithic metals, it can be easily incorporated into current strength justification procedures, without the necessity to develop new damage tolerance principles.

B. Visible Damage Mechanisms

High strength and stiffness composite materials, such as carbon-fiber reinforced polymers (CFRP), show strains to failure below 2% without any ductility. As a result, the current design practice for CFRP is to apply maximum design strain levels of 0.35% [40], which significantly reduces the overall strength of the material, especially for quasi-isotropic layups.

An advantage of metallic constituents in composite material is the presence of ductility. The plastic behavior of the metallic constituents above their yield strength spreads the stresses over a larger area ahead of the tip. In addition, as a result of the plasticity, the effective stiffness of the metal layers is reduced (see Fig. 5) resulting in load transfer to the fiber layers. This load transfer results in shear stresses at the interfaces and, as a consequence, delamination. Because of the delamination, the fibers have a longer free length to deform, reducing the fiber stresses.

Therefore, the plasticity of the metal layers avoids very high local peak stresses in all the layers of the FML structure. Because the high stresses are distributed over a larger area within the material, a large amount of energy is consumed by plasticizing of the metal, which increases the load-bearing capability of the overall structure.

On a material level, the failure strength of an FMC is dependent on the failure strength of the applied unidirectional fiber layers. For example, the FML Glare has a failure strain near 4.5% [5], which corresponds to the failure strain of the S2-glass fibers. However, the load-bearing capability of a structure containing damages originating from fatigue or impact is higher if plasticity and delamination occurs [29].

The combination of plasticity in the metal layers and delamination at the interfaces with the fiber-reinforced polymer layers leads to an enhanced residual strength failure sequence, as compared with either metallic or full fiber-reinforced polymer (FRP) structures. High peak loads near notches or damages in FMCs will induce yielding of the metallic layers, which redistributes the high stresses in-plane in the metal layer to a larger area, but also in the thickness direction into the FRP layers. The load transfer to the FRP layers prohibits premature failure, but induces shear stresses at the interface, resulting in delamination. Subsequently, cracks will initiate in the metallic

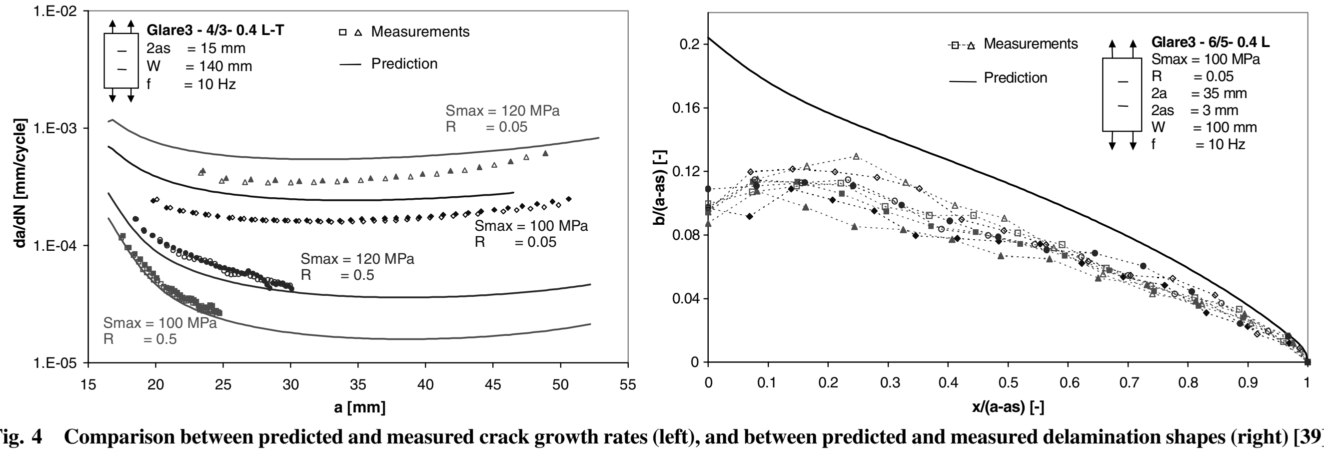

Fig. 4 Comparison between predicted and measured crack growth rates (left), and between predicted and measured delamination shapes (right) [39].

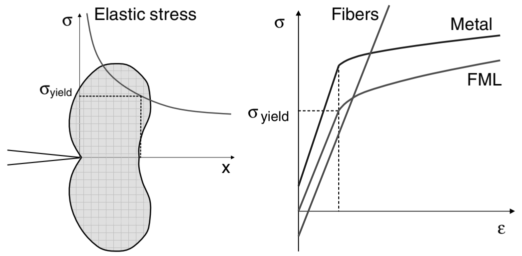

Fig. 5 Crack tip plasticity in an FML.

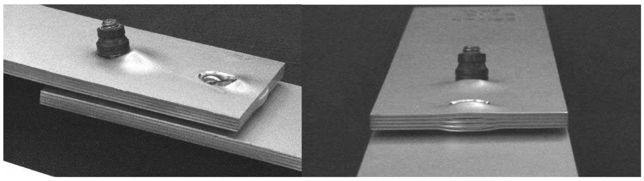

Fig. 6 Plasticity in a fastened lap joint.

layers, increasing the load transfer in the wake of the crack and inducing delamination growth (see Fig. 5). The combination of crack tip plasticity ahead of the cracks and delamination in the wake of the cracks enables the intact FRP layers to elongate with the cracked metallic layers over a longer length, keeping the overall fiber strain below failure strain. The consequence of this sequence is that damage growth occurs in a controlled and stable way, redistributing the load over a larger portion of the structure, which increases the overall residual strength of the structure.

In fact, careful selection of the FMC constituents and the layup enables the designer to tune the balance between delamination and crack growth, and, therefore, the residual strength of the structure.

Another advantage of plasticity in FMCs is related to the strength of mechanically fastened joints. Figure 6 illustrates the effect of plasticity in a symmetric lap-shear joint containing two Hi-Lock fasteners. Instead of shear failure, the fastener tends to rotate due to the plastic deformation of the FMC in-plane and out of plane. In a structural lap joint, this deformation will redistribute the load to the adjacent fasteners, loading all fasteners equally. Compared to an FRP structure, where all the peak stresses remain locally, this FMC joint has a higher overall joint strength.

The example shown in Fig. 6 also illustrates the manufacturing advantage of FMCs. A consequence of the plasticity in FMCs is that the material will respond to small manufacturing flaws similar to the deformation shown in Fig. 4. The stress induced by small flaws will induce local yielding of the metallic constituents, resulting in the redistribution of stress to the remaining structure. In practice, this means that the material is forgiving to small manufacturing flaws.

C. Durability Aspects

As mentioned before, metals are sensitive to several forms of corrosion damage. This is, in general, not the case for fiber-reinforced polymers, although some evidence is published on stress corrosion cracking in glass-fiber-reinforced polymers, induced in the long term by moisture ingress [41]. This highlights another aspect of material durability: the sensitivity of fiber-reinforced polymers to moisture ingress [42].

The sensitivity of polymer matrix systems to absorption of moisture and the related degradation of the material properties demands thorough research on the effect of the moisture absorption on the material performance, in terms of plasticizing, hydrolytic, or chemical degradation. Without accurate prediction models, severe knockdown factors need to be applied to take the long-term durability behavior into account.

The advantage of fiber/metal composites toward both environmental aspects is that the combination of metals and fiber/polymer layers results in natural barriers within the structural material. The metal layers protect the composite layers from moisture absorption, whereas the composite layers act as a barrier against corrosion damage (see Fig. 7). The overall material degradation as a result of environmental aspects is significantly lower as compared to either metallic structures or composite structures. In Fig. 7, it is clear that the monolithic aluminum is completely penetrated, whereas in Glare, only the outer aluminum sheet is corroded.

Fig. 7 Corrosion damage in an FML (left) and in monolithic 2024-T3 (right) [46].

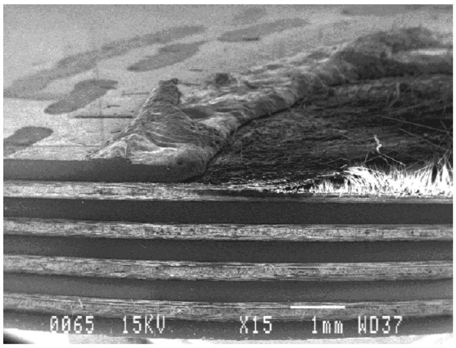

Fig. 8 Lightning strike damage in an FML.

Nevertheless, environmental aspects still need to be considered in the design of fiber/metal composites. Although the metal layers protect the composite layers in thickness directions, the effect on structural edges and fastener holes need to be addressed. In principle, all edges need to be protected to avoid moisture ingress. Extensive research on this topic for the aluminum-glass fiber-reinforced polymer laminates has been reported by Beumler [43], who measured diffusion depths in an open hole specimen, as well as holes filled with clearance fit rivets without the application of sealant. The latter is in fact the only relevant test to assess the moisture ingress, because either a filled hole or the application of sealant has been observed to completely block moisture ingress.

The advantage of natural barriers within the FML is also clearly visible for cases of lightning strike and flame penetration. Monolithic aluminum exposed to a lightning strike is fully penetrated, whereas the FML only shows a melted outer aluminum layer and adjacent damaged fiber-reinforced polymer layers (see Fig. 8). Note that the damage of the fiber layers in the FML is representative for full fiber-reinforced polymer composites. In addition, the FML has inherent electrical conductivity, necessary for lighting strike considerations, whereas fiber-reinforced polymer composites need additional lighting protection, such as, for instance, with copper meshes.

D. Structural Repair

Fiber-reinforced plastics are known for their poor bearing properties, which makes limiting repair to bonded repairs almost inevitable. Although bonded repairs significantly outperform their riveted counterparts, the latter is often preferred in service. Riveted repair procedures, worldwide experience, and available tooling make this repair technique cost efficient.

It has been proven for current FML grades that riveting repair techniques used for metallic structures can be applied in a similar way to repair FML structures. Therefore, the application of metal constituents in composite materials can be very efficient to increase the bearing strength of these materials at the joint locations.

IV. Road Ahead

The benefit of combining the metallic world with the fiber-reinforced polymer world has been discussed. The question remains how to proceed with the development of the fiber/metal composite concept.

The first step is to change the approach from a semimetallic material approach to a complete full composite approach. Currently, FMLs such as Glare have been qualified as a material with standard grades [5], whereas full composites are applied in a different manner. The composite nature does not allow such a simple overall material approach. The development of the fiber/metal concept should therefore follow a full composite approach in which the metals and fiber constituents are completely tailored toward the application.

However, one should be aware that, in addition to the increased potential of this composite approach, there will also be some drawbacks. Similar to current composite technology, the design allowables for primary structural applications need to be determined by a reliable amount of experiments. For the standard grades qualified for Glare, the laminate properties can be defined by simple metal volume fraction (MVF) based tools [44], which limit the necessary experimental data for qualification.

As result of the large amount of fiber and matrix types, which are being updated and modified each year, no handbook with design data for composite materials can be developed. To deal with this aspect for fiber/metal composite technology, one might benefit from the fact that several material properties are determined to a great extent by the metallic constituent. This aspect formed for Glare the basis of the MVF-based material property prediction. Especially, static properties could be determined based on the metallic constituent contribution for a range of fiber properties.

Another important step in the development of fiber/metal composite technology is the manufacturing-related aspects. In the development of FMLs, the emphasis has, to a great extent, been focused on structural performance. Development of different production techniques could lead to manufacturing cost reduction.

Based on the discussion presented in this paper, the main emphasis, however, should be put in the research on fiber/metal composite performance. Despite enormous efforts, only a minor step has been made with the development of FMLs for fuselage skin structures. Engineers and designers should be keen on the potential of the fiber/metal combination in primary aircraft structural materials. Specifically, the benefit of having theoretical prediction models on hand to describe the long-term behavior of these types of structural materials enables the engineer to tailor the FMC toward the application. Because of the combination of two different worlds, the freedom in tailoring increases the freedom the designer has for either monolithic metals or fiber-reinforced polymer composites. The main advantage, however, is that the strength justification prediction models necessary for structural integrity assessment remain significantly less complicated as compared to so-called full composites.

From the experience obtained with bringing the concept of FMLs toward technology readiness and full-scale application in aircraft structures, the authors conclude that development of FMCs should always be performed with actual applications in mind. Research on various combinations of fiber-reinforced matrix systems and metals may seem interesting from a scientific perspective, but could at the end remain useless, because the principle nature of FMCs contains the ability to tailor the material. This tailoring cannot be done in a way that makes sense without structural applications in mind, because the design of FMCs for a structure is directly linked to the required operational material performance, as well as the cost effective manufacturing concepts.

V. Conclusions

To conclude, the development of future structural materials for aerospace applications still has a long way to go, due to the potential in combining the various engineering metallic and composite materials. Fiber/metal composite technology must be further explored to identify the possible combinations and material characteristics in relation to potential applications. Developing full composite structures because everyone believes the future will be black, does not testify to a strategic vision on future structures. Engineers and designers should be aware of the enormous potential of combining the worlds of metals and fiber-reinforced polymers, especially in (pressurized) primary aircraft structures, where the design is dictated by fatigue and damage tolerance aspects. It is here one can gain a lot of weight reduction through the application of fiber/metal composite technology.

Depending on the application, fiber/metal combinations can be developed that are tailored toward the location in the structure. This tailoring must include the structural design and manufacturing analysis to become cost effective.

References

[1] Larder, B., Azzam, H., Trammel, C., and Vossler, G., "Smith Industries HUMS: Changing the M from Monitoring to Management," *Proceedings of the IEEE Aerospace Conference*, Vol. 6, Inst. of Electrical and Electronics Engineers, New York, 2000, pp. 449–455.

[2] Land, J. E., "HUMS. The Benefits: Past, Present and Future," *Proceedings of the IEEE Aerospace Conference*, Vol. 6, Inst. of Electrical and Electronics Engineers, New York, 2001, pp. 3083–3094.

[3] Dunsdon, J., *Integrated Vehicle Health Management Systems*, *25th Congress of the International Council of the Aeronautical Sciences*, International Council of the Aeronautical Sciences 2006-4.7.12006.

[4] Vlot, A., *Glare, History of the Development of a New Aircraft Material*, Kluwer Academic, Dordrecht, The Netherlands, 2001.

[5] Vlot, A., and Gunnink, J. W., *Fibre Metal Laminates, an Introduction*, Kluwer Academic, Dordrecht, The Netherlands, 2001.

[6] Vlot, A., "Towards Technology Readiness of Fibre Metal Laminates: GLARE Technology Development 1997–2000," *Proceedings of the 22nd International Congress of Aeronautical Sciences* [CD-ROM], Optimage, Edinburgh, 2000, pp. 1–15.

[7] Liebeck, R. H., "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft*, Vol. 41, No. 1, Jan.–Feb. 2004, pp. 10–25. doi:10.2514/1.9084

[8] Hawley, A. V., "Structural Design Aspects of a Blended-Wing-Body Aircraft," *International SAMPE Symposium and Exhibition*, Vol. 48, Pt. 2, Society for the Advancement of Material and Process Engineering, Covina, CA, May 2003, pp. 1808–1820.

[9] NASA, "Blended-Wing Body, NASA Facts," NASA FS-1997-07-24-LaRC, July 1997.

[10] Ko, Y. A., "Multidisciplinary Design Optimization of a Distributed Propulsion Blended-Wing-Body Aircraft," Ph.D. Dissertation, Virginia Polytechnic Inst.and State Univ., Blacksburg, VA, 2003.

[11] Miller, M., Rufin, A. C., Westre, W. N., and Samavedam, G., High-Speed Civil Transport Hybrid Laminate Sandwich Fuselage Panel Test, Fatigue and Fracture Mechanics, Vol. 29, American Society for Testing and Materials, STP 1332, 1999.

[12] Sakata, I. F., Davis, G. W., Robinson, J. C., and Yates, E. C., "Design Study of Structural Concepts for an Arrow-Wing Supersonic Cruise Aircraft," *Journal of Aircraft*, Vol. 13, No. 11, 1976, pp. 880–888.

[13] Schmidt, H.-J., Schmidt-Brandecker, B. K., and Trey, H., "Airbus A300 Fuselage Program for Life Extension and Widespread Fatigue Damage Evaluation," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft* [CD-ROM], Federal Aviation Admin./U.S. Dept. of Defense/NASA, 1999.

[14] Federal Aviation Administration, Damage Tolerance and Fatigue Evaluation of Structure, *Federal Aviation Regulations Part 25: Airworthiness Standards, Transport Category Airplanes*, Sec. 25.571, Federal Aviation Administration, Dept. of Transportation, Washington, D.C., 1997.

[15] Harris, B., *Fatigue in Composites*, Woodhead Publishing, Abington, Cambridge, England, 2003.

[16] Vlot, A., "Impact Loading on Fibre Metal Laminates," *International Journal of Impact Engineering*, Vol. 18, No. 3, 1996, pp. 291–307. doi:10.1016/0734-743X(96)89050-6

[17] Zhou, Z. Q., Chiu, W. K., and Bannister, M. K., "Health Monitoring of Aircraft Fuselage Structures Using Ultrasonic Waves," *Proceedings of the 25th International Congress of the Aeronautical Sciences* [CD-ROM], Optimage, Edinburgh, 2006.

[18] Schütz, W., "History of Fatigue," *Engineering Fracture Mechanics*, Vol. 54, No. 2, 1996, pp. 263–300. doi:10.1016/0013-7944(95)00178-6

[19] Alderliesten, R. C., and Homan, J. J., "Fatigue and Damage Tolerance Issues of Glare in Aircraft Structures," *International Journal of Fatigue*, Vol. 28, No. 10, Oct. 2006, pp. 1116–1123. doi:10.1016/j.ijfatigue.2006.02.015

[20] Verbruggen, M.L.C.E., "Aramid Reinforced Aluminium Laminates: Arall, Adhesion Problems and Environmental Effects," Ph.D. Dissertation, Delft Univ. of Technology, Delft, The Netherlands, 1987.

[21] Marissen, R., "Fatigue Crack Growth in ARALL, A Hybrid Aluminium-Aramid Composite Material, Crack Growth Mechanisms and Quantitative Predictions of the Crack Growth Rate," Ph.D. Dissertation, Delft Univ. of Technology, Delft, The Netherlands, 1988.

[22] Roebroeks, G. H. J. J., "Towards GLARE - The Development of a Fatigue Insensitive and Damage Tolerant Aircraft Material," Ph.D. Dissertation, Delft Univ. of Technology, Delft, The Netherlands, 1991.

[23] A380: Flying 21st century technology, Airbus Press Release, Airbus Industrie, Toulouse, France, May 2004.

[24] Gunnink, J. W., Vogelesang, L. B., and Schijve, J., "Application of a New Hybrid material (ARALL) in Aircraft Structures," *13th Congress of the International Council of the Aeronautical Sciences/AIAA Aircraft Systems and Technology Conference*, International Council of the Aeronautical Sciences, Seattle, WA, 1982, pp. 990–1000.

[25] Langelaan, J. W., and Kok, L. J. J., Damage Tolerance Modelling of Fibre/Metal Laminate Fuselage Structures, *Collection of Technical Papers: AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Material Conference*, Vol. 4, AIAA, Reston, VA, 1997, pp. 2809–2818.

[26] Pettit, R. G., *Damage Tolerance Philosophy for Fiber/Metal Laminates*, Society of Automotive Engineers Transactions 100, Sec. 1, Pt. 2, 1991, pp. 2828–2833.

[27] Burianek, D., A., and Spearing, S. M., "Fatigue Damage in Titanium-Graphite Hybrid Laminates," *Collection of Technical Papers: AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Vol. 3, AIAA, Reston, VA, 1998, pp. 2088–2097.

[28] Liu, Y.-L., "Study on the Fiber Metal Laminated Panel for Blast-Resistant Container," *Proceedings of the International SAMPE Symposium and Exhibition*, Vol. 48-2, Society for the Advancement of Material and Process Engineering, Covina, CA, 2003, pp. 2405–2413.

[29] deVries, T.J., "Blunt and Sharp Notch Behaviour of Glare Laminates," Ph.D. Dissertation, Delft Univ. of Technology, Delft, The Netherlands, 2001.

[30] Peters, S. T., "Ten Common Mistakes in Composite Design and Manufacture and How to Avoid Them," *SAMPE Journal*, Vol. 42, No. 5, Sept.–Oct. 2006, pp. 53–59.

[31] Yan, W., Liu, H. Y., and Mai, Y. W., "Mode II Delamination Toughness of Z-Pinned Laminates," *Composites Science and Technology*, Vol. 64, Nos. 13–14, 2004, pp. 1937–1945. doi:10.1016/j.compscitech.2004.02.008

[32] Partridge, I. K., and Cartié, D. D. R., "Delamination Resistant Laminates by Z-Fiber Pinning, Part 1: Manufacture and Fracture Performance, *Composites, Part A: Applied Science and Manufacturing* Vol. 36, 2005, pp. 55–64.

[33] Cartié, D. D. R., Troulis, M., and Partridge, I. K., "Delamination of Z-Pinned Carbon Fibre Reinforced Laminates," *Composites Science and Technology*, Vol. 66, No. 6, 2006, pp. 855–861. doi:10.1016/j.compscitech.2004.12.018

[34] Chang, P., Mouritz, A. P., and Cox, B. N., "Properties of Failure Mechanisms of Pinned Composites Lap Joints in Monotonic and Cyclic Tension," *Composites Science and Technology*, Vol. 66, No. 13, 2006, pp. 2163–2176. doi:10.1016/j.compscitech.2005.11.039

[35] Mouritz, A. P., "Compression Properties of Z-Pinned Sandwich Composites," *Journal of Material Science and Technology (Sofia)*, Vol. 41, No. 17, Sept. 2006, pp. 5771–5774.

[36] Cartié, D. D. R., Dell'Anno, G., Poulin, E., and Partridge, I. K., "3D Reinforcement of Stiffener-to-Skin T-Joints by Z-Pinning and Tufting," *Engineering Fracture Mechanics*, Vol. 73, No. 16, 2006, pp. 2532–2540. doi:10.1016/j.engfracmech.2006.06.012

[37] Hooijmeijer, P. A., "Repair of Fibre Metal Laminates," *Proceedings of the 22nd International SAMPE Europe Conference*, edited by G. R. Griffiths, and R. F. J. McCarthy, SAMPE Europe, Aalsmeer, The Netherlands, 2001, pp. 63–74.

[38] Homan, J. J., "Fatigue Initiation in Fibre Metal Laminates," *International Journal of Fatigue*, Vol. 28, No. 4, April 2006, pp. 366–374. doi:10.1016/j.ijfatigue.2005.07.030

[39] Alderliesten, R. C., "Analytical Prediction Model for Fatigue Crack Propagation and Delamination Growth in Glare," *International Journal of Fatigue*, Vol. 29, No. 4, April 2007, pp. 628–646. doi:10.1016/j.ijfatigue.2006.07.006

[40] Hinrichsen, J., "Requirements for "Care Free" Aircraft Structures and Expected Benefits from Hybrid Structures/Materials", *65th Annual Conference of Society of Allied Weight Engineers*, Society of Allied Weight Engineers Paper No. 3387, 2006.

[41] Khennane, A., and Melchers, R. E., "Durability of Glass Polymer Composites Subject to Stress Corrosion," *Journal of Composites for Construction*, Vol. 7, No. 2, 2003, pp. 109–117. doi:10.1061/(ASCE)1090-0268(2003)7:2(109)

[42] Jones, F. R., "Effect of Aggressive Environments on Long-Term Behaviour," *Fatigue in Composites*, edited by B. Harris, Woodhead Publishing, Abington, Cambridge, England, 2003, pp. 117–146.

[43] Beumler, Th., "Flying GLARE, a Contribution to Aircraft Certification Issues on Strength Properties in Non-Damaged and Fatigue Damaged GLARE Structures," Ph.D. Dissertation, Delft Univ. of Technology, Delft, The Netherlands, 2004.

[44] Hagenbeek, M., van Hengel, C., Bosker, O. J., and Vermeeren, C. A. J. R., Static Properties of Fibre Metal Laminates, *Applied Composite Materials*, Vol. 10, Nos. 4–5, 2003, pp. 207–222. doi:10.1023/A:1025569316827

[45] Hancox, N. L., and Mayer, R. M., *Design Data for Reinforced Plastics, A Guide for Engineers and Designers*, Chapman and Hall, London, 1994.

[46] Vogelesang, L. B., and Vlot, A., "Development of Fibre Metal Laminates for Advanced Aerospace Structures," *Journal of Materials Processing Technology*, Vol. 103, No. 1, 2000, pp. 1–5. doi:10.1016/S0924-0136(00)00411-8