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Development of Fibre Metal Laminates: concurrent multi-scale modeling and testing

J. Sinke

Abstract Fibre Metal Laminates (FML) represent a family of hybrid materials, consisting of alternating layers of thin metal sheets and fibre reinforced epoxies. The concept, invented in the late 1970s, has resulted in laminates like ARALL and GLARE. The first material is made of aluminum alloys, aramid fibres and an epoxy resin, GLARE laminates use similar constituents except for the aramid fibres, which are replaced by glass fibres. Besides, a specific laminate is determined by its layer thickness, fibre orientation, number of layers, etc., parameters, which can be regarded as variables. The first large scale application of the GLARE laminates is the fuselage of the Airbus A-380 aircraft. Large sections of the fuselage, both in the front and aft section will have a GLARE skin and some local GLARE doublers. Before this material could be applied to the A-380, it took more than 20 years of research and development, and the R&D is still continuing. The research that is performed is a mixture between testing and modeling: testing is necessary for the optimization of the laminates, and a lot of test evidence is required for certification and qualification purposes. In addition also analytical and numerical tools have been developed to limit the number of tests, to determine design allowables, and to predict the material behavior in a multitude of structural applications and details. Current and future research on FML has at least two objectives. On one hand the research is focused on generating new laminates based on the same concept, on the other hand the modeling is advancing in order to improve existing models and to develop new ones (tools for the analysis of structures). The tendency for the modeling is from macro-scale towards meso- and even micro-scale modeling. From the modeling and experimental point of view these hybrid materials, mixtures of metal and composite layers, offer specific challenges. Since fibres are embedded in the matrix and the materials have a layered structure, typical composite characteristics and failure modes are involved like anisotropy, fibre–matrix interfaces, matrix cracking, and delamination. On the other hand due to the metal constituents the laminates show plastic behavior and have discrete interfaces between the metal and the resin. In this paper an overview is presented of the research and development of FML, in particular the development of GLARE. The emphasis in this overview will be on the understanding and analysis of these laminates, and the development of appropriate tools (models). Over the years the development was a concurrent one: both testing and modeling were performed simultaneously. Special attention will be paid on the current and future research that is planned for a further understanding of this structural material. This research is dominated by numerical calculations and simulations and is aiming for topics like the prediction of the fracture energy, the crack bridging effect, and the blunt notch behavior of laminates.

Introduction

Fibre Metal Laminates, a brief introduction

Fibre Metal Laminates (FML) are hybrid materials, consisting of alternating layers of thin metal sheets and composite layers. These layers are bonded together with the matrix material of the composite layer. FML represent a

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Fig. 1 Composition of a GLARE 2-3/2-0.4 laminate

family of new materials: the three main components, the metal alloy, the fibre system and the matrix or resin, are variables, which may result in a wide range of different materials. The variety in laminates is further increased by variation of the thickness of the layers, the number of layers in a laminate, and the fibre orientations.

To illustrate the concept Fig. 1 presents a GLARE 2-3/2-0.4 laminate. This laminate is made of the Aluminium 2024-T3 alloy, and a UD-ply consisting S-glass fibres and the FM94 epoxy resin. In this laminate each composite layer is made of two UD-plies, positioned in the same direction, resulting in a Uni-Directional (UD) laminate. The laminate has a symmetrical lay-up. The laminate has five layers: three metal layers (each 0.4 mm thick), and two composite layers. The thickness of a composite layer depends on the thickness and number of the used plies; e.g. the two glass-epoxy plies of the GLARE-3 laminate have a combined thickness of about 0.25 mm.

Brief history of the development of FML [1]

The history of FML starts with the bonding technology Fokker used for the F-27 aircraft, about 50 years ago. The main reasons for the development of bonded structures were costs and structural stability, but it turned out that these layered structures also had better fatigue resistance. In the ‘60s and ‘70s, the bonding technology was further developed. One of the research topics at Fokker’s was to improve the fatigue resistance by applying fibres in the bond layers. The fatigue resistance was improved, but Fokker stopped further research since the results were positive but not excellent. Additional reasons were that Fokker had no new aircraft to apply the material, and replacing existing material with the laminates was too expensive. The Technical University of Delft, continued the research in the late ‘70s, and start changing the materials and the thickness of the layers. The reduction of metal layer thickness in particular, resulted in a big improvement of the fatigue resistance.

In 1979 the first prototype of a fibre metal laminate was tested at the University. This laminate was named ARALL: ARamid ALuminium Laminate, a FML based on aramid fibres. From the early ‘80s onwards, the research on the laminates expanded and some industries showed their interest. Companies like ALCOA (US) and AKZO (NL) sponsored the research. The first large application came with the cargo-door of the C17 military transport. The door performed well, but was replaced later by a metal one because the ARALL-door was too expensive.

In 1986 research started on a second FML: GLARE, based on glass fibres. The main reason to switch to glass fibres is that aramid fibres failed at some loading conditions. But, fibre failure is unacceptable for the excellent fatigue resistance of FML, because the fatigue resistance relies on the mechanism of crack bridging. The glass fibre ply in GLARE does not have the disadvantage of failing fibres, and therefore GLARE became the most important variant for FML. During the development of GLARE the scaling problem was solved. By so-called ‘‘splicing’’ of the metal layers (see Fig. 2), very large skin panels can be manufactured without the need of (riveted) joints. In the ARALL-period the laminates were treated as metal sheets: flat laminates were manufactured, subsequently formed and joined to large structures. For GLARE however, the shells are made using composite technology: the large skins (and reinforcements) are made by lay-up processes.

In the early ‘90s Airbus Industry started a design study for a very large passenger aircraft. This aircraft should complete the range of aircraft to be offered to customers. The final design was released in 1996, named the ‘‘A3XX’’. At that time GLARE was already regarded as a potential candidate for the fuselage of the aircraft and the

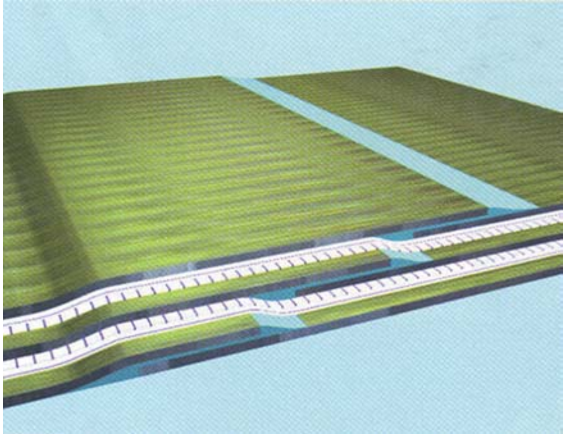


Fig. 2 Schematic picture of an overlap splice

research in Holland (University of Delft, the National Aerospace Laboratory and Stork Fokker) increased significantly. The government supported this basic research, which had the objective to make the GLARE ready for application in full size structures. As a final result the GLARE laminates are applied in a significant part of the A380 fuselage, and most skin panels are produced by Stork Fokker. The GLARE laminates are also applied in the leading edges of the vertical and horizontal tail planes of the A380.

Outline of the paper

In this paper selective items of the FML-research are described. These items are related to the modelling and testing of these hybrid materials.

In the second section the concept of FML is further explained, in particular those features and phenomena, which are important for the sections ‘Current research topics for FML’ and ‘Trends and future developments’. ‘Current research topics for FML’ is the main part of this paper, describing several recent research topics concerning GLARE. In the researches mentioned in this section, there is a mixture between modelling and testing. In the penultimate section an overview of current trends and future developments is presented. In the last section, some concluding remarks are given.

The concept of FML

FML are primarily developed for their excellent damage tolerance (DT) properties, amongst which the fatigue resistance is the most important one. In this section the concept of FML is further explained by its properties, variables and its (dis)advantages.

Properties

Fatigue

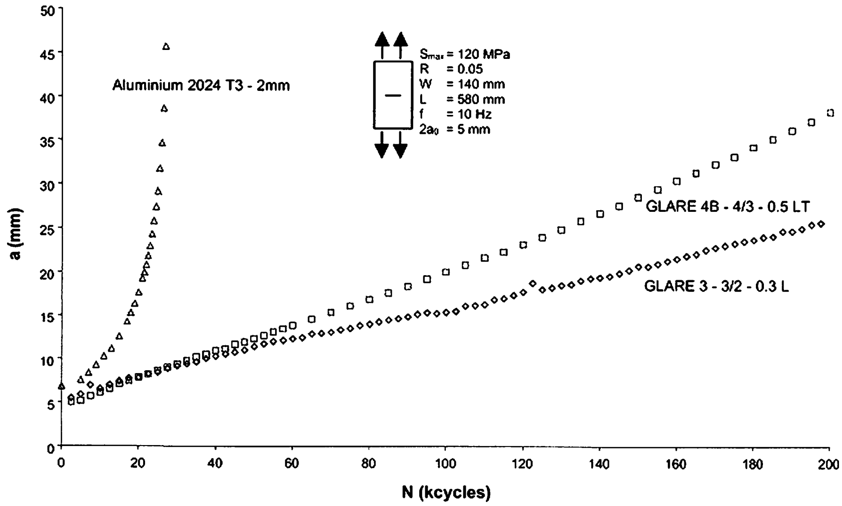
During fatigue, just like in metals, cracks may originate in FML when the stress level is high enough. The crack initiation starts at a free surface, i.e. an outer layer of the laminate, and the crack tends to grow. In metal alloys this crack growth is increasing with the size of the crack, but for FML there is a reduced crack growth (see Fig. 3) and in some cases even a stop of the crack growth.

The reduced crack growth is caused by the crack bridging of the fibres (see Fig. 4). When loaded in fatigue the crack propagates in the metal layer. The fibre layers however, stay intact and bypass the stresses over the crack, thereby reducing the stress intensity factor at the crack tips in the metal layers. Also metal laminates show some crack bridging but this effect is (much) smaller than for FML with fibres in the adhesive layers.

Effective fibre bridging is only possible in combination with an adequate and local separation of the metal and composite layer, so-called delamination. This delamination is necessary, to give the fibres enough length for elongation. From the crack propagation and delamination growth observed in experiments, it is concluded that both mechanisms are in balance with each other [2]. If this delamination was absent, fibre failure would occur, and increasing crack growth would take place. When the debonding becomes too large, e.g. when the thickness ratio metal layers and composite layers is too large, the crack bridging is less effective and the retardation of the crack growth too small.

Also the layered build-up of the laminate has a large impact on the fatigue life of a FML. As stated before, crack initiation starts at an outer surface. Once a crack starts to grow, it takes quite some time to initiate a crack in the

Fig. 3 Crack growth curves for Al-2024-T3 and GLARE-types based in this aluminium alloy, GLARE-3 and -4



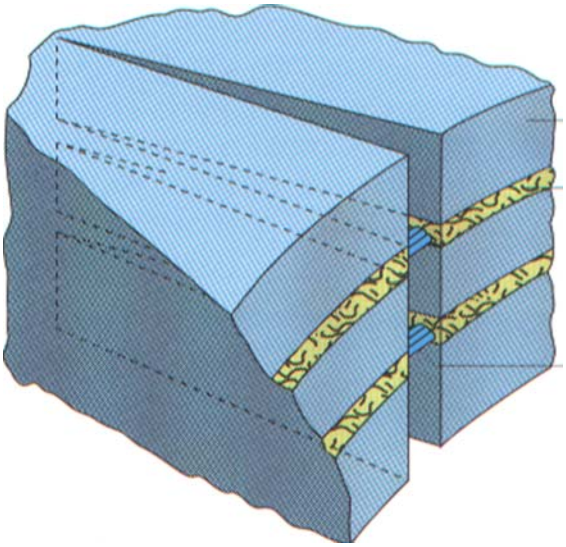


Fig. 4 The bridging of the fibre layers of the cracked aluminium layers

second layer of the laminate. A through crack in FML therefore is rare and feasible only by some outside source, like a damage of a foreign object.

Residual strength

The residual strength of a specimen or part is the strength that remains when some damage has occurred. This damage could be a fatigue crack, an impact dent or else. Generally, like in fatigue, the fibres stay intact and this has a significant influence on the value for the residual strength. When compared to common aluminium alloys, comparable laminates may offer a significant residual strength increase; this increase is small for a 50/50 Cross-Ply laminate like GLARE-3 but much larger for laminates with a dominant fibre direction. The improved residual strength further strengthens the potential of FML for applications where Damage Tolerance properties are the design drivers.

Impact/blast resistance

For application of materials in aircraft an important property is its impact resistance. During operation aircraft encounter many impacts by dropping tools, flying in hail storm, bird impact, etc. When compared to aluminium alloys and composites, FML offer the best impact properties. For many types of impact the metal constituent in the laminate absorbs a lot of energy by plastic deformation, and, by introducing membrane stresses, the fibres enlarge the affected area. Additional advantages are the visual dents, which ease the inspection for impact damages, and the large residual strength as mentioned before. FML are even better in case of blast impacts, when the membrane stresses carry a significant part of the loads and distribute them over a large area. Thus far, FML are used for blast resistant luggage containers for aircraft.

Fire resistance

The last property to be discussed briefly is the fire resistance of these laminates. For thicker laminates, from 4/3-lay-ups and thicker, FML are capable of retarding flame penetration due to its lay-up. When flames impinge on the surface of a laminate, the outer aluminium layer melts away rather rapidly. However, the next layer is a composite layer that carbonises and creates a barrier for further flame penetration. Simultaneous delaminations caused by the large temperature differences in the laminate, create air cavities acting as isolators for the heat. Also the excellent heat dissipation of aluminium alloys helps to improve the fire resistance.

Parameters involved

The mechanical behaviour of the laminates is influenced by a wide range of different parameters; most of them are directly related to the properties of the laminate constituents.

The fibres have a significant impact on the stiffness and strength properties of the laminates. The high strength of the laminates, in fibre direction, depends mainly on the strength of the fibres. In transverse direction however, the metal constituent dominates the strength of the laminate. Concerning the stiffness: fibres often have a higher Young's modulus than metals, but due to the addition of the matrix material, the stiffness of the composite layer for example in GLARE, is smaller than for the reference aluminium alloy. Other parameters which are dominated by the fibres are the failure strain and the anisotropy. The failure strain of the laminate is in fibre directions is as large as the failure strain of the used fibres.

The metal constituent also contributes to the strength and stiffness of the laminates. Improving these properties for the metal alloy is reflected directly in the properties of the laminate. The most significant contributions of the metal alloy are the plasticity and its isotropic behaviour. The plasticity results in a more damage tolerant behaviour than for full composites: stress concentrations are more easily levelled, and the laminates allow some plastic work/energy absorption before failure. With its isotropic behaviour the metal constituents contributes to acceptable mechanical properties in off-axis directions. Also the shear stiffness and the shear strength of FML are reasonable, due to metal constituent.

The matrix material does not have significant impact on the major mechanical properties, but has its influence on a small scale, the durability and the temperature resistance. The limits for the applicability of a particular FML depend strongly on the T_g of the polymer, used as matrix material. In the current FML these polymers are toughened epoxies and the temperature is limited to about 80–90 °C. Other polymers may improve the temperature resistance, but at the cost of higher internal stresses. Secondly the durability depends on the matrix material. Temperature and moisture effects may influence the matrix properties, in particular at edges, cut-outs and holes. Finally, the matrix material plays an important role in the stress transfer and fracture of the laminate at a local level. In these cases the fracture energies at different mode mixes are important.

Besides the constituents the lay-up of the FML is an important material parameter. The number of layers to be used in a particular design is generated by preliminary stress calculation. Nevertheless, the designer has the freedom to select not only the fibre systems, the metal alloy and the matrix material, but also the fibre orientation and the stacking order. The last two parameters have an important impact on the performance of the FML.

Advantages/disadvantages

The combination of metals and composites in one laminate offers both advantages and disadvantages.

The advantages are partly related to the original objectives of the FML development: the damage-tolerant properties. FML are, when compared to metals, very damage tolerant with respect to fatigue, corrosion, impact, and residual strength. When compared to full composites the advantages in the domain of DT are mainly impact, durability, and fracture toughness.

FML has advantages with respect to manufacturing issues. For the fabrication of the skin panels, leading edges and small structural elements, conventional manufacturing processes can be used: lay-up techniques, some forming processes, and cutting processes. As result, the investment costs to change from metal to FML production are limited.

During the research in the past, FML showed also other advantages, like its high blast resistance, its fire resistance, lightning-strike resistance, etc.

FML does also have some disadvantages. A few of these drawbacks are related to the manufacturing. Since large panels are made by lay-up techniques, a good ability to drape the material would be beneficial. However, FML do have rigid metal layers and their suitability for lay-up processes is limited.

Concerning the mechanical properties FML have a limited stiffness. In combination with aluminium alloys this is a disadvantage since the stiffer aluminium will attract higher loads. Another disadvantage is that not every combination is feasible. The combination of carbon fibres and aluminium alloys would greatly improve the attractiveness of the FML-concept, but the galvanic corrosion does prevent the combination of these two materials. Other disadvantages come with the introduction of a new material: the time-consuming build-up of experience and dissipation of knowledge.

Current research topics for FML

In this chapter four different modelling topics are briefly described; for details about these topics one is referred to the references mentioned. One topic is dealing with the design of a large fuselage panel; the second and third examples are discussing the modelling of the fatigue behaviour of FML, one using analytical tools, the second using numerical tools. Both models are validated using experimental test data. The last topic in this chapter is the modelling of bending of FML that is also validated with test results.

Design of fuselage panels [3]

The design of FML fuselage panels is a complex activity. Viewed from a design engineer, FML structures are like composite structures, where not only the structure but also the laminates have to be designed. On one hand this gives the designer the opportunity to tailor the structure; on the other hand the number of possible solutions has increased exponentially. In order to deal with the latter, the design process has become a subject of research.

In the research the Knowledge-Based Engineering (KBE) principles are investigated and applied, which are used during the repetitive tasks during design. This should reduce the time needed for the design of skin panels and alleviate the design engineers from non-creative, repetitive work. The knowledge that is fed into a (KBE) rule base consists of requirements and rules used for the detail design and analysis of the panels. The requirements include rules with respect to dimensions, manufacturing, etc.

The current design of fuselage skin panels consist of the following stages:

- Requirement definitions and pre-design, including principles, material selection and a first sketch of the panel lay-out
- Structural sizing, first design of the panel lay-out including dimensions (sizes, thickness)
- An iterative design process in which all panel details are designed

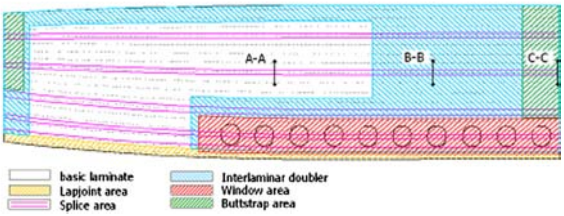


Fig. 5 First design of a fuselage skin panel

- Creation of the dossier of the panel, including 3D models, drawings, etc.

FML skin panels have a lot of different details. Figure 5 shows a typical skin panel, which is the result of the second design stage. This panel is made from many metal and composite layers; it has four splices, and local reinforcements due to the overall loads, local loads (window belt area) and in the joint areas (lap joint and butt joint). All these features, together with the back-up structure consisting of stringers, clips and frames, result in the third stage in a time-consuming detail design process. Most of the time is required for the local matching of all design rules and principles.

The research is focusing on the automation of the iterative parts of the design process using KBE principles. This KBE approach consists of creation of a knowledge database, definition of parametric model of the panel (laminate and substructure), and implementation of a design rule base (design principles). Applying these tools reduces the time-consuming iteration during detail design, as illustrated by the following example.

The FML skin panels are riveted to a back-up structure. These panels include local reinforcements like doublers and splices. Design rules state that rivets should have some minimum distance to the edges of individual metal layers, edges of structural elements like stringers, and so-called joggles, gradual thickness steps in the inside surface of the skin panel. This holds for splices and doublers. Thereby, the number of possible rivet locations is reduced. Combining this with the locations of structural elements of the back-up structure like stringers, frames and frame clips, a number of violations to the design rules will be present in skin panel. KBE-tools are used to optimize the panel and to look for the best detail design with respect to all requirements including weight and cost. An example of the outcome of this detailed design is presented in Fig. 5, where the skin is attached to the backup structure (Fig. 6).

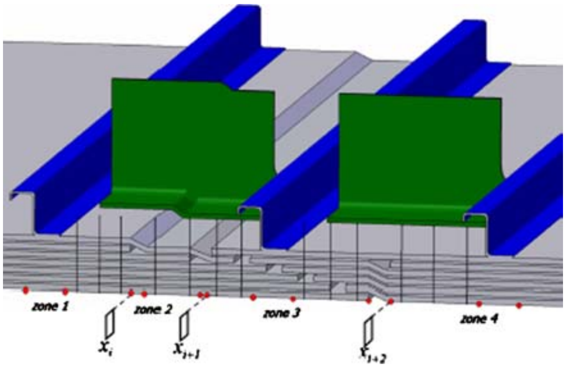


Fig. 6 The design of a skin panel, at the location of the splice. The skin has to be riveted to the stringers and the clips without conflict with the local design rules, like edge distances, rivet pitches, etc

Crack growth modelling [4–6]

In the section 'The concept of FML' a brief outline of the fatigue behaviour of FML has been presented. Since the fatigue resistance is the most important asset of FML, a lot of work is dedicated to the understanding and modelling of the crack growth in FML, in particular in GLARE. In this subsection, two different approaches are viewed: a method based on an extension of the stress intensity factor concept as described by Alderliesten [4] and a numerical model made by Suiker and Fleck [5].

In Fig. 7 a schematic presentation is given for the analytical model. The model developed by Alderliesten is an expansion of the stress intensity factor concept as used for monolithic alloys. For the investigation of through cracks in GLARE he used an effective stress intensity factor for the crack tip in the aluminium layers. In this model K_{tip} is the superposition of the far field stress intensity factor K_{farfield} and the stress intensity factor related to fibre bridging stresses, K_{bridging}:

$$K_{\mathrm{tip}} = K_{\mathrm{farfield}} + K_{\mathrm{bridging}} \tag{3.1}$$

$$K_{\mathrm{farfield}} = \sigma_{\mathrm{al.}}\sqrt{(\pi \cdot \mathrm{a})} \tag{3.2}$$

In order to determine the K_{tip}, it is necessary to define the K_{bridging} (K_{farfield} is based on the actual stresses in the aluminium layers calculated using the Classic Laminate Theory).

However, the fibre bridging stress is dependent on the size of the delamination at a particular location along the crack, and therefore the K_{bridging} is dependent on the delamination size and shape. For the development of this relationship, different delamination tests (without transverse effects) have been performed: tests in a mixed mode and in a pure mode II fracture (although at the start of the latter, the mode was also mixed). For capturing the results of the delamination growth tests as function of the stress intensity, a Paris-type equation is used.

$$\mathrm{d}b/\mathrm{dN} = C_{\mathrm{d}} \cdot \Delta K_{\mathrm{II}}^{m} \tag{3.3}$$

II reflects the mode II fracture; C_{d} and m constants for delamination between layers.

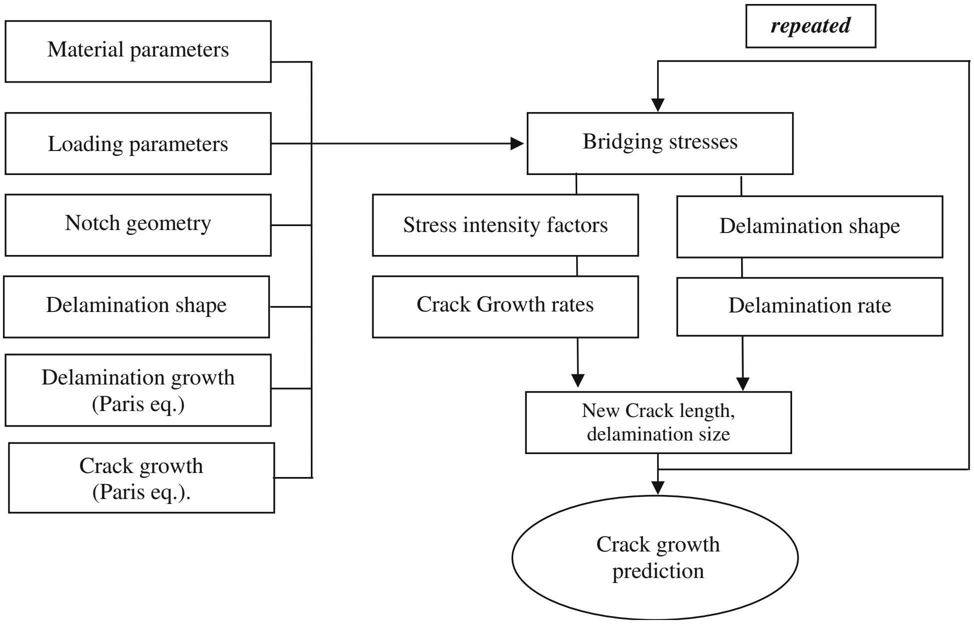


Fig. 7 Scheme of the analytical model for the prediction of fatigue crack growth for through cracks in FML

Subsequently the delamination growth results are related to the crack opening, crack growth and bridging stresses, which are in balance with each other.

By choosing an arbitrary initial delamination contour, using the Paris equations for the delamination growth at the interfaces and crack growth in the aluminium sheets, and given the notch geometry, the bridging stresses are calculated. These stresses are calculated by numerical routines, because no closed-form solution exists. The bridging stresses have a large impact on the stress intensity at the crack tip. The larger these stresses, the smaller the stress intensity and the smaller the crack growth rate, which is the ultimate result (see Fig. 8).

The model has been validated by a large number of test data that were available from the large research programs, performed in the period 1997–2002. The comparisons showed that the model gives a good prediction for the crack growth rates (delamination growth and crack opening shapes) in GLARE laminates.

In another study by Suiker and Fleck [5] Finite Element models are used to calculate the crack growth and delamination growth in laminated solids like FML. In this research, the steady-state tunnelling and plane-strain delamination of an H-shape crack are examined. As materials elastic and isotropic multi-layered materials are selected, which can also represent FML like ARALL and

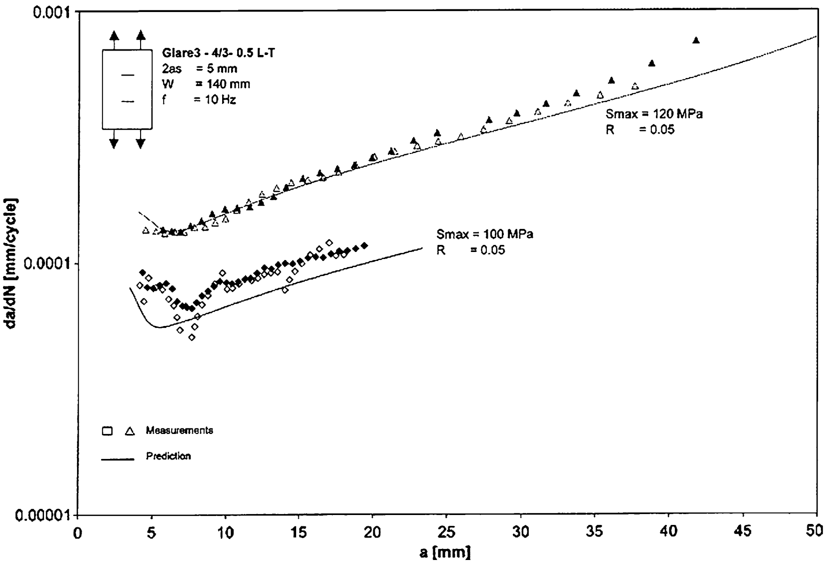


Fig. 8 Comparison of the results by the analytical calculations and test results

GLARE. In the article the mechanisms are described and the procedure to calculate the different limiting stresses is presented. A further step is the creation of fatigue fracture maps, which can be used for design studies of new laminates.

In the fatigue of FML it is observed that the interfaces between the different layers act as barriers and that crack turning occurs. In most cases the crack turns and a delamination between the cracked an uncracked layers starts. As have been discussed in the previous section, there is a balance between the crack growth in the metal layer and the delaminations between the metal layer and the adjacent composite layers.

In the study three different facture mechanisms are distinguished. The first one with crack tunnelling without delaminations; the second one with crack tunnelling and a constant delamination length, and the third one with crack tunnelling and increasing delamination length. For the model they selected primarily H-type cracks, as presented in Fig. 9. But also surface cracks and multiple cracks have been investigated. In the H-type crack the delamination fractures (except for very small delamination lengths) in a pure mode II. The fracture in the cracked layers is in mode I.

The calculations were preformed using the FE program ABAQUS Standard. The models they used had about 16,000 to 20,000 plain strain 8-node iso-parametric elements, with a 3 × 3 Gauss quadrature. Using this code, the displacements, the J-integral at the delamination tip, and the (complex) stress intensity factor at the delamination tip are calculated. Subsequently these data are used to calculate the energy release rates for plain-strain delamination, the mode mix, the crack opening displacement, and finally the tunnelling stress. When the minimum tunnelling stress is plotted for different stiffness ratios $\bar{E}_2/\bar{E}_1$ ($\bar{E}_\mathrm{i} = E_\mathrm{i}/(1\text{-}\upsilon_\mathrm{i}^2)$) as function of the ratio of the energy release rates ($G_\mathrm{dc}/G_\mathrm{Ic}$) for the delamination and the mode I crack in the metal layer, the fatigue fracture maps are obtained (see for an example Fig. 10). These maps can be used to determine at what minimum stress the fatigue crack grows and what mechanism of crack tunnelling will occur, given the material combinations. Mechanism 2 is the preferred one,

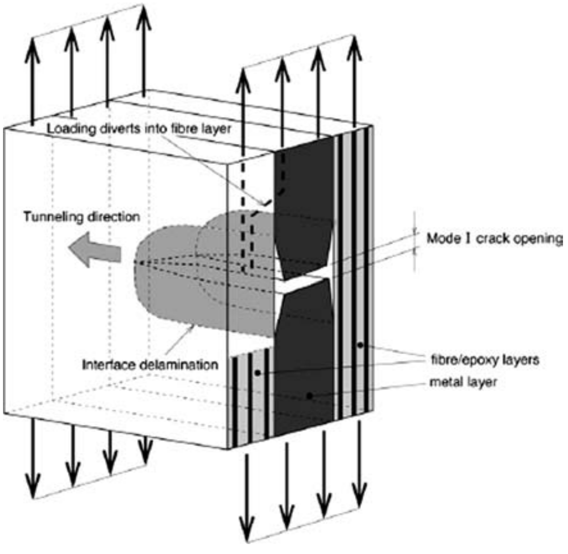


Fig. 9 H-shape crack tunnelling in a multi-layer material

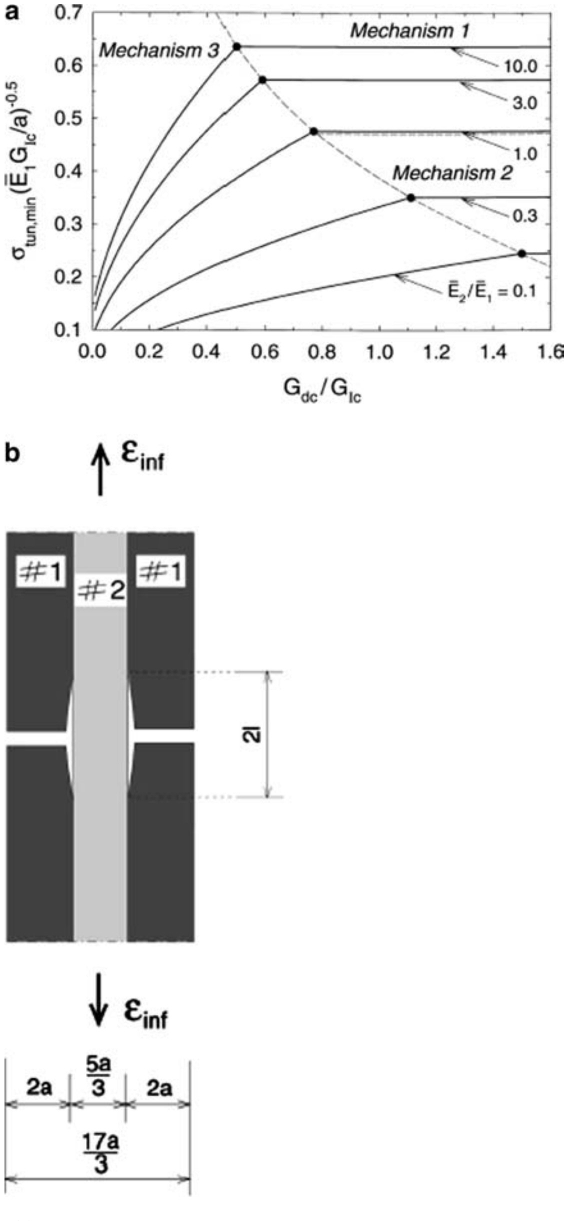


Fig. 10 An example of a fatigue fracture map expressing the minimum normalised tunnelling stress as function of the toughness ratio (delamination toughness/fracture toughness crack) for several stiffness ratios. The material is a 2/1-lay-up with fractures in the outer layers

according to the authors, since it gives a stable crack growth.

Forming [6]

Fibre Metal Laminates consist of metal and composite layers stacked in an alternating sequence. The metal layers are often aluminium alloys, are isotropic and have elastic–plastic properties. The composite layers consist of 2–4 plies; the fibre orientation of the layers is a variable. Each ply is unidirectional, consists of fibres in one direction embedded in a resin or matrix material (often a metal adhesive/epoxy system).

It can be deduced from the properties of the constituents that the deformation of composite layers in fibre direction is elastic until failure and that the failure strain is small (2–2.5% for aramid fibres (ARALL) and about 4–5% for glass fibres (GLARE)). The in-plane deformation in the metal layers can be significant (depends on the metal alloy) and most of the strain is plastic strain. For a laminate assembled from these materials, the in-plane deformations are limited too, since fibre failure (often followed by delamination of layers) restricts permanent deformations. As a consequence only a few FML-parts are manufactured by forming processes. Large skin panels are made by lay-up methods; frames, ribs and clips are often too complex to be formed from a FML sheet. This leaves prismatic profiles like stringers, or parts made by special manufacturing routes, like first forming of the metal sheets, followed by assembly into a FML-part.

Profiles like stringers are made by bending processes. At the moment several different bending principles are available. One method is to reverse the sequence of assembly and curing, and forming, as mentioned before. Another is roll forming of uncured stacks, which are cured after forming. Roll forming of thin laminates is also a possibility. Most common is to fabricate the laminates first, followed by a press brake bending process. This method is only applicable to a limited laminate lay-up, but thicker profiles can be made by subsequent bonding of several profiles on top of each other.

In the research described in [6], the objective is to develop a model that predicts the formability properties of FML and supports the designer with manufacturability evaluations of his designs. Due to the formability limitations as described above, the main focus is on the bending process for stringers as shown in Fig. 11.

The development of the model has been focused on those features for which the laminates differ from monolithic materials. One of the differences is the type of failures for laminates and metal sheet. The most common failure for metals is (brittle or more ductile) fracture. In FML, several failures may occur: fibre failure, matrix cracking, delamination, fracture of the metal layer, buckling of metal or composition layer, or a combination of these. These different failures result in different failure criteria in formability model.

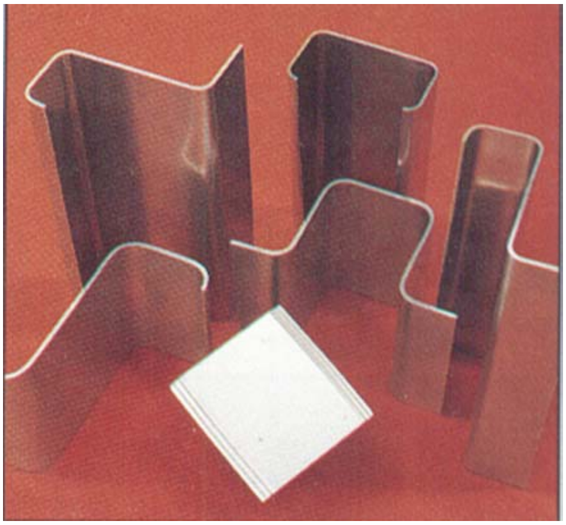


Fig. 11 Some stringer examples of FML, made by simple bending processes

The model that is developed is a model to calculate the stresses and strains in a cross-section and to evaluate the results for failure that might occur. When the calculations are fully elastic no difficulties arise, but when plasticity is involved several assumptions for bending are no longer valid. One of these assumptions is that straight cross sections remain straight. Also the negligence of the stresses in thickness directions is no longer allowed. This makes the modelling rather complex, in particular the non-linearity in the deformations of the metal layers, and the compatibility of the stresses and strains. A typical stress situation in a cross section during bending is presented in Fig. 12.

Based on the stress and strain distribution in a cross-section, the model indicates when a particular stress or strain causes failure. As stated before, FML do have several failure modes, so for a particular situation several failure criteria have to be checked. In Fig. 13 a result of bending evaluations is presented; the laminates may fail by cracking of the outer metal layer or by delamination of the central layer of the laminate.

Such plots help designers to verify their designed structural elements, in this case stringers.

Trends and future developments

In the past decades a tremendous amount of research has been done to bring the FML (in particular the GLARE) laminates to the aerospace market. In this period large

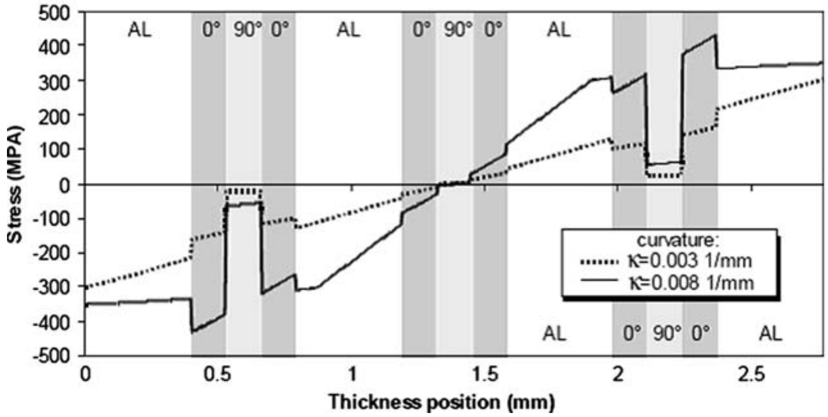


Fig. 12 Typical stress distribution in a FML (GLARE 4B-4/3 lay-up) *Note: GLARE 4B has 3 plies per composite layer*

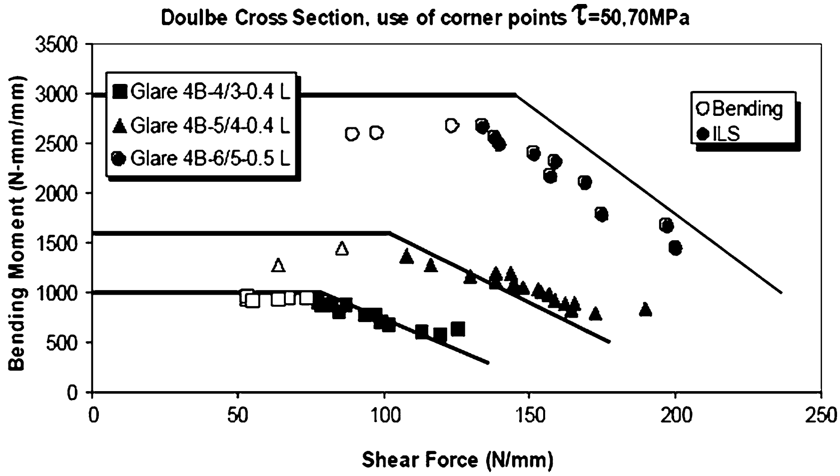


Fig. 13 A bending moment/ transverse force plot for three FML (model – solid lines – and test results)

programs have been performed in which the laminates were thoroughly tested and preliminary analytical and numerical tools were developed. Some of these models have been described in paragraph 3. In that period there was an abundant quantity of test date available, although primarily on GLARE laminates.

Future research on FML will involve modelling at smaller length scales, like modelling of structural details and micro-modelling, modelling of more generic problems, applicable to more types of FML, and improving the existing models by reducing the number of simplifications. In addition to that, the amount of test data will decrease significantly, which is disadvantageous for the fine-tuning of the models, but the modelling of the FML becomes more important. A few examples of these tendencies are presented below.

Hagenbeek [7] works on the implementation of thermo-mechanical behaviour of FML in numerical models. Therefore, he used a special element, a solid-like shell element, and adapted the element to cope with thermal effects. The element is also a rather generic one and can be applied to different laminates. The reason to start this research a few years ago is that the FML are used in a temperature range between –60 °C and +80 °C. The FML consisting of materials with different thermal properties has additional stress and strains due to thermal loading. All models at that time did not have the opportunity to take these effects into account. With the new code the material responses to mechanical loads and temperature loads can be evaluated.

The second example is a project focused on the bearing strength of FML [8]. In this project the failure of the laminate is modelled. The model is made using a commercial FE-code (ABAQUS) and the fracture model includes plasticity and delamination. This model is a step forward in the description of what happens in the laminate when it fails in bearing. The previous ''model'' was a rule based on a Rule of Mixtures approach, see Fig. 14, in which the bearing strength of particular laminate was related to its metal volume fraction [9]. For this approach both the bearing strength of the composite and metal alloy are input values. This approach works reasonably well as a first estimate, but it will not give details about the influence of matching of the hole and pin, the clamping forces, etc, as the new model can do.

In the context of the 6th Framework Program of the European Commission, the DIALFAST [10] project is

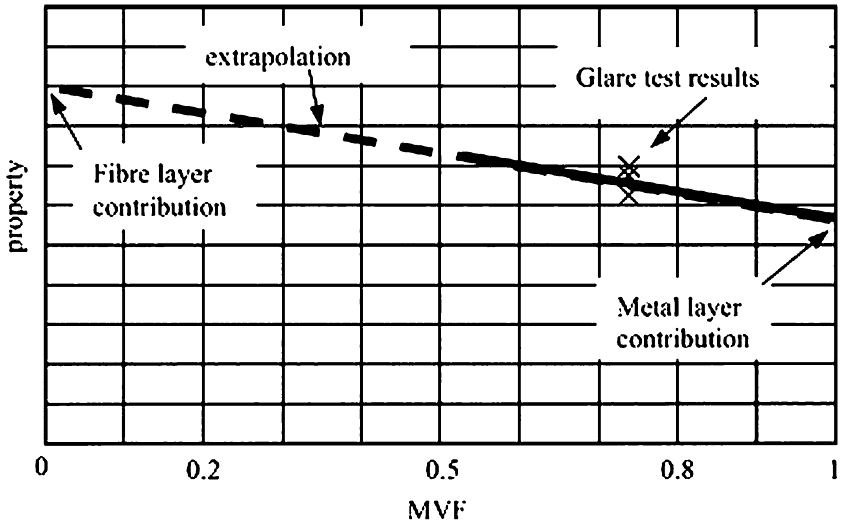


Fig. 14 The concept of the metal volume fraction (MVF) approach

performed, and some parts of the project are about detail modelling of FML. In one part numerical models are build using a commercial code (ABAQUS), for the failure prediction of structural details like riveted joints [11]. In the model only one or two rivets are modelled. For the modelling subroutines of ABAQUS are used, fine tuned to the problem and the input material properties are obtained by testing. These material tests consist of testing of the ply properties and the fracture energies of the interfaces. The properties of the metal alloys were readily available. Preliminary results show good agreement between experiments and the numerical predictions of the fracture of small riveted joint specimen. During testing the yielding, the damage development and the final failure are recorded.

Besides the ongoing research new projects are coming up, like the improvement of the fatigue models for FML. In the current models the predictions are valid only for constant amplitude loading, through cracks, and no eccentricities. In reality the fatigue of aircraft structures is dominated by variable amplitude loading (represented in flight spectra); the crack initiation in FML starts in one layer (an outer layer), and it takes quite some time to grow and to initiate a crack in the next layer. Fatigue analysis is most important for structural joints like riveted joints. However, the load transfer in joints is eccentric, resulting in additional bending stresses when loaded. The fatigue damage concentrates on one side of the joint. For the incorporation of these effects the current models need to be expanded and improved.

Finally, modelling should be used for the development of new FML and for new hybrid concepts. The models should become as generic as possible, and the lessons learned during the last 20 years should be used to tackle current and future problems where metal alloys and fibre-reinforced composites are joined.

Concluding remarks

In this paragraph some final remarks are made to summarize:

- The first remark is about the specific features and properties of FML. Though most features and properties are directly related to its constituents, the FML should not be treated as metals nor as composites, but as a true hybrid. FML gives a combination of features, which are not present in metals or full composites, such as: isotropic and anisotropic behaviour, plasticity, layered structure.
- The fact that FML have ‘‘metal’’ and ‘‘composite’’ features can be exploited. For some properties the metal constituent gives the FML an additional benefit with respect to composites (in damage tolerance properties), for other properties it is the other way (strength, fatigue). Also in the manufacturing of FML structures, the composite lay-up technology and some metal bending processes give the FML some advantages over the parent materials.

About the modelling of FML:

- Many numerical calculations are performed for linear elastic problems, for this set of problems the FML can be modelled rather easy. For a number of problems plasticity is involved and the plastic behaviour of the metal layers cannot be neglected. This includes problems like fatigue, the modelling of riveted joints, and the modelling of forming processes. These models are much more complicated.
- In FML there are many very distinct interfaces between the constituents. In the composite layers the interfaces are between the fibres and the matrix material, both materials have large differences in properties. But in FML there are also the interfaces between the metal

layers and the composite layers, with significant differences in material properties at both sides of the interface. In particular these interfaces should be modelled properly, since delamination is involved in most failure modes of FML.

- Until this moment most of the modelling of FML has been focused on the development of tools and models that should be applied directly in an industrial environment. That means that often the length scale of the models was large and most models were used to predict and calculate properties of GLARE laminates. In the future the modelling of FML will shift to more detail modelling of all kind of structural and material problems, and the models will become more generic, applicable to a range of other laminates.
- The modelling of FML will improve the development of new FML and new hybrid concepts. In particular the metal–composite interaction of the different layers will be an asset, when in the long-term future, structures will become more and more multi-material structures.

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