Fiber Metal Laminate Structure, a good replacement for monolithic and composite materials

Ehsan Sherkatghanad1,*, Lihui Lang1, Hamza Blala1, Lei Li1 and Sergei Alexandrov1

1School of Mechanical Engineering and Automation, Beihang University, 100191, Beijing, China

E-mail: ehsan_shgh@yahoo.com

Abstract. Lightweight materials such as aluminium alloys, magnesium alloys, and composite material present a significant possibility for applications in automobile and aerospace structures. In order to consider the feasibility of selecting and replacing such materials in the form of hybrid laminated materials, calculations and simulations are investigated with different lightweight materials such as single layer aluminium, fiber-reinforced composite materials, and the aluminium composite laminates, the carbon and glass cloth as the middle layer, under the constant force condition. The stiffness and deflections of these materials are discussed and compared in details. According to calculations, FE and experimental results validate that the deflections and the stiffness of different materials can be predicted well. In order to finalize the material selection, especially for aerospace-based components, the weight ratios are very determinative. Actually, a material with the superior specific stiffness and strength will be the best one considering some other limitations such as corrosion. Calculating the mass ratio of the suggested lightweight materials were done to find an appropriate one. In fact, these kinds of materials have the advantages of both metallic alloys and composites. In addition, in cases where corrosion resistance, environmental protection, fatigue resistance, and impact resistance are needed, FMLs can be the best choice.

1. Introduction

In order to decrease the fuel consumption and also to reduce pollutions in transportation, research on advanced lightweight materials having equal stiffness can be a popular research issue [1, 2]. After procurement of advanced laminated hybrid materials like fiber metal laminates (FMLs), the tendency to produce modern aerospace or automobile parts with composite materials is also growing manifolds [3, 4, 5]. In one hand, some composite materials such as carbon-reinforced composites, consisted of fabric and epoxy, are widely utilized for components production of aileron, landing gear doors, flaps, and other artefacts used in aeronautical industry [6, 7]. In addition, the composite materials can be applied in other applications like home construction, military, automobile and sport industries [8, 9]. Carbon/Epoxy composites show mechanical properties similar or superior than the conventional monolithic and metallic materials such as Aluminium. In most cases an advanced polymeric composite offers high specific strength and specific stiffness ratios [7, 10, 11]. FMLs are hybrid materials consisting of alternating thin layers of metal sheets and composites (fiber-reinforced epoxy prepreg). Aluminium is the most conventionally used metal, and Kevlar, glass or carbon can be used as fibers. GLARE is the trade name of FML using glass fibers in the middle layers, ARAL is the trade name of
FML using Kevlar fibers in the middle layers and CARAL is the trade name of FML using carbon fibers in the middle layers. They have been evaluated for potential usages in aerospace structures. Glare contains thin aluminium layers stuck together with unidirectional/biaxial reinforced prepregs of high-strength glass fibers. This material offers a pioneer combination of characteristics such as distinguished fatigue resistance, superior specific static properties, significant impact resistance, flame resistance and corrosion properties. In addition, for normal and easy-shaped parts, manufacture and repair are not challenging. GLARE laminate was selected for the upper fuselage skin structures of Airbus A380, as shown in figure 1. This is the first structural application of GLARE laminate in a commercial airline. This structure resulted in providing a new group of the hybrid laminate system which is able to prevent and stop crack growth caused by dynamically cyclic loading, with excellent impact and damage tolerance properties while having low density and high specific strength and stiffness [12, 24].

Figure 1. Glare application in Airbus A-380 [24].

As already mentioned, FMLs and conventional composite materials have been demonstrating prosperity in their applications especially in low volume aerospace components and defence applications because of their superior fatigue and impact characteristic [13]. While, there has been restricted use of these kinds of hybrid materials in the high volume productions such as automotive, construction, and consumer goods due to long production times. Also, for complex-shaped parts forming using these materials there are still big challenges. In addition, design for this kind of materials is not very simple and in many cases, former calculations for metals and isotropic materials cannot be useful. In fact, the experiences and findings obtained over the years about the metallic materials’ behaviour do not apply to hybrid and composite structures. Composites and Hybrid Materials offer significant variety in design and manufacturing, but still there are some difficulties in these two fields.

Some investigations have been occurred to solve the manufacturing process of these materials. Zafar R. et al. modified an innovative way named as “3A method”. Their methodology is based on the generating of any number of metallic blanks in the desired shape simultaneously utilizing hydroforming process [14]. Also, Sherkatghanad E. et al. investigated an innovative approach using hydroforming method and applying semi-cured Glare blanks instead of a solidified blank to form complex shaped FML components [15].

Another problem is how to satisfy the design requirements for a component while a FML is desired to use and how it can be replaced by these materials. Actually, in some cases monolithic materials and composite materials are not appropriate and they must be replacing by FML to enjoy their advantageous properties. In one hand, in the condition of replacing a FML or composite material, usually, there is not enough information to design the component. In the other hand, in most applications of lightweight materials especially in structures, the mainly loading mode is bending. Generally, bending stiffness and bending strength are the limiting parameters in replacing parts. In fact, according to the “materials performance index” concept, in the condition of bending load for a component, the minimum feasible thickness (t), can be calculated when the mass (m) is minimized [12,
Also, mechanical properties predictions for textile composites have been widely surveyed with most investigations focusing on plain woven composites. Primary models for the woven lamina analysis can be traced back to the 1970s when Halpin et al. investigated the stiffness of 2D and 3D composites [17]. After that, the theory was improved by Chou and Ishikawa [18, 19]. Great reviews were expressed for modelling, design, and calculations in this field and most of our main formulas were derived which are mentioned in References [20, 21].

In fact, the result of this study, help us to understand the behaviour of FMLs behaviour.

2. Materials and method
A material index evaluates the superiority of a material in a given demand and application. Material indices are applied to rank materials that satisfy the requirements imposed by a design. Depending on the condition, deflections can be calculated considering the principle static equations. Generally, in the material replacement of a component, the part geometry is kept constant excluding the thickness of the part. In fact, in most cases thickness changing is possible and the mass is the limiting factor. So as it is obvious, a material selection with a high specific stiffness and strength is needed. It means that mass, stiffness, and strength must be considered simultaneously to find the most appropriate material with the minimum mass. In fact, to boost the lightweight design popularity in its different applications in the industries, this research is carried out in the area of stiffness limited design. There are some calculations for understanding and measuring the stiffness of monolithic material as well as multilayer materials. In this research Al 2024-T3, epoxy prepreg glass fiber (50%-50%), epoxy prepreg medium strength carbon fiber (50%-50%), GLARE, and CARAL are compared to each other to find the most suitable material in the condition of Bending Stiffness. The standard properties of each material are depicted in table 1 and the whole calculations and simulations are according to these properties. Al layer thicknesses are 0.3 and 0.8 mm and each fibers epoxy laminate is 0.2 mm. In fact, it is tried to find the stiffness of a specimen with different material to show which of them is the best one related to requirements of the design. After that, some simulations are carried out to validate the calculations as well as the experiments. Finally, the most important parameters are discussed in details.

| Table 1. Nominal Properties of suggested materials. |
|-----------------------------------------------|
| **Elasticity Modules (Gpa)** | **Density (gr/cc)** |
| Aluminium 2024-O | 73 | 2.78 |
| Carbon Epoxy (50%-50%) | 75 | 1.6 |
| Glass Epoxy (50%-50%) | 31 | 1.8 |
| GLARE | 60 | 2.5 |
| CARAL | 72 | 2.4 |

3. Calculations
In this part, some calculations and material performance indices are presented. The bending stiffness for the one-layer material can be calculated as follows:

$$D_{Bending} = \frac{E t^3}{12(1-v^2)} \quad (1)$$

Where $E$ is Elastic Modulus, $t$ is the thickness of material, $v$ is the Poisson ratio, and $D$ is the stiffness in the bending condition. In addition, the main formula for multi-layer material, to calculate the bending stiffness, is as follow [21, 23]:

$$D = \frac{1}{3} \sum_{k=1}^{n} D(z_{k+1}^3 - z_k^3) \quad (2)$$

So, by substituting the parameters for three-layer (2+1) FMLs condition, the bending stiffness can be calculated as follow [21]:

$$D = \frac{1}{3} \sum_{k=1}^{2} D(z_{k+1}^3 - z_k^3)$$
Where $E_f$ is Elastic Modulus of face, $\nu_f$ is the Poisson ratio of the face, $t_c$ is the thickness of the core, $t_f$ is the thickness of the faces and $\nu_c$ is the Poisson ratio of the core. The parameters are shown in figure 2.

\[
D_{Bending} = \frac{1}{3} \left\{ \frac{2E_f}{(1-\nu_f^2)} \left[ \frac{3}{4} h_c t_f^2 + \frac{3}{4} h_c^2 t_f + t_f^3 \right] + \frac{E_c}{(1-\nu_c^2)} \frac{h_c^3}{4} \right\}
\]  
(3)

Figure 2. The definitions of the 2+1 FMLs parameters, used in the formulas.

In addition, the bending stiffness for five-layer (3+2) FMLs can be calculated as follow:

\[
D_{Bending} = \frac{1}{3} \left\{ \frac{2E_f}{(1-\nu_f^2)} \left[ 15h_c t_f^2 + \frac{15}{2} h_c^2 t_f + 8t_f^3 \right] + \frac{E_c}{(1-\nu_c^2)} \left[ \frac{27}{4} h_c^3 + 12h_c^2 t_f + 6h_c t_f^2 \right] \right\}
\]  
(4)

As a case study, it is considered that displacement, force, width, and length are 5 mm, 5 N, 30 mm and 150 mm respectively. In addition, according to the use of woven fabrics, our materials are quasi-isotropic. So it can be stated that:

\[
\delta = \frac{FL^3}{48EI}
\]  
(5)

And

\[
I = \frac{bh^3}{12}
\]  
(6)

So,

\[
\delta = \frac{12FL^3}{48Ebh^3}
\]  
(7)

Finally, the thickness equation is obtained as follows:

\[
t = \left( \frac{12\left(\frac{L}{2}\right)^3}{48Eb} \right)^{1/3}
\]  
(8)

Where $\delta$ is the displacement in the middle, $F$ is the applied force, $L$ is the length, $b$ is the width, and $h$ is the thickness of the sheet as shown in figure 3.

Figure 3. The parameters in 3-point Bending test

The first step is to calculate the bending stiffness for the above-mentioned lightweight materials in table 1. Bending stiffness has been obtained by their own Formula according to material structures. The calculated results are shown in table 2.
### Table 2. Calculated Stiffness for Suggested Materials.

| Material                                      | Bending Stiffness (N·m²) |
|-----------------------------------------------|----------------------------|
| Aluminium 2024-O (t=0.8 mm)                   | 4.34                       |
| Carbon/Epoxy (three layers, total thickness=0.8 mm) | 3.98                       |
| Glass/Epoxy (three layers, total thickness=0.8 mm) | 1.6                       |
| GLARE 2+1 (Al, t=0.3 – Glass, t=0.2 – Al, t=0.3) | 4.26                       |
| CARAL 2+1 (Al, t=0.3 – Carbon, t=0.2 – Al, t=0.3) | 4.33                       |

In the following diagram, figure 4, the stiffness ratios of different materials vs. Aluminium, based on calculations, is depicted. As it is depicted the lowest ratio belongs to Glass/epoxy composite and it has a big space in comparison to the others, whereas Caral has the highest one with a minimum space and CARAL and GLARE stiffness ratios are very close together.

![Figure 4](image)

**Figure 4.** Calculated Stiffness Ratio for Carbon/Epoxy, Glass/Epoxy, Glare and Caral vs. Aluminium

The calculated thicknesses in the case of equal stiffness are as mentioned in table 3 which means, as a cases study, if having the same stiffness in the condition of force 10 Newton is desired, the thicknesses of different suggested materials must be as table data. In this case as well as stiffness ratios, it is shown that Carbon Epoxy composite, Caral and Glare have really close results and it may be found as a good replacement for each other.

### Table 3. Calculated thickness in the condition of equal stiffness while a force of 10 Newton applied

| Material       | Calculated thickness in the condition of equal stiffness (mm) |
|----------------|--------------------------------------------------------------|
| Carbon Epoxy   | 0.721                                                        |
| Glass Epoxy    | 0.968                                                        |
| Al             | 0.727                                                        |
| GLARE 3        | 0.776                                                        |
| CARAL 3        | 0.731                                                        |

In other word, in the case of the material replacement, if the whole parameters and the geometry, excluding the elasticity modulus and thickness, are considered as a constant parameter, so $Eh^3$ must be constant.

According to the above-mentioned formula 5, 6, and 7, in the condition of comparing two materials for the same stiffness, the effective parameters can be calculated as follows:

$$\frac{h_1}{h_2} = \frac{E_2}{E_1}$$  \( \text{(9)} \)

Equation No. 9 can be calculated by using Formula 5, 6, and 7 and comparing two kinds of materials as well as using material performance index table in the references of material selection [16]. Also, mass is calculated as $m = pbhl$. So, it can be obtained that:
Hence,

\[ m = \rho b l \left( \frac{12 (F/E)_t}{4b} \right)^{1/3} \]  

\[ \text{(10)} \]

So it is obvious that Material Performance Index to maximize for minimum mass is \( \left( \frac{E^{1/3}}{\rho} \right) \). In order to compare two or more different materials, it can be defined as:

\[ \frac{m_1}{m_2} = \frac{\rho_1}{\rho_2} \left( \frac{E_2}{E_1} \right)^{1/3} \]  

\[ \text{(12)} \]

In fact, for selection and replacement of materials, some other parameters such as thickness ratio, mass ratio, and even cost ratio must be considered. It should be noted that in order to select the superior materials, the total mass ratio and the thickness ratio must be minimized. In this paper, after the calculation of bending stiffness, in order to have an accurate selection of the material, a comprehensive survey for thickness ratio and mass ratio are done.

Figure 5. Calculated Sums of thickness and mass ratios for Carbon/Epoxy, Glass/Epoxy, Glare and Caral vs. Aluminium

The calculate sums of thickness and mass ratio for different material are depicted in figure 5. Considering this factor, carbon epoxy can the best choice but in many cases this kind of material is susceptible to expose to the environment as well as corrosion. So, depending on the ambient condition of the component, an appropriate material should be selected.

4. Simulations and Experiments

4.1. Simulations

In this section, simulation results are discussed. In fact, in this research, hired software to simulate the process of tests is ABAQUS. The supports are completely constrained in the process where the specimen is able to move and the force applied in the Z-axis direction in the middle of the specimen to simulate the 3-point bending test. In fact, the same force (5 newton) is applied for the whole combinations of materials and the related displacements were measured in both simulations and experiments. The resultant data are depicted in table 4. The whole experiments and simulations were done in the condition of the same thickness. The simulation results as typical ones for stress and strain distributions in the specimen are depicted in figure 6. As mentioned in the previous section, simulations and experiments including the investigations into the mechanical properties of different kinds of fiber metal laminates, the Aluminium 2024-T3, glass fiber epoxy composite (EWR200-100
prepreg), carbon fiber epoxy composite (T700-12K prepreg) are considered. In another word, specimens of Aluminium alloy, Caral, Glare, Carbon epoxy, and glass epoxy were cut into rectangular shaped specimens with mentioned size according to the test standards. In addition, in order to avoid the debonding phenomenon between the metal layer and glass fiber layer, the phosphoric acid anodizing of the aluminium alloy utilized before making the FML for both methods.

![Figure 6. Typical simulation result of (a) stress and (b) strain distributions in 3-point Bending Test](image)

4.2. Experimental results
Different thicknesses of this Al alloy and prepregs were obtained by 0.8, 0.3, 0.2 and 0.1 mm of thicknesses, to see the cumulative effect of the different combinations of materials by simulations and experiments, which are depicted in Table 4. Furthermore, the differences between simulations and experiments value can be understood as a quality parameter of the FML manufacturing. In fact, there are many effective factors on the manufacturing of an FML such as anodizing the Al, laying up the prepreg, the quality of the prepreg fibers, optimizing the curing curve and temperature. The method of 3-point bending test is shown in figures 7.

| No. | Material definition | Layers Orientations | Layers Th. (mm) | Displacement (mm) | Experimental Results (mm) |
|-----|--------------------|---------------------|-----------------|-------------------|--------------------------|
| 1   | A Glass Composite  | 0/0/0/0             | 4*0.2           | 0.718             | 0.90                     |
| 2   | B Glass Composite  | 0/90/0/90           | 4*0.2           | 1.150             | 1.3                      |
|     | C Glass Composite  | Woven               | 4*0.2           | 0.945             | 1.1                      |
|     | D Carbon Composite | 0/0/0/0             | 4*0.2           | 0.247             | 0.30                     |
|     | E Carbon Composite | 0/90/90/0           | 4*0.2           | 0.45              | 0.52                     |
|     | F Carbon Composite | Woven               | 4*0.2           | 0.427             | 0.50                     |
| 3   | G Glare (Al/Glass/Glass/Al) | Al/0/0/0     | 0.3/2*0.1/0.3  | 0.427             | 0.47                     |
|     | H Glare (Al/Glass/Glass/Al) | Al/0/90/Al   | 0.3/2*0.1/0.3  | 0.429             | 0.50                     |
|     | I Glare (Al/Woven Glass/Al) | Al/0/0.90/Al | 0.3/2*0.1/0.3  | 0.427             | 0.48                     |
| 4   | J Caral (Al/Carbon/Carbon/Al) | Al/0/0/0 | 0.3/2*0.1/0.3  | 0.419             | 0.51                     |
|     | K Caral (Al/Carbon/Carbon/Al) | Al/0/90/Al  | 0.3/2*0.1/0.3  | 0.424             | 0.49                     |
|     | L Caral (Al/Woven carbon/Al) | Al/0/0.90/Al | 0.3/2*0.1/0.3  | 0.423             | 0.50                     |
| 5   | M Al 2024 – T3     | -                   | 0.8             | 0.423             | 0.47                     |
5. Conclusions
It is found that the behaviour of the specimens in the experimental results are in accordance with 3-points bending simulations and calculation. Although, the values of the experiments are not completely the same as the simulations and calculations but the trend of the results are in an agreement with each other and prove that the material behaviour can be predicted in order to our method. According to close results for the stiffness, it is validated that Fiber Metal Laminates with composite fibers as the middle layer are able to be an appropriate substitution for lightweight metal alloys and composites materials, especially where the equal-stiffness is the limiting factor. In fact, material design can be done innovatively and conditionally. Changing the middle layer thickness, number of layer and their orientation are other flexible parameters which can be investigated.

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