A PRELIMINARY INVESTIGATION OF FIBER-METAL-LAMINATES WITH GRIP METAL™

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ABSTRACT

Consisting of alternating layers of composites and metal, Fiber-Metal-Laminates (FMLs) are lightweight and have the potential to achieve better mechanical properties than monolithic materials, thus making them ideally suited for applications in the aerospace industry. This preliminary work explored the implementation of GRIP Metal™, a micro-hooked sheet metal, in a FML configuration to determine if improvements to the common FML can be achieved. Upon review of existing FML variations and manufacturing techniques, FML panels were created in-house with both GRIP Metal™ and non-hooked equivalent sheet metal. Variations in the composite material, specifically glass-fiber and carbon-fiber pre-impregnated (prepreg) weaves, was also explored. The method of manufacture, as well as the cutting of the panels, will be described in the paper. Tensile tests revealed that GRIP Metal™ decreased the modulus of elasticity by about 3-6% for both carbon-fiber and glass-fiber FMLs, respectively compared to their non-grip counterparts. The hypothesized reason for this is that the creation of the hooks from the base metal produces a reduction in effective cross-sectional area, and may also introduce stress concentrators. Additionally, three-point bend tests showed that panels constructed using GRIP Metal™ exhibited reduced flexural modulus of elasticity, however, with only a 3% reduction for the glass-fiber case. This introductory work serves as a foundation for future studies in which the effect of hook configuration and FML design parameters (e.g., fiber type and orientation, thickness of metal or prepreg, surface preparations, hook design and density) can be explored to optimize the GRIP Metal™ FML performance.

1 INTRODUCTION

Fiber-Metal-Laminates (FMLs) are composite materials consisting of alternating metal layers and fiber layers bonded together with an adhesive. Depending on the desired characteristics of the FML, a variety of metals, types of fibers, fiber orientations, thicknesses of layers and adhesives can be combined producing an FML that incorporates properties of both the metallic materials and the fibrous composites. For this reason, FMLs typically offer excellent fatigue properties, impact and damage tolerance, low weight, as well as strength, making them an ideal material choice for aerospace applications. A common example of an FML is GLARE (GLAss REinforced aluminium laminate), employed in the aerospace industry on the fuselage and cargo floors due to its light weight, and its improved fatigue and impact resistance properties compared to aluminium sheets [1]. GLARE is commonly manufactured using 3-5 sheets of Al 2024-T3 ranging in thickness from 0.2 mm to 0.5 mm. At least two sheets of unidirectional composites are used per layer, resulting in a fiber layer thickness of about 0.2 mm. Depending on the orientation of the fiber sheets with respect to the metal rolling direction, different properties can be obtained in each direction with combinations allowing for balanced properties.

GRIP Metal™ is manufactured from a thin gauge sheet metal for which a patented GRIP Tooling process forms hooks on one, or both sides of the metal sheet. As shown in Figure 1, the hooks are produced by extruding directly from the surface of the metal and can be hooked or pointed in profile. The hooks can range in height from 0.2 mm (nano) up to 2.4 mm (heavy-duty), and are available in various widths. The hooked surface increases the interfacial bonding area, and reduces the potential reliance on adhesive based bonding techniques. Furthermore, the hooks provide a mechanical bond which transfers the shear line to a greater depth within the mating surface and reduces the detrimental impact of environmental effects, such as moisture. Therefore, GRIP Metal™ is an attractive method to effectively bond materials together, where adhesives are normally relied upon.

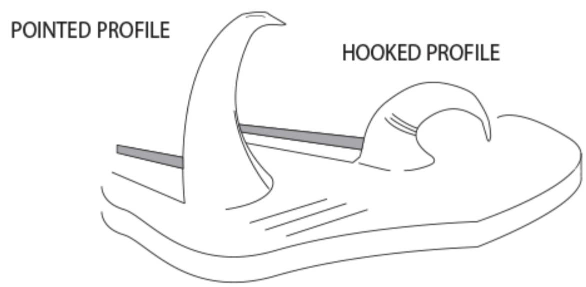

Figure 1: A schematic showing the extrusion of hooks from the metal surface in either a pointed or hooked profile [2].

Although FMLs have been found to be approximately 5-10 times more costly per kg than conventional metallic structures, a weight reduction of 15-20% can be realized by their use. Furthermore, better corrosion and fatigue resistance compared to aluminium alone results in less frequent replacement of parts. The high strength and low weight of FMLs also means that less material is required, which can reduce aircraft fuel consumption and the number of fasteners required for large panels. It is hypothesized that if fuel savings, reduced maintenance, and the reduced number of fasteners are considered, the price of monolithic aluminium and FMLs are comparable [3]. Advancements in the properties and manufacture of FMLs, such as through the addition of GRIP Metal™, could help to further lower the cost and increase the usage of FMLs in the aerospace industry. In an attempt to create an aerospace grade material using GRIP Metal™ technology, FML specimens based on similar composition and thicknesses to GLARE were manufactured and tested in-house at Carleton University.

2 DESCRIPTION OF GRIP Metal™ FIBER METAL LAMINATES

In this study, GRIP Metal™ FML specimens as illustrated in Figure 2, consisting of three metal layers (2 single-sided and 1 double-sided GRIP Metal™ layers) with alternating pre-impregnated (prepreg) fiber layers are investigated and compared to their respective non-grip FML specimens. Their specifications, outlined in Table 1, were established based on GLARE-3, which comprises of 0.2-0.5 mm thick Al 2024-T3 sheets and 0°/90° cross-plies of S2-glass unidirectional fibers, each having an average thickness of 0.127 mm with Cytec FM-94 adhesive [3]. Due to availability and manufacturing restrictions, specimens with dimensions of 11” by 6” (279 mm by 152 mm) were manufactured (described in more details later). Note that throughout this paper, the 11” by 6” FML will be referred to as a “panel”, and the term “coupon” represents specimens cut to size for testing purposes.

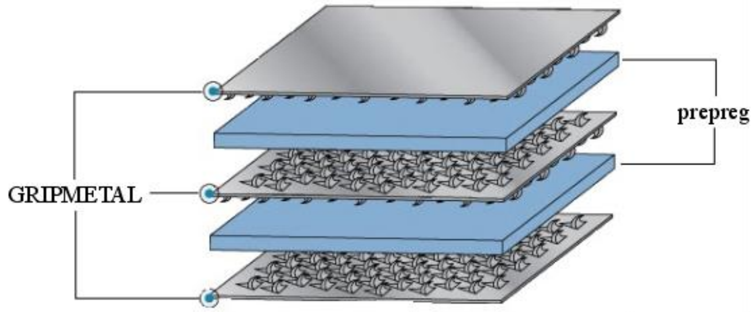

Figure 2: GRIP Metal™ FML consisting of 2 single-sided metal layers, 1 double-sided metal layer, and 2 prepreg layers. Adapted from [2].

Specimen	Carbon Non-grip	Carbon Grip	Glass Non-grip	Glass Grip
Metal Layer	Al 2024-T3	Al 2024-T3	Al 2024-T3	Al 2024-T3
Metal Thickness	0.010" (0.25 mm)	0.010" (0.25 mm)	0.010" (0.25 mm)	0.010" (0.25 mm)
No. of Non-Grip Layer	3 sheets	—	3 sheets	—
No. of Grip Layer	—	2 single-sided, 1 double-sided	—	2 single-sided, 1 double-sided
Hook Type	—	Pointed-profile nano hooks	—	Pointed-profile nano hooks
Hook Height	0.008" (0.20 mm)	0.008" (0.20 mm)	0.008" (0.20 mm)	0.008" (0.20 mm)
Hook Width	0.0012" (0.03 mm)	0.0012" (0.03 mm)	0.0012" (0.03 mm)	0.0012" (0.03 mm)
Hook Density	—	250-260 hooks/in^2 (single-sided), 240-250 hooks/in^2 per side (double-sided)	—	250-260 hooks/in^2 (single-sided), 240-250 hooks/in^2 per side (double-sided)
Prepreg Layer (ACP Composite)	3K carbon-fiber impregnated with a thermosetting epoxy resin system	3K carbon-fiber impregnated with a thermosetting epoxy resin system	E-glass fabric impregnated with a thermosetting epoxy resin system	E-glass fabric impregnated with a thermosetting epoxy resin system
Prepreg Thickness	0.012" (0.30 mm)	0.012" (0.30 mm)	0.008" (0.20 mm)	0.008" (0.20 mm)
Prepreg Type	13x13 2x2 Twill Weave	13x13 2x2 Twill Weave	57x54 8H Satin Weave	57x54 8H Satin Weave
Resin Content	36% +/- 3%	36% +/- 3%	30% +/- 3%	30% +/- 3%

Table 1: Summary of FML specimens investigated.

2.1 Fiber Layer

Although GLARE-3 uses S2-glass unidirectional fibers, carbon-fiber and glass-fiber room temperature prepregs from ACP Composites Inc. [4] were selected for this preliminary investigation of FML using GRIP Metal™ technology due to their availability, cost, and storage requirements. Each fiber layer in GLARE-3, typically consists of two unidirectional sheets, about 0.010” (0.25 mm) thick, oriented at 0° and 90° with respect to the metal rolling direction. Due to the aforementioned reasons, single sheets of prepreg weaves consisting of either 2x2 Twill carbon-fiber weave or 8H Satin glass-fiber weave, having 0.012” (0.30 mm) and 0.008” (0.20 mm) thicknesses, respectively, were used in place of the unidirectional sheets used in conventional GLARE. The addition of Cytec FM-94 adhesive was not required since the fibers from ACP were pre-impregnated with 36% and 30% thermosetting epoxy for the carbon-fiber and glass-fiber, respectively.

2.2 Metal Layer

A thickness of 0.010” (0.25 mm) was employed for the Al 2024-T3 metal used to manufacture all the specimen types investigated. This thickness falls within the range of 0.008” to 0.020” (0.2 mm to 0.5 mm) used for GLARE-3. With GRIP Metal™’s capability to fabricate nano hooks, having a pointed-profile (straight hook) or hooked profile (curved hook), on single-sided and double-sided metal sheets with a minimum thickness of 0.008” (0.2 mm), hook height was selected as a function of the fiber layer thickness so that they do not interfere with the subsequent metal layer. Since the thickness of prepregs used in this study ranges from 0.008” (0.20 mm) to 0.012” (0.30 mm), straight hooks, 0.008" (0.20 mm) in height, were used.

Due to tooling restrictions, a maximum of 4.5” (114 mm) wide strip of hooks were manufactured onto a 6” (152 mm) wide metal coil or sheet. In addition, the hot-press size used for manufacturing of FMLs and test coupon dimensions further limits the specimen dimensions. Therefore, 6” by 11” (152 mm by 279 mm) metal sheets, with a 4.5” by 11” (114 mm by 279 mm) hooked area, and hook density of 250-260 hooks/in^2 for single-sided and 240-250 hooks/in^2 per side for double-sided were used.

Tensile tests for the three types of metal sheets: non-grip, single-sided, and double-sided were evaluated with the same coupon size and procedure as described in Section 4.1, to determine if the hooks had any effect on the tensile properties of the metal. Figure 3 below shows the averaged stress-strain curves for three metal sheet types with the computed elastic modulus recorded in Table 2. As the number of hooks increases, the modulus of elasticity decreases; it is hypothesized that voids may have been created during the extrusion of the GRIP Metal™ hooks, which consequently has a detrimental effect on the strength properties of the thin metal sheets. These hooks may reduce the effective area in the pulling direction and potentially act as stress risers.

Specimen	Mean Elastic Modulus [GPa]	Standard deviation
Flat sheet	72.1	0.9
Single-sided hooked sheet	71.1	0.7
Double-sided hooked sheet	66.8	2.3

Table 2: Comparison of the modulus of elasticity of Al 2024-T3 sheets for various hook configurations.

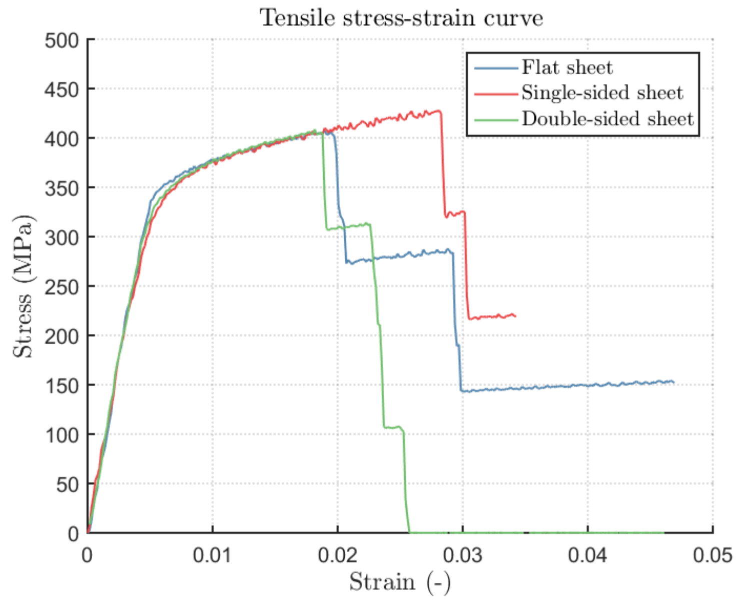

Figure 3: Averaged stress-strain curve of three type of metal sheets: flat, single-sided hooks, and double-sided hooks.

2.3 Theoretical Estimation with Rule of Mixtures

The properties of a composite material, which is made up of continuous and unidirectional fibers, can be predicted from the properties of the individual materials and the layup of the material using the Rule of Mixtures method. Defined as the weighted mean of properties of the material, such as the elastic modulus [3], the estimated upper and lower bounds of the property ($X_{c\,MAX}$ and $X_{c\,MIN}$, respectively) for the combined materials can be calculated as shown in Equations 1 and 2 [5] and tabulated in Table 3.

$$X_{c\,MAX} = f_f X_f + (1 - f_f) X_m \tag{1}$$

$$X_{c\,MIN} = \left(\frac{f_f}{X_f} + \frac{(1 - f_f)}{X_m} \right)^{-1} \tag{2}$$

where X is the property of the material, f_f is the volume fraction of the fiber with respect to the whole composite, and the subscripts f and m represent the fiber and metal layers respectively. Based on the material properties provided by ACP Composites Inc., and the measured material properties for the metal sheets, the estimated modulus of elasticity (E), for both carbon-fiber and glass-fiber FMLs were evaluated and tabulated in Table 3. Note that for cases where hooked metal was used, a weighted sum between two sheets of single sided hooks, and one sheet of double sided hooks was used. Due to the similar modulus of elasticity of the Al 2024-T3 and carbon-fiber prepreg, very little difference between the upper and lower (*MAX* and *MIN*, respectively) theoretical bounds are obtained.

Layer	Thickness [mm]	Elastic Modulus of Non-grip FML [GPa]		Elastic Modulus of Grip FML [GPa]	
		Carbon-fiber			
Metal	0.75	72.1		69.7	
Fiber	0.60	70.0		70.0	
Composite	1.35	*MAX:* 71.2	*MIN:* 71.2	*MAX:* 69.8	*MIN:* 69.8
		Glass-fiber			
Metal	0.75	72.1		69.7	
Fiber	0.40	25.0		25.0	
Composite	1.15	*MAX:* 55.7	*MIN:* 43.6	*MAX:* 54.2	*MIN:* 43.0

Table 3: Estimated modulus of elasticity, yield strength and ultimate tensile strength of the carbon-fiber and glass-fiber GRIP Metal™ FMLs.

3 MANUFACTURING OF GRIP Metal™ FMLs

To manufacture the GRIP Metal™ FMLs, a three-step process of cleaning, lay-up and curing was used. The grip and non-grip metal sheets were first cleaned in an ultrasonic bath filled with water (1 L) and 5 drops of soap for a period of 15 minutes. After a thorough rinsing in flowing water, the sheets were gently dabbed using lint-free wipes and further dried using a heat gun. Next, the protective covering was removed from one side of the prepreg, and the metal sheet was placed on the exposed composite. Using a sharp knife, the composite was trimmed to the size of the pre-cut metal sheets. The protective covering on the other side of the prepreg was then removed and subsequent layerswere stacked in a similar fashion. Note that during every step of the process, clean nitrile gloves were used to handle the material in an effort to prevent contamination.

Once the FML panel was laid-up, the next step was to cure the panel. The panel was placed in a hot-press and a pressure of 55 psi was applied. The temperature was then ramped up at a rate of 5°F/min from 70°F to 310°F as per Ref. [6, 7]. The high pressure and temperature were kept constant for 1 hour, and then the hot-press was turned off and the sample was allowed to cool slowly back to room temperature.

The panels were cut to the appropriate coupon sizes for tensile and three-point bend tests using a wet-saw. A wet-saw with a diamond blade and water for lubrication and dust control was used to cut the coupons to size with a precision of 0.005" (0.13 mm). For the three-point bend tests, coupons were cut to 0.5" by 2.6" (13 mm by 66 mm) in accordance with ASTM D7264/D7264M [8], whereas for tensile tests, the coupons were cut to 1" by 10" (25.4 mm by 254 mm) in accordance with ASTM D3039/D3039M [9]. Although some coupons delaminated during the cutting process, at least four sound coupons of each FML variety and size were used for testing after visual inspection.

4 RESULTS AND DISCUSSION

In this preliminary work, two static material characterization tests, namely tensile and three-point bend, were performed on each of the FML types (carbon grip, carbon non-grip, glass grip, glass non-grip). All tests were performed using an 810 Material Testing System (MTS) with specialized fixtures for each respective test. The test procedure and results for the tests will be highlighted below. It should be noted that the toe region of the measured data, which results from alignment or seating of the specimen, was corrected along the deflection axis in accordance with ASTM standards.

4.1 *Tensile Tests*

To characterize the tensile strength of a material, rectangular or dog-bone shaped coupons were subjected to controlled increasing tension until failure occurs. Due to the wet-saw cutting limitations, rectangular shaped coupons were preferred to dog-bone shaped, although the latter would focus the deformation and failure to occur in the gauge section. Based on the geometry recommended by the ASTM D3039/D3039M [9], the 10" by 1" (254 mm by 25 mm) coupons were tested on the MTS machine with 1.85" (47 mm) of gripping length and a sufficient gripping lateral pressure of 5 MPa to prevent slippage between the grips and the coupon. In accordance with the ASTM standard, the tensile coupon was pulled at a displacement rate of 0.05 in/min (1.3 mm/min) with the axial force (F_i) and displacement (δ) recorded at a frequency of 5.0 Hz. After performing several tensile tests trials, 0.28 in (7.0 mm) of elongation was found to be sufficient for the material to fail. Failure occurred when the material exhibited edge-delamination and/or lateral fracture. The recorded data were then post-processed to evaluate the average tensile stress ($\sigma_i = F_i/A$ where A is the average cross-sectional area) and average tensile strain ($\varepsilon_i = \delta_i/L_g$ where L_g is the gauge length) at each data point. The averaged stress-strain curve for each FML type can be seen in Figure 4.

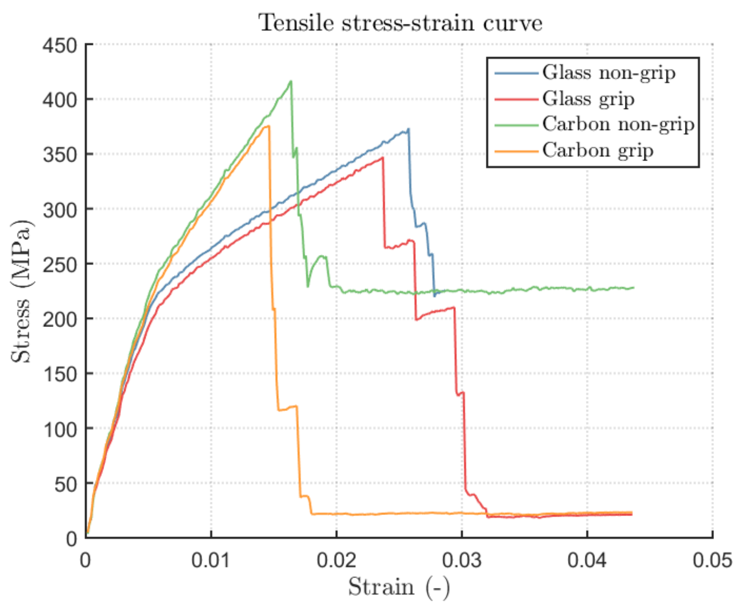

Figure 4: Averaged stress-strain curve of four types of FML: carbon grip, carbon non-grip, glass grip, and glass non-grip.

It can be observed that for both glass-fiber and carbon-fiber cases, similar trends were obtained, with the carbon-fiber FMLs failing at lower levels of strain. The averaged modulus of elasticity, yield strength, and ultimate tensile strength of each type of FML investigated are summarized in Table 4 along with their respective standard deviations. Note that the number in brackets indicates the percent difference between the theoretical maximum and minimum elastic modulus, respectively as calculated in Section 2.3. The modulus of elasticity (E), which is defined as the ratio of the change in tensile stress to the change in tensile strain (i.e. the slope of the stress-strain curve) of the elastic deformation region, was found to be consistently lower than both the theoretical upper and lower bounds. This shows that the bond between the layers has to be improved by modifications to the manufacturing process. Furthermore, the values obtained for the theoretical modulus of elasticity from ACP Composites Inc. may not be truly representative of the panels cured in-house, therefore testing of the in-house cured composites should be performed.

Property	Non-grip FML		Grip FML	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**
		Carbon-Fiber		
E [GPa]	46.0 (-43.0%, -43.0%)	0.4	44.6 (-44.1%, -44.1%)	1.0
YS [MPa]	283.8	6.7	278.4	5.8
UTS [MPa]	426.1	9.8	388.2	8.9
		Glass-fiber		
E [GPa]	42.9 (-26.0%, -1.5%)	0.6	40.4 (-29.1%, -6.2%)	0.2
YS [MPa]	242.3	2.3	234.5	0.9
UTS [MPa]	382.4	7.6	368.8	16.0

Table 4: Resulting material properties from tensile tests

Comparing the elastic modulus values of carbon-fiber and glass-fiber, similar results were obtained, with about 3-6% difference between the grip and non-grip FMLs, respectively. Taking into consideration the effect of the hooks on the metal sheets described in Section 2.2, this difference may be largely due to the reduced elastic modulus of the hooked sheets, as the generation of hooks reduced the cross sectional areas where the metal was extruded out of the planes. Furthermore, the yield strength (YS) and the ultimate tensile strength (UTS), which are defined as the tensile stress at which the material starts to plastically deform (usually taken as 0.2% of the unstressed gauge length), and the maximum tensile stress that a material can withstand while being stretched or pulled before failure, respectively, were again found to be similar with a maximum of 9.3% difference between the grip and non-grip case.

4.2 Three-Point Bend Tests

The three-point bend tests were performed to determine the flexural stiffness of the GRIP Metal™ FMLs in accordance with ASTM D7264/D7264M [8] which specifies the geometry of the coupon and the associated test rig. The coupon had a constant rectangular cross-section with a standard width of 0.5” (13 mm) and a length of 2.6” (66 mm). The coupon rested on two supports having a span to thickness ratio of 32:1, and a load was applied at the midpoint at a constant rate of 0.05 in/min (1.3 mm/min) with the axial force and displacement recorded. Due to the geometry of the test rig, the maximum displacement of the center support into the coupon was limited to 7 mm.

The measured three-point bend response curves, which have been averaged for each FML type, are shown in Figure 5. The results were consistent throughout the deflection range for all sample types, with the exception of the carbon-fiber samples. The carbon-fiber sample responses exhibited lower consistency due to failure of the fiber-metal interface adhesion during the testing. Notably, the carbon-fiber samples manufactured with GRIP Metal™ failed at a lower strain compared to their non-grip counterparts, indicating a potentially poor interfacial bond between layers that was not detected during visual inspection after the manufacturing process. Carbon-fiber FMLs exhibited higher elastic modulus than the ones with glass-fiber. The flexural modulus of elasticity was calculated using Equation 3 (see Ref. [8]) and reported in Table 5.

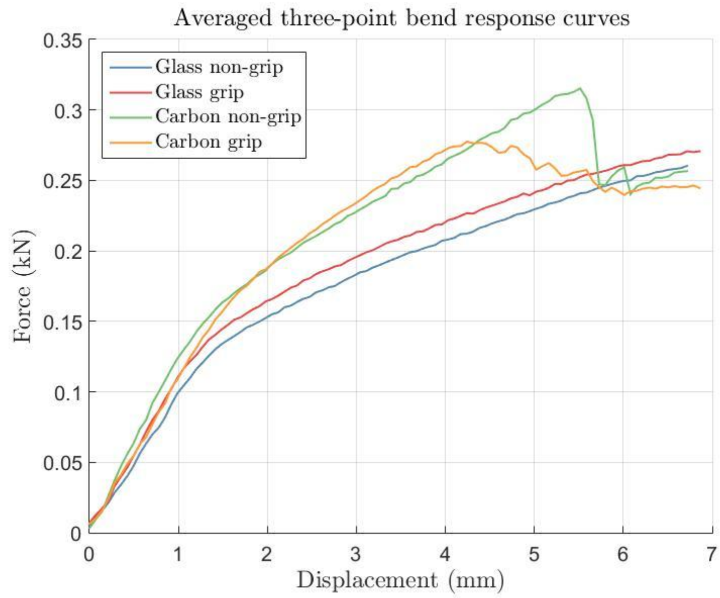

Figure 5: Averaged three-point bend response curves.

$$E_f = \frac{L^3 m}{4bd^3} \tag{3}$$

where, E_f is the modulus of elasticity in bending, L is the span of the coupon, m is the slope of the linear portion of the force-displacement curve, b is the width of the beam, and d is the depth of the beam.

Specimen type	Mean E_f (MPa)	Standard deviation
Carbon Non-grip	64.8	1.6
Carbon Grip	47.3	1.3
Glass Non-grip	58.5	2.1
Glass Grip	56.8	2.1

Table 5: Computed flexural stiffness from three-point bend tests.

Comparing the mean flexural stiffness of grip and non-grip specimens, it was found that in both cases, the non-grip specimen exhibited a higher stiffness. However, the difference between the glass grip and non-grip was significantly less (3%) than the carbon grip and non-grip (31%) specimens indicating potential for GRIP Metal™ to be used in conjunction with glass-fiber prepreg. Since carbo- fiber is more brittle than glass-fiber, the effect of hooks on the fiber may have potentially introduced high stress concentrations, and as a result caused the earlier onset of failure. In addition, it is possible that the more interlaced structure of the Twill weave (carbon-fiber) as compared to the 8H-Satin (glass-fiber) prevented the hooks from penetrating the fiber, hence, reducing the mechanical bond between the hooks and the fiber.

5 FUTURE WORK

Supplementary analyses and improvements are required to fully characterize the potential of combining the GRIP Metal™ technology with fiber-metal-laminates (FMLs); some of which are listed below:

1) An optimization of the FML design for type of composite (i.e. material, fiber direction, orientation, and thickness), hook design (i.e. height, density, shape), and panel configuration (i.e. 1 double-sided hook panel with 2 non-grip panels, or 1 non-grip panel with 2 single-side hook panels) should be studied.
2) Since the FML is pressed together during the curing process, the hooks may be bent or damaged. Also, the hooks may interfere with the fiber or with the adjacent metal surface. These should be verified utilizing a microscope or scanning electron microscope after pressing.
3) A parametric study for the manufacturing procedure using hot-press should also be conducted to investigate the effects of ramp-up or cooling rate, curing time, temperature and pressure on the final FML products. Furthermore, surface preparation techniques such as anodization may be explored.
4) More repetitions should be performed to obtain better statistical data.
5) Further testing in the form of impact, fatigue, shear and peeling are expected in the next research phase.

6 CONCLUSIONS

During this preliminary work, the mechanical properties of fiber-metal-laminates with GRIP Metal™ technology were investigated as a potential aerospace grade material. Four types of FML, consisting of three 0.010” (0.25 mm) thick metal layers with and without straight hooks, and two alternating fiber layers of either carbon-fiber or glass-fiber prepreg weave, were manufactured and tested at Carleton University. Tensile and three-point bend tests were performed for each type. After performing an appropriate data reduction, the mechanical properties such as the flexural and tensile elastic modulus, tensile yield strength, and ultimate tensile strength were obtained and compared with their respective fiber type. A resulting 4.5% average difference was obtained between the tensile elastic modulus of grip and non-grip specimens for both fiber cases. Much of this difference may be attributed to the negative effect of the hooks on the strength of such thin metal. Very little difference (3%) in the grip and non-grip glass-fiber FML flexural modulus of elasticity was obtained. Since there are many variables involved in this study, further investigations in the manufacturing process, hook design, FML configuration and more are required.

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