The Fracture Properties of Novel Sandwich Structures

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Technical Project Report

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1. Synopsis

The use of sandwich structures based on a light-weight foam metal matrix composite as the core component of hybrid systems with fiber-metal laminates as the skin layers represents a feasible technological approach for the development of novel automotive, aerospace and rail transportation components. These sandwich structures offer valuable physical and mechanical features such as weight reduction, improved safety, and superior impact and vibration properties. The main goal of the present project is to develop a novel sandwich structure based on an Interpenetrated Phase Composite foam and skin layers constituted by a metal/high-impact composite. The research program has been divided in two phases. The first phase, which is presented in this report, mainly concentrates on the development, analysis and characterization of the skin layers, with an initial mechanical evaluation of the foam and the sandwich structure. The second phase focuses rather on the dynamic properties of the foam and the sandwich material. Indeed, a full investigation on the sandwich system is currently in progress and will be presented in the subsequent final report.

2. Significance of the project

Currently, the land based transportation sector strongly depends on the use of conventional materials such as steel and aluminum, while the aerospace sector uses sandwich structures based on glass fiber reinforced thermosetting skin layers and cores constituted either by aluminum foam or aluminum honeycomb [1]. The current sandwich structures used in the civil transportation sector require long and expensive manufacturing cycles associated to the curing process of the thermosetting skin layers [2]. Additionally, sandwich structures based on thermosetting materials show a brittle performance and tend to generate hazardous volatiles during their curing process. A suitable option to overcome these drawbacks is the use of a high performance lightweight foam coupled with advanced thermoplastic composites. In principle, the use of metal-matrix ceramic foam as the core system in the sandwich structures is a suitable option due to the impressive mechanical performance that these Interpenetrating Phase Composites (ICP) offer at low and high loading rates. In the case of the skin layers, the use of a self-reinforced thermoplastic composite seems to be an appropriate option due to its high- impact toughness and damage tolerance features. These thermoplastic materials are easy manufactured and repaired, representing a reduction in costs and time. Indeed, they can be processed in one single stamping operation, without the need of long curing times. The combination of these two systems represents a new breed of sandwich structures as an alternative material for the transportation sector. The sandwich structure investigated here has never been attempted before; its study will provide the technical platform for alternative materials in the transportation sector.

3.Objectives

The present research program investigates the development and fracture properties of a new breed of sandwich structures based on metal-ceramic foams as the core element and fiber metal laminates as the skin material. Specifically, this report studies the following tasks:

- Analysis of the interlaminar fracture toughness of a new high-impact, self-reinforced composite material
- Analysis of the interfacial fracture toughness of a fiber metal laminate based on a thermoplastic composite
- Evaluation of the tensile properties of high-impact fiber metal laminates
- Characterization of the low and high velocity impact properties of high-impact fiber metal laminates
- Initial mechanical analysis on the metal-ceramic foam TCON composites
- Preliminary manufacturing attempts of the sandwich structures and their mechanical testing

4. Background

Sandwich structures are used in the transportation sector due to their high stiffness, and strength, and mechanical absorption capabilities in junction with low weight features. Current sandwich structures are based on glass fiber reinforced thermosetting materials and either aluminum foam or honeycomb materials (see figure 1). Besides the drawbacks associated with thermosetting materials, as previously mentioned, there is a need to enhance the mechanical performance of these advanced materials. There has been a marked improvement on the mechanical properties of the skin material by considering fiber metal laminates instead of plain fiber reinforced plastics. Fiber Metal laminates consist of alternating plies of metal and fiber-reinforced polymer matrix composite (see figure 2). Previous work on FMLs [3] has shown that these multilayered materials exhibit excellent impact properties, superior fatigue performance, and good environmental resistance. Alderliesten et al. [4] as well as Vlot et al. [5] have submitted various FMLs to low velocity impact tests and found that their impact performance is superior to that exhibited by monolithic metallic materials due to the delamination process and the efficient membrane stretching effect that take place in the laminates during the impact event [6,7]. As a result, FMLs are being considered as primary structures in the transportation sector. Improvements have also been achieved in the core material of sandwich materials. Metal foams appear to be a robust material capable of absorbing impact and shock vibrations [8]. They offer a unique combination of properties such as low density, high stiffness and strength, low thermal conductivity and toxicity under fire [9]. Indeed, aluminum foams have been used in composite integral armor for developing ballistic materials. It has been reported that metal foams resulted in a reduced dynamic deflection in backing plates [10]. Hence, the combination of a foam material and fiber metal laminates (see figure 3) represent a promising material for dynamic conditions in the transportation sector. Previous research work on sandwich structures based on aluminum foam have also been carried out under high impact velocity conditions and it has been reported that its penetration performance is similar to that offered by steel armor components [11]. Reyes and Cantwell [12] tested sandwich structures based on aluminum foam as the core material and FMLs as the skin layers under high velocity impact conditions; and they reported that the structures were capable of supporting impact energies

Fig. 1. Sandwich structures commonly used on the aerospace sector.

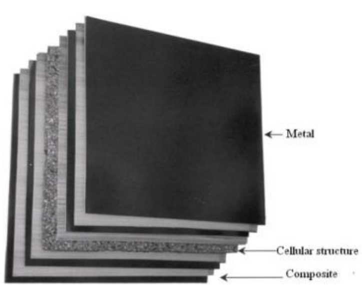

Fig. 3. Schematic of a sandwich structure based on a metal foam and FMLs [12].

around 120 Joules. However, further improvements are required to fully maximize the mechanical performance of sandwich structures. One promising option is the integration of lightweight high-performance metal-matrix ceramic composite foams and high-impact FMLs as the primary constituents of sandwich structures.

5. Approach

The sandwich structures studied here consisted of a closed pore MMC foam and FMLs based on a high-impact composite. The MMC material was manufactured by the TCON Division of Fireline, Inc., (located in Youngstown, Ohio). Fireline utilizes a Reactive Penetration Metal (RPM) process to create continuous ceramic-metal Interpenetrating Phase Composites (IPCs). In the TCON process, a pre-designed ceramic structure is reacted with a metal alloy phase to transform the ceramic preform into a MMC. This process allows the retention of the original structural design, representing a robust synthesis technique with inherent complex shape-design capabilities. A representative figure of one of the alumina/aluminum IPC materials manufactured by Fireline is shown in figure 4. Indeed, the current manufactured TCON composites have resulted in a very successful material for wear-corrosion resistant applications as well as in strong components for military armor protection. In this specific research program, a foam structure based on the TCON process was manufactured and initially studied as the core material component of sandwich systems. Here, the TCON foam had a general composition based on aluminum (Al), silicon carbide (SiC), aluminum oxide (Al_2O_3) and silicon (Si). The foam samples were fabricated with closed-cell alumina spheres and SiC particles bonded together to an Al_2O_3-Al IPC matrix (see figure 4). In the case of the FMLs, these were constituted by aluminum alloy 2024-T3 from OnlineMetalsCo., US., and a high-impact twill self-reinforced Polypropylene composite material known as PURE® from Lankhorst, PURE Composites BV, Germany. The

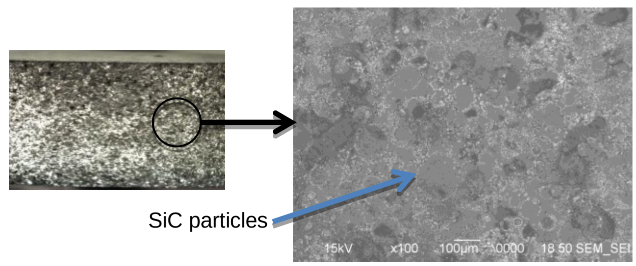

Fig.4. TCON foam. a) As-received material (left). b) Microscopic view of the polished as-received sample (right).

sandwich structures studied were manufactured by bonding the FMLs materials to the core MMC TCON foam (see figure 5).

Figure 5. Manufactured sandwich structure based on TCON foam and FMLs

The experimental approach initially concentrated on the manufactured process of the FMLs; the manufacturing methodology consisted on stacking alternating layers of aluminum and PURE™ composite in a picture-frame mold. In order to achieve a strong bond between the aluminum and the composite, a 0.1 mm thick polyethylene-modified interlayer (from Can-DoTape, US) was placed at their common interface. The samples were then heated in a hot press at 151°C and 6 bars for 5 minutes. Subsequently, the temperature was turned off and the mold was allowed to cool down to room temperature at constant pressure. In order to characterize their interfacial adhesion, a SCB geometry was used (see figure 6). Here, an aluminum foil was embedded between the metal and the adhesive interlayer to act as a crack initiator. The SCB samples were tested on a Universal Instron machine using a wide range of load displacement rates. Here, the crack propagation was monitored visually on the edges of the samples.

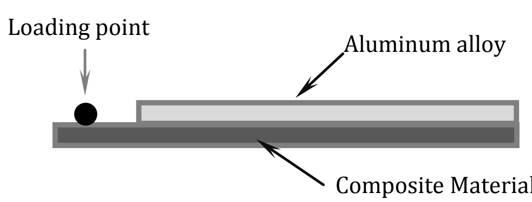

Figure 6. Schematic figure of the SCB samples.

The interfacial fracture energies of the SCB were obtained using the experimental compliance method where the critical strain energy release rate is given by:

— — (1)

Where *P* is the applied force, b the width of the specimen, *C* the specimen compliance and *a* the crack length. Here, the specimen compliance was expressed by:

(2)

The constant *k* was obtained from the slope of the plot of the compliance *C* against the cube of crack length, a^3, and the constant C_o was obtained from the intersection of the curve with the vertical axis. The interlaminar fracture properties of the plain PURE composite were also characterized at different loading rate conditions. Mode I, Mixed-Mode I/II (3/4 ratio) and Mode II, where studied using a Double Cantilever Beam (DCB), Mixed-Mode Flexure (MMF) and Edge Notch Flexure (ENF) geometries respectively. Figure 7 shows the interlaminar geometries considered in this study. The samples for the interlaminar fracture toughness study were manufactured by stacking 16 layers of the PURE composite. Here an aluminum foil was inserted at the middle of the specimens to act as a crack starter (see figure 7).

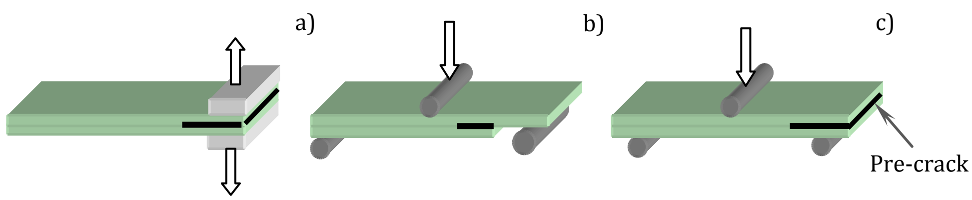

Figure 7. Schematic figures of a)DCB, b)MMF and c)ENF geometries.

Due to the large displacements, the shear deformations, the stiffening effect of the end tabs and the rotation at the crack tip associated with the fracture Mode I, the following experimental calibration beam theory equation was used in this research program:

—— (3)

Where δ is the crosshead displacement, and according to beam theory, n is equal to 3.

The evaluation of MMF was carried out by using the general formula of Linear Elastic Fracture Mechanics (LEFM) given by equation (1). In contrast, the data reduction of the ENF geometry was studied using the simple beam theory given by the following equation:

———— (4)

The tensile properties of FMLs with different composite volume fractions were evaluated at 2mm/min. The elastic modulus and strength were modeled using a simple rule of mixtures.

Previous studies carried out on FMLs have shown that the rule of mixture successfully predicts their tensile properties [13]. In this research program, the following equation was used for predicting their tensile modulus and strength:

(5)

Where σ and V represent the elastic modulus (or strength) and volume fraction of the appropriate material respectively.

Low velocity impact tests were also carried out in a drop weight impact tower. Here, 10cm x 10cm samples were clamped on a square fixture and subjected to an impact event. The impactor was released from different heights in order to determine the impact perforation energy of the FMLs. Various stacking arrangements and composite volume fractions were studied to explore the effects of the constituents on the dynamic performance of the hybrid structure. Table 1 shows the different stacking sequences studied. The FML configuration is displayed by two numbers. The first digit indicates the number of metallic layers and the second the number of composite plies.

Table I: Stacking configurations evaluated in this research program

Samples	Composite Volume Fraction (%)	Thickness (mm)
Plain Al	0	0.5
FML 2/2	37	2.0
FML 3/4	42	3.6
FML 3/8	60	5.1
FML 2/6	64	3.6
Plain Composite	1	2.3

Initial mechanical tests were also carried out on the plain MMC TCON foam. Fireline carried out some non-destructive ultrasonic tests to determine the elastic and shear modulus. The company also carried out density measurements and mechanical tests for determining the modulus of rupture. Additional compression, flexural strength, fracture toughness and low velocity impact were performed at YSU on the plain MMC foam.

High strain loading rates using a Hopkinson bar as well as high velocity impact tests using a gas-gun were also carried out on the FMLs. These results and the high velocity modeling will be presented in the upcoming report titled: *The dynamic properties of sandwich structures*.

6. Results

A typical load-displacement curve of the interfacial adhesion in the metal-composite system is observed in figure 8a. From the figure, it can be shown a relatively smooth crack propagation, which is associated to the ductility of the self-reinforced polypropylene composite material. From the plot observed in figure 8a, and from the recorded crack propagation, the constant *k* was obtained by graphing the compliance *C* against the cube of the crack length, a^3.

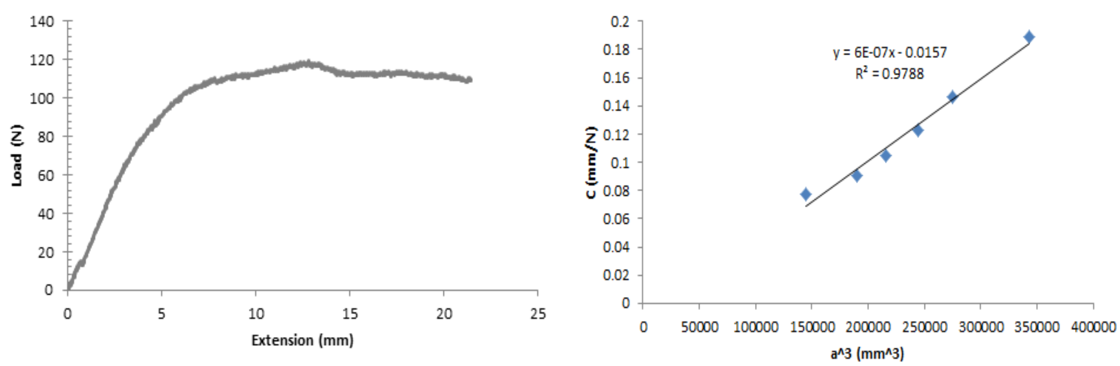

Fig. 8. Single cantilever beam results of the bi-material PURE-Aluminum system. A) Load vs. displacement plot at 10mm/min and room temperature. B) Constant k value; obtained from the slope C vs. a^3.

Figure 8b shows the constant *k* for the SCB samples tested at 10mm/min. The interfacial fracture toughness (G_c), was subsequently calculated, and the R-curve can be appreciated in figure 9. From the figure, it can be seen that the bi-material samples seem to reach a plateau value of 2700J/m^2. These results are encouraging since they suggest that the polyethylene interlayer enhances the composite-metal interfacial adhesion. Indeed, the polyethylene adhesive layer appears to provide a fracture toughness 30% higher than adhesive systems based on polypropylene and polyurethane [14]. Additional SCB tests at 1mm/min showed that the fracture toughness was 20% lower than the samples tested at 10mm/min. These results appear to be associated to the viscoelastic properties of the polyethylene layer. Previous studies carried by Cortes [15] on composites materials have shown that thermoplastic systems are rate sensitive.

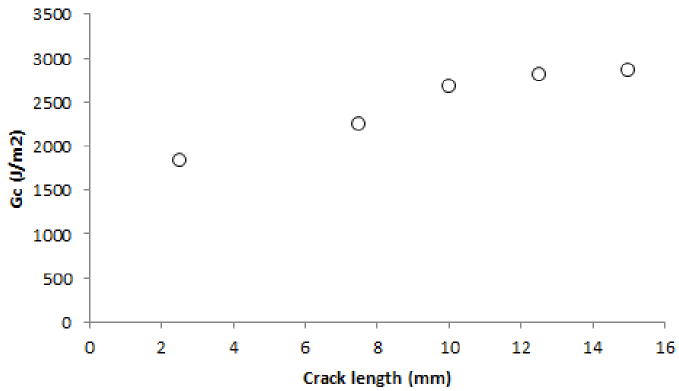

Figure 9. Interfacial fracture toughness of the PURE-Aluminum system tested at 10mm/min.

The interfacial fracture energy of the aluminum-self-reinforced material under a wide range of crosshead displacement rates is displayed in figure 10. It is interesting to note that the fracture energy is relatively constant over a range of two orders of magnitude.

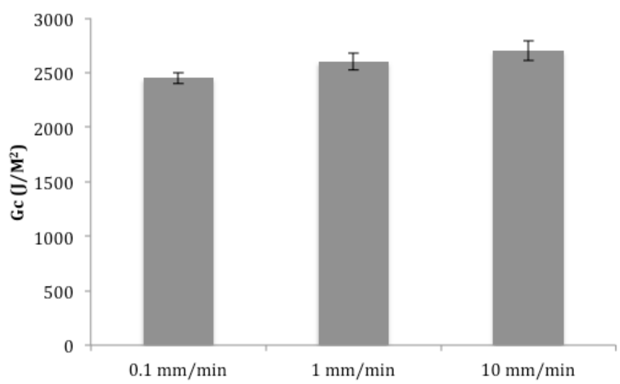

Figure 10. Interfacial fracture energies of the aluminum-self-reinforced composite under different loading rates.

An optical analysis of the fractured surfaces of the SCB samples showed that significant amounts of composite remained bonded to the aluminum layer following the delamination test (see figure 11). This clearly shows the excellent adhesion at the interface.

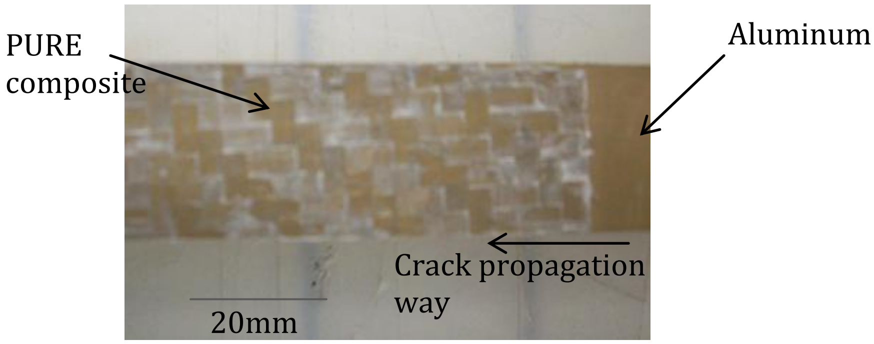

Figure 11. Micrograph of the debonded aluminum layer following a SCB test under 1mm/min. The photograph shows remaining composite adhered to the metallic layer after the interfacial test.

Interlaminar fracture toughness tests were also conducted in this research program, and as in the case of the SCB test geometry, it was found that the fracture energy depended upon the loading rate used during the interlaminar delamination test. Figure 12 shows the load-displacement curves of ENF tests at two different crosshead displacement rates. From the figure, it can be observed that increasing the loading rate results in an increase in the maximum load, which clearly shows the loading rate sensitivity features of the PURE composite.

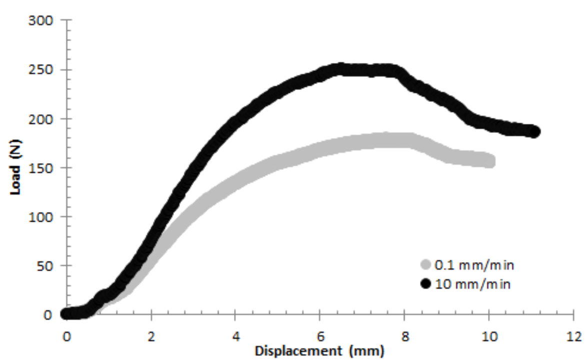

Figure 12. Typical load-displacement curve following an ENF test on two different loading

The figure also shows that the samples exhibit relatively smooth stable crack propagation through the specimens in the different crosshead displacement rates studied. Indeed, crack propagation in thermoplastic composites tends to grow in a steady manner due to their ductility properties. The interlaminar fracture toughness of the PURE composite under different loading rate conditions is shown in figure 13. From the figure, it can be observed that by increasing the crosshead displacement rate, the fracture toughness of the composite on the three modes also increases. This behavior has previously been reported by Cortes on a study carried out on reinforced composite materials [3]. This trend appears to be strongly related to the viscoelastic effects of the PURE composite.

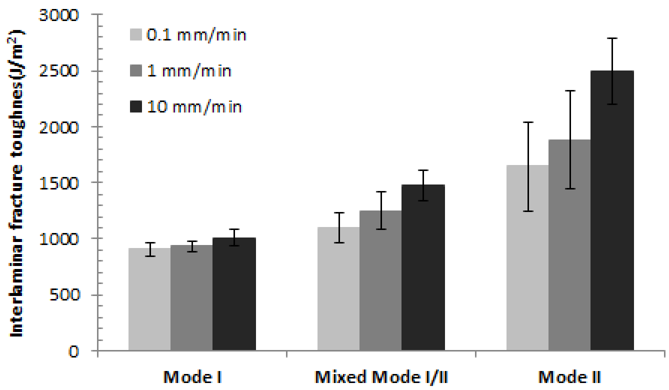

Figure 13. Interlaminar fracture toughness of the PURE composite under diverse loading

The figure also shows that the shear mode of fracture is superior to that observed under mixed mode and splitting mode; being the latest, the lowest fracture toughness found in this study. Similar results have been reported by a number of researches on reinforced plastic materials [16]. It is also interesting to note that the values of *G*c are very similar to the interlaminar fracture toughness of the plain PURE composite. This again highlights the impressive adhesion of the hybrid system at the interface.

The tensile tests of the FMLs were also studied in this research project. Figure 14 shows the typical stress-strain curve of the PURE composite based FML as well as those of their constituent materials. It can be noted that the FML curve shows a knee around a strain of 0.02 mm/mm, which appears to be linked to the yielding point of the aluminum alloy. After such yielding, the FML seems to follow the tensile behavior of the PURE composite. Figure 15 shows an FML tested under tensile conditions following a quasi-static loading rate. Here, the rolling direction of the alloy was aligned in the test direction at all times. It is interesting to note that the PURE composite formed fibrils during the tensile tests. These fibrils suggest a polymer chain orientation during the test, which could certainly enhance the tensile properties of the FML.

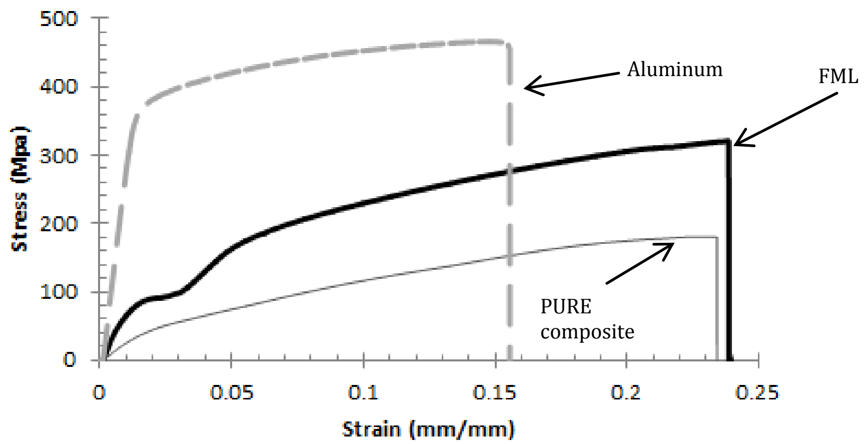

Figure 14. Typical tensile stress-strain curves of the FML and its constituent materials at 1mm/min loading rate.

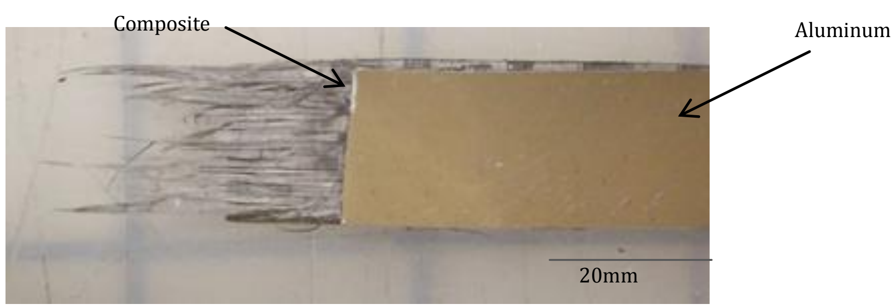

Figure 15. Typical failure mode in an FML based on PURE composite following a tensile test.

The tensile properties of the FMLs were also predicted using a simple rule of mixture approach. It was observed that such approach effectively predicts the tensile modulus and strength stress of these high-impact FMLs (see figure 16). Figure 16 also shows that the tensile properties of these FMLs strongly depend on the volume fraction of the composite within the layered system. Similar results have been observed in other FMLs systems [13].

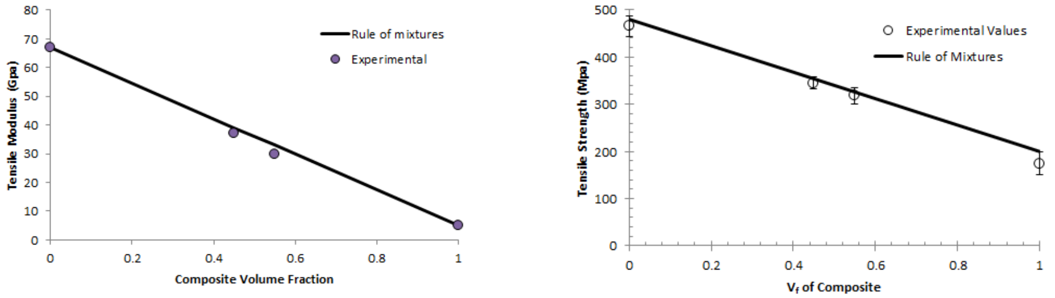

Figure 16. Variation of tensile properties of the FMLs with the volume fraction of composite

Impact tests were also carried out in this research work and figure 17 shows the damaged samples after being subjected to a low velocity impact test. The figure shows that an impact energy of about 175 Joules induced a perforation damage in the FML 3/8 sample. Included in figure 17 is the micrograph of the FML 3/8 after being subjected to an impact energy of 52 Joules. The figure shows a pronounced deformation around the impact area with a visible crack on the impacted face. Further optical analysis on the internal sections of the samples showed that the FMLs fractured in shear mode.

Figure 17. Low velocity impacted FMLs. A) 52J. B) 175J.

Figure 18 shows the transversal internal section of the impacted FML 3/4 and the plain composite after being subjected to a low velocity impact energy of 50 Joules. The figure shows that whereas the plain composite shows a marked deformation and fracture at the impact point, the FML displays a constrained deformation without perforation. Indeed, it was recorded that while the plain composite perforated at 50 Joules, the FML 3/4 perforates at 70 Joules, a damage tolerance value 1.4 times higher than the plain composite. The impact energy of the different systems here investigated can be observed in figure 19. The figure shows that the highest crack and perforation energy was achieved with a FML based on a 3/8 stacking configuration.

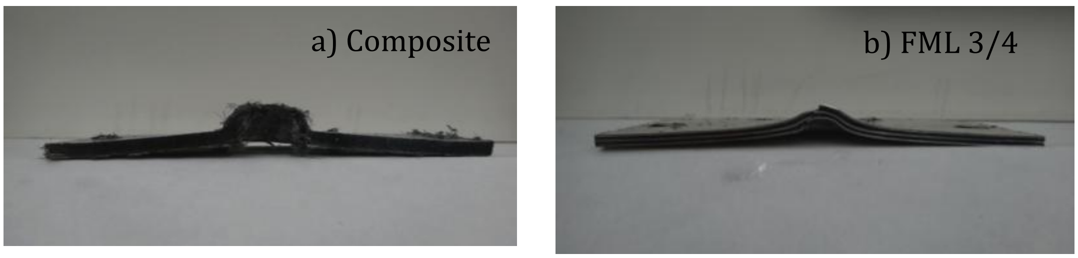

Fig. 18. Low velocity impact micrograph of the internal section of the plain composite and FML ¾ after being subjected to an impact energy of 50 Joules.

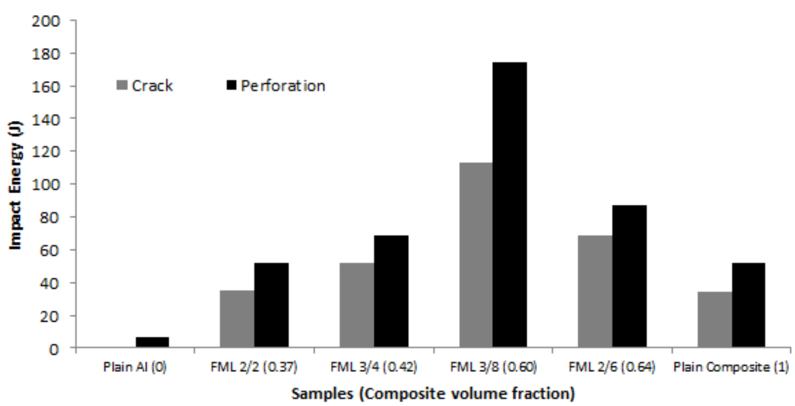

Figure 19. Low velocity impact tests of the FMLs and their constituent materials. The volume fraction of composite on each configuration is shown in parenthesis.

Figure 19, shows that the perforation energy of the plain composite materials was seven times higher than that shown by the plain aluminium alloy. It is interesting to note that the composite volume fraction of FML 2/6 is slightly superior to that of the FML 3/8. However, the perforation impact energy of the FML 3/8 is two times higher that the FML 2/6. This result suggests that the incorporation of more hybrid layers into the FML results in a higher energy absorption system. Similar results have been reported by Vlot and Krull [7] when hybrid materials are subjected to impact tests. They reported that the individual plies of the FML can behave as thin membrane layers increasing their impact performance.

The initial characterization of the plain MMC foam is shown in Table 2. The values displayed on the table compare favorably to those data reported on studies done on closed-pore metal foam structures [17]. These are the data of the first generation of TCON foam. Indeed, Fireline is currently working on enhancing the mechanical performance of TCON foams and is expecting a substancial improvement on the mechanical properties of the foam.

Table 2. Physical and mechanical properties of the initial characterization of the plain MMC foam

Property	Value
Density (g/cm^3)	2.45
Elastic modulus (GPa)	85.7
Shear Modulus (GPa)	37.2
Modulus of Rupture (MPa)	140
Apparent open porosity (%)	3
Quasi-static compression strength (MPa)	350
Fracture toughness (MPa) $m^{1/2}$	4.6
Low velocity impact (J)	3.89

The low velocity impact tests on the MMC were also carried out using a drop impact tower. Here, the samples were supported on a hollow circular frame and tested at velocities around 3 m/s. A micrograph of the TCON foam after being subjected to a low velocity impact event is shown in figure 20; the figure, illustrates limited deformation. The figure shows a crack along the sample, suggesting brittle performance during the low velocity impact test. Indeed, deflections on MMCs are constrained by the presence of the ceramic phase. This results suggests the need of high-impact layers to enhance the impact properties of the sandwich structure as a sytem.

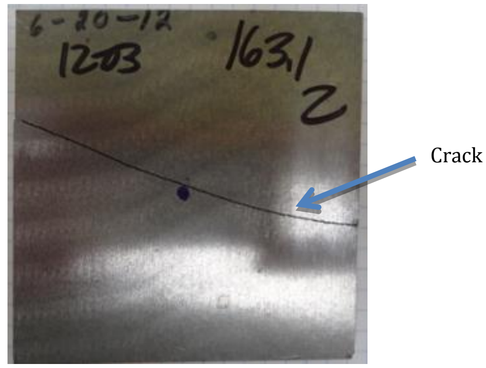

Fig. 20. TCON foam following a low velocity impact test.

The low velocity impact properties of the preliminary sandwich structures here studied are shown in figure 21. The sandwich were manufactured using a FML 3/4 stacking sequence. Figure 21, shows a pronounced indentation, with a clear deflection on the back FML plate. The initial testing on these sandwich structures yielded impact energies aroung 180 Joules. These results are encouraging, since they are superior than those reported on sandwich materials based on closed-pore aluminium metal foams [12].

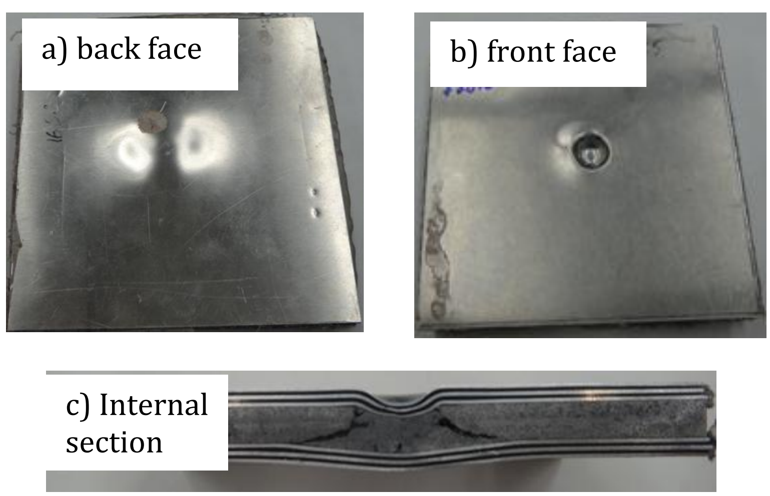

Fig. 21. Sandwich structure subjected to a low velocity impact energy of 180J.

Included in the figure is the internal section of the sandwich structure following a low velocity impact test. The figure shows an impressive adhesion between the FMLs and the FOAM material as well as a remarkable impact performance in the structure. The micrograph shows a shear fracture on the foam with a distinguished compression in the impact area. Similar results have been observed on celluar materials exposed to impact events [18]. The impact energies of the sandwich material is shown in figure 22, and it is observed that its energy values are well above its individual constituents. It is expected that future optimization on the TCON foam will result in very promising materials for sandwich structures in the transportation sector.

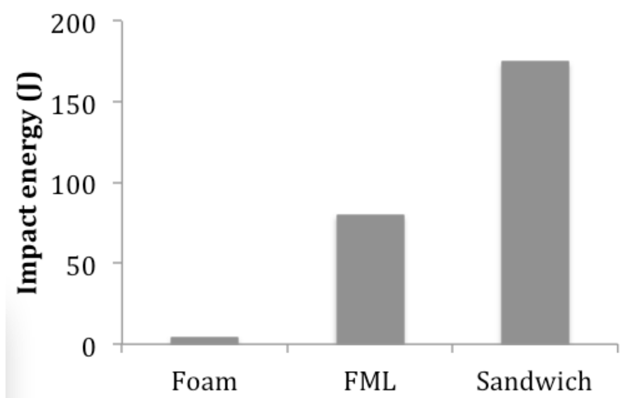

Fig. 22. Low velocity impact response of the sandwich structure and its constituent materials

7. Conclusions

A novel sandwich structure for static and dynamic applications is currently under development. Initial studies on the skin layers have shown that an enhanced adhesion can be achieved through the incorporation of a modified polyethylene interlayer at the bi-material interface. Their interlaminar tensile and impact properties have also been characterized. It has been shown that the cohesive fracture toughness of the composite strongly depends on strain loading rates, suggesting reliable mechanical performance of the skin layers under high-strain rate conditions such as impact. Tensile tests on the skin layers have also shown that their tensile modulus and strength follow a simple rule of mixtures. Low velocity impact tests have also displayed that the incorporation of composites in the laminate seems to enhance its impact properties. It has also been shown that increasing the number of layers in the hybrid system results in a superior impact performance material. Preliminary low velocity tests on the plain foam, and on the sandwich material showed that the combination of a high-performance metal matrix ceramic composite and a high-impact laminated structures results in a sandwich structure with dynamic properties superior than those hybrid systems based on metallic foam. A continuous improvement on the MMC is currently in progress and the results of their evaluation will be presented in phase two of the present project.

8. References

1. A.S. Hermann et al. Sandwich Structures 7: Advancing with Sandwich Structures and Materials. 2005. 13-26.
2. N.W. Bailey et al. Experimental method for dynamic residual strength characterization of aircraft sandwich structures. International Journal of Crashworthiness. 18. 2013. 64-81.
3. P. Cortes. The mechanical properties of high-temperature fiber metal laminates. PhD Thesis. Liverpool. UK. 2005
4. R.C. Alderliesten, et al. fatigue and Damage Tolerance of GLARE. Applied Composite Materials. 10. (2003) 223-242.
5. A. Vlot et al. Fiber Metal Laminates for high capacity aircraft. Int. SAMPE Tech. (1998). 456-470.
6. J. Harding and L.M. Welsh. A tensile testing technique for fibre-reinforced composites at impact rates of strain. Journal of Materials Science. 18 (1983) 1810-1826.
7. A. Vlot and M. Krull. Impact damage resistance of various fibre metal laminates. Journal of Physics IV. 7 (1997) 1045-1050.
8. J. F. Rakow and A. M. Waas. Size effects in metal foam cores for sandwich structures. AIAA. Journal. 42 (2004) 1331-1337.
9. A.G. Evans et al. Cellular Materials. Solid State and Materials Science. 3 (1998) 288-303.
10. B.A. Gama et al. Aluminum foam integral armor: a new dimensions in armor design. Composite Structures. 52 (2001) 381-395.

11. M. de Freitas et al. Numerical evaluation of failure mechanisms on composites specimens subjected to impact loading. Composites Part B. 31 (2000) 199-207.
12. G. Reyes and W.J. Cantwell. The high velocity impact response of composite sand FML-reinforced sandwich structures. Composites Science and Technology. 64 (2004) 35-54.
13. P. Cortes and W.J. Cantwell. The tensile and fatigue properties of carbon fiber-reinforced PEEK-Titanium Fiber-Metal Laminates. Journal of Reinforced Plastics and Composites. 23 (2004) 1615-1623.
14. P. Cortes et al. Structure-properties relations in a hybrid laminate based on self-reinforced composite material. SAMPE Tech. (2011). 1-8.
15. P. Cortes and W.J. Cantwell. Interfacial fracture properties of carbon fiber reinforced PEEK/titanium fiber-metal laminates. Journal of Materials Science Letters. 21, 2002, 1819-1823.
16. K.-Y. Kim. Interlaminar fracture toughness of CF/PEI and GF/PEI composites at elevated temperatures. Applied Composite Materials. 17 (1986) 289-303.
17. M.I. Idris. Structural Integrity of Carbon Fibre/Aluminium Foam Sandwich Composites. PhD Thesis. The University of New South Wales. 2010.
18. H. Kiratisaevee and W.J. Cantwell. The impact response of aluminum foam sandwich structure based on a glass fiber-reinforced polypropylene fiber-metal laminate. Polymer Composites. 25 (2004) 499-509.