VIBRATION CHARACTERISTICS OF THERMALLY CYCLED GRAPHENE NANOPLATELET (GNP) REINFORCED 3D-FIBER METAL LAMINATES (3D-FML)

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ABSTRACT

Harsh environmental conditions may cause materials to degrade and eventually fail, or even worse, it can be coupled with undesirable vibrations in mechanical systems, resulting in premature failure of the system. Such combined loading scenarios are often encountered by transport vehicles (i.e., airplane cabins, and train and automobile components). Today, fiber metal laminates (FMLs) and sandwich composites are often used in the fabrication of various components of transport vehicles. Therefore, it is of paramount importance to study the static and dynamic characteristics of such materials under combined loading scenarios and ensure their durability and safety. A recently introduced class of 3D fiber metal laminate (3D-FML) in our research group has shown exemplary mechanical response characteristics; however, the vibration characteristic of this novel hybrid material system under harsh environmental conditions has not been studied. Therefore, exploring the effect of environmental parameters on the frequency response of this class of materials shapes the main objective of this research. Specifically, the main goals of this research are to characterize and understand the frequency response of 3D-FMLs under thermal fatigue and attempt to improve their vibration response by incorporation of an effective solution. To do so, 3D-FMLs specimens are exposed to combined thermal and humidity cycles. Subsequently, the vibration characteristics of the system are experimentally evaluated. An attempt is also made to improve the damping characteristics of the material system by incorporation of graphene nanoplatelet within the interface layers of the hybrid system. It is also demonstrated that recently developed nondestructive techniques can be effectively used to assess the influence of environmental conditions on the static and dynamic behavior of 3D-FMLs and evaluate their potential degradation under thermal fatigue.

KEYWORDS: *fiber-metal laminate; non-destructive testing; thermal fatigue; vibration; damping*

1. INTRODUCTION

The superior strength- and stiffness-to-weight ratios of fiber-reinforced composite materials (FRPs) have increased their applications as load-bearing structural components in automobiles, trains, airplanes and even pipelines. Fiber-metal laminates (FMLs) also possess similar, and in some cases, even more positive attributes than FRP, thus making them even more attractive for incorporation in such potential applications. Therefore, several researchers have explored techniques that would ensure the safe and reliable performance of such materials when used under harsh environmental conditions [1–7]. A new rendition of FMLs, in the form of a new class of three-dimensional FMLs (3D-FMLs), exhibiting superior static and dynamic attributes and excellent crashworthiness was recently introduced by Asaee and Taheri [8]. Good damping property is also an important feature of this class of materials, since unwanted and unharnessed vibrations in structures could result in undesirable noise and potential mechanical failure, or even worse, coupled with harsh environmental conditions, could cause the material to degrade and eventually result in the permanent failure of the system. De Cicco and Taheri [9], and Soltannia et al. [10], experimentally investigated the vibration characteristics of laminated and sandwich composite beams using non-destructive testing techniques (NDT). Other researchers have also examined the vibration characterizes of composites with innovative techniques. For instance, Cheraghi et al. [11] used the impulse excitation technique to establish material damping characteristics of polyvinyl chloride pipes by using piezoelectric sensors to record the vibration response. Hajikhani et al. [12] used an acoustic emission NDT technique to determine the presence and extent of defects.

With respect to the technical literature addressing the issue of thermal fatigue in conventional 2D-, and 3D-fiber metal laminates is quite scarce; in fact, only a few works have studied the influence of thermal fatigue on honey-comb sandwich structures or FMLs. The emergence of addressing this issue is essential and inevitable for the aerospace, automotive, and other industrial sectors that use FML composites. The following is a summary of the notable studies.

Khosravani and Weinberg [13] studied the loading and aging effects on honeycomb sandwich T-joints subject to thermal fatigue in the range of -35 °C up to 70 °C. They studied the failure behavior of the T-joints using fractographic analysis. They verified their results with 3D finite element analysis using cohesive zone modelling. They observed their specimens to experience brittle failure. They also noticed that the application of 25 and 100 cycles degrade critical fracture stress (σ_c) of their specimens by 2% and 40%, respectively. Their results show that the exposure time has more influence compared to the exposed temperature. They also reported that their specimens sustained 60% less load because of thermal fatigue, and the mode of failure changed in the thermally cycled specimens. Li et al. [14] studied the effect of thermal fatigue on 2D-FML, which had aluminum-lithium alloy as its metallic constituent. They observed no degradation or sign of failure after 1000 cycles. Ironically, they even found that the tensile and flexural strengths of their specimens increased after the application of thermal cycles due to a positive age-hardening response of the aluminum–lithium laminate. Khalili et al. [15] also studied the thermal effect on hybrid single-lap joints (SLJs) made of fiber metal laminate and stainless steel adherends both bonded and bolted. They investigated the influence of thermal cycles on the mechanical properties of their hybrid SLJs through conducting a series of tensile tests. Their specimens were subjected to 40 °C to 100 °C and -40 °C to -100 °C cycles. Their results showed 52% and 50% strength recovery after heating and cryogenic cycles, respectively. Mosse et al. [16] showed that a glass fiber-reinforced thermoplastic fiber metal laminate (GFRT-FML) system had better formability (stamp forming) compared to aluminum, so long as the GFRT-FML was pre-annealed and rapidly transferred to heated casting process tool (punch-die tool). Muller et al. [17] studied the effect of thermal cycling on interlaminar shear strength (ILSS) or bending rigidity (BR) of heater element-integrated glass-FML used in anti- or de-icing applications. Having heater elements embedded in FMLs gives the opportunity of thermally cycling (heating up) the specimens internally while cooling them down externally. They found that the interlaminar shear strength (ILSS) of their specimens that were subjected to thermal gradient of 120 °C slightly increased by 6.9% after 8000 cycles of 60-90 sec., compared to the non-cycled specimens' response. In contrast, ILSS of internally heated and externally heated/cooled specimens was mitigated by 7.8% after 12000 cycles. Jakubczak et al. [18] also studied thermal cycling effects on ILSS of 2D aluminum-carbon fiber laminates, by applying 1500 thermal cycles. As per their findings, thermal cycles did not affect the strength of their specimens. Da Costa et al. [19] studied the effect of thermal-shock cycles on the mechanical characteristics of aluminum-glass fiber-reinforced polymer FML composites, bonded using an epoxy adhesive tape. They exposed their specimens to 130 °C temperature gradient with a rapid transition and cycled their specimens to 1000 and 2000 cycles, stating that 2000 cycles would mimic a typical C check interval for a commercial aircraft maintenance program. They observed that thermal-shock cycles did not have a significant effect on the mechanical properties of their FML. Majerski et al. [20] studied the hygrothermal effect on the mechanical properties of 2D FMLs and FRPs. They exposed their specimens to 60 °C and 99% RH to investigate the effect of elevated temperature and moisture together. They identified that moisture absorption in their FMLs was significantly lower than in their FRPs. They also found that the ILSS of their FMLs and FRPs was degraded by 9-11% and 27%, respectively, and the tensile strength was decreased by 1-15% and 7-30%, respectively. Hu et al. [21] studied the effect of cyclic temperature on mechanical properties of adhesively bonded joints, and they reported a severe weakening effect due to a post-curing process. Through the Response Surface method (a statistical-based technique of design of experiment), they determined that exposure to lower temperatures could cause greater and steeper degradation compared to degradation due to exposure to elevated temperatures. Brewis et al. [22] studied the effect of heating (16 °C to 85 °C) and moisture exposure for 2500 hours on mechanical properties of single lap joints (SLJs). They reported that moisture resulted in plasticization of the bonding adhesive and consequently degradation of mechanical properties of the SLJs.

Improving the damping characteristics of 3D-FMLs can be realized using nanoparticles (NPs) as an effective passive technique for enhancing the dynamic damping properties of composite materials and structures. The advantages of including small amounts of NPs to improve the mechanical and electrical properties of resins used as the matrix in composite structures, as well as for adhesives, have also been investigated extensively by several researchers in the past [23–27]. Mohamed and Taheri [28,29] investigated the contribution of graphene nanoplatelets (GNPs) in fracture toughness enhancement of a commonly used room-cured epoxy resin, and its performance and degradation, using the double cantilever beam specimen subjected to the various number of thermal cycles (to a maximum of 1000 heating/cooling cycles). They observed that in general, GNPs improved the performance of the adhesive. They observed that the adhesive performance degraded initially (up to 300-400 cycles), and then the response was improved after exposure to a higher number of cycles up to nearly 600 cycles), after which the performance suffered upon increased numbers of thermal cycles.

In this work, an investigation is conducted to assess the damping characteristics of GNP-reinforced 3D-FMLs subjected to thermal fatigue. It will be demonstrated that the inclusion of 1 wt% GNPs within the interface layers of the hybrid system improved the fundamental frequency of the 3D-FML specimens marginally and their damping ratio quite significantly at room temperature. However, when the specimens were subjected to thermal fatigue, the gain in the properties reverted back to the values observed for the non-reinforced FML.

2. MATERIALS AND METHODS

2.1 Materials

A three-dimensional fiberglass fabric (3DFGF) was obtained from China Beihai Fiberglass Co. (Jiujiang City, Jiangxi, China). Magnesium alloy sheets (AZ31B-H24; 0.5 mm thick) were acquired from MetalMart International (Commerce, CA, USA). As a benchmark for test comparison, 6061-T6 aluminum sheets with 4mm thickness were obtained from a local distributer. The hot-cure epoxy resin used to fabricate the 3DFGF and the core part of the 3D-FMLs composed of two parts (bisphenol-A-based Araldite LY 1564 resin and Aradur 2954 (cycloaliphatic polyamine) hardener) was purchased from Huntsman Co. (West Point, GA, USA). A two-part cold-cure thermoset epoxy resin (the West System (WS) 105 resin, and 206 hardener (Bay City, MI, USA)) was used for bonding the magnesium sheets to the core. The NP filler to be dispersed into the epoxy resin was GNPs with an average diameter of 25 μm, thickness of 6 nm, surface area of 100 m^2 /g, and more than 95% purity (obtained from XG Science Ltd., Lansing, MI).

2.2 Specimen Preparation

Five groups of specimens were prepared as reported in Table 1. 3DFGF core sheets of 3D-FMLs were fabricated in situ using the hot-cure epoxy resin system, by a hand brushing technique. Each panel was then cured in an oven at 60 °C for 2 hours and at 120°C for 8 hours. At least five beam specimens with dimensions of 200 mm × 20 mm × 4 mm (length × width × thickness) were extracted out of each plate.

For the magnesium skins the bonding surfaces were roughened by grit-blasting, cleaned with an air gun, acetone washed and air-dried. The skins were then bonded to the core panels either using the neat cold-cure epoxy resin or a NP-modified version of this resin, and kept under vacuum for at least 24 hours at room temperature to assure optimal bonding. More details on the fabrication of 3D-FMLs can be found in De Cicco and Taheri [9] and Soltannia et al. [10].

For the NP dispersion, NPs were first distributed in the cold-cure resin system using a mechanical stirrer set at a speed of 2000 rpm for 10 minutes. Then, the NP resin slurry was calendered using a three-roll mill homogenizer (Torrey Hills Technologies LLC, San Diego, CA, USA). The roller gap was adjusted at 30 µm using a filler gauge for a 1 wt% (by weight) concentration of GNPs. In this study, the roller speed and calendering frequency were set constant at 174 rpm. To maximize the dispersion quality, calendering was conducted seven times. The curing agent was subsequently added to the slurry and mixed for 4–6 minutes using a stirrer set at a speed of 400 rpm. The mixture was then degassed under 28″ Hg vacuum for 2 to 3 minutes.

Table 1 Specimen configurations and nomenclature.

Specimen ID *	**Interface resin modification**	**NP filler loading**
Al		
Neat-4-3DFML-0 Cycle	Neat	0 wt%
GNP-4-3DFML-0 Cycle	GNP	1 wt%
Neat-4-3DFML-333 Cycle	Neat	0 wt%
GNP-4-3DFML-333 Cycle	GNP	1 wt%

*”4” indicates the 3D-FML thickness of 4mm, and “0 cycle” and “333 cycle” refers to specimens prior to thermal cycling and after 333 thermal cycles, respectively.

2.3 Cyclic thermal fatigue test

As briefly stated earlier, cyclic thermal fatigue is a common and critical loading scheme experienced by structures and materials. In service, materials often experience temperature fluctuation (warm-cold and vice versa). Table 2 summarizes the results of some studies that considered the influence of temperature fluctuations on the response of various composite materials and structural configurations.

Table 2 Temperature range, type of specimens and results.

Reference #	Type of specimen	Temp. range (°C)	# of Cycles	RH %	Results
[13]	T-joint honeycomb	-35 to +70	0, 25, 100	N/A	-2% and -40% reduction in strength at 25 and 100 cycles, respectively
[14]	FML	-65 to +135	0, 250, 500, 750, 1000	N/A	Qualitative study
[15]	FML	-100 to -40 & +40 to +100	0, 5, 10	50%	50% increase in tensile strength
[18]	FML	-50 to +80	1500	N/A	Qualitative study
[19]	FML	-50 to +80	1000 & 2000	100%	12% reduction in tensile and ILSS
[20]	FML	+60	0	99%	1% - 15% reduction in tensile strength 9% - 11% reduction in ILSSS

In the present investigation, the specimens were exposed to −60 °C to +60 °C thermal cycles with 55 % relative humidity. This thermal fluctuation is often experienced by transport vehicles in a given year. Note that the exposure cycle was limited to +60 °C as the glass transition temperature (T_g) of the WS cold-cure epoxy resin used for bonding the magnesium sheets to 3DFGF of 3D-FML is 65 °C. Cyclic thermal testing was conducted within an environmental chamber (Associated Environmental Systems, Model ZBHD-205 benchtop humidity chamber, Acton, MA, USA). The temperature within the chamber was monitored continuously.

Each heating/cooling cycle included four stages, as illustrated in Figure 1(a). A typical thermal cycle consisted of a 30-minute hold period for each the high and low temperature level of +60 °C and -60 °C, respectively, with 30-minute intervals for ramping linearly between hold periods. For each test, the initial heating cycle started at room temperature.

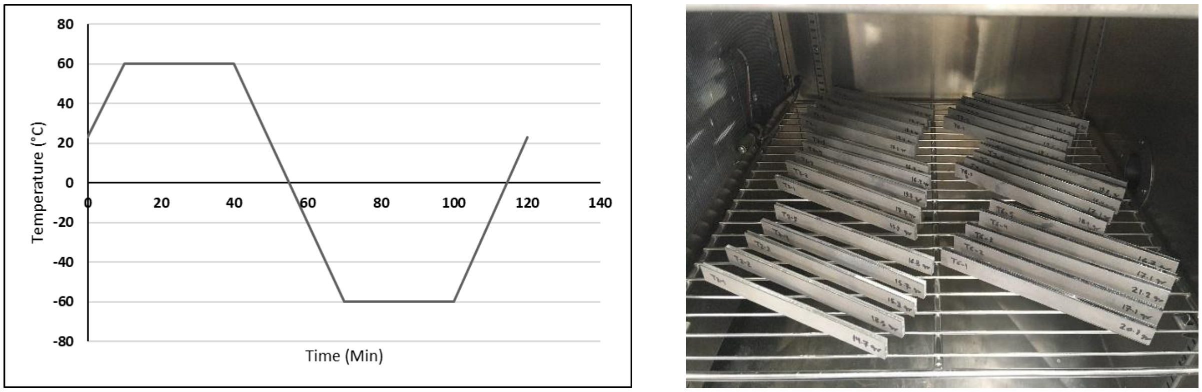


Figure 1. (a) Typical heating/cooling cycle, and (b) specimens in the environmental chamber.

A total of five specimens was tested per specimen group in order to investigate the influence of thermal fatigue on vibration characteristics of 1 wt% GNP reinforced 3D-FMLs at the interface. The five groups of specimens were tested, each being subjected to a different total number of cycles, as reported in Table 1.

2.4 Testing and analysis procedures

The experimental instruments used to acquire vibration signals are shown in Figure 2. Vibration data were recorded using a contact type device, i.e., a GrindoSonic (GS) instrument model MK5i (Leuven, Belgium). Two prismatic pieces of low-density foam were used as supports to resemble free-free boundary conditions. A lightweight hammer, consisting of a steel ball as the stiff tip attached to a thin wooden rod ('steel-wood hammer') was used to excite the specimens.

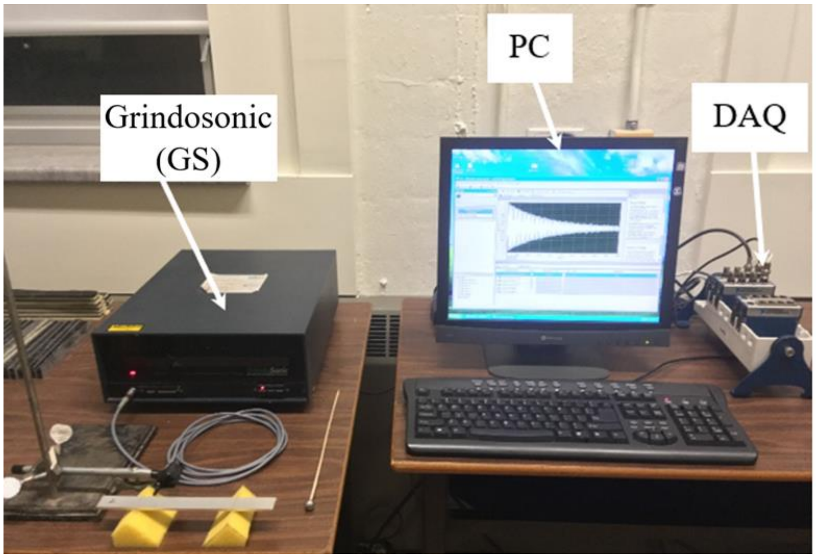
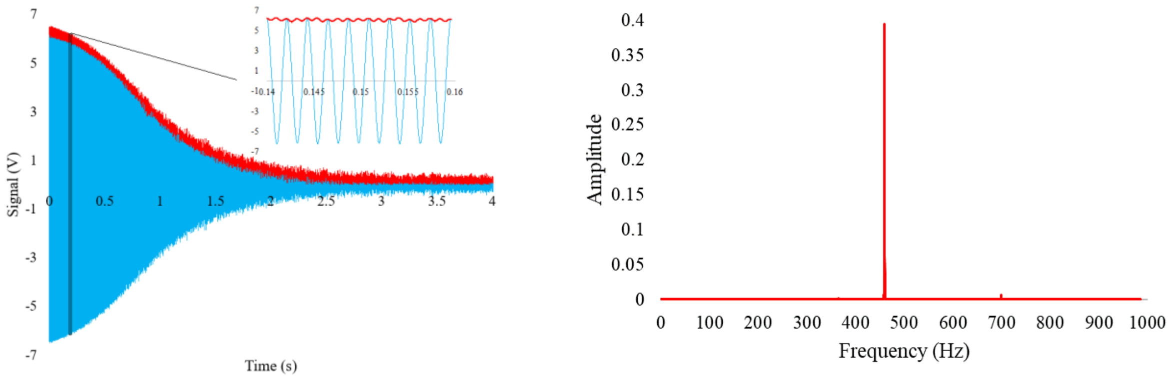


Figure 2. Experimental test setup for recording vibration signals of specimens with free-free boundary conditions using a Grindosonic device.

To extract the fundamental frequency (f_1) and Damping Ratio (ξ), one should capture the entire vibration oscillation spectrum. Hence, the GS was connected to a data-acquisition system, and the Signal Express software (National Instruments, Austin, TX, USA) was used to record the entire oscillation spectrum of each specimen at a 100 kHz sampling rate. The recorded data was then processed using LabVIEW (National Instruments).

2.5 Vibration signal extraction and analysis

The frequency obtained from each complete vibration signal spectrum and more particularly, the power spectrum, was computed using the Spectral Measurements subroutine of LabVIEW. This subroutine takes the vibration signal from the GS and provides the amplitude of each frequency within the signal spectrum by subjecting the signal to a Fast Fourier Transform algorithm. Subsequently, the fundamental frequency is the frequency corresponding to the one with the largest amplitude, as shown in Figure 3(b).



(a) (b)

Figure 3. (a) Typical vibration signal and its representative envelope; (b) power spectrum (aluminum specimen).

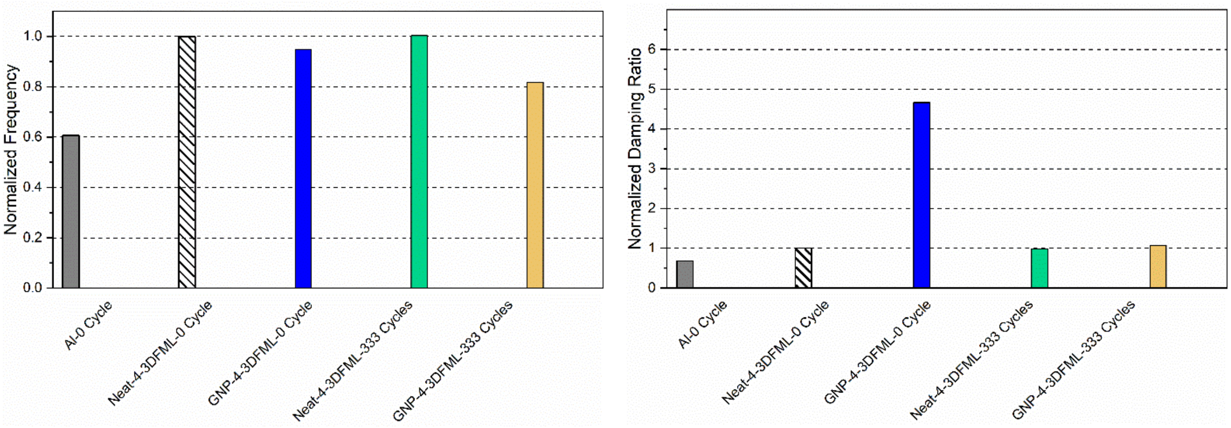
To calculate the damping coefficient, first, the signal was filtered in LabVIEW with a bandpass of ±30 Hz to mitigate noise. The envelope was then retrieved from the filtered signals using the Hilbert transform through the procedure described by Cheraghi et al. [11], as schematically illustrated in Figure 3(a), using the following mathematical operation:

$$\mathrm{H}(\mathrm{t}) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \mathrm{u}(\tau)\,\frac{\chi(\tau)}{\mathrm{t}-\tau}\,\mathrm{d}\tau \qquad (1)$$

In practice, if the envelope contains a complex number, its real part includes the signal's amplitude and its imaginary part contains the Hilbert operator, as it has been explained by Yang and Song [31], as implemented in LabVIEW. In the end, the averaged damping coefficient was calculated based on the decremental logarithm method over 50 successive oscillatory points of the signal within the envelope. As the damping coefficient of the aluminum specimens is relatively low compared to that of the 3D-FML specimens, a cut-off value of a 3-second time period was applied to aluminum specimen signals while a 0.1-second long signal duration was considered for 3D-FML specimens as the time period through which the decremental logarithm (and hence the damping coefficient) were calculated.

3. Results and discussion

In the following, the results of the experiments and analyses are presented. It is worth mentioning that at least nine tests were conducted per specimen and the reported results are the average of at least 45 tests and analyses for at least five specimens within each category. External noise was minimized during impulse excitation. Specimens were excited by tapping each specimen on the same location between the two supports, close to the center span of each specimen. Tapping on a different location could cause excitation of a different vibration mode and frequency. Figure 4(a) shows all the averaged fundamental frequency values of each category obtained experimentally through the use of the GS. The reported results indicate that the inclusion of 1 wt% GNP in the interface of the 3D-FMLs undergone 333 thermal cycles resulted in lower normalized fundamental frequency. Results were normalized by dividing them to their respective bending rigidity first, and then dividing the obtained values to the one obtained for the 3D-FML with neat resin. Thermal cyclic loading also had a significant degrading influence on the normalized damping ratio of the NP-reinforced specimens; however, NP-reinforced specimens exhibited higher damping compared to the non-NP-reinforced specimens, especially without thermal cycling, see Figure 4(b).



(a) (b)

Figure 4. (a) Specimen averaged normalized fundamental frequencies, and (b) damping ratios.

4. CONCLUSIONS

The presented research study explored the frequency response of 3D-fiber metal laminates undergoing cyclic thermal loading and the effect of nanoparticle modification of the interface layers of the hybrid system. In general, the inclusion of GNP in the interface of specimens decreased the frequency response. For specimen experiencing 333 thermal cycles the damping characteristics were essentially maintained compared to specimen prepared with neat resin. It should be noted that the specimens are being exposed to additional thermal cycles beyond the values reported in this study. The influence of additional thermal cycles on the vibration response of the 3D-FML will be reported in a future publication.

5. ACKNOWLEDGEMENTS

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7. BIOGRAPHY

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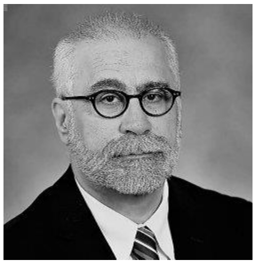
Pierre Mertiny, is a full professor of Mechanical Engineering and Associate Chair (Undergraduate) at the University of Alberta. He received his Diploma of Engineering in Mechanical Engineering from University of Hannover, Germany, in 1999, where he worked for Airbus as well, and his Ph.D. in Mechanical Engineering from University of Alberta, in 2005. He is a licensed professional engineer. Amongst his several national and international awards are: August-Wilhelm Scheer Visiting Professorships at the Technical University of Munich, Germany; Vargo Teaching Chair at University of Alberta; and Excellence in Education Award from Association of Professional Engineers and Geoscientists of Alberta; Dedicated Service Award from the American Society of Mechanical Engineers. He is the current President of Canadian Association for Composite Structures and Materials (CACSMA). Dr. Mertiny has focused his research on advanced polymer composite materials, including material behavior, damage mechanisms, failure prediction and structural health monitoring under multiaxial loadings; nanocomposite materials and adhesively bonded joints. Component fabrication by filament winding is a particular area of his expertise. He has collaborated with TransCanada Pipelines, Syncrude Canada, Schlumberger Canada, ShawCor, Imperial Oil, Owens Corning, Rosen Group, and Kamenny Vek (Russia).



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