Behavior of Lightweight Smart Sandwich Panels Subjected to Tensile and Bending Loads- An Experimental Study

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Abstract: In this research work, sandwich composite panels made by fiber metal laminate (FML) as the facesheets and polymer foams as the core material are investigated in tensile and bending loads. To change or enhance the behaviour of sandwich panels in tensile and bending loads, shape memory alloy wires with pseudoelastic behaviour are also embedded in between FML layers in facesheets. The shape memory wires are also pre-strained in the FML facesheets of sandwich panels. To study the tensile and flexural properties of sandwich panels with smart FML facesheets three types of sandwich panels are considered and made including panels without shape memory alloy wire, panels with shape memory wires with 0% tensile pre-strain, and panels with shape memory wires with 5% tensile pre-strain for the same cross section. By placing SMA wires in the FML, the strength and stiffness of the smart sandwich specimens are increased significantly in tensile and bending loads. However, the effect of pre-straining the SMA wires is more predominant on stiffness of the specimens. The tensile and flexural toughness or energy absorption is much higher in case of the specimen with 5% pre-strained SMA wires. At the expenses of adding the SMA wires in the sandwich structures, the densities of various specimens are changed by nearly 1% to 5% for various specimens, but a significant increase in mechanical properties such as the strength and particularly the stiffness and toughness were achieved by the present lightweight smart sandwich structures.

Keywords: Bending Test, Fiber Metal Laminate (FML), Pseudoelastic Behavior, Sandwich Composite Panel, Shape Memory Alloy Wire, Tensile Test

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1 INTRODUCTION

Composites are one of the fundamental materials in today's engineering applications. The reason for that popularity is because they combine high strength and stiffness with low weight. In particular, sandwich panels are a type of laminated composite structure that has been available due to its high stiffness, high strength and lightweight [1-2]. The most common sandwich structure consists of two thin skins and an inner core made of honeycomb or polymer foam. The high thickness of the core provides a higher moment of inertia and improves the bending stiffness of the sandwich panel [3]. The facesheets are made of high-strength materials such as aluminum or fiber-reinforced composite laminates consisting of layers of fiber/epoxy lamina, and the core is made of lightweight materials such as foam. Foam and plastic cores are very flexible relative to the facesheets and this may lead to different behaviour patterns in the top and the bottom facesheets.

Sandwich composite structures are used extensively in many structural applications, such as aerospace, shipbuilding, construction and transport industries. One of the excellent properties in sandwich panels is high capacity in energy absorption. Since, these structures are frequently used to tolerate in-plane and transverse loadings, investigation on tensile and flexural behaviour of sandwich structures with flexible cores when subjected to tensile and bending loads is significant. Many research works were conducted analytically, numerically and experimentally by various researchers on sandwich structures subjected to tensile and bending loads in the last two decades [1-9]. The investigations were focused on various core shapes and materials, various fiber composite laminated facesheets, fiber orientations, modes of failure, etc. All these efforts were made to increase load-bearing capacity and enhance various mechanical properties of sandwich structures subjected to tensile and flexural loadings.

Dinesh et al. [6] investigated various types of structural sandwich composites panels with different core materials such as aluminum honeycomb, Rohacell and HDPU foam. Various tests such as three-point bending test, tensile and compressive tests were carried out in order to validate the design. Foam based sandwich panels tend to have better tensile and compressive load bearing capacity as compared to aluminum honeycomb due to their structure and aluminum has better flexural properties. Correia et al. [7] studied experimentally the structural behaviour of composite sandwich panels for civil engineering applications. The performance of rigid plastic polyurethane (PU) foam and polypropylene (PP) honeycomb combined with glass fibre reinforced polymer (GFRP) facesheets, and the effect of using GFRP ribs along the longitudinal edges of the panels were investigated. Tests confirmed the considerable influence of the core, namely of its stiffness and strength, on the performance of the un-strengthened panels; in addition, tests showed that the introduction of lateral reinforcements significantly increases the stiffness and strength of the panels, with the shear behaviour of strengthened panels being governed by the ribs.

Salleh et al. [8] investigated the mechanical properties, such as the compressive, tensile and flexural behaviour, of sandwich composites formed from glass fibre sheets used as the skin and glass microballoon/vinyl ester as the syntactic foam core. This syntactic foam core is sandwiched between unidirectional glass fibre reinforced plastic (GFRP) using vinyl ester resins to build high performance sandwich panels. The results show that the compressive and tensile strengths decrease, when the glass microballoon content is increased in syntactic foam core of sandwich panels. Meanwhile, the flexural stiffness and effective flexural stiffness for edgewise position have a higher bending as 50% and 60%, respectively.

Yaakob [9] made an extensive investigation on the effect of metal wire mesh (MWM) layer arrangements in the thermoset laminated hybrid composite plate on mechanical properties and projectile penetration. This research used unsaturated polyester resin as matrix material and two types of reinforcement materials which are glass fibre (FG) and MWM. The thin plate panel was subjected to mechanical tests such as tensile test, flexural test, hardness test and pendulum impact test. Shifting of MWM position in the layered structures in this research towards the bottom of the force/impact action has increased the mechanical strength much better at 11.8 % on average, as compared to MWM position which was fixed in the middle of a layered structure.

Fibre Metal Laminates (FMLs) comprise of an alternating layered arrangement of advanced composites such as glass, carbon or aramid fibre reinforced polymers and metallic alloy sheets such as aluminum or titanium alloys. This hybrid material system offers the combined features of outstanding specific strength, stiffness and fatigue properties associated with fibre composites and the machinability and toughness of metals [10]. The existence of fibers in the polymer composite layers acts as a barrier against crack propagation and increases the burn through resistance as well as damping and insulation properties, while the metal layers help the ductility and impact resistance and damage tolerance. Hence, due to the engineered designed of combination of metal and composite material layers, FMLs take advantages of metal and fiber reinforced composites together [11-12].

One of the most applicable types of FMLs in various structural applications which is called as GLARE is the combination of glass fiber reinforced epoxy composite layers with aluminum sheets. Salve et al. [12] studied on different manufacturing techniques for FMLs with excellent properties under tensile, flexural and impact conditions and also reviewed recent modelling techniques on FML's. In many cases, FMLs are superior in mechanical properties. Rajkumar et al. [13] investigated the tensile and bending behaviour of aluminum-based hybrid fiber metal laminates. The effect of strain rate and lay-up configuration on tensile and flexural behaviour of fiber metal laminates were investigated. Bhat et al. [14] studied the experimental techniques for measurement of mechanical properties of GLARE in tensile, flexural and shear strengths and inter-laminar fracture toughness. Recently, Eslami-Farsani et al. [15] presented a review study on advanced FMLs reinforced with nanoparticles such as carbon nanotubes, carbon nanohorns and graphene nanoplatelets under various mechanical loadings.

Dariushi and Sadighi [16] investigated experimentally and analytically a sandwich beam with glass fiber metal laminate (FML) faces in three-point bending and compared with similar sandwich beams with fibrous composite faces. Two types of cores, that is, polyurethane (PU) and ethylene vinyl acetate (EVA) foams were used to study the effect of core types on bending behavior. FML faces had good resistance against transverse local loads and minimized the stress concentration and local deformations of skin and core under the loading tip.

Baştürk and Tanoğlu [17] investigated a sandwich panel made by FMLs facesheets containing Glass Fiber Reinforced Polypropylene (GFPP) and Aluminum (Al) sheet consolidated with three thicknesses of Al foam cores. Comparison of the flexural properties of FML/Al foam sandwich panels bonded with various surface modification approaches was investigated. Also, they provided the energy dissipated by each constituent in the sandwich panel by bending load.

In recent years, smart materials are known to improve and enhance the properties of composites structures and has attracted the interest of many researchers. Very important group of smart materials are Shape Memory Alloys (SMAs). Shape memory alloys are capable of absorbing high deformation and return to its original shape and size through changes in temperature and stress [18]. This effect is due to the presence of two crystalline phases, namely, austenite and martensite. In these alloys, the stable phase at high temperature and low stress is called austenite and the stable phase at low temperature and high stress is called martensite.

These two phases can be converted to each other due to the applied stress and temperature. By applying stress at temperatures above A_f (the end temperature of martensite to austenite conversion), the material moves from the austenite phase to the martensite phase. Upon unloading, it switches again from the martensite phase to the austenite phase and returns to its original state, leaving no residual strain. This behavior is called superelasticity or pseudoelasticity [19]. The use of shape memory alloys has been highlighted as a possible approach to introduce morphing capabilities in conventional aerospace materials. As a result of their ability to undergo shape recovery while exhibiting a large recovery stress, shape memory alloys have been selected for use in many applications [20].

A very interesting review work on SMA was done by Jani et al. [21]. They explored the attributes of SMAs that make them ideally suited to actuators in various applications, and addresses their associated limitations to clarify the design challenges faced by SMA developers. Khairikhah et al. [22] investigated numerically the effect of embedded SMA wires in composite laminated facesheets in bending behaviour of sandwich plates and the effects of plate dimensions, boundary conditions, shape memory alloy wire's diameter and embedding positions are studied.

Khalili and Akbari [23] studied the buckling behaviour of the carbon/epoxy composite cylindrical shells embedded with SMAs experimentally. The SMA wires with the shape memory effect and superelastic properties are placed in the mid-plane of the laminate with zero and 5% tensile pre-strain. Also, the effects of the number of embedded shape memory alloys wires including zero, four, and six wires are studied. The critical buckling load of the laminated cylindrical shells increased by using the shape memory alloy wires.

Eslami et al. [24] investigated the buckling behaviour of SMA reinforced Fiber Metal Laminates (FML) experimentally. The SMA reinforced FML specimens with three different pre-strain levels (1, 2 and 3 %) and different number of the embedded wires (2, 4 and 6 wires) were prepared by a specific mold and hydraulic pressure. The effects of the applied pre-strains in the SMA wires, as well as the stacking sequence of the laminate, SMA volume fraction and the location of the wires were studied on the axial and lateral force-displacement diagrams for the specimens during buckling tests.

Cortes et al. [25] studied on the fracture properties of a smart fiber metal laminate. They investigated the interfacial, tensile and fatigue properties of a novel smart fiber metal laminate based on a nickel-titanium (NiTi) shape memory alloy and a woven glass fiber reinforced epoxy.

In the present study, the tensile and flexural behavior of lightweight smart sandwich panels made by GLARE FML facesheets reinforced with and without SMA wires are investigated. The specimens are prepared for tensile and three-point bending tests according to ASTM standards. The pre-strain effect of SMA wires are also considered in the present study. Furthermore, the energy absorption and the fracture behaviour of the above said sandwich panels are studied in tensile and bending loads.

2 EXPERIMENTAL PROCEDURES

2.1. Materials

For fabrication of the fiber metal laminates, the aluminum sheet grade 3000 series (Aluconam-Tehran) is used in the present study. Unidirectional glass fiber reinforced epoxy composite layers with glass fiber of Type T (90/M225-E10) (C-L Sp. company-Poland) of 0.26 mm thickness with Araldite-LY 5052 epoxy resin (Huntsman Co.) as polymer matrix are used along with aluminum sheet with 0.27 mm thickness and the properties [26] given in “Table 1” for fabrication of GLARE facesheets. Airex C70 PVC polymer foam (Zauba Tech.-India) with the thickness of 5.02 mm [27] and polyamide (PA) polymer sheet (NING E-plastics, China) [28] with the thickness of 5.2 mm were selected as the core materials. The properties available for each material is given in “Table 1”. FML panels were prepared by hand layup technique. A Nickel Titanium (NiTi) wire (Hiland Metal Inc.-USA) with 0.3 diameter, is used as SMA alloy embedded at the center of each FML facesheet to make smart GLARE facesheets for flexural tests of lightweight smart sandwich panels, while for tensile tests, one and two NiTi wires were used at each FML facesheet for lightweight smart sandwich paenl. The SMA wires are used in pseudoelastic condition with the properties [29] given in Table 1. The wires are embedded along the fiber direction of the glass fibers.

Table 1 Properties of the materials used in the present work

Properties / Materials	Density (gr/cm^3)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Shear Strength (MPa)	Shear Modulus (GPa)
Aluminum grade 3000 [26]	2.700	295	70	180	26.7
UD- Glass Fiber composite (by test) [11] $V_f = 25\%$	1.460	419	20.7	30	3.895
C70 PVC Foam [27]	0.040	0.7	0.028	0.45	0.013
PA sheet [28]	1.140	40	1.9	----	-----
Shape memory alloy- NiTi [29]	6.450	-	Austenite – 49 Martensite – 20.8	$M_f = 18^\circ C$, $M_s = 33\ ^\circ C$, $A_s = 40\ ^\circ C$, $A_f = 75\ ^\circ C$	$C_M = 20$ MPa, $C_A = 28$ MPa $\sigma_s^{cr} = 100$ MPa, $\sigma_f^{cr} = 170$ MPa

2.2. Specimen preparation

Tensile test and three-point bending test specimens according to ASTM standards were prepared. For bending test, the first specimens’ type had no wires, the second specimens’ type had 2 SMA wires with 0% tensile pre-strain and the third specimens’ type had 2 SMA wires with 5% tensile pre-strain. For tensile tests, two more cases were studied, the fourth specimens’ type had 4 SMA wires with 0% tensile pre-strain and fifth specimens’ type had 4 SMA wires with 5% tensile pre-strain. Using an engineered designed fixture, the tensile pre-strain was applied first to the SMA wires. Then, the pre-strained SMA wires are placed at the center of the FML (GLARE) facesheets, i.e. embedded on the mid-plane between the glass fiber reinforced epoxy composite layers to make smart FML facesheets, “Fig. 1”. Then, the PA sheet and PVC foam were attached between the two smart FML facesheets. The total thickness of the sandwich panel is about 7.6 mm. Specimens were prepared according to ASTM standards D 638 [30] for tensile test and ASTM standards C 393 [31] for three-point bending test. Since, the semi-rigid plastic material was used as core material and the SMA wires are embedded by FML facesheets in the longitudinal direction of the specimens, to study the tensile behaviour, the specimens were considered as dog-bone shape according to the standard D 638. For each case, a minimum of four specimens were fabricated and tested. All specimens were prepared under same conditions for comparison purpose. Figure 1 shows the configuration of the specimens, “Fig. 2” shows the standard specimens for tensile test and “Fig. 3” shows the specimens for flexural tests. The gauge length, width and thickness is about 50 mm x 10 mm x 7.8 mm for tensile test and the width and thickness of the specimens are approximately 25 mm x 7.5 mm for flexural test.

The specimens were coded for future investigation. FML 1 means the sandwich panel without the SMA wires in the facesheets, FML 2 means the sandwich panel with the embedded two SMA wires and 0% tensile pre-strain in the facesheets, FML 3 means the sandwich panel with the embedded two SMA wires and 5% tensile pre-strain, FML 4 means the sandwich panel with the embedded four SMA wires and 0% tensile pre-strain and FML 5 indicates the sandwich panel with the embedded four SMA wires and 5% tensile pre-strain applied to the wires in the facesheets.

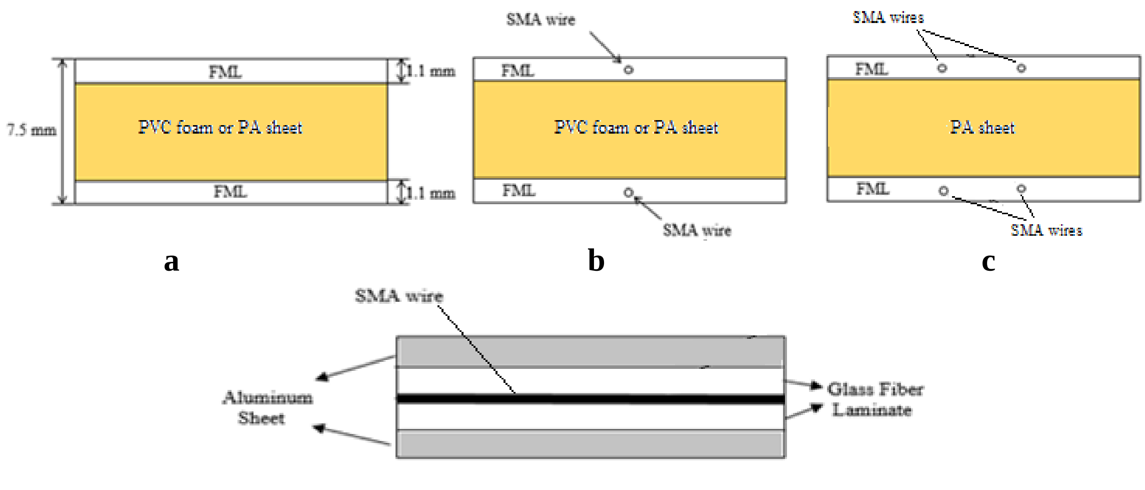


Fig. 1 Specimens configuration: (a): Without the SMA wire (width view), (b): With 2 SMA wires (width view), (c): with 4 SMA wires (width view), and (d): Sequence of the smart GLARE layers for facesheets (longitudinal view).

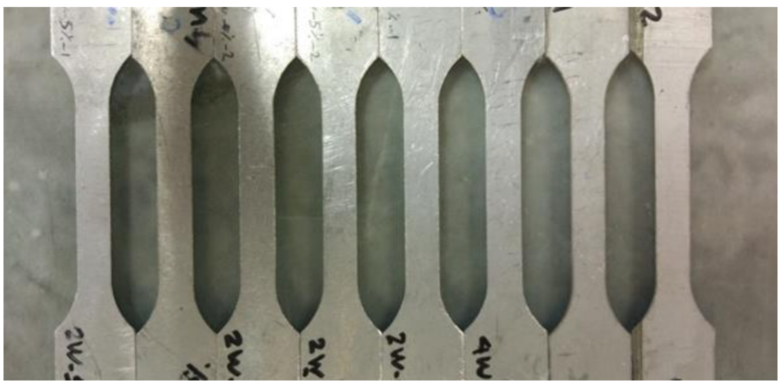


Fig. 2 Standard specimens for tensile test.

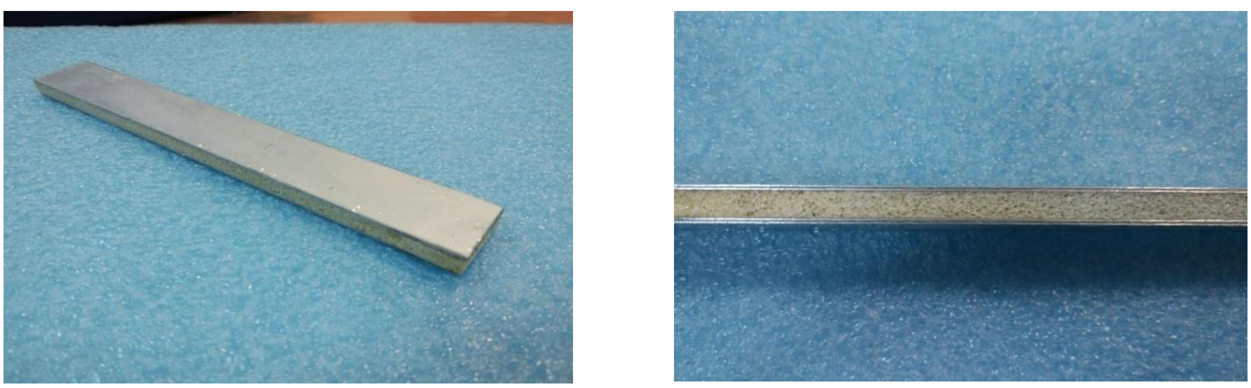


Fig. 3 Standard specimens for flexural test.

2.3. Tensile test

Tensile test is the important indication of strength and stiffness and other significant properties in materials and structures and is a measurement of the ability of a material to withstand tensile loads. By tensile test of the structures and obtaining the stress-strain curves for the structures, various properties such as stiffness, ultimate strength, energy absorption, strain to failure can be determined. According to the ASTM standard D 638, the specimens were cut in the shape of dog-bone by water jet cutting machine, and then each specimen was positioned vertically in the grips of the testing machine. Since the sandwich panels are fixed firmly in the grips, the semi-rigid core should be used for these tests. Therefore, the PA material was used as the core materials in the sandwich panels for tensile tests. The fiber direction and SMA wires are along the longitudinal direction of the specimens, that is, the direction of tensile loading. The Hounsfield HK25S Universal Testing Machine was used for performing the tensile test. Figure 4 shows the testing machine and the specimen during tensile test. The testing speed of the crosshead was 2 mm/min to simulate quasi-static test. The elongation of the specimens were continued until complete rapture and it was recorded by the machine. The load value at break was also recorded as an ultimate or breaking load. All the specimens were tested under same conditions for comparison purpose. The results of tensile tests in the form of load-displacement are converted and shown in the form of stress-strain curves and numeric values are presented from the curves to compare the results.

Fig. 4 Tensile test machine with tensile specimen under loading performance.

2.3. Flexural test

Flexural test is an important part of the characterization process of any material or structures, because the test result provides relevant information for how the materials behave under actual conditions and for its design purposes. Flexural test is carried out by three-point bending method as per ASTM C393 standard by using Hounsfield HK25S universal testing machine on all the specimens. Specimens were mounted over the three-point bending fixture and gradually loaded (3.2 mm/min) in bending. The span of the supports was set during the bending test as 122 mm. The core material for sandwich panels is PVC foam for flexural tests. Figure 5 shows the flexural test of the specimen by three-point bending method, where the load is applied at the mid span of the specimen and the corresponding values of load and displacement are recorded. All the specimens were tested under same conditions for comparison purpose. The results of the flexural tests are presented in the form of flexural force-displacement curves. The numeric values are also recorded from the curves to compare the details.

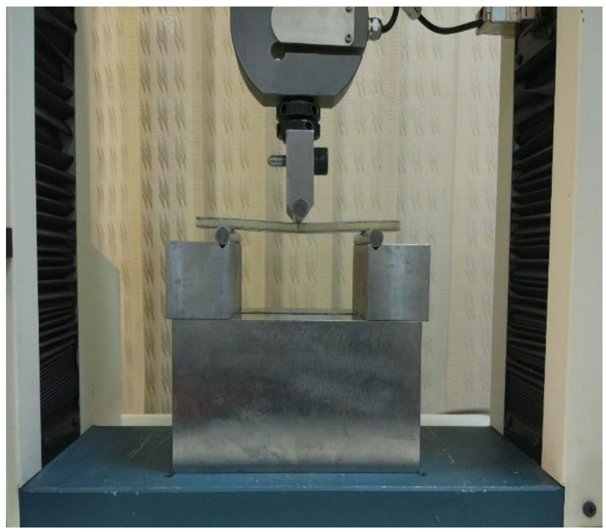


Fig. 5 Flexural test machine with the three-point bending fixture and the specimen.

3 RESULTS AND DISCUSSION

3.1. Tensile test

The fractured specimen after tensile test is shown in “Fig. 6”. The results of tensile test in the form of stress-strain curves are shown in “Fig. 7” and the numeric results are given in “Table 2”. The standard deviations for all the obtained results in “Table 2” and in the “Figs. 7 and 8” are within ± 1.75.

Fig. 6 Specimen after rapture in tensile test.

Table 2 Numeric results obtained from tensile tests

Samples	Density ρ gr/cm^3	t (mm)	W (mm)	F_{max} (N)	F_{Break} (N)	Displacement (mm)	Ultimate Strength (MPa) S	S/ρ	Stiffness (GPa) E_1	E_1/ρ
FML 1	1.439	7.86	10.48	8014.167	385	47.621	97	67.40	1.10	0.76
FML 2	1.440	7.88	10.7	8100.12	469.166	47.499	95	65.56	1.33	0.92
FML 3	1.436	7.9	10.6	8206.667	569.166	50.047	98	68.24	1.76	1.23
FML 4	1.456	7.88	10.3	8120.833	725	47.134	100	68.68	1.90	1.30
FML 5	1.452	7.85	10.4	8961.666	570.833	49.613	110	75.75	2.21	1.52

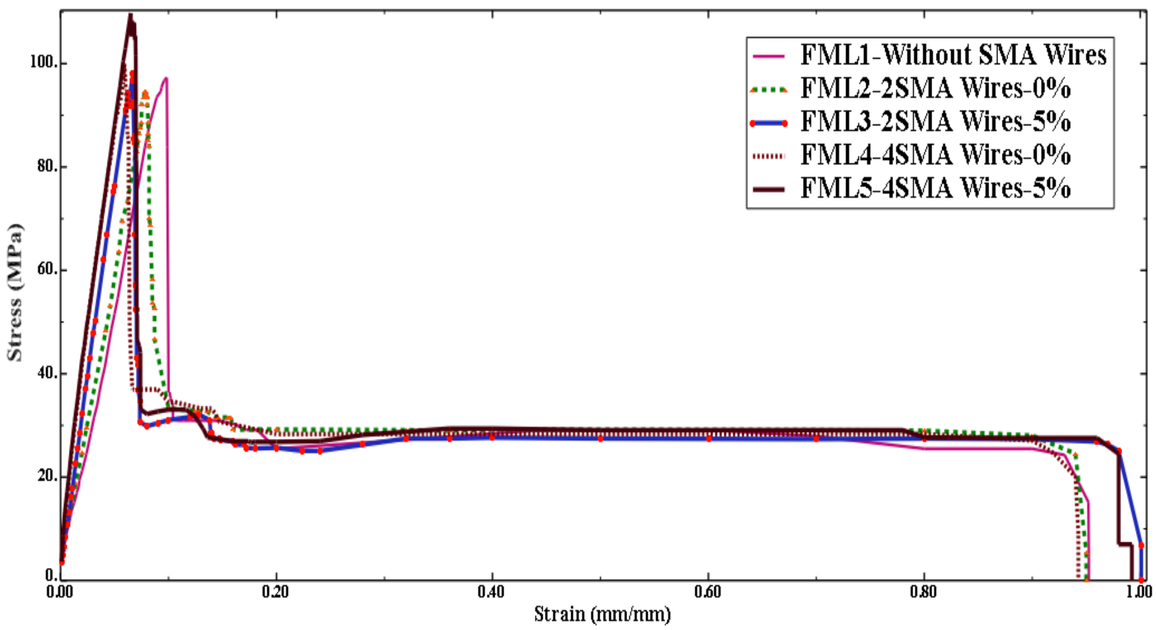


Fig. 7 Stress-strain curves for various specimens.

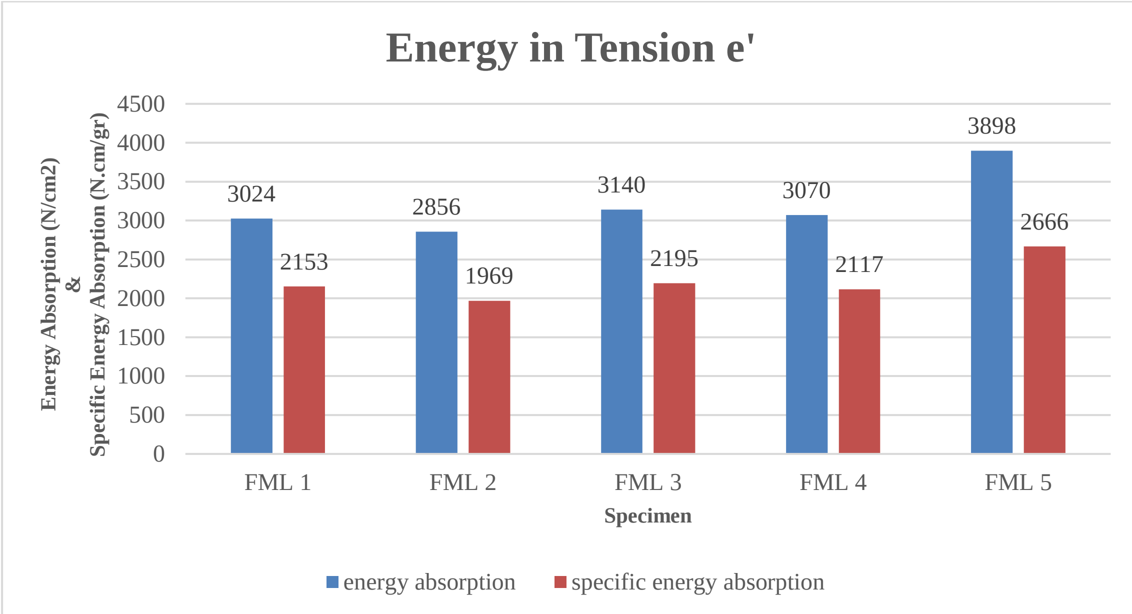
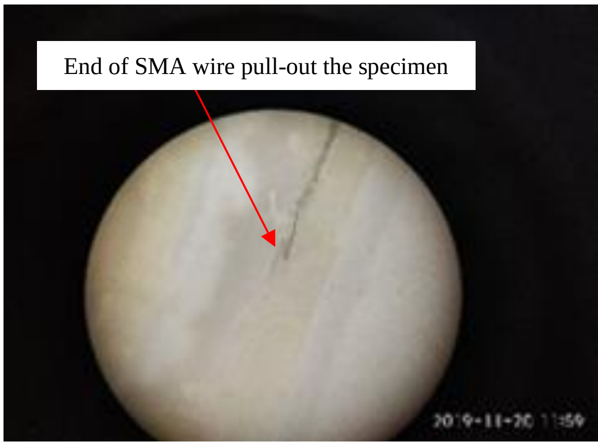


Fig. 8 Energy absorption in tensile test by the specimens.

It can be seen that the specimen FML 5 with 5% pre-strain and four SMA wires had shown better properties in tensile test in comparison with other specimens. The stiffness, the maximum load and the maximum displacement for various specimens are observed in stress-strain curves in “Fig. 7”. In “Table 2”, the ultimate tensile strength and the stiffness of the specimens are shown. Also, the specific strength and the specific stiffness are shown in “Table 2”. By placing SMA wires in the GLARE, the stiffness of the smart sandwich specimens is increased by 21% for FML 2 and 72% for FML 4 and by pre-straining the SMA wires, the stiffness is increased by 60% for FML 3 and 100% for FML 5 as compared to FML 1. But, the increase in strength is by nearly 1% for FML 3 and FML 4 and 13% for FML 5. By comparing the maximum displacements for various specimens, no significant increase was achieved even by specimen FML 5 (1% increased), which indicates that by embedding SMA wires, not much changing occurred in the failure strain.

This is because the bonding between the SMA wires and the composite layers is not enough to withstand the debonding and pulling-out the SMA wires inside the composite layers. The same reason can be used for strength values. The specific stiffness for FML 5 is increased by 100% and for FML 3 by 62%, and 71% for FML 4 and 21% for FML 2 as compared to FML 1. The specific strength increased by nearly 2% for FML 3 and FML 4 and by 12.3% for FML 5 as compared to FML 1. The effect of pre-straining the SMA wires is more predominant on stiffness of the specimens. At the expenses of adding the SMA wires in the sandwich structures, the densities of various specimens are changed by nearly 1%, and hence the increase in mechanical properties such as strength and particularly stiffness was achieved by lightweight smart sandwich structures.

Figure 8 shows the energy absorption and the specific energy absorption values for the specimens in tensile test. The energy absorption values are obtained by calculating the area under the stress-strain curves for the specimens and the specific energy absorption values are calculated by energy absorbed for each specimen divided by its density. This absorbed energy is equivalent to toughness of the specimen. FML 5 absorbed 29% more energy than the specimen FML 1. Even the specific energy absorption is 23% higher as compared to FML 1 specimen. As can be seen, the effect of pre-straining the SMA wires is more significant. The shape of sandwich structure and also the lightweight materials used in these specimens, show a very high specific toughness for the present structures. The high toughness and specific toughness values are significant in crashworthiness phenomena. The dog bone tensile specimens for mild steel ST12 and 5083 aluminum alloy were prepared and tested and results are given in the form of stress-strain curves by liu et al. [32]. The area under these curves (toughness) were calculated and the specific energy (energy/density) was obtained. The numeric values for specific toughness for aluminum and steel specimens are approximately 1207 N.cm/gr and 943 N.cm/gr, respectively, and as compared to the presented FML 5 specimen result (2666 N.cm/gr), the smart lightweight sandwich specimen shows an increase of 120% compared to aluminum alloy and 182% as compared to steel specimen.



(a) **(b)**

Fig. 9 (a): The SMA wire pull-out in composite layers, and (b): Fractured specimen.

Figure 9(a) shows the process of SMA wire pull-out in the composite layers in the FML facesheets. This phenomenon occurred when the glass fibers break first, then the composite layers debond and fracture; and as a result of excessive elongation, the aluminum sheets break, before the SMA wire pulls-out.
The fractured tensile specimens due to the presence of SMA wires are shown in “Fig.9 (b)”. The SMA wires tried to bond both sides of the fractured specimen together. The integrity of the specimens with the SMA wires is more predominant.

3.2. Flexural test

The results of three-point bending test in the form of force-displacement curves for three specimens’ types (FML 1, FML 2 and FML 3) are shown in “Fig. 10” and the numeric results are given in “Table 3”. The standard deviations for all the results obtained in “Table 3” and in the “Figs. 10 and 11” are within ± 1.68. By the placement of the SMA wires at the center of the FML facesheets (smart sandwich), the maximum bearing bending load as well as the breaking load and the maximum displacements are higher than the specimens without the SMA wires. Comparison of the 0% tensile pre-strained SMA wires specimen (FML 2) and the specimen without SMA wires (FML 1) showed 13% increase in maximum load and 84% increase in breaking load and 10% increase in maximum displacement. The FML 3 specimen with 5% pre-strained SMA wires shows an increase of 11% in maximum load, 44% increase in breaking load and 26.5% increase in maximum displacement, when compared to FML 1. The stiffness, strength and displacement are the parameters affected by the SMA wires. Placement of the SMA wires is increasing the stiffness of the FML 2 and FML 3 by 29% as compared to FML 1. The stiffness of the FML 2 and FML 3 specimens are almost the same. Therefore, increasing the pre-strain on the SMA wires is not affecting significantly the stiffness of the present sandwich panel. Regarding the strength of the sandwich panels, the presence of the SMA wire increased the strength by 13% when comparing FML 1 and FML 2 specimens. In the present work, sandwich strength was increased by placement of SMA wires. By applying pre-strain to SMA wires, the strength is reduced slightly. It means that the amount of 5% tensile pre-strain on the SMA wires is affecting to reduce instead of increase the strength. Either the number of SMA wires or the amount of pre-strain has to be changed to see the effect more obvious. But, the maximum displacement as well as the overall behaviour of the structure are much affected by pre-straining the SMA wires.
The structure shows more brittle at first instant, but due to the debonding phenomena occurring in the FML facesheet, the flexibility of the structure becomes higher in case of pre-strained SMA wires. Due to the pre-strained conditions, the SMA wires are breaking at higher strains. It means that the wires are tolerating the loads till debonding or pull-out of the SMA wires and from that moment onwards, more strain is released to complete breakage of the specimen. Actually, it seems that the specimens with pre-strained SMA wires spend more period of time to break. The increase in density of the specimens by adding two pre-strained SMA wires is almost 5.4%. The specific strength and stiffness of FML 2 show an increase of 7.8% and 23%, respectively when compared to FML 1. Even, the FML 3 specimen shows an increase of 5.5% and 22% in specific strength and stiffness respectively. It means that, at the expenses of small increase in density due to the presence of the SMA wires, it is possible to manufacture lightweight sandwich structures with higher stiffness and slight increase in strength in bending.

Table 3. Comparison of the experimental values for flexural properties.

Samples	Density (gr/cm^3)	Thickness t (mm)	Width W (mm)	F_{max} (N)	F_{Break} (N)	Displacement (mm)	Specific strength	Specific stiffness
FML 1	0.740	7.52	25.13	309.166	75.215	11.3	417.8	191.3
FML 2	0.777	7.57	24.7	350.833	138.333	12.521	450.4	236
FML 3	0.780	7.62	24.9	344.166	108.333	14.302	441	234

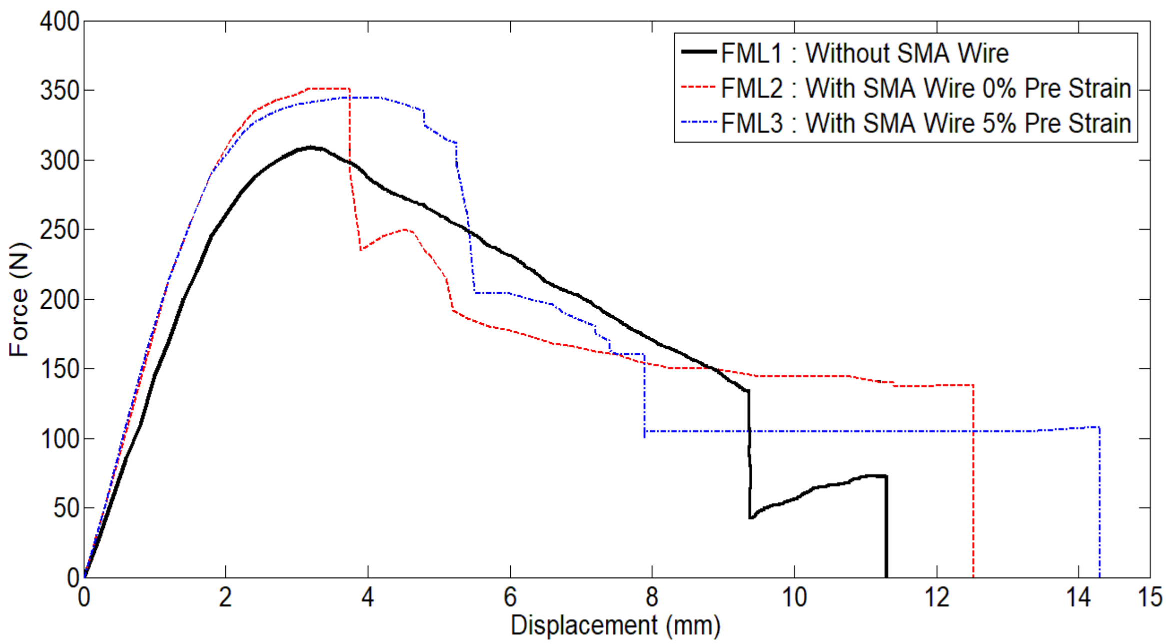


Fig. 10 Flexural force-displacement test results.

The area under the curves which shows approximately the energy absorption during the flexural test is greater in case of the FML 3 specimen by almost 37% as compared to the FML 1 specimen. For the FML 2, the area is almost 21% greater than the area for the FML 1 specimen. This behaviour shows the static bending toughness of the specimen. The values obtained by calculation of the areas under force-displacement curves for all the specimens are shown in “Fig. 11”. Similar conclusion was obtained in Refs. [16-17] for various sandwich panels with FML facesheets and aluminum and polymer foam cores with various core thicknesses, i.e., enhancement of the area under the force-displacement curves. In the present work, the placement of a single SMA wire in FML facesheets resulted in a similar behavior for energy absorption without increasing the sandwich thickness and weight. In “Fig. 11”, the specific energy absorptions for various specimens are also shown. Same trend and behaviour is observed for specific energy, that is, 30% increase for lightweight FML 3 specimen compared to FML 1 specimen. The presence of SMA wires affect the stiffness and the strength of the panel and hence the FML 2 and FML 3 sandwich panels are not easily bend under the same loading conditions, when compared to the FML 1 specimen.

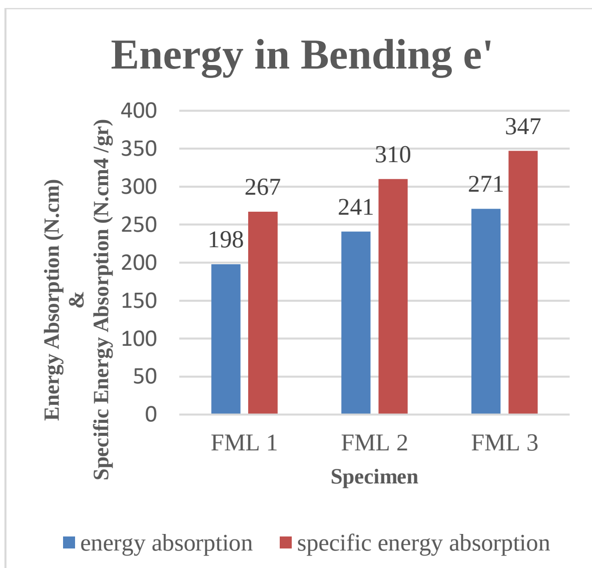


Fig. 11 Energy absorption in three-point bending test by the specimens.

Even the spring-back in the specimens with SMA wires are higher. The typical fractured specimens after flexural tests are shown in "Fig. 12". At the maximum load in the FML 1 specimen, the crack starts at the bottom side of the core and propagates transversely to the top facesheet. But, the break in the FML1 curve in "Fig. 10" occurs when debonding occurred between the facesheet and the core and then continued till propagation of debonding and further bending to complete failure. The damage development appeared to be steady and consistent with the increase of the displacement. In a three-point bending test, both core shear and sandwich bending are observed for the FML 1 specimens, as the same conclusion obtained in Ref. [17]. The length/thickness ratio of all the specimens are almost same. But, the fractured behavior of the FML2 and FML 3 specimens shows apparent plastic yielding at the midpoints of the specimens. Therefore, their dominant deformation mode was evaluated as skin bending.

The first break in the FML 2 and FML3 curves in "Fig. 10" indicates separation and debonding occurred in the FML facesheet between the aluminum and glass fiber composite and then propagates at a slower rate due to load bearing of the facesheet and at last the debonding of the facesheets and then complete bending failure, "Fig. 12".

In all the FML 1 specimens, the core crack initiation and propagation and the debonding of the facesheet and the core are obvious as the failure process. In all the FML 2 and FML 3 specimens, no evidence of core crack initiation was observed. The main failure process was due to debonding of the aluminum sheet from the fiber composite layer. There was no evidence of the SMA wire debonding and even its breakage.

No noticeable crack was observed in the core in the FML 2 and FML 3 specimens. The integrity of the specimens with the SMA wires are more predominant. The pre-strain prevented the amount of delamination and helped the integrity of the structure after the failure. Due to pseudo-elastic behaviour of the SMA wires, even the spring-back is higher in the FML 2 and FML 3 specimens. The FML 2 specimen deforms by almost 12 mm transversely, but after the failure and unloading, the permanent deformation is only 3 mm. The effect of pre-strain on the SMA wires is more predominant. The FML 3 specimen deforms by almost 14 mm transversely during loading, but after the failure and unloading, the permanent displacement is only about 1 mm. In the case of FML 1 specimen, the bending deformation is almost 10 mm after the failure. It means that for the FML 1 specimen, the deformation in the structure is almost permanent after failure, but in the FML 2 and specially FML 3 specimens, the spring-back action is very high due to the presence and the pre-strain effect of the SMA wires.

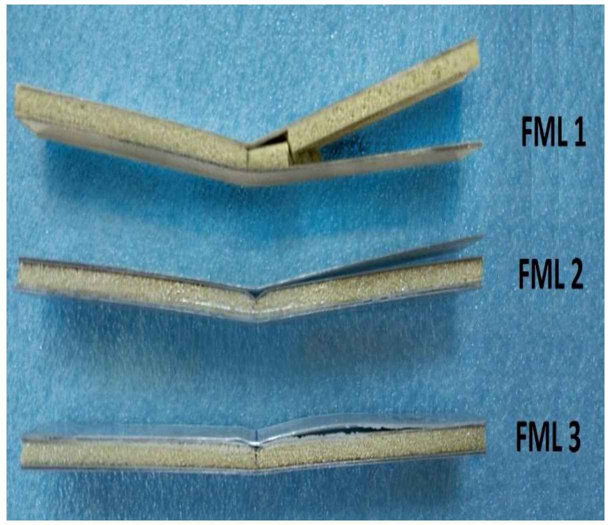


Fig. 12 Flexural test specimens after failure.

4 CONCLUSIONS

In the present paper, the tensile and flexural behaviour of lightweight sandwich structure made of smart GLARE facesheets and flexible core are investigated. The GLARE facesheets are reinforced by SMA wires. The SMA wires are used in pseudo-elastic condition and also pre-strained in tensile by 0% and 5%. The tensile properties such as strength and stiffness and energy absorption and the flexural properties such as maximum bending load, bending stiffness, bending displacement and the area under the curves in flexural force-displacement of the lightweight sandwich structures with and without the SMA wires and also the effect of pre-straining of the SMA wires are studied. The following conclusions can be highlighted from the results obtained:

1- By placing SMA wires in the GLARE, the tensile stiffness of the smart sandwich specimens are increased by 21% for FML 2 and 72% for FML 4 and by pre-straining the SMA wires, the stiffness is increased by 60% for FML 3 and 100% for FML 5 as compared to FML 1. Placement of the SMA wires in bending specimens, increases the stiffness of the FML 2 and FML 3 by 29% as compared to FML 1.

2- The specific stiffness in tensile specimens for FML 5 is increased by 100% and for FML 3 by 62%, and 71% for FML 4 and 21% for FML 2 as compared to FML 1. The specific strength and stiffness of bending specimens of FML 2 shows an increase of 7.8% and 23% respectively when compared to FML 1.

3- The effect of pre-straining the SMA wires is more predominant on stiffness of the specimens.

4- The tensile and flexural toughness or energy absorption is greater in case of the specimen with 5% pre-strained SMA wires by almost 37% and 29% for FML 3 bending specimen and FML 5 tensile specimen, respectively, as compared to the specimen without the SMA wires.

5- The specimens with the pre-strained SMA wires show better integrity of the structure after the failure in tensile and bending.

6- At the expenses of adding the SMA wires in the sandwich structures, the densities of various specimens are changed by nearly 1% for tensile specimens and 5.4% for bending specimens, but a significant increase in mechanical properties such as strength and particularly stiffness and toughness were achieved by lightweight smart sandwich structures.

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REFERENCES

[1] Herranen, H., Pabut, O., Eerme, M., Majak, J., Pohlak, M., Kers, J., Saarna, M., Allikas, G., and Aruniit A., Design and Testing of Sandwich Structures with Different Core Materials, Materials Science, Vol. 18, No. 1, 2012, pp. 45-50.

[2] Mudassir, S., Ravi Shankar, D. V., and Manzoor Hussain, M., Flexural Behavior of Sandwich Composite Panels Under 4-Point Loading, International Journal of Materials Science, Vol. 11, No. 1, 2016, pp. 47-55.

[3] Khan, M. A., Syed, A. K., Ijaz, H., and Shah, R. M. B. R., Experimental and Numerical Analysis of Flexural and Impact Behaviour of Glass/PP Sandwich Panel For Automotive Structural Applications, Advanced Composite Materials, Vol. 27, No. 4, 2018, http://doi.org/10.1080/09243046.2017.1396199.

[4] Fiedler, T., Ochsner, A., Experimental Analysis of The Flexural Properties of Sandwich Panels with Cellular Core Materials, Materials Science and Engineering (Materialwissenschaft und Werkstofftechnik), Vol. 39, No. 2, 2008, pp. 121-124.

[5] Marx, J., Rabiei, A., Tensile Properties of Composite Metal Foam and Composite Metal Foam Core Sandwich Panels, Journal of Sandwich Structures and Materials, 2020, DOI: 10.1177/1099636220942880.

[6] Dinesh, S., Rajasekaran, T., Dhanasekaran, M., and Vigneshwaran, K., Experimental Testing on Mechanical Properties of Sandwich Structured Carbon Fibers Reinforced Composites, 2nd International conference on Advances in Mechanical Engineering (ICAME 2018) IOP Publishing, IOP Conf. Series: Materials Science and Engineering 40, 012180, doi:10.1088/1757-899X/402/1/012180, 2018.

[7] Correia, J. R., Garrido, M., Gonilha J. A., Branco, F. A., and Reis, L. G., GFRP Sandwich Panels Pu Foam and Pp Honeycomb Cores for Civil Engineering Structural Applications, Effects of introducing strengthening ribs, International Journal of Structural, Integrity, Vol. 3, No. 2, 2012, pp. 127-147.

[8] Salleh, Z., Mainul Islam, M. D., Ananda, J., and Haibin, S. U., Mechanical Properties of Sandwich Composite Made of Syntactic Foam Core and Gfrp Skins, AIMS Materials Science, Vol. 3, No. 4, 2016, pp. 1704-1727.

[9] Yaakob, M. Y., Mechanical and Ballistic Properties of Laminated Hybrid Glass Fiber/ Metal Wire Mesh Reinforced Unsaturated Polyster Composite of Hard Panel Products, Ph.D Thesis, The Centre for Graduate Studies, Universiti Pertahanan Nasional Malaysia, 2014.

[10] Khalili, S. M. R., Mittal, R. K., and Gharibi Kalibar, S., A Study of The Mechanical Properties of Steel/Aluminium/GRP Laminates, Materials Science and Engineering A, Vol. 412, No. 1-2, 2005, pp. 137–140.

[11] Sinmazçelik, T., Avcu, E., ÖzgürBora, M., and Çoban, O., A Review: Fibre Metal Laminates, Background, Bonding Types and Applied Test Methods, Materials & Design, Vol. 32, No. 7, 2011, pp. 3671-3685.

[12] Salve, A., Kulkarni, R., and Mache, A., A Review: Fiber Metal Laminates (FML's) Manufacturing, Test methods and Numerical modelling, International Journal of Engineering Technology and Science (IJETS), Vol. 6, No. 1, 2016, pp. 71-84.

[13] Rajkumar, G. R., Krishna, M., Narasimhamurthy, H. N., Keshavamurthy, Y. C., and Nataraj, J. R., Investigation of Tensile and Bending behaviour of Aluminium Based Hybrid Fiber Metal Laminates, Procedia Materials Science, Vol. 5, 2014, pp. 60-68.

[14] Bhat, S., Narayanan, S., On Fabrication and Testing of Glare, ARPN Journal of Engineering and Applied Sciences, Vol. 9, No. 9, 2014, pp. 1606-1614.

[15] Eslami-Farsani, R., Aghamohammadi, H., and Khalili, S. M. R., Recent Trend in Developing Advanced Fiber Metal Laminates Reinforced with Nanoparticles: A Review Study, Journal of Industrial Textiles, 2020, Doi: 10.1177/1528083720947106

[16] Dariushi, S., Sadighi, M., Surface with a Crack Propagation Through the Foam Cells, The Damage Development Appeared, Appl Compos Mater, Vol. 20, 2013, pp. 839–855.

[17] Baştürk, S. B., Tanoğlu, M., Development and Mechanical Behavior of FML/ Aluminium Foam Sandwiches, Appl Compos Mater, Vol. 20, 2013, pp. 789-802.

[18] Klaput, J., Studies of Selected Mechanical Properties of Nitinol - Shape Memory Alloy, Archives of Foundry Engineering, Vol. 10, 2010, pp. 155-158.

[19] Kuang, K. S. C., Quek, S. T., and Cantwell, W. J., Active Control of a Smart Composite with Shape Memory Alloy Sheet Using a Plastic Optical Fiber Sensor, Sensors and Actuators A: Physical, Vol. 201, 2013, pp. 182-187.

[20] Hartl, D. J., Lagoudas, D. C., Aerospace Applications of Shape Memory Alloys, Proc. IMechE, Vol. 221G, 2007, pp. 535-552.

[21] Jani, J. M., Leary, M., Subic, A., and Gibson, M. A., A Review of Shape Memory Alloy Research, Applications and Opportunities, Materials and Design, Vol. 56, 2014, pp. 1078-1113.

[22] Kheirikhah, M. M., Khadem, M., and Farahpour, P., Bending Analysis of Soft-Core Sandwich Plates with Embedded Shape Memory Alloy Wires Using Three-Dimensional Finite Element Method, Proceedings of the Institution of Mechanical Engineers Part L Journal of Materials Design and Applications, Vol. 226, No. 3, 2012, pp. 186-202.

[23] Khalili, S. M. R., Akbari, T., Study on the Effective Parameter of Buckling Behavior of Cylindrical Composite Shells with Embedded SMA Wires, Journal of Reinforced Plastics and Composites, Vol. 38, No. 16, 2019, https://doi.org/10.1177/0731684419842316.

[24] Eslami-Farsani, R., Mohaseb Karimlou, M. R., Saeedi, A., and Zamani, A., Effect of Shape Memory Alloy Wires on the Buckling Behavior of Fiber Metal Laminates, Fibers and Polymers, Vol. 20, 2019, pp. 1690–1695.

[25] Cortes, P., Cantwell, W. J., and Kuang, K. S. C., The Fracture Properties of a Smart Fiber Metal Laminate, Polymer Composites, 2007, pp. 534-544.

[26] Navard Aluminum MFG Co., Arak Provience, I. R. Iran, https://www.navard-aluconam.com, (accessed Feb. 24, 2020).

[27] Zauba Technologies Private Limited, Bangalore, India, https://www.zauba.com, (accessed Feb. 24, 2020).

[28] Guangzhou Ning E-Plastics Co.Ltd, Guangzhou, China, https://www.ningeplastics.com, (accessed Feb. 24, 2020).

[29] G and H Orthodontics Company, Franklin, USA, https://www.ghwire.com, (accessed Feb. 24, 2020).

[30] ASTM D638-14. Standard Test Method for Tensile Properties of Plastics D638-14, 2015.

[31] ASTM C393-00. Standard Test Method for Flexural Properties of Sandwich Constructions C393-00; 2000.

[32] Liu, B., Villavicencio, R., and Guedes Soares, C., Failure Characteristics of Strength-Equivalent Aluminium and Steel Plates in Impact Conditions, Analysis and Design of Marine Structures – Guedes Soares & Romanoff (eds), ISBN: 978-1-138-00045-2, 2013, pp. 167-174.