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Investigation of Tensile and Bending behavior of Aluminum based hybrid fiber metal laminates

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Abstract

Present investigation was focused on the effect of strain rate and lay-up configuration on tensile and flexural behaviour of four combinations of fiber metal laminates. Tensile and flexural tests were conducted on universal test machine as per standards. The result shows that the tensile strength increased with increasing strain rate. However the flexural strength decreased with increasing strain rate. Both tensile and flexural strength are maximum for carbon based FML structures, minimum for glass based FML and hybrid FML structure lies between them. The observations on both tensile and flexural failure mechanisms deduced from a microscopic study of the fractured specimens are presented.

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*Keywords:*Fiber metal laminates, Tensile test, Flexural test, Delamination, strain rate.

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1. Introduction

Presently, fiber metal laminates (FMLs) have received an increasing amount of interest in aircraft, marine and automotive industry, due to their better resistance to fatigue, impact and fire resistance [Alderliesten R.C et al (2003)] with specific strength [S.M.R. Khalili et al (2005)]. Glass fiber /aluminium laminates (GLARE) is one of the important members in FML family which is found in number of applications. Many research studies have shown that GLARE combine the durability [Wu HF et al (1994)] and superior machinability associated with metals with the excellent specific properties [S Ebrahim et al (2010)], fatigue and fracture characteristics of high performance composites materials [Krishna Kumar S et al (1994)]. [Vlot et.al (1996)] reported that low velocity impact response of GLARE is better than monolithic aluminium alloy. GLARE offers a range of specific properties that exceed those of the traditional fiber reinforced laminates [M R Abdullah and W J Cantwell (2006)]. Further a combination of

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cross plyfiber composite and aluminum alloy offers a wide range of specific properties for aerospace applications [Tamer Sinmazcelik et al (2011)].

GLARE still have their disadvantages like lower yield strength due to its low and different modulus in longitudinal and transverse direction. Hence it fails to find application in higher load bearing structures [E C Bohlho et al (2007)]. To overcome this disadvantage a much stiffer carbon fiber instead of glass fiber was used for FML structures and it popularized carbon fiber / aluminium laminates (CARAL). Combination of high stiffness of carbon fibers and impact resistance of aluminium metal layer allow for extremely efficient crack arresting and retard crack propagation rate. Hence CARAL laminates have a great advantage for space applications [A.Vlot (2001)]. Although CARAL laminates possess higher specific modulus, but has relatively low strain to failure [Dong et al (2012)] and also high manufacturing costs [L B Vogelesang and A Vlot (2000)]. To improve low strain to failure Corties and Cantwell (2004) replace aluminium layer with magnium layer, which improve in fatigue life of FML. In the same direction many researchers made attempt [Caprino G et al (2004), Cantwell W J et al (2001)] to substitute instead of Al both glass and carbon fibers replaced by aramid and polypropylene fiber to full fill the required properties. Although FML improved fatigue life of the components but possess poor compressive strength. As per authors knowledge no work was focused on hybridization of glass fiber (high elongation fiber) and carbon fiber (low elongation fiber) with Al layer FML structure to improve tensile as well as flexural strength.

Hence the objective of present work was to develop and characterize glass / carbon hybrid fiber metal laminates for various combinations of glass/epoxy, carbon/epoxy and Al layers. Both tensile and flexural tests were performed at various strain rates. The outcome results provide a useful guideline to the design of glass and carbon fiber reinforced polymer FML structures for various applications.

2. Experimental studies

Al 6061 alloy 0.8mm sheet thickness (composition is Cu-3.8%, Si-1.3%, Mn-0.5% and Al balance by weight), bidirectional (0° / 90° orientations) glass fiber, carbon fiber of 600 gsm, epoxy resin (LY 556) and hardener (HY 917) were selected. Al sheets were cleaned with acetone to remove grease, dirt and chromated for better adhesion between the layers. FML panels were prepared by hand layup technique followed by heating to 150°C followed by pressuring them during curing process. The GFRPs and CFRPs are oriented parallel to the edges of Al panels, with a staking sequence mentioned in Table1. Four identical specimens were used for each condition, and average value is taken for discussion. The tensile tests were conducted on straight edged rectangular samples in order to avoid the need to machine potentially complex dog bone geometries [H F Wu and L L Wu (1996)].

Table 1: Details of the layup, staking sequence and type of characteristics

Sl. No.	Test name	Layup	Staking configuration	Nomenclature	Average size of the specimen
1	Tensile test	3/2	Al/C/C/C/Al/C/C/C/Al	A_3C_6	150x20x3.5mm
			Al/C/G/C/Al/C/G/C/Al	$A_3C_4G_2$	
			Al/G/C/G/Al/G/C/G/Al	$A_3C_2G_4$	
			Al/G/G/G/Al/G/G/G/Al	A_3G_6	
2	Flexural test	3/2	Al/C/C/C/Al/C/C/C/Al	A_3C_6	130x13x3.5mm
			Al/C/G/C/Al/C/G/C/Al	$A_3C_4G_2$	
			Al/G/C/G/Al/G/C/G/Al	$A_3C_2G_4$	
			Al/G/G/G/Al/G/G/G/Al	A_3G_6	
Al- Aluminium, C-one layer of Carbon fiber & G-one layer of Glass fiber					

Tensile test for each of the specimen was carried out on Zwick/Roell Z-100 Universal testing machine at a cross head speed of 1, 2, and 3 mm/min for loading and the gauge length (grip to grip separation) was maintained at 90mm. For inter laminar shear strength (ILSS) by three points bend test, the gauge length of the specimen selected as 100 mm and crosshead speed of 1, 2, and 3 mm/min.

Failed samples were observed to study the failure modes using low magnification optical microscope. ILSS is computed by using the formula

$$ILSS = \frac{3P_{\max}}{4Wt}$$

Where ‘P’ is the max load, ‘W’ is the width and ‘t’ is the thickness of the specimen.

3. Results and discussion

3.1 Tensile test

Stress strain curves for A_3C_6, $A_3C_4G_2$, $A_3C_2G_4$ and A_3G_6 FML specimens are presented in Fig. 1(a), 1(b), 1(c) and 1(d) respectively for strain rate of all the strain rates. Similarly, stress-strain curves for all specimens for strain rate of 1mm/min, 2mm/min and 3mm/min are plotted in Fig. 2(a), 2(b) and 2(c) respectively. The curves (Fig.1) exhibit typical linear response up to 1% strain and then zigzag response could be observed up to maximum peak. The load carrying capacity of all FMLs in linear region is around 35% of their maximum load. In this region both metal layer and FRP assumed to act as a single component. The zigzag response observed from 1% strain load up to their peak strength and increases with increasing strain rate. This appearance of zigzag behavior at higher loading rates along with increasing failure strain with increase in the strain rate has also been observed by Kevin A et.al (2010). During this region the aluminium plate and FRP layers share loads unevenly due to their different elasticity (Poisson ratio). Less ductile FRP layers (up to 5%) bears the more load than high ductile aluminium layer (16%) hence some of fibers are cut thus zigzag pattern could be seen.

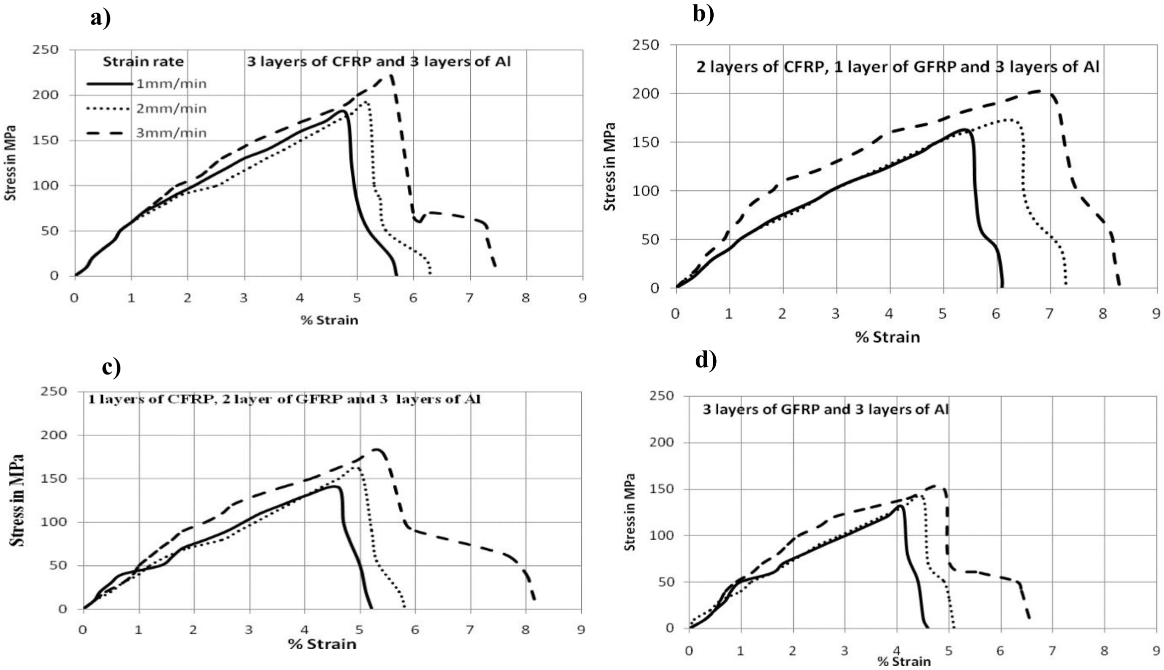

Fig.1 Effect of strain rate on stress-strain behaviour of a)A_3C_6 b)$A_3C_4G_2$ c)$A_3C_2G_4$ and d)A_3G_6 fiber metal laminates

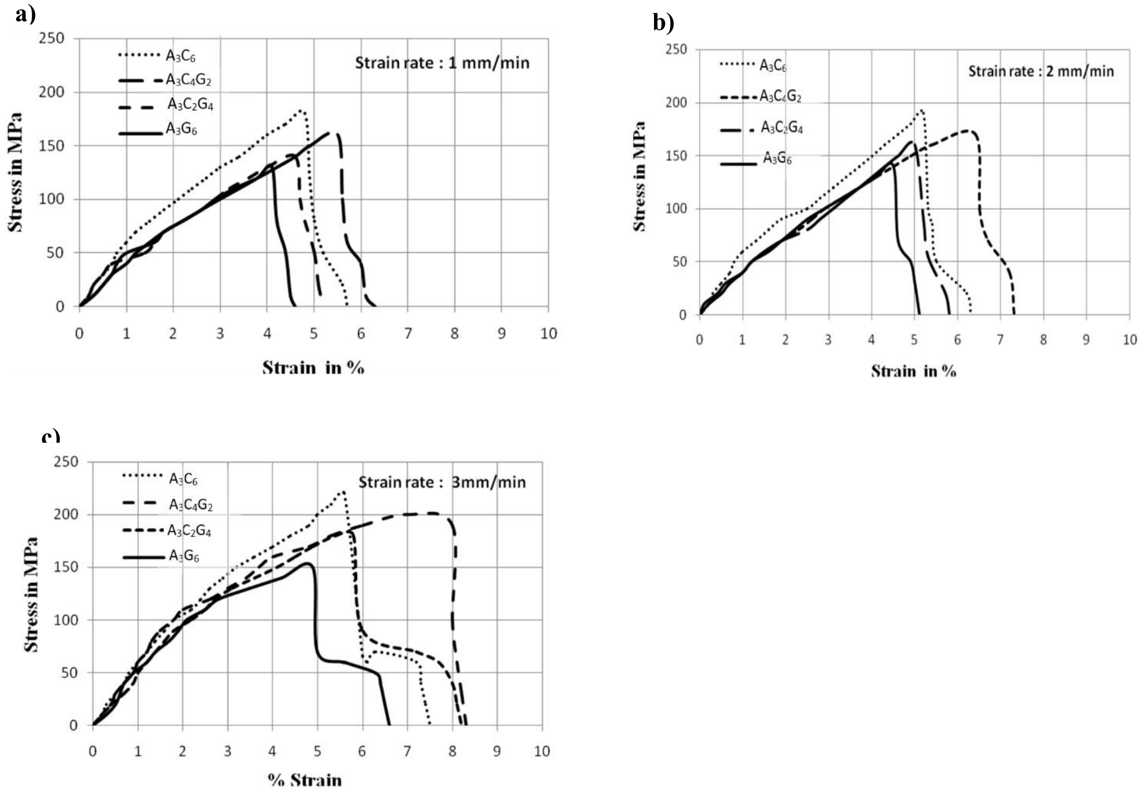

Fig.2 Effect of lay-up type on stress-strain behaviour of different fiber laminates at strain rate of a) 1 mm/min, b) 2mm/min and c) 3 mm/min

Although brake down of few fibers observed, the curves attained peak stress and its variation depend upon strain rate and compositions. The maximum stress peak i.e. ultimate tensile strength (UTS) increases with increasing strain rate i.e. 180MPa at 4.8% strain, 190MPa at 5.2% strain and 220MPa at 5.6% of strain for A_3C_6 FML for strain rate of 1mm/min, 2 mm/min and 3 mm/min respectively. Similarly for $A_3C_4G_2$ FML 160 Map at 5.5% strain, 170MPa at 6.4% strain and 200MPa at 7% strain for a strain rate of 1mm/min, 2mm/min and 3mm/min respectively. For $A_3C_2G_4$ specimen the minimum stress was 140MPa at 4.6% strain at 1mm/min and 160MPa at 5% strain, 180MPa at 5.8% strain for 2mm/min and 3mm/min strain rate respectively. Likewise, for A_3G_6 the least stress is 130MPa at 4.1% strain, 140MPa at 4.5% strain and 160 at 4.9% strain for strain rate of 1mm/min, 2mm/min and 3mm/min. After attaining the peak, the aluminum plates immediately failed and hence the drop of the curve appears steep until some stress level in the same strain. Some unbroken fiber may take little load then the FML fail; hence the complete failure is prolonged. The response at higher strain is stiffer than at the lower strain rates. The maximum stress increases somewhat with strain rate.

The Fig. 2 show that UTS of A_3C_6, $A_3C_4G_2$, $A_3C_2G_4$ and A_3G_6 are ranging 180 - 220 Mpa, 160-200 MPa, 140 - 180Mpa and 130-160MPa respectively for 1mm to 3mm strain rate. This shows the type of reinforcements and their quantity effects on both strain rate and tensile strength of FML. The highest strength could be seen A3C6 due to combination of high strength carbon fiber based polymer laminates with Al layers. Replacing of carbon layers by glass fiber leads to decreasing UTS of the FML. A higher carbon fiber content FML is less sensitive to strain rate, therefore, higher the stiffness and strength than the other type of configuration.

3.2 Tensile fracture behavior

Fig. 3 (a), (b), (c) and (d) show the fractured surfaces of A_3C_6, $A_3C_4G_2$, $A_3C_2G_4$ and A_3G_6 FML samples respectively. It clearly shows that aluminum layers in FML for all combinations (Fig.3 a-d) were fractured at angle of≈ 65° to the loading direction due to direction of dislocation related slip plane and slip direction of metal crystal [J G Carrillo and W J Cantwell (2009)]. The premature failure of the FRP in FML through matrix cracking and localized warp fiber fracture could be seen in CFRP (Fig.3 (a &b)), and weft fiber pullout and delamination could be seen in GFRP (Fig. 3(c&d)). In Fig.3(a) and (b) the fiber fractured almost angle of 90° to loading direction. This is due to good bonding strength between carbon fiber and epoxy matrix material. In other hand the Figs.3(c) and (d) show the extensive debonding of fibers from the matrix over a considerable distance to either side of the fracture surfaces. The specimen disintegrated into two pieces but was pulled down from the two ends which were attached to the loading bars. In GFRP the debonding between pullout fibers and the matrix becomes easier. Welsh and Harding [1985] suggest that the strain rate effect is also influenced by the type of reinforcement of composites. According to visco-elastic theory, fiber-governed behavior should not be influenced to a great degree because of the glass fiber sensitivity to strain rate is considered to be small or none. Hence more fiber pullout could be seen in GFRP.

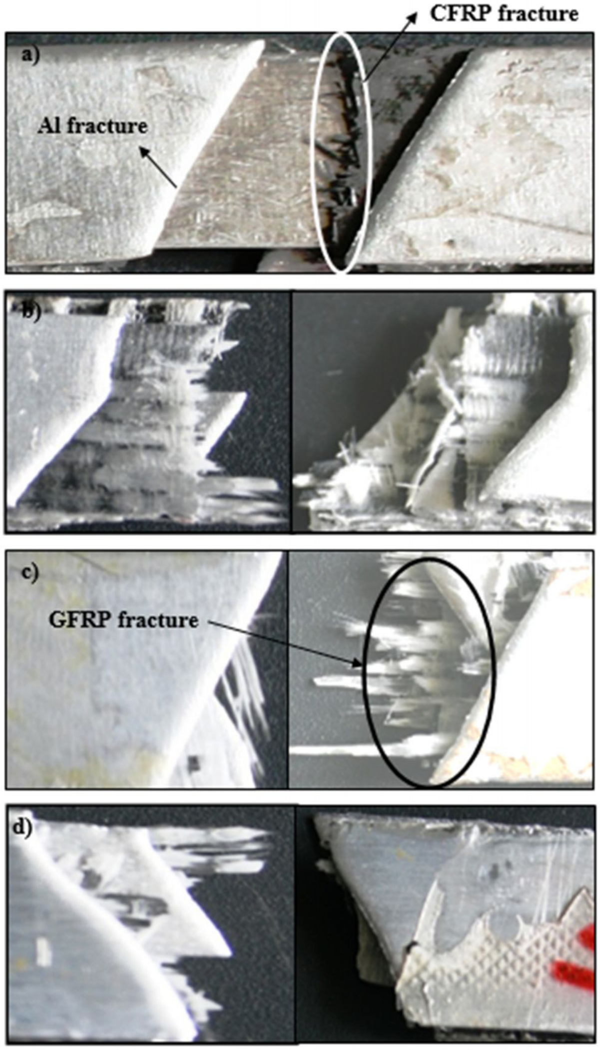

Fig.3 Tensile failed samples of a) A_3C_6 b) $A_3C_4G_2$ c) $A_3C_2G_4$ and d) A_3G_6 for strain rate of 3mm/min

3.3 Flexural test

The flexural behavior of A_3C_6, $A_3C_4G_2$, $A_3C_2G_4$ and A_3G_6 FML specimens in the form of shear stress-strain curves are presented with different strain rate as shown in Fig. 4(a), 4(b),4(c) and 4(d) respectively. Similarly for strain rate of 1 mm/min, 2 mm/min and 3 mm/min for the same specimens are presented in Fig. 5(a), 5(b) and 5(c) respectively. The maximum stress peak decreases with the strain rate for all type of configuration i.e. Maximum stress peak for A_3C_6 488MPa at 0.027 strain, 347MPa at 0.029 strain, 261MPa at 0.17 strain for strain rate of 1mm/min, 2mm/min and 3mm/min respectively. Similarly, for $A_3C_4G_2$ FML 320MPa for at 0.023 strains, 269MPa at 0.017 strain and 220MPa for 0.017 strain, for a strain rate of 1mm/min, 2mm/min and 3mm/min respectively. For $A_3C_2G_4$ specimen the maximum stress was 259MPa at 0.31 strain, 209 for 0.027 strain and 150 MPa for 0.022 strain for strain rate of 1mm/min, 2mm/min and 3mm/min respectively. Likewise, for A3G6 the maximum stress was 178MPa for 0.030 strain, 130MPa for 0.0.34 strain and 114MPa for 0.035 strains at the strain rate of 1mm/min, 2mm/min and 3mm/min respectively. Shear strength of A_3C_6 and $A_3C_4G_2$ FMLs structure show higher than that of $A_3C_2G_4$ and A_3G_6 FML structures. In former cases the CFRP placed in exterior which improve the flexural strength due to its more strain to failure of the layer, where as in the later cases the GFRP placed in exterior, which has lesser stiffness than CFRP, which leads to possible damage / deformation evolution in extreme GFRP layer is constrained because of surrounding Al layer. Even though CFRP is placed at the location at neutral axis of the sample would not help in increasing the bending strength and stiffness of FML structures.

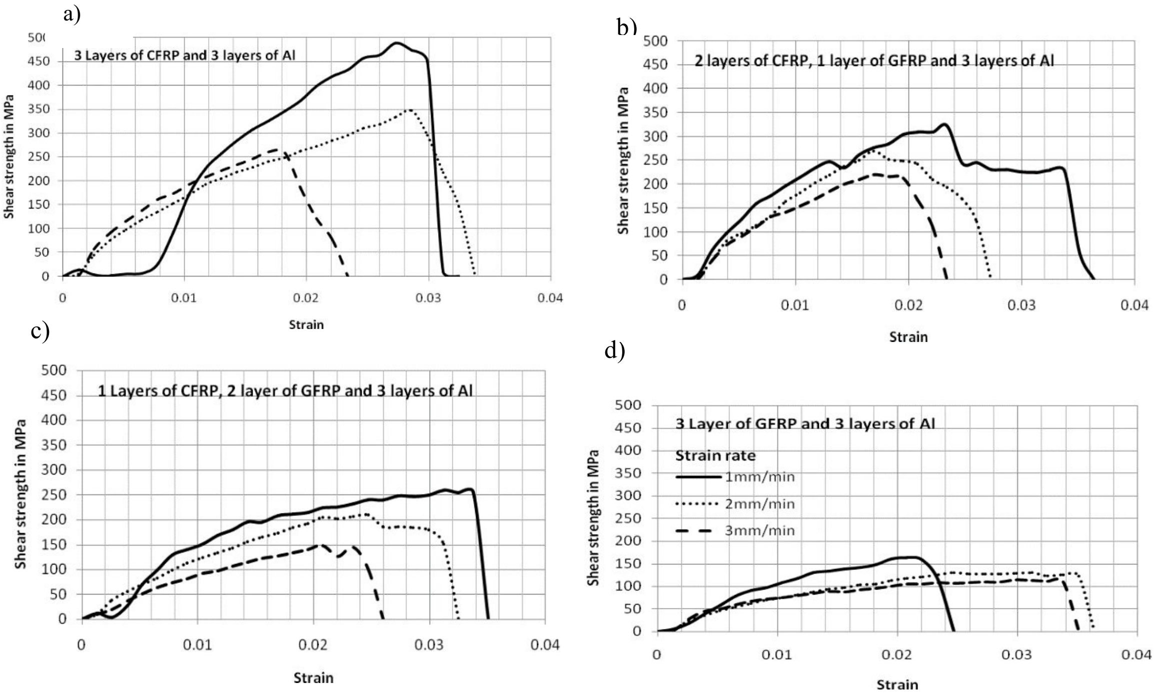

Fig 4. Effect of strain rate on shear strength-strain behaviour of a) A_3C_6 b) $A_3C_4G_2$ c) $A_3C_2G_4$ and d) A_3G_6 fiber metal laminates

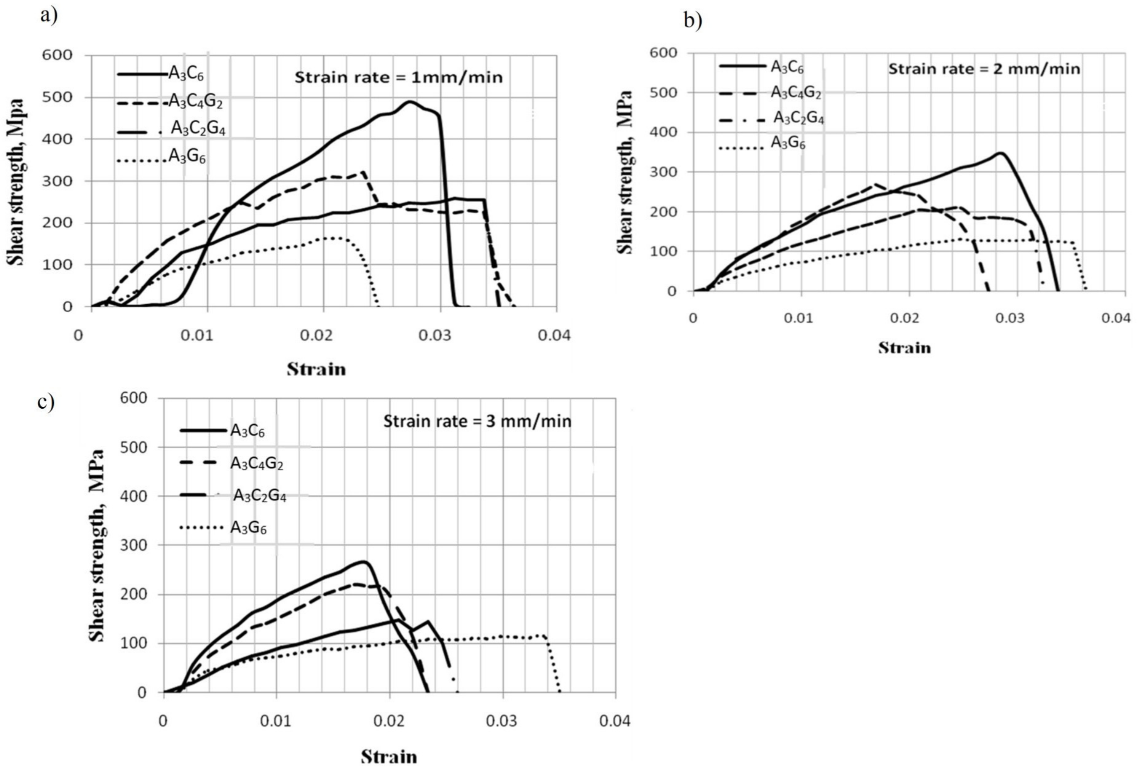

Fig 5. Stress-strain curves of FML structures for strain rate of a) 1 mm/min, b) 2 mm/min and c) 3 mm/min.

The variation of ILSS values for all configurations are plotted against strain rate of 1mm/min, 2mm/min and 3mm/min are shown in the Fig 6. There is a decrease in the ILSS with the increase in strain rate. At lower strain rates the polymer gets more time for recovering, hence less plastic deformation therefore higher ILSS can be observed for all configurations. With increase in the strain rate the rupture density increases due to structural integrity losses and shorter relaxation time for polymers which are incapable to transfer the load properly which deteriorates the ILSS values irrespective of fiber-metal configuration. At higher strain rate the load is like an impact due to this several damage mechanisms such as fiber fracture, fiber pullout, matrix cracking and delamination occur.

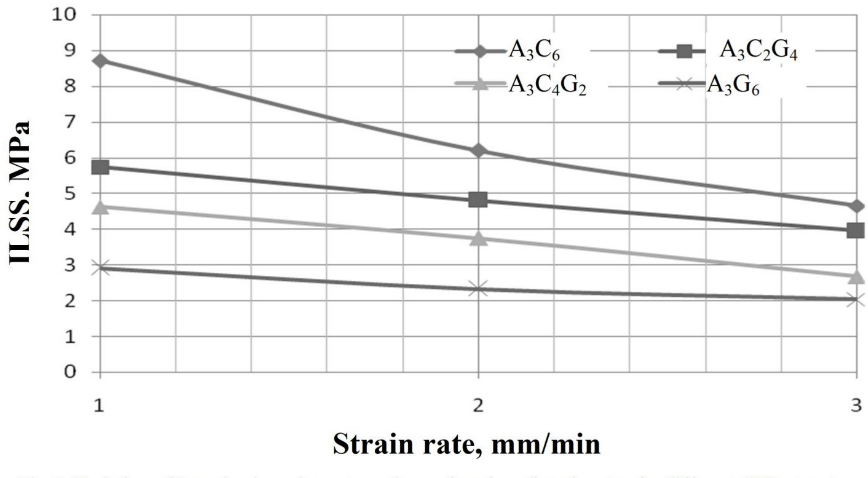

Fig 6. Variation of Inter-laminar shear strength as a function of strain rates for different FML structures.

3.4 Flexural fracture behaviour

Fig.7 shows different types of failure modes of failed flexural FML specimens. It is clear that the delamination (crack) is extended along bi-material interfaces that is, between Al and FRP and between two layers of FRPs. In damage of flexural FML structure, few fiber pull-out and fiber breakage was observed but the delamination was main cause for failure of the specimen. The width of the delamination cracks are very nominal for $A_3C_2G_4$ (Fig. 7(a)) specimen and the central part i.e. FRP and metal plate act as a single entity due to heterogeneous fibers. The glass and carbon alternate layers have good adhesive bond between them and hence there is no crack, delamination and fiber pullout. The same nature of failure could be seen in $A_3C_2G_4$ (Fig. 7(b)) specimens, but in this case most of fibers are pulled out from the centre of the specimen. In the case of A_3G_6 (Fig. 7(c)) the delamination can be seen in all the layers, which is due to less adhesion between the identical FRP layers. The same trend could be seen in A_3C_6 (Fig. 7(d)) specimens. But in A_3G_6 and A_3C_6 specimens, fiber cut can be seen hence the strength of individual layers have higher integrity, thus it can bear higher load and higher tendency of delamination which leads to lower ductility.

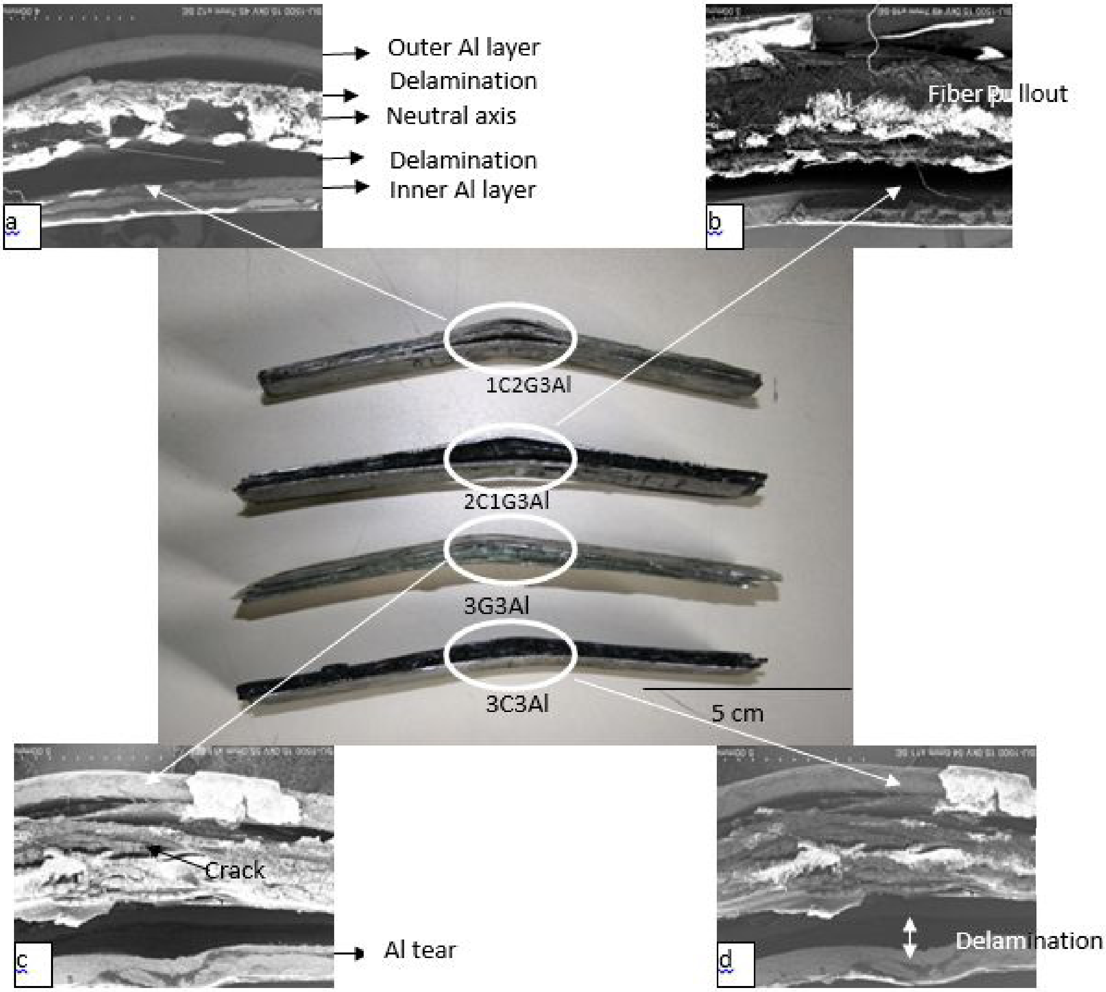

Fig 7. Delamination between FRP and metal laminates during Flexural testing for different FML structure

4. Conclusions

The tensile and flexural behaviour of A_3C_6, $A_3C_4G_2$, $A_3C_2G_4$ and A_3G_6FML has been obtained at different strain rate. Results show that the tensile strength increased with increasing strain rate. However, in contrast, the flexural strength decreased as strain rate increased. Hierarchy of tensile and flexural strength are summarized as A_3C_6> $A_3C_4G_2$> $A_3C_2G_4$> A_3G_6. By placing carbon fiber layer in the exterior than glass fibers will enhance the mechanical strength of FML. Damage fracture mechanism of four FML based in different constituents materials have been assessed by tensile and flexural tests. The good bonding strength between Al and CFRP leads to crack arresting in the flexural test of the A_3C_6 and $A_3C_4G_2$ laminates. On other hand, A_3G_6 and $A_3C_2G_4$ specimens showed a change in fracture mode resulting from the greater tendency for debonding between fiber and the resin matrix.

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