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Impact face influence on low velocity impact performance of interply laminated plates

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Fibre Metal Laminate (FML), a metal sandwiched hybrid composite material is well-known for its enhanced impact properties and better damage tolerance and it has been successfully implemented in diverse engineering applications in aviation industry. With heterogeneous constituents, the stacking sequence of FML is believed to play a critical role to govern its overall energy absorption capability by means of controlling delamination of metal composite interface and plastic deformation of metal layers. As a precursor, low velocity impact experiments were conducted on interply configured transparent plastic plates in order to extract the significance of stacking sequence and realize the characteristics of each layer through naked eye which is not possible in FML due to opacity of metal layer. The stack configuration constitute hard acrylic (brittle) and soft polycarbonate (ductile) plates analogous to composite (brittle) and metal (ductile) layers on FML laminate and the impact event is performed on either hard or soft facing sides separately. Hard side samples resemble more protective than soft side impact sample, with large peak resistant force and expose smaller damage growth in all experimented cases.

Keywords: Transparent plastics, Fibre Metal Laminate, Low velocity impact, Impact face

1. Introduction

In engineering applications, structures made of heterogeneous composition fulfill majority of anticipation in terms of robustness, reliability and durability. The investigation of bi-material structure often provides a fundamental understanding of role played by the individual material constituents and also pave the way to enhance and optimize its influence. Wear resistant structures, coated substrates, sandwich panels, and laminated composites are some of the

commonly encountered bi-material morphological structural components. In general, the bi-material constituents are integrated together using an adhesive interface whose material properties are intermediate between those of the adherent to ensure rigid continuity. Thus, the overall performance and mechanical behavior are limited not only by the bulk properties but also by the interface characteristics. The demand of heterogeneity is attributed mainly to acquire unique and tailorable material properties with reduced cost, weight and easy manufacturing process. One such example is the revolution of light weight composite material technology starting from antique age to the current state of art.

Like composites, other materials such as ceramic, glass and acrylic or polymethyl methacrylate (PMMA) are brittle in nature and often susceptible to fracture. Fracture often occurs during the service life mainly by the impact of foreign bodies to the exposed surface. Many painstaking and tedious efforts are carried out to improve the fracture behavior of above materials especially composites because, over the past five decades its usage is overwhelmingly expanded in distinct fields. One such persistent technique is the interply hybridization of ductile metal layer with in the brittle composite layers so called Fibre Metal Laminates (FML). FML is well known for its enhanced impact and fatigue resistance than conventional composites whose characteristic behavior and overall performance are extensively reviewed and documented by many researchers [1-7]. Meanwhile, the low velocity impact (LVI) often induce barely visible impact damage and so the boundary of impact damage around the vicinity of impact point is difficult to mark for further repair process. This insist many researchers to carry out LVI experiments on FML laminates in order to quantitatively substantiate the impact damage and rehabilitate it before subject to any catastrophe during the service.

FML are sequentially stacked in an order with opaque aluminium ply as an outermost layer. Consequently, the damage extension of in-house composite, metal and interface layers are difficult to measure and require more advanced inspection techniques. To alleviate this circumstance and without relaxing any generality, a simple laminate configuration consisting of transparent bi-layered plates having hard (brittle) acrylic (PMMA) and soft (ductile) polycarbonate (PC) layers analogous to composite (brittle) and metal (ductile) layers of FML configuration were tested in order to assess the fracture process and resulting damage surface.

Many research activities related to fracture behavior of glass, transparent ceramics and polymeric materials are carried over for many decades [8-10]. Such materials are widely used as a transparent enclosure for canopies and windshields in aircraft and utilized as armors with high optical clarities in military in order to protect against armor-piercing and riot control applications. For better protection, the front layer of armor is placed as hard as possible to damage the projectile in maximum range and high stiff and tough backing layer are mounted to catch the residual projectile fragments and hindering the crack propagation by interface layer [11]. The dynamic fracture of brittle blocks under impact loading is generally characterized by complex cracking surface having radial, conical, circumferential, median and lateral form of cracks [8]. In case of firmly bonded bi-layered plate made of hard and soft layers, the damage pattern is either incomplete penetration along with interfacial fracture or on the other hand complete perforation with severe form of damage like spalling, plugging and petalling if the impact kinetic energy is quite enormous [12].

Such impact studies on transparent plastic surface supports and motivates the authors to clone its visual fracture observation and characteristic response towards the understanding of dynamic response of FML under LVI. Based on that, the present study is organized in to two sections; (i) Similitude LVI experiment study on adhesively bonded transparent bi-layered isotropic PMMA/PC plastic plates. (ii) Equivalent impact face effect study on interply 1/1 FML laminates.

2. Drop weight impact experiment

2.1. Materials and specimen configuration

For the similitude experiments, acrylic plate of different thickness ranges between 1mm to 4mm and 1mm constant thick polycarbonate (PC) sheet were firmly adhered using 3M Scotch-Weld DP-100 room temperature cured epoxy adhesive. On the basis of side which receive the impactor i.e acrylic or PC side, two different groups of bi-layered plastic laminates were fabricated. Each category contains four different sample classified based on volume fraction of PC (PVF) defined as volume of PC to volume of complete laminate.

The authors would like to insist the reason why the thickness of PC sheets is kept constant in the present study. The main theme of the current study is to derive the characteristics of FML from

the equivalent transparent plastic materials. In such case, the PC sheet replicates the situation of ductile metal layer in FML. On increasing its thickness will directly reflect the increase in overall weight of the specimen which is not optimum and defeat the advantage of FML over monolithic metals.

Fig.1. Schematic diagram of experimented bi-layered target samples.

FML samples were fabricated using aluminium AL 2024-O and 7781/L-530 epoxy coated glass fabric prepreg as metal and composite layers respectively. As like above, two different groups of bi-layered specimens having constant thick metal layer and variable thick composite layers were tested. All the target plates were trimmed to a square shape having a side length of 10cm. Similar to PVF; different thick brittle composite layers are identified by accounting fraction of metal volume to the volume of laminate so-called metal volume fraction (MVF).

Table 1

Details of experiment cases

Sample	Thickness [mm]			Volume fraction	Areal weight [kg/m ²]
	Polycarbonate	Acrylic	Total panel	PVF*	
Plastic	1	1	2	0.5	2.46
	1	1.5	2.5	0.4	3.24
	1	3	4	0.25	4.75
	1	4	5	0.2	5.58
FML	Metal GFRP			MVF**	
	0.5	0.5	1	0.5	2.25
	0.5	0.75	1.25	0.4	2.46

* PVF = Polycarbonate volume fraction

**MVF = Metal volume fraction

The schematic illustrations of experimented configuration are shown in Fig. 1 and its corresponding geometric details are tabulated in Table 1. Here onwards for convenience, the acrylic side and PC side impact samples are designated as hard and soft face samples respectively. An impact velocity of 2 m/s corresponds to incident impact energy of 6J was utilized throughout the study. After the impact test, specimens and spall fragments are carefully removed for further post impact optical damage evaluation.

3. Results and discussion

The main emphasis of the present study is to understand the impact behavior of each individual layer of FML by qualitative and quantitative perspective. For the optimum course of evaluation, the transient characteristic parameters are elaborately manifested in terms of side of impact.

3.1. Similitude study on transparent plastic laminates

The influence of dissimilar face impact on acrylic/PC plastic samples of PVF 0.5 and 0.4 are investigated with the help of contact resistant force (F) and absorbed energy (E_a) evolution curve in terms of respective impactor displacement (w). The typical static mechanical properties of target constituents are listed in Table 2.

Table 2

Static mechanical properties of cast acrylic and polycarbonate (PC).

Material	Density (kg/m ³)	Young's Modulus (GPa)	Ultimate tensile strength (MPa)	Flexural strength (MPa)	Poisson's ratio	Failure strain
Cast acrylic	1190	3	75	100	0.4	3%
Polycarbonate (PC)	1200	2.4	60	90	0.37	110%

Having similar young's modulus for acrylic and PC laminates as listed in Table 2, the initial slope of force-displacement curve attained by both the hard and soft face impact samples in Fig. 2 were apparently look-alike. Despite that, the abrupt drop in the contact force significantly explores the influence of stacking sequence of bi-material configuration where the soft side impact samples experience a sudden drop in contact force quite earlier than hard side impact samples. In the context of normal transverse impact, contact stresses are dominated in the impact side while non-impact faces are subjected to severe tensile stresses. With the inferior fracture

toughness and smaller strain to failure (only 3%), the generation of small fraction of tensile stress by impact deformation on the bottom face acrylic layer for soft impact case is enough to promote a severe earlier fracture irrespective to the thickness of acrylic layer reinforced. In other words, no significant improvement on bending stiffness was attained by increasing the back face brittle acrylic layer thickness. One can notice such independency where the deflection at which the abrupt drop in contact force occurs is more or less constant ($\sim 2\text{mm}$) for all PVF.

Fig 2. Force – deflection curve of PMMA-PC plastic laminates; (a) PVF=0.5 (b) PVF=0.4 (c) PVF=0.25 (d) PVF=0.2.

With no backing layer, the fractured region finally ensued to spalling fracture as shown in Fig. 3 where a small area of acrylic layer underneath the impact region has been broken off. This argument dictates that after an earlier abrupt drop, the rest of the impact resistance in soft side impact sample is solely provided by the ductile PC layer. However, in hard side impact samples, the ductile PC layer on the non-impact face act as a shock absorber and such damping effect

protect the directly contact brittle acrylic layer with no spalling fracture but having few radial cracks except the thin PVF 0.5 sample where the impact portion of brittle acrylic layer is utterly crushed. Due to these features, it can be seen that the peak contact resistance force accomplished by the soft side impact samples is quite smaller than its counterpart hard side impact samples except PVF 0.5 case where crushing of acrylic layer reveals significant drop in contact force value as in Fig. 2. However, on comparing the force-deflection curve of different impact face, it is perhaps worth mentioning here that the stiffness of hard side impact samples are lasting for long time than soft side impact samples for all PVF.

Fig 3. Damage patterns of impacted PMMA/PC plastic laminates.

Fig.4 portrays the energy-displacement curve of hard and soft side impact samples of PVF 0.5 and 0.4 respectively. After the moment when soft side sample relaxed its bending stiffness due to spalling of brittle layer, the rate of energy absorption per impactor displacement i.e. the slope of energy-displacement curve reduces more significantly. On close scrutiny, it is interesting to note that the magnitude of energy to induce such abrupt degradation is about 0.5 J i.e. approximately 8% of total impact energy only. The indication shows the level of energy required to initiate and propagate a damage surface in acrylic layer is very small. The probable reasons for these exacerbations are having an inferior fracture toughness and higher crack propagation velocity. For a thin brittle plate, the crack propagation speed was found equivalent to the speed of elastic stress waves and it was given by a relation [13];

$$\dot{a} = \frac{0.696 + 0.896v}{1 + v} \sqrt{\frac{E}{2\rho(1 + v)}} \quad (5)$$

Based on the mechanical properties listed in Table 2, the above propagation velocity measures around 800 m/s. According to the present scenario, the calculated speed consume only 47 μ s to

cover the maximum target plate radius of 38 mm which is negligibly small when compared to recorded average contact duration of 13ms. Thus, the sudden high velocity fracture of acrylic layer consumes only negligible fraction of total impact energy and the remaining 90% has been dissipated by the ductile PC layer either in the form of denting (localized indentation) or elastic dishing (flexural and stretching deformation) or by both in and around the impact point respectively. Thus, these circumstances dictate that reinforcing a brittle lamina on the back side of thin impact resistant structure is not optimum.

Fig 4. Energy – deflection curve of PMMA-PC plastic laminates; (a) PVF=0.5 (b) PVF=0.4 (c) PVF=0.25 (d) PVF=0.2.

In addition, there is an optimum brittle layer thickness (here, it is PVF 0.4) in which there is no significant drop in contact force prevails. Thus, in order to enforcing enhanced tolerance, the thickness of brittle layer laid with the ductile layer should be neither thin nor thick but should be intermediate enough to withstand the contact pressure and able to flexure well enough. The

deformation mechanism of such optimum target panels are further analyzed via the in-plane and transversely bisected damage patterns.

In the classical work of Hertzian impact between steel ball and glass block in elastic half space by Tsai and Kolsky [9], they found a radially symmetrical wave with a cylindrical wave front called Rayleigh surface wave is propagated over the glass surface from the impact center. Also, the intensity of such wave front is greatly decayed with respect to depth of glass block. Acquiring a ductile PC layer as an elastic foundation in the present case, a pattern of cylindrical region was observed in the interlaminar region which indicates the dislocation of interface adhesive layer believed to be caused by the above stated surface stress waves. Furthermore, similar to Tsai and Kolsky prediction, an extent of dislocation was found smaller for sample having thicker impact face (i.e PVF 0.2) as shown in Fig. 3c and 3d. From the bisected optical image as shown in Fig 4b, it is evident that the dislocation in interlaminar adhesive region eventually leads to debonding or delamination.

However, incorporating a brittle PMMA layer under the PC layer appeared to have constrained the ability of soft face impact samples to retain the absorbed energy. The testimony for above circumstance is addressed by considering the unloading energy – displacement curve of Fig. 4 where, even though the soft side sample deforms larger, only lesser amount of energy has been absorbed compared to hard side impact samples. This scenario strongly anticipates the energy dissipation in hard side impact is mostly conserved via plastic deformation in PC layer and generating interlaminar delamination. Whilst in soft face impact samples, apart from local indentation in PC layer, large percentage of incident energy is dissipated by global elastic deformation during loading stage after the PMMA layer loses its flexural resistance and repelled the same by spring back effect during the unloading stage as confirmed through Fig. 4 where at the end of impact event the locus of soft side energy curve lies lower to the hard face energy curve.

Interim summary

- Impact resistance of PMMA/PC is higher (i.e. larger peak impact force and small damage) if impacted on brittle (hard) PMMA layer than ductile (soft) PC layer.

- The degradation of structural stiffness in impact samples are found independent of PMMA thickness. Because the deflection at which the abrupt drop happens in contact force is merely constant for all cases of PVF.
- Neither too thin nor too thick, the layer of intermediately thick PMMA layer provide optimum impact performance whose characteristic curve resembles smooth and kink free distribution which dictates its deformation and damage dissipation mechanism are in control throughout the impact event.
- The extent of delamination appears to be proportional to the position of interface region from the impact surface. With increase in PMMA thickness, the delamination envelope of hard face impact samples are steadily decreases.

3.2 LVI study on FML

In this section, efforts were made to characterize the impact behavior of metal bonded composite laminates and study the influence of stacking order with respect to impact direction. Two different sets of target had been experimented based on the relative volume proportion of metal layer in the target (i.e $V_{\text{metal}}/(V_{\text{metal}} + V_{\text{comp}})$) or simply MVF similar to PVF in preceding similitude experiments. The static material properties of constituent material are summarized in Table 3.

Fig 5. Contact force and energy absorption variation of MVF 0.5 FML laminates in terms of impactor displacement.

Representation in the Fig. 5(a) and 5(b) are the force and energy variation plots of MVF 0.5 test case in relation to impactor displacement. Due to the higher order vibration between impactor and target, the contact is almost lost at the onset of impact and the force values registers almost

zero for the smaller displacement range in both hard and soft side impact cases as shown in Fig 5(a). Following that, the contact force increases with increase in impactor displacement. The initial period of contact is controlled by the layer which receives the impactor. By analogy, soft side sample acquiring higher elastic stiff aluminum layer ($E=70$ GPa) on the impact face and able to bear larger force than hard side sample in which comparatively lower stiff composite layer ($E=23$ GPa) receive the impactor first.

On further deflection, the compressive contact stress generated close to the point of impact causes severe localized plastic deformation on soft face impact sample leads to indentation dent on the surface. Regarding hard face sample, because of rigid and sufficiently high compressive strength of composite layers ($X_{-1, -2} = 458$ MPa) which is 2.5 times greater than ultimate strength of aluminum, there is no evidence of initial indentation provided on impact face. On energy absorption perspective, this behavior suggests that the corresponding incident energy would be dissipated either by means of global flexure or by interlaminar separation (delamination) of metal composite interface (MCI) because MCI is a resin rich region and the strain energy required to create new fracture surface is negligibly small (Note: Fracture toughness of typical epoxy resin is 0.07 kJ/m²). Meanwhile in conjunction with global flexure, the confined plastic deformation of front aluminum layer believes larger energy dissipation in soft side sample than its counterpart. This characteristic behavior confirmed through energy deflection curve as illustrated in Fig. 5(b) where the energy absorption in soft side sample is slightly higher than hard side impact sample for wide range of initial impactor deflection.

Table 3

Static mechanical properties of metal and composite layer.

Metal layer Al – 2024-O	Young's modulus	$E = 70$ GPa
	Poisson's ratio	$\nu=0.33$
	Yield tensile strength	$\sigma_y = 70$ Mpa
	Ultimate tensile strength	$\sigma_{ult} = 180$ Mpa
	Density	$\rho=2700$ kg/m ³
Composite layer Woven Glass-epoxy	In-plane tensile Young's modulus	$E_1 = E_2 = 24$ GPa; $E_3=8$ GPa
	Shear Modulus	$G_{12}=3.6$ GPa; $G_{13}= G_{23}=2.8$ GPa
	Poisson's ratio	$\nu_{12}=0.1$; $\nu_{13}= \nu_{23}=0.25$
	In-plane tensile strength	$X_1 =X_2 =414$ Mpa
	In-plane Compression strength	$X_{-1}= X_{-2}=458$ Mpa
	Shear strength	$S_{12}=105$ MPa; $S_{13}= S_{23}=65$ GPa
	Density	$\rho=1100$ kg/m ³

As the impactor advances, both the constituents would start to share the incident kinetic energy. In addition to the plastic indentation on front face, soft side sample would dissipate the incident energy in the form of nucleating new tensile crack surface on rigid back face composite layers as shown in Fig. 6a. This is probably because of its inferior impact toughness of GFRP whose tensile fracture strain is only around 4%. However, the kink free and smooth distribution of load-deflection curve dictates controlled crack propagation in these layers. This was believed due to the larger ultimate tensile strength (414 MPa) of composite layer and superior fracture toughness of glass fibres (35 – 40 KJ/m²).

Fig 6. Damage patterns of impacted FML laminates (a) soft side (b) hard side

On concerning the hard side sample, composite layer on front face was crushed with small multitude tiny cracks nucleated around the impact region as illustrated in Fig. 6b. Meanwhile, the bottom aluminum layer underwent noticeable plastic deformation in conjunction with finite indentation dent under the impact center. The aluminum layer hardens as it plastically deforms due to strain hardening effect, the overall bending stiffness of the sample increases which in turn gradually raise the slope of load deflection curve until the impactor transform all of its kinetic energy and as well the peak contact force value ($F_{\max}$).

Table 4

Impact characteristic parameters

Parameter	PVF 0.5		PVF 0.4		MVF 0.5		MVF 0.4	
	Soft	Hard	Soft	Hard	Soft	Hard	Soft	Hard
$F_{\max}$ (kN)	1.346	1.265 (-6.02%)	1.329	1.697 (27.7%)	1.434	1.707 (19%)	1.554	1.990 (28.1%)

$\Delta_{\max}$ (mm)	11.092	9.839 (-11.3%)	10.084	6.949 (-31.1%)	8.618	8.287 (-3.8%)	7.826	7.741 (-1.1%)
$E_{\text{sp. abs}}$ (Jm ² /kg)	1.307	1.456 (11.4%)	0.937	0.884 (-5.7%)	2.561	2.385 (-6.87%)	2.305	2.175 (-5.6%)
$E_{\text{sp. reb}}$ (Jm ² /kg)	1.137	0.985 (-13.4%)	0.925	0.969 (4.76%)	0.114	0.181 (58.8%)	0.138	0.261 (89.1%)

The whitening region exists on hard face sample was anticipated to be the delamination of MCI. Perhaps, the inability of composite layer to undergo great degree of plastic deformation equivalent to bottom aluminum layer might cause such greater separation of MCI. The above statement was confirmed by sectioning the impacted sample along the impact center. It should be noted the MCI of soft side sample was also separated up to the length of tensile crack but its extension range was found smaller than its counterpart. A close scrutiny of drops in load-deflection curve suggests damage in composite layer of soft side sample was initiated earlier than hard side sample.

The behavior and evolution of impact characteristic curves of MVF 0.4 looks rather similar to that of MVF 0.5. Thus, only its quantitative metrics of corresponding characteristic parameters are collected and depicted in comparison form in Table 4. It is not surprising, with larger composite thickness the overall stiffness and peak contact force value of MVF 0.4 samples are slightly enhanced.

4. Conclusion

From the comparative description of impact characteristic parameters of experimented plastic and FML samples of volume fraction 0.4 and 0.5 as shown in Table 4, it is obvious that the hard side sample resists larger contact force (except for thin PVF 0.5 case) and smaller impactor displacement for both the experimented cases. On concerning the metrics of energy absorption, with earlier loss of structural integrity in plastic samples, hard side samples looks to absorb most of the incident impact energy in case of transparent plastic sample. But, one can notice that it can absorb it with smaller displacement which dictates most of the energy is absorbed in irreversible manner with enhanced structural integrity than soft side impact sample. Soft impact samples losses its stiffness too earlier and absorb most of the incident energy by reversible elastic strain energy and at last register less absorbed energy.

Unlike transparent plastic samples, neither soft side nor hard side FML sample has lost its structural integrity because of having high strength reinforcements which offer effective backing in either of the case. Thus, soft side impact sample will absorb most of the incident energy by irreversible plastic deformation of metal layer by producing an indentation dent while such scenario is less intense for hard side impact sample. As a result, the former samples can absorb larger percentage of incident energy than latter case which is direct contradictory to transparent plastic sample. However, rationalize the comparison based on structural integrity (stiffness loss and impactor displacement) it is apparently manifested that hard face sample can dissipate the energy in more efficient way than soft side impact samples. With transparency features, similitude experiments of low cost plastic samples will provide a rigid base to understand the impact characteristic features of opaque FML samples.

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