RESIDUAL MECHANICAL PROPERTIES OF HYBRID FIBER-METAL LAMINATES SUBJECTED TO SINGLE AND MULTIPLE IMPACTS

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Abstract: *Residual mechanical properties of hybrid fiber-metal laminates potentially applicable to airframe structures were determined after exposure to single and repeated low energy impacts. Results were tentatively correlated to the nature of the laminate, as well as to impact testing variables, e.g., impactor diameter, specimen clamping condition and impact energy. Smaller hemispherical impactors produced highly concentrated damage, whereas larger impactors generated widespread internal damage, with the latter condition being more detrimental to the residual performance of the laminate for a given impact energy. Locking the impacted testpiece favoured internal damage development impairing substantialy its residual performance. Young's modulus was the most reliable mechanical property in assessing the structural integrity of pre-impacted laminates. A close and well-defined relation was found between residual stiffness and the indentation area measured on the impacted surface of the laminate. Glare™ was, in a weight basis, the most promising fiber-metal laminate in terms of impact damage-tolerance, although it was low damage-resistant to dynamic loads.*

Keywords: *aircraft material, fiber-metal laminate, impact damage, residual strength.*

1. OBJECTIVE

This prospective study aimed at determining the residual three-point–bend mechanical strength of hybrid fiber-metal laminate (FML) after single and multiple low-energy impacts. Correlations of residual mechanical properties to the nature of the hybrid laminates, impact tests variables and macroscopic damage parameters have been attempted.

2. INTRODUCTION

Aircrafts are the fastest, safest and most efficient way to transport passengers and pay-load for long distances. The development of lighter and more resistant materials (i.e., higher structural efficiency) has significantly increased and improved such area of mobility industry, e.g., by increasing pay-load, reducting motorization, saving fuel, extending flight autonomy, extending service lifespan and ensuring better performance of structures and components, which reflects directly on the operational cost reduction, particularly those related to fleet maintenance, more specifically related to periodical nondestructive inspection, failure analysis and prevention.

Fiber-metal laminate composites constitute one of the most promising classes of structural materials for civil aircracft construction. They are built up from aeronautical-grade alloy sheets interspersed with and bonded to layers of fibers reinforcing plastic resin.

In general, FML display high fatigue crack growth resistance combined with other very attractive properties to the aeronautical industry, such as low density, high impact toughness, and corrosion and flame resistances. The superior endurance to fatigue crack propagation of Glare relies in the so-called crack bridging mechanism [1], by which high-strength glass-fibers, even partially fractured, debonded and pullout from the epoxy matrix, still withstand a considerable parcel of the applied load acting in the structural component, so that crack driving force in the adjacent aluminum layers, in which cracks progress preferentially, is substantially reduced and overall damage growth is slowed down.

Commercial aircrafts structures potentially made with FML include fuselage and wing skins, as well as leading and traling edges, floors, liners and the like, components that in large extent are prone to impact events during both in-fligh and overhaul circumstances [2-12].

In spite of FML have succeded in medium and high-energy impact experiments, including ballistic ones with complete perforation of the laminates [3,13-16], their performance under single and multiple low-energy impacts, of a few Joules only, has not been properly evaluated yet. Examples of low-energy impact events that the aforementioned structures may experience during their service lifetime include the tool box problem, runaway debris impelled by the rolling tyres, shoes heels, on-board catering service and cargo carts wheels contact, the conveyor belt luggage problem, to mention a few possibilities [17-21].

Recalling the well-known concept of barely visible impact damage - BVID [22-25], when, despite the relatively shallow external damage created by impact, a significantly impairment of the residual resistance can be verified, it seems to be worthwhile to address the low-energy impact problem in FML. In this paper, several FML are evaluated in regard to impact damage-resistance and tolerance within the BVID energy range, i.e. impact energies up to 10 Joules.

3. MATERIALS AND TEST SPECIMENS

All the evaluated FML followed a 2/1 configuration, in which two outer 2024-T3 Al-sheets sandwich continuous fiber reinforcing polymer resin. Strenghtening fibers were either in unidirectional tape or bi-directional waving fabric forms. More specifically, tested FML arquitectures were as follows:

1. Glare-5, supplied by Comtek Advanced Structures Company (CAN), is a 1.6 mm full-thickness laminate with 0.65 mm-thick surface treated metal layers encasing four unidirectional tapes (disposed according a $[0^{o}/90^{o}]_S$ configuration) of high-strength glass-fiber embedded in thermosetting epoxy resin. The metallic phase comprises 82% of the FML volume;
2. Curv, obtained by one of the authors (JRT) in laboratory scale at the Liverpool University (UK) via hot-press consolidation of 0.80 mm-thick surface treated metal sheets sandwiching two bi-directional fabric layers of polypropylene fibers ($[0^{o}/90^{o}]_S$ configuration) reinforcing polypropylene thermoplastic resin matrix (Amoco-BP-UK). A 2.43 mm-thick laminate was obtained, with the metal phase occupying 65% in volume;
3. PPG, obtained at the Liverpool University (UK) via hot-press consolidation of 0.80 mm-thick surface treated metal sheets sandwiching 1 layer of bi-directional fabric glass-fibers [(0/90)] impregnated with polypropylene thermoplastics resin (Twintex by Saint Gobain). A 2.18 mm-thick FML was produced, with the metal phase present in a volumetric proportion of 73%.

Besides these 3 FML, two baseline materials were also tested:

1. Metal laminate composed by two 0.80 mm-thick surface treated 2024-T3 Al-alloy layers jointed by melted polypropylene thermoplastic resin in a hot-press. A final laminate thickness of 1.84 mm was achieved, with the metal phase comprising 87% in volume;
2. Conventonal 1.6 mm-thick 2024-T3 Al-alloy single sheet widely utilized in aircraft industry.

The tablet-shape test specimens had in-plane dimensions of 27.5 x 65 mm².

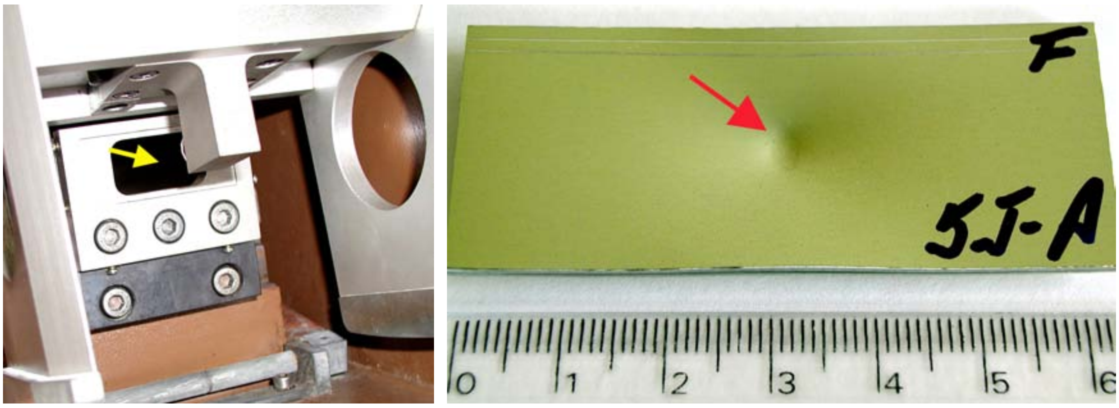
4. EXPERIMENTAL

Impact tests were conducted in a specially adapted semi-instrumented Charpy testing system (Fig.1a), which directly provided the absorbed energy due to the mechanical shock (Fig.1b), and in a laser-Doppler device, when energy calculations relied on the impactor's velocity variation (i.e., its deceleration) during the impact event.

Quasi-static three-point-bend tests were also conducted at ambient temperature in order to determine residual mechanical properties of impacted FML. A constant displacement rate 1 mm/min was applied at the mid-span position of the testpeices.

Residual properties determined were: Ultimate Strength (US), Modulus of Elasticity (ME) and Tenacity at Maximum Load (TML), the latter obtained by integrating the bend loading curve up to the maximum load beared by the specimen.

Typically, three impact and bend tests were carried out for each material and testing condition, so that furnished results in the present study correspond to average values of three trials. Zero values indicate that the experiment was not performed under that specific condition.



(a) (b)

Figure 1. (a) Adapted Charpy impact testing system at the SMM-EESC-USP laboratory; (b) Glare testpiece after a single impact experiment with energy of 5 Joules.

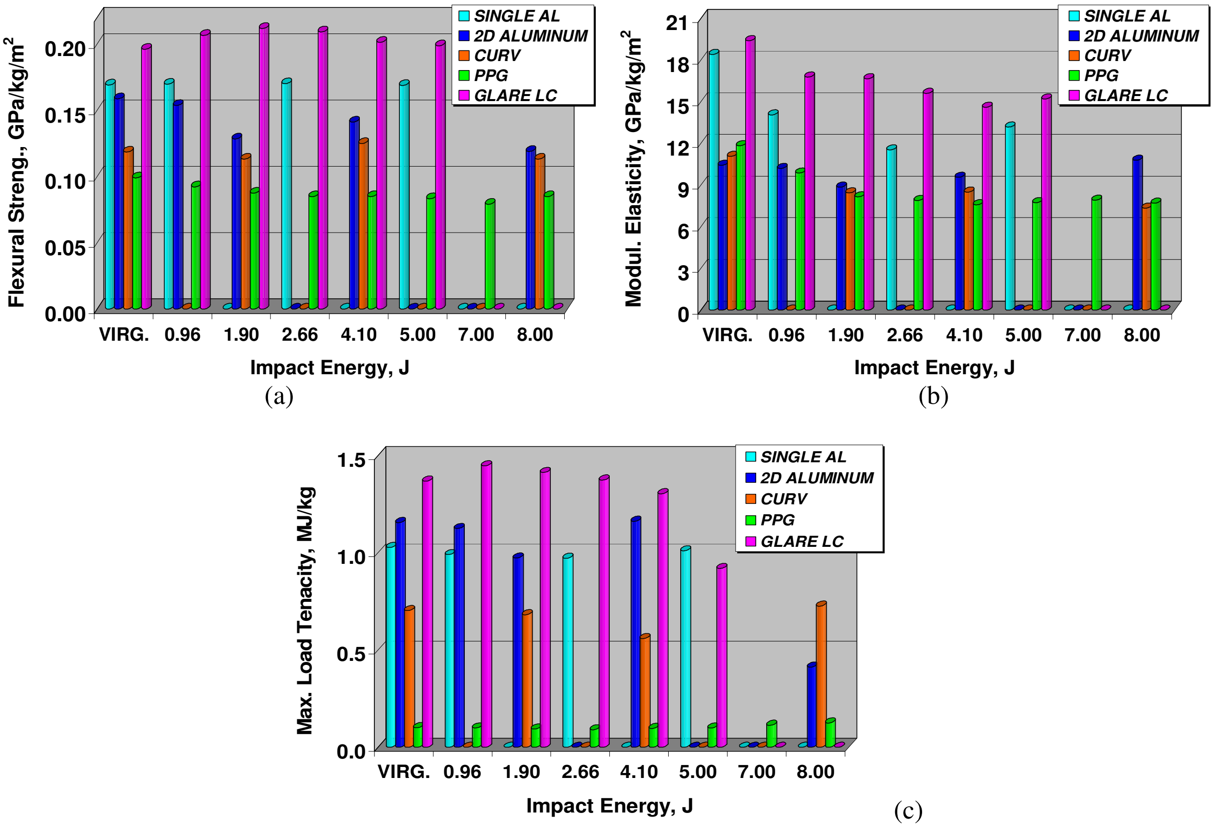
5. RESULTS AND DISCUSSION

5.1 Mechanical Tests

5.1.1 FML Nature and Single Impact Energy Effect

Figure 2 plots residual flexural properties of FML after single impact with a 5 mm diameter hemispherical steel impactor, within the energy range from 0.96 to 8.0 Joules and with testpieces clamped to the anvil frame. Results are furnished in terms of relative (specific) performance by considering the so-called areal density (Kg/m²) of the tested laminates. Such comparison is mandatory when dealing with structural aircraft materials, since their mechanical performance by unity of weight estabilishes to a large extent their potencial of application in the aeronautical industry. A conflicting behavior is noticed in Fig.2(a) indicating the possibility of test specimen reinforcement due to impact loading. In this sense, it can be argued that the increasing bending strength results essentially from modifications on the laminate structural geometry, as, for example, the surface callote creation during previous impact event.

In general, Glare-5 is the top-rank material followed by 2024-T3 Al-alloy in the forms of single and double-bonded sheets, respectively. However, one can observe that the latter material, whose metal layers were consolidated with polypropylene resin in a hot-press, overcomes the Al-alloy single sheet in regard the tenacity criterion. Probably, this behavior was due to the presence of the polymeric phase in-between the metal sheets, since the widely-recognized high strain ability of polypropylene (under both quasi-static and dynamic loading conditions) allows for large energy absorption during impact. On the other hand, Curv and PPG laminates displayed a disappointing after impact behavior, specially the latter hybrid composite material.

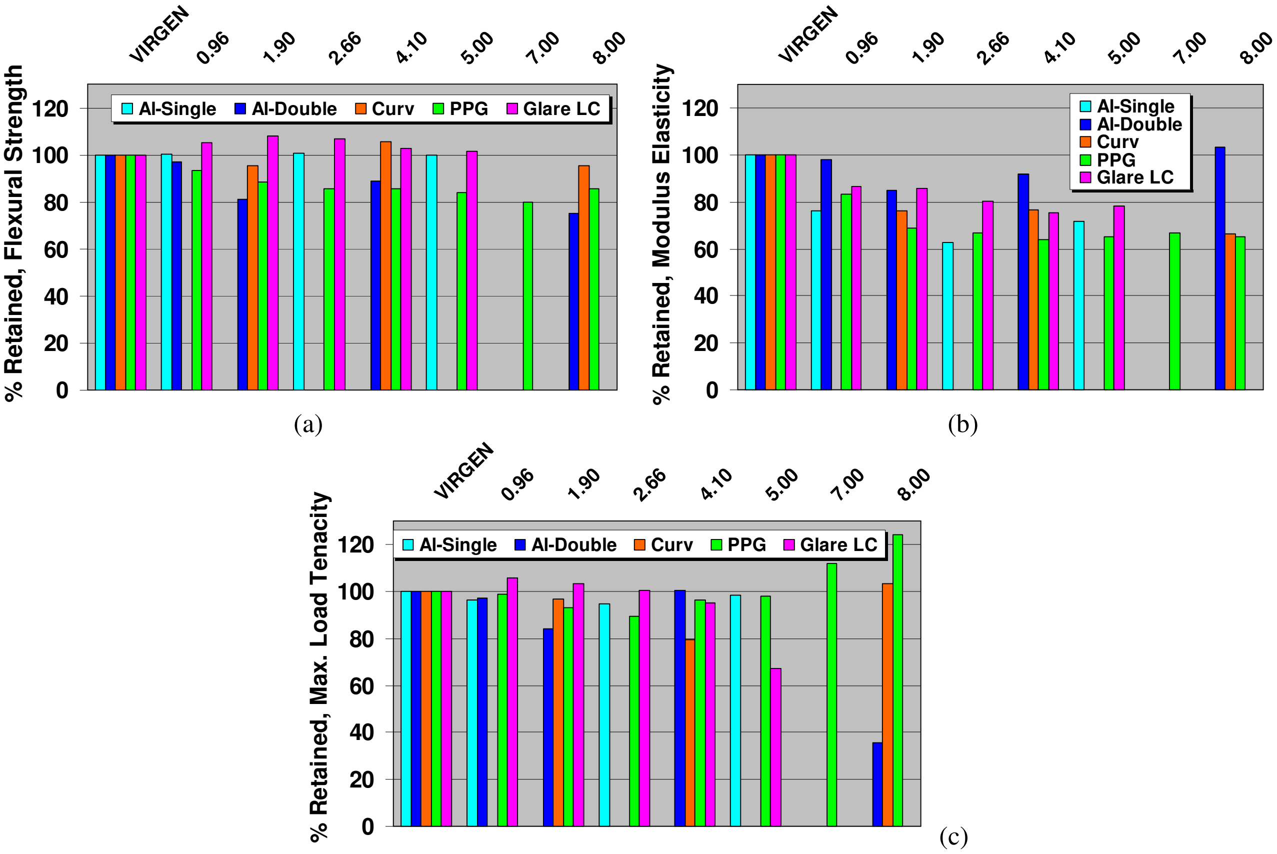


(a) (b) (c)

Figure 2. Residual mechanical performance of tested laminates in a weight basis: (a) Ultimate Strength; (b) Modulus of Elasticity; (c) Tenacity at Maximum Load.

Figure 3 plots, in percentage terms, the retained flexural properties of previously impacted testpieces regarding the performance of pristine materials. In other words, Figure 3 basically describes materials' damage-tolerance in a normalized basis. While Glare is the most tolerant FML according to the strength criterion, double-bonded Al-2024 sheets is it regarding the Young's modulus, whereas PPG composite is concerning the tenacity after impact. From Figures 2 and 3, one can conclude that the modulus of elasticity is the residual mechanical property that more consistently respond to different impact energy levels applied to the materials, showing a clear trend to decrease as the impact energy is increased. For instance, residuals strength and tenacity of single 2024-T3 Al-alloy sheet remain practically constant if compared to the original properties, being absolutely tolerant, in terms of both mechanical criteria, to previous impact damage; on the other hand, if the residual modulus of elasticity is considered, a great sensitivity of this property to the impact energy is noticed.

Nevertheless, it should be mentioned that Glare laminates are industrially produced, while all other hybrid materials were laboratory-made. Therefore, the better performance of Glare laminate before its concurrents can be credited in large extent to the more elaborated, standardized and widely established practices employed in large-scale production environments.



(a) (b) (c)

Figure 3. Normalized damage-tolerance to single-event impact of materials tested under various energy levels: (a) Ultimate Strength; (b) Modulus of Elasticity; (c) Tenacity at Maximum Load.

5.1.2 Testpiece Clamping Effect

A maximum constraint condition imposed to the tablet-shape specimens during impact testing was acchieved by clamping firmly their borders to the anvil frame. This basically reduced the materials' ability to absorb energy by deformation mechanisms; therefore, energy relief by fracture mechanisms was favoured. This situation resembles that tipically found in fuselage skin sheets next to structural details designed to improve structural modulus in aircrafts, like stiffeners and ribs.

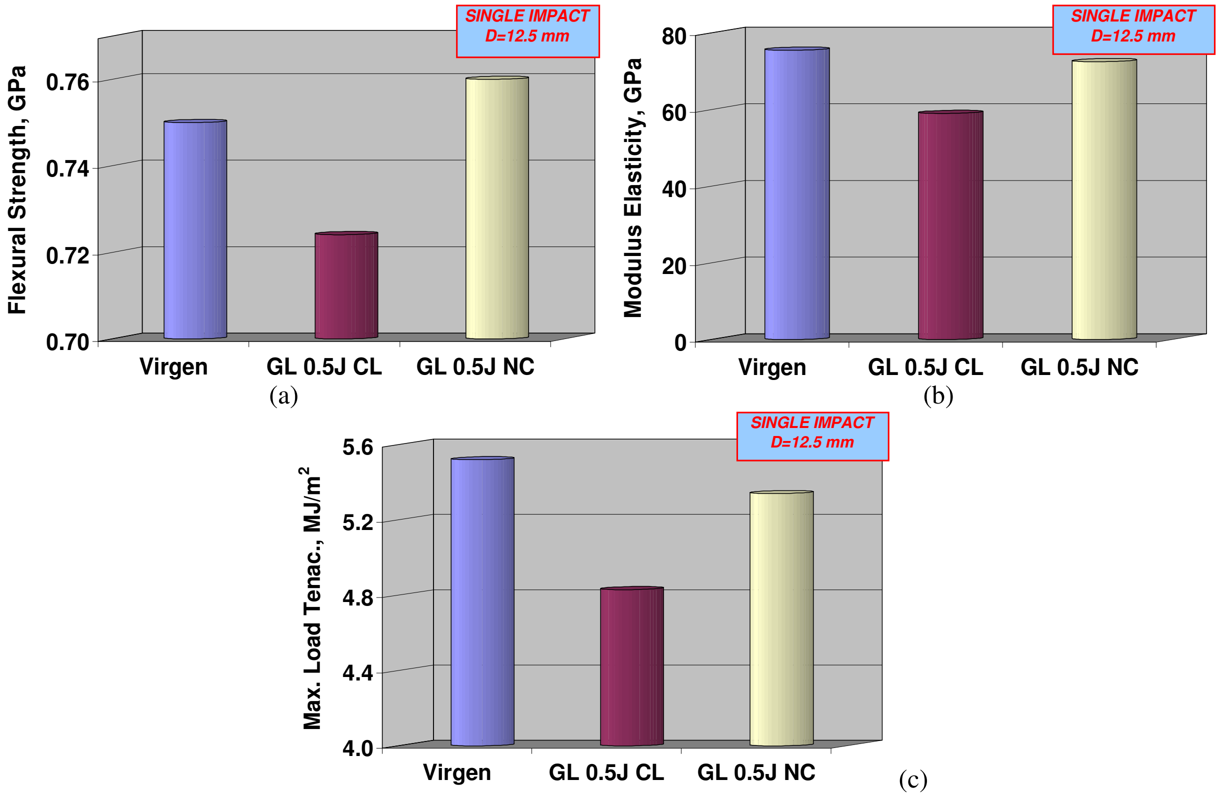
Figure 4 shows the effect, in the residual mechanical properties of Glare testpiences, of clamping (CL) and non-clamping (NC) the specimens during previous single event impact of 0.5 J by using a 12.5 mm diameter hemispherical impactor.

It can be concluded that even for slight impacts of 0.5 J the specimen clamping effect is significant in impairing structural integrity of the laminate. Percentual differences between clamped and non-clamped residual properties were 5%, 18% and 10% for US, ME and TML, respectively. Again, modulus of elasticity is the most sensitive propertie to changing impact test variables.

5.1.3 Impactor Diameter Effect

Hemispherical steel impactor diameters of, respectively, 5 mm and 12.5 mm were utilized to impact Glare specimens. Figure 5 shows residual mechanical properties after single impact application, under clamped conditions and impact energy of 0.5 J.

More expressive loss in residual properties was obtained with the larger impactor. Optical microscopy observation of cross-seccional surfaces of FML indicated that widespread internal damage results from the blunter impactor [26].



(a) (b)

(c)

Figure 4. Residual mechanical performance of Glare laminates after a single 0.5 J impact event under, respectively, clamped and non-clamped conditions: (a) Ultimate Strength; (b) Modulus of Elasticity; (c) Tenacity at Maximum Load.

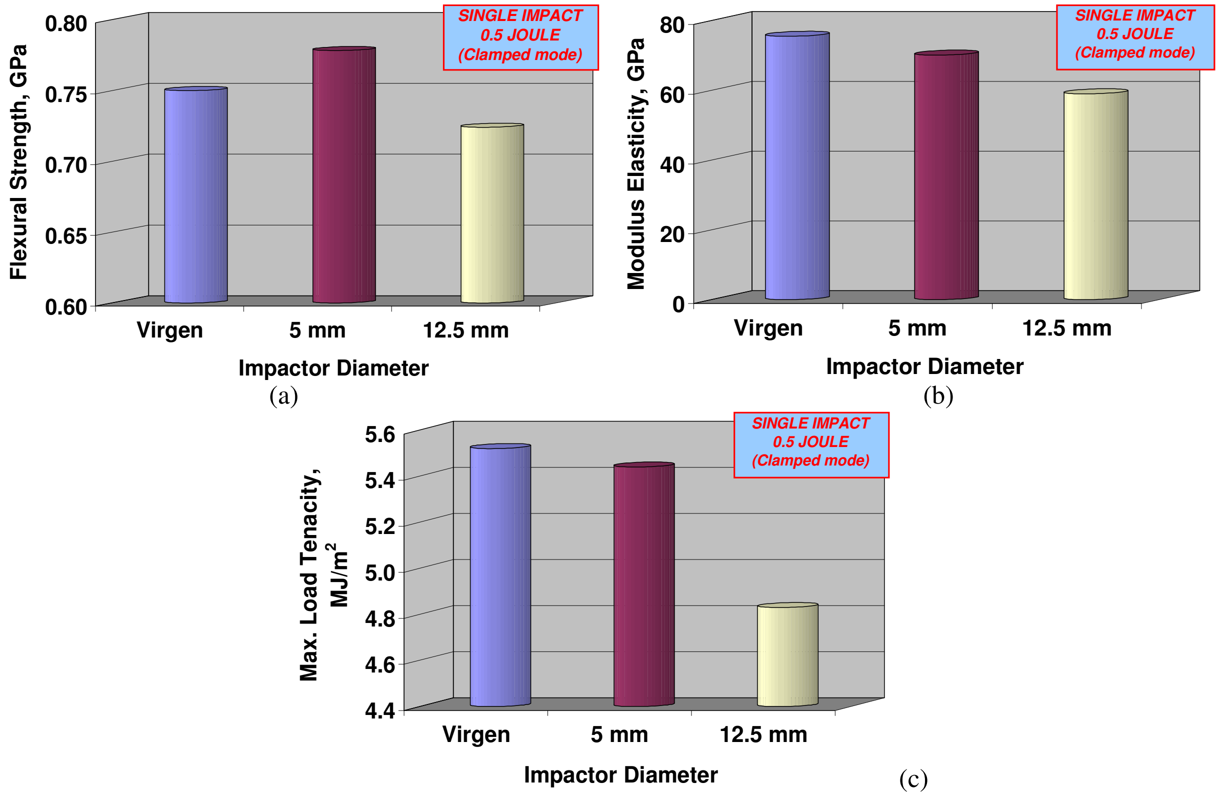


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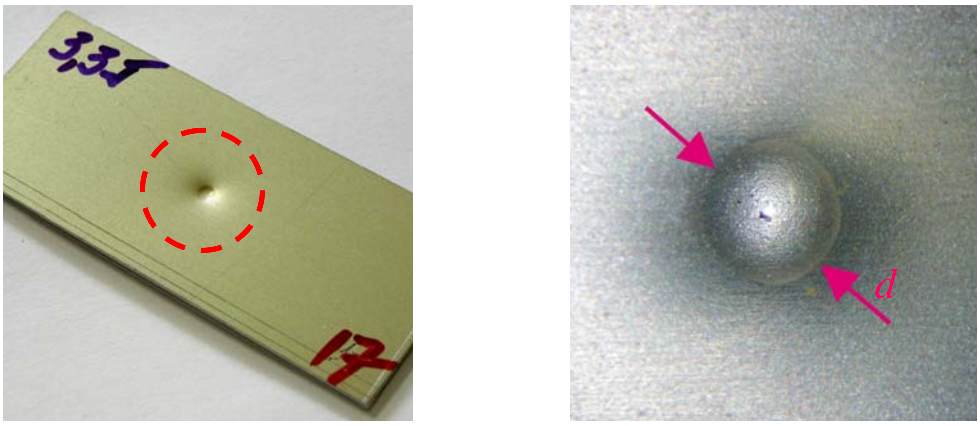
Figure 5. Residual mechanical performance of Glare FML after a single 0.5 J impact event under clamped condition and two different impactor diameters: (a) Ultimate Strength; (b) Modulus of Elasticity; (c) Tenacity at Maximum Load.

On the other hand, the smaller hemispherical impactor caused highly localized damage, which was confined to a much less extension than that created by the bigger hemispherical impactor, for a given impact energy.

Once more, the modulus of elasticity is confirmed as a worthwhile parameter to monitor structural integrity of FML. E.g., the percentage change in this parameter was 17%, against 8% and 12% for ultimate strength and tenacity at maximum load, respectively.

5.2 Visual Damage vs Residual Strenght

Considering the callote-shape indentation created by the impactor tup contacting the FML's frontal surface (Figure 6a), the corresponding spherical callote shell shape area A could be estimate by simply measuring the indentation diameter (Figure 6b). In this regard, well-known geometric relations were employed, as given in Figure 7 caption.



(a) (b)

Figure 6. (a) Impactor indentation as seen on the frontal surface of a Glare specimen; (b) Detail of the spherical callote with its diameter (*d*) indicated by arrows.

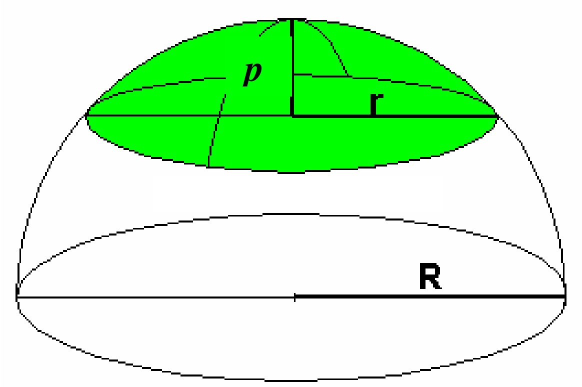
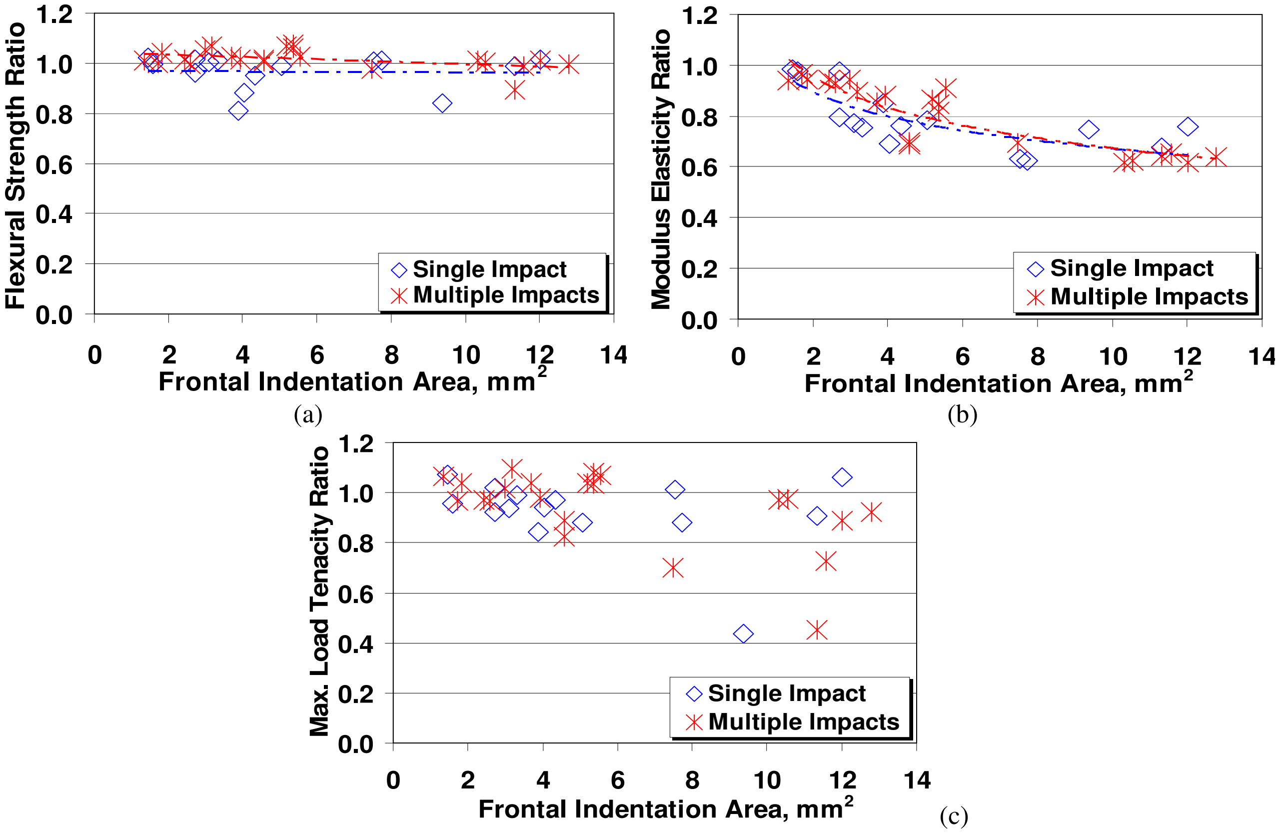


Figure 7. Schematic of the spherical callote shell shape and its geometrical relationships. Where $p = R - \sqrt{(R^2 - r^2)}$ and $A = 2 \cdot \pi \cdot R \cdot p$; *d* = 2r is the indentation diameter, *D* = 2R is the impactor tup diameter, and *p* is the indentation depth.

Empirical correlations between the macroscopic external damage severity parameter, *A*, and the residual mechanical performance of the laminates were attempted. Figure 8 shows the obtained results for the tested laminates, including some results derived under multiple impact conditions [26].

It can be verified that, while the maximum flexural strength varies only slightly with *A*, if it does so, high data scattering is obtained for the parameter of tenacity. On the other hand, the modulus of elasticity correlates very well with the macroscopic damage parameter *A*, corroborating previous conclusions in this work regarding the possibility to monitor structural integrity of FML through this mechanical property. Results shown in Figure 8 signilizes, therefore, the possibility of estimating damage-tolerance of FML based exclusively on ready/easy-to-do measurements of outer surface indentations created by impact in laminate structures.

It is worth of mention that, differently from the BVID concept, which is defined in terms of a permanent mark depth (*d*) only, the *A* parameter takes in account both indentation depth (*p*) and diameter (*d*). According to Mitrevski et



(a)

(b)

(c)

Figure 8. Correlation between normalized residual properties: (a) Ultimate Strength; (b) Modulus of Elasticity; (c) Tenacity at Maximum Load, relatively to the pristine materials properties, and the frontal indentation spherical calotte superficial area *A* created by impact(s).

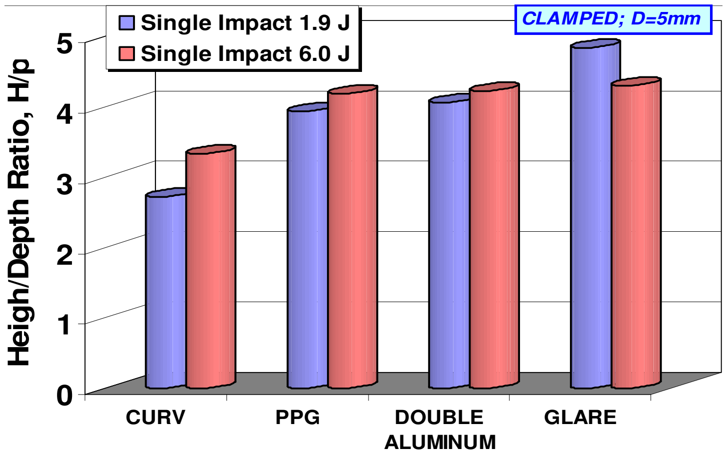


Figure 9. Damage quantification to the FML here tested, considering two distinct single impact energy levels [26].

al [27,28], composite laminates subjected to sharper (thinner) impactors absorb most energy as a result of local penetration, a fiber breakage-dominated mechanism, instead of widespread internal damage generation. On the other hand, the authors state that blunter (wider) impactors cause internal delamination-dominated damage quite well beyond the limits established for the corresponding permanent indentation. This is to say that, for a given impact energy, the blunter the impactor is (i.e., the more extensive the impact damage) the lower will be the residual properties of the composite laminate. This completely agrees with results presented in this work (refer to item 5.1.3).

It is worthwile to note as well that thinner impactors are much proner to attain the indentation depth of 0.3 mm (established as the BVID criterion [25]) than blunter ones [26]. Therefore, it is not difficult to antecipate a situation were misleading predictions (unduly non-conservative if blunter impactors are involved!) will certainly result in regard to the actual structural integrity state of a component if one relies on the impact indentation depth only.

Finally, it is interesting to observe that notwithstanding Glare is the most damage-tolerant FML tested, as shown in Figures 2 and 3, it is otherwise the least resistant to damage introduction. Figure 9 plots the ratio between the spherical calotte depths produced, respectively, at the front and back surface of several hybrid fiber-metal laminates, for two distinct single-impact energy levels. The parameter *H/p* has been proposed by Gualberto&Tarpani [26] as the best visual measure of the whole damage impinged to FML subject to non-penetrating impact. Glare exhibits the highest *H/p* ratio, and, in a damage-detection basis, this is a huge advantage over concurrent materials, as highlighted by Vlot et al [3].

6. MAIN CONCLUSIONS

The experimental results obtained in this on-going study permit to conclude that:

1. The modulus of elasticity is the most valuable and reliable mechanical property to monitor structural integrity degradation in FML previously submited to single or multiple impacts;
2. Thinner hemispherical impactors cause highly localized superficial damage to the laminate, while thicker ones produce widespread through-the-thickness damage, the latter condition being the most critical to the residual performance of the material;
3. Glare is the least damage-resistent material, but it is the most damage-tolerant laminate in both absolute and relative terms;
4. Clamping the fiber-metal laminate during impact restricts its deformation and, therefore, enforces fracture-based mechanisms significantly, so that residual strength is dramatically reduced;
5. The possibility of estimating damage-tolerance (i.e. residual resistance) of impacted FML through dual-parameter indentation size measurements has been envisioned regardless the impactor size (as opposing to the widely-accepted BVID criterion).

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