LOW VELOCITY IMPACT ON WOVEN GLASS COMPOISTES REINFORCED WITH METAL MESH LAYERS

Tahira J. Ahmed[*,], Harald E.N. Bersee[**] and Adriaan Beukers [**, ***]**
[T.Ahmed]: t.ahmed@tudelft.nl
[*]The Netherlands Institute for Metals Research, **Delft University of Technology, ***Fellow Doshisha University

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Abstract

This study investigated the impact-energy absorbing potential of woven glass fibre reinforced epoxy reinforced with stainless steel mesh layers. The composites were subjected to low-velocity impact using the drop-weight impact test. In general, the presence of a metal mesh as a reinforcing layer delayed the perforation energy and changed the failure mechanisms at higher impact energies, while behaving similarly to the plain laminates at lower energies. It was found that the addition of metal mesh, placed in the tensile face of the laminate, resulted in an increase in perforation energy and reduced the damage area at lower energies compared to a plain laminate of equivalent thickness. A delay in the perforation energy of 21% (for a 5.3% increase in weight) over that of the plain epoxy laminates was achieved.

1 Introduction

Aerospace composite structures are often subjected to low velocity impact threats, which can result in extensive damage. Credited to the ease of application of advanced manufacturing techniques such as compression moulding and vacuum assisted resin infusion, woven fabric composites are adopted in the manufacture of many primary structural components. Due to the interlacing of the fibre tows in two directions, woven fabric composites offer better impact resistance and good out of plane properties as compared to cross-ply laminates made of unidirectional layers [1].

In the constant endeavour to improve the impact properties of fibre-reinforced polymer composites, several methods have been employed, such as matrix toughening [2], fibre hybridising [3] and 3-D composites [4], for example. This investigation takes the hybridising approach to improvement in impact properties through the incorporation metal mesh layers into the laminate. Fibre Metal Laminates (FMLs) are the successful results of hybridising metal with composite layers. To take the idea one step further, replacing the metal sheet with metal fibre woven mesh layers may also offer many benefits. The inclusion of metal fibres as opposed to a sheet immediately opens the possibility of manufacturing techniques that are being used with fibre-reinforced composites, such as those mentioned previously. Hence more complex structures may be manufactured. The inclusion of metal mesh also results in inherent electromagnetic shielding (EMS) capabilities of the composite thereby adding an additional functionality of the material. More specific to this investigation, the ability of the metal mesh to plastically deform could be beneficial in the event of impact, as plastic deformation is an extra energy absorption mechanism, and also to delay the perforation threshold energy.

It was the aim of this investigation to determine the effects of stainless steel metal mesh layers in glass fibre-reinforced epoxy composites under drop-weight impact testing.

2 Method

2.1 Materials

The thermoset laminates were composed of 8-harness satin weave glass fabric, which was vacuum infused with Hexion Epikote/Epikure 4908 epoxy resin. Laminates of 16 plies were produced corresponding to 4.3mm thickness, with a stacking sequence of $[0/90]_{8s}$.

Plain woven AISI 304 stainless steel mesh was used, with a wire diameter of 112µm and mesh opening of 358µm, corresponding to a weight of $0.33kg/m^3$. Before use, the mesh was cleaned in an alkaline soap bath for 30 minutes followed by a rinse in deionised water. Some of the meshes were further treated using an anodising procedure to examine the effect of improved adhesion on impact. In order to keep the thickness of all the laminates the same, a glass layer was removed when mesh was inserted into the stack. The mesh was placed in different layers within the stack, as shown in Fig. 1, to determine where the most beneficial contributions may be obtained.

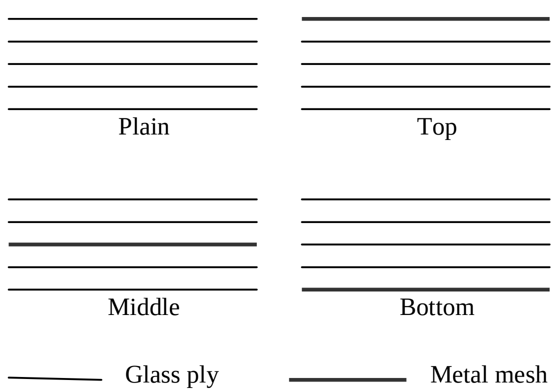


Fig. 1: Lay-up configuration and nomenclature

2.2 Impact

The drop-weight impact tower employed in this study consisted of a double column impactor guide mechanism that releases an impactor at the desired height. The contact force between the impactor and the specimen was measured by a load cell placed in the impactor tup. Infrared photo transistors connected to a counter were positioned close to the impact surface and used to measure the impact velocity. The exit velocity was then derived from the integration of the force-time graph.

A circular test geometry of 80mm diameter with four bolts clamping at 30Nm torque was used as the holding jig for the impact specimens. A hemispherical tup allows the material to reach the highest peak force and produces the shortest contact duration [5]. A hemispherical tup of 15mm diameter and 2.128kg was used.

The laminates were impacted to produce damage from barely visible impact damage (BVID) to perforation, defined as the point at which the impact tup is able to pass completely through the laminate resulting in the formation of a permanent hole. The results are displayed in terms of absorbed energy, taken from the area underneath the force-displacement graph, versus the impact energy, determined from the tup velocity. The data display, known as energy profiling [6], is a convenient way to compare the impact data.

2.3 Damage inspection

Ultrasonic c-scan inspection was performed to determine the damage area of the samples after impact. In addition, post-impact samples were cut in the regions of interest and examined using optical microscopy.

3 Results and Discussion

3.1 Influence of number of mesh layers

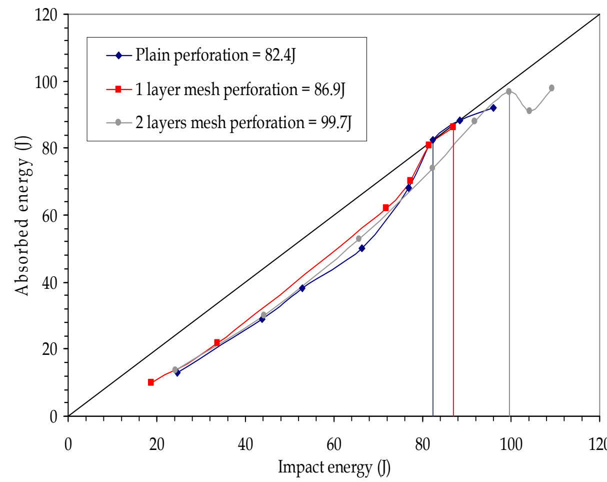
Fig. 2 presents the results obtained to describe the influence of the number of mesh layers. The results for one and two mesh layers are shown because more additions did not improve the impact behaviour any further after weight increase was considered. The mesh addition was placed in the bottom layer of the laminate in this case, as similar trends were expected with other configurations.

Fig. 2(a) shows the energy profile for the Plain and hybrid laminates. The diagonal line represents the equal energy line. If the data points fall below this line, and perforation has not occurred, the laminate returns enough energy to the impactor for rebound. Data points lying on the line indicate that the impactor neither rebounds nor perforates the laminate and maximum energy is absorbed. Next, the data points drop below the line because the impactor has sufficient energy to continue through the laminate and perforate. Vertical lines have been plotted to each curve to mark the perforation energies of each laminate type. Fig. 2(b) is the damage plot of the plain and hybrid laminates.

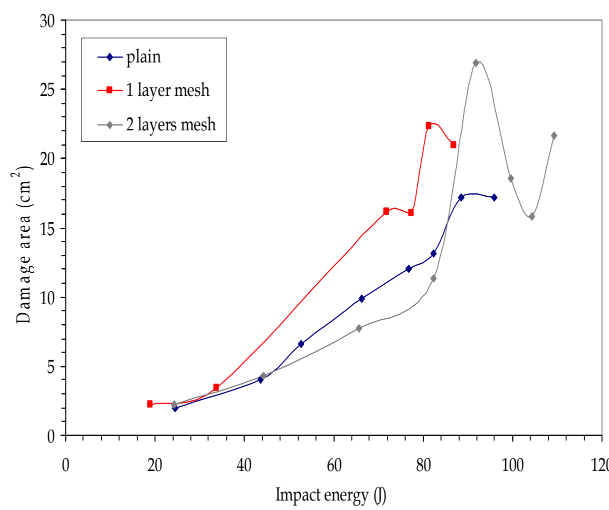
The energy profiles show that a similar trend in absorbed energies before perforation occurred with all the laminate types. At perforation however, the behaviour varied greatly. The plain laminate perforated at 82.4J, which was exceeded by 5.4%, for a weight increase of 1.5%, with the one layer hybrid and 21%, for a weight increase of 5.3%, for the two layer hybrid. The increase in perforation was attributed to a combination of two factors. The first was due to the sufficient adhesion between the epoxy matrix and the surface of the metal fibres that constitute the mesh. At the point of perforation, glass fibres on the back surface of the laminate fail in tension and cracks propagate away from the impact zone. Energy is absorbed through the plastic straining and consequent failure of the metal fibres thus delaying perforation further. For the plastic straining to occur however, there must be a certain amount of adhesion to allow load transfer. The second factor was attributed to the epoxy matrix used in this investigation, which has a relatively high plastic strain to failure of around 9%. From Fig. 2(a), at the perforation energy of the plain laminates, the two layer hybrid laminates had not reached maximum absorbed energy, and enough energy was returned to the impactor for rebound. The resin rich matrix layer on the tensile side of the hybrid laminates was able to deform in more of a membrane-type deformation due to higher achievable strain of the combined mesh and epoxy than the plain laminates. The mesh reinforced the epoxy, and due to the adhesion properties, received the tensile load from the matrix. This plastic-like energy-absorbing process delayed the perforation energy and also continued to return energy to the impactor for rebound. Of the two factors mentioned, the second factor will be shown in Section 3.3 to be the most important.

There was also a difference in the amount of damage created by the plain and hybrids, Fig. 2(b). The single layer hybrid produced the greatest damage area close to perforation than the other configurations. This was attributed to the high volume fraction of the epoxy matrix, and hence easier initiation of energy dissipating mechanisms such as crack formation and propagation. The mesh delayed laminate splitting on the tensile face and absorbed energy through plastic deformation, also delaying perforation. The addition of a second layer of mesh, which did not increase the overall laminate thickness due to packing, reduced the damage area compared to the single layer hybrid laminates. This was attributed to good load transferral from the matrix to the mesh which reduced the stresses in the matrix. Moreover, the mesh was able to deform (strain) with the matrix. There was less crack initiation and propagation as the volume fraction of matrix was less in mesh layer.

The perforation damage mode on the back surfaces for the plain and the hybrid laminates are presented in Fig 3. The plain laminate, Fig 3(a), perforated in a diamond shape, with tensile-cracks formed along the diagonals. Buckling occurred along the edges of the damage area from compression failure. The addition of the mesh layers, Fig.3(b) and (c), changed the failure shape from diamond to circular because buckling was completely eliminated. The membrane deformation was further evidenced by the formation of “stretch contours”, which formed from the impact point radially outwards. The contours were formed due to the epoxy, which was allowed to plastically strain over a larger tensile area than possible in the plain laminates. The result was a more metal-like deformation as the mesh layers allowed the laminate to deform and accommodate the impactor.

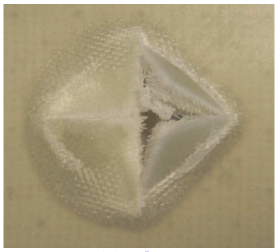


(a) Energy profile of plain and hybrid laminates

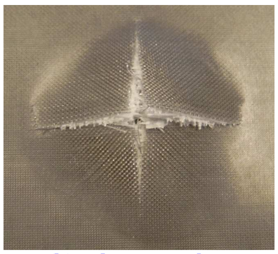


(b) Damage plots of plain and hybrid laminates

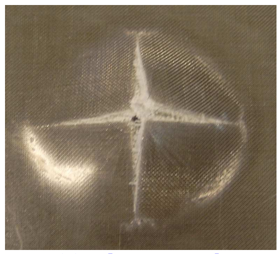
Fig. 2: Influence of number of mesh layers



(a) Plain



(b) 1 layer mesh



(c) 2 layers mesh

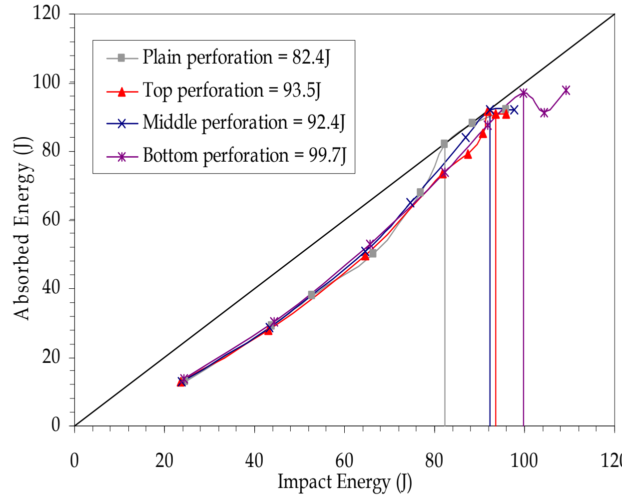
Fig. 3: Images of the back surface of the Plain and hybrid specimens at perforation

3.2 Influence of mesh position

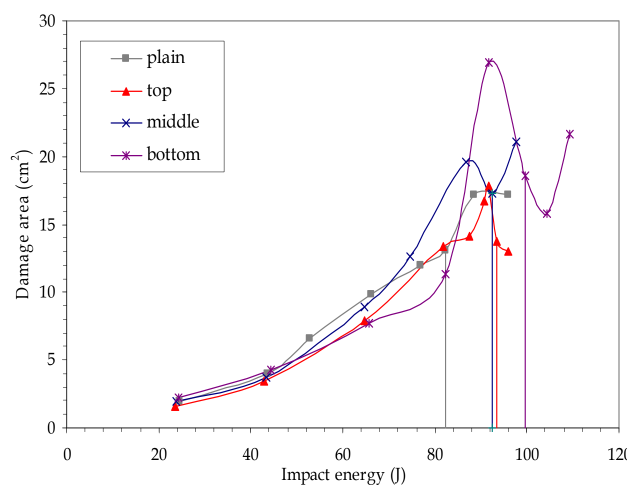
Fig. 4 presents the results obtained to describe the influence of mesh position. After considering the results of the previous section, all hybrid laminates were prepared with two layers of mesh.

According to the energy profiles, Fig. 4(a), at impact energies below the perforation energies, all laminates performed similarly and differences are only apparent from the perforation energies. The Plain laminate perforated at 82.4J, which was exceeded by 13.5%, 12.1% and 21.0% for the top, middle and bottom configurations respectively.

The difference in impact behaviour is, however, more discernable in the damage area plot, Fig. 4(b). As the impact energy tends towards the perforation values, the differences in energy absorption vary with each laminate configuration. The Plain and Middle laminates produce the largest damage areas, whereas the Top laminates produced the least. The damage plot shows that just before perforation a change in failure mode occurs and the Bottom laminate produced the largest damage area. The damage curves all increased in a roughly exponential manner up to a peak, before decreasing with increasing impact energy. It is interesting to note that the Plain laminates perforated before the peak in the damage plot, whereas all hybrid configurations perforated afterwards. The metal mesh reinforces and supports the laminate up to a certain impact energy, which means that the extra energy that the laminate can absorb is released through more extensive damage, resulting in an increase in damage area. Eventually, the impact energy increases to a point such that the area of mesh that can respond decreases and damage becomes more localised, resulting in a drop in damage area at perforation.



(a) Energy profile of plain and hybrid laminates



(b) Damage plots of plain and hybrid laminates

Fig. 4: Influence of mesh position

Fig. 5 shows the cross-section of the plain and hybrid laminates after perforation. The plain laminate displays fibre and matrix crushing on the impact side, with multi-level delamination through the thickness, and finally tensile failure and buckling on the back surface. The Top laminate displays little evidence of crushing in the mesh regions, where the tough combination of mesh-reinforced epoxy absorbs much of the impact energy. There are also fewer delamination layers. The Middle laminate displays the largest delaminations, none of which occur at the mesh layer. While it is not clear from the results, nor the images obtained, what exactly contributed to the increase in perforation energy, two possible reasons may be proposed. The first reason could be due to the energy absorbed to create extensive delamination. The second reason may have been due to the reinforcing effects of the mesh. At higher impact energy, the laminate undergoes a great amount of deflection and as a result, in middle of the laminate there are high shear stresses. The metal mesh, which has a higher stiffness and strength than a glass layer of 8-harness satin weave, may restrict the shear stresses and reinforce in this region. The result is a delay in perforation energy. Finally, the Bottom laminate shows similar failure to the Plain laminate on the impact side, and also displays multi-level delaminations, but is the only laminate to eliminate buckling on the back surface, as described in the previous section.

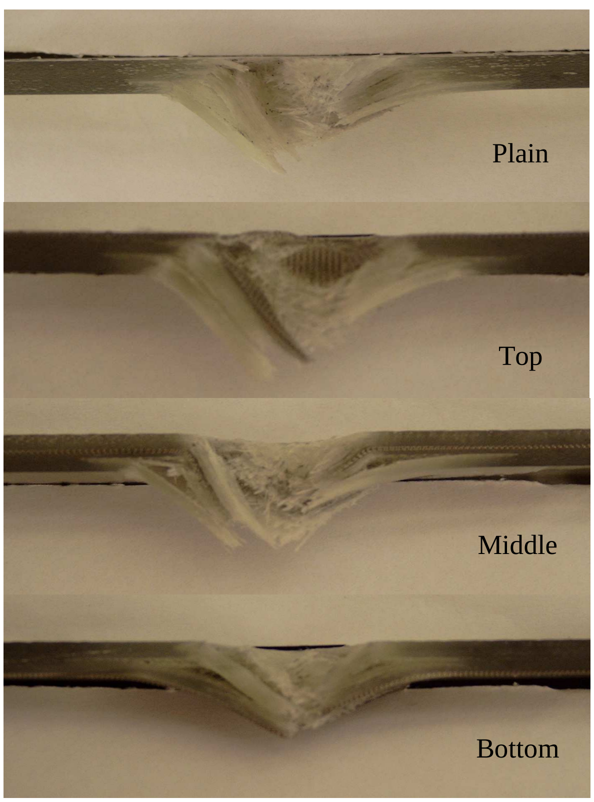
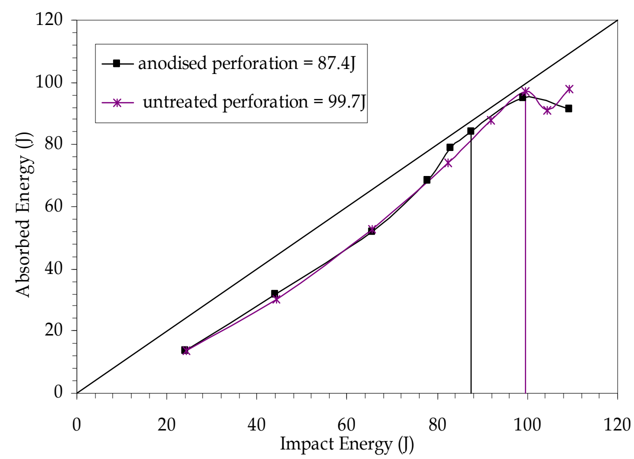


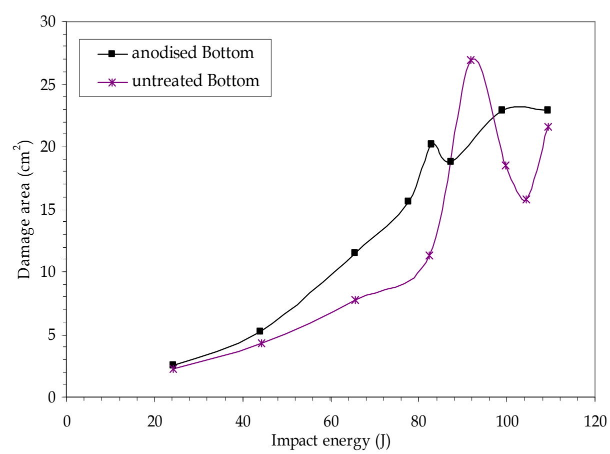
Fig. 5: Cross-section of Plain and hybrid laminates at perforation

3.3 Influence of mesh surface treatment

In an attempt to improve the impact properties even further, it was aimed to investigate the effect of metal fibre/matrix adhesion. Fig. 6 presents the results obtained to describe the influence of mesh surface treatment. The energy profile shows that the treatment of the mesh had a negative influence on the impact properties. The increased adhesion between the metal fibres and the matrix led to difference in stiffness between the mesh layer and the bulk of the laminate. A stiffness gradient was present with the stiffer region in the mesh layer decreasing sharply to a lower stiffness in the glass/epoxy region. The stiffness mismatch resulted in extensive damage, even at lower impact energies, Fig. 6(b). The result was a laminate with lower resistance to impact, and hence a lower perforation energy.



(a) Energy profile of plain and hybrid laminates

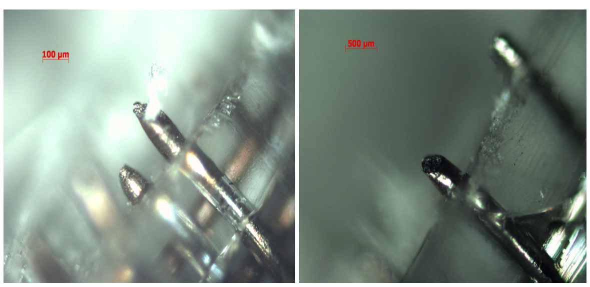


(b) Damage plots of plain and hybrid laminates

Fig.6: Influence of mesh surface treatment

Fig.7 presents micrographs of the untreated and treated mesh layers after impact. Upon inspection of the failure surfaces, very little differences can be seen. In both cases, plastic deformation of the metal fibres had clearly occurred, indicated by the obvious necking at the fibre ends. Although this was initially thought to be a major energy absorption mechanism, the fact that the extent of the plastic straining of the fibres was similar in the untreated and treated case suggested otherwise. It is now thought that that energy absorption is mainly due to more global mechanisms, such as membrane deformations, than local plasticity of the metal fibres.

Therefore, it is important that the metal fibres are not restricted, due to too great adhesion, to the point that the mesh layer is too stiff to strain with the laminate as it deforms upon impact. Hence in the case with stainless steel and epoxy, the adhesion level in the untreated case is already sufficient that improvements in impact behaviour can be realised.



(a) Untreated (b) Anodised

Fig.7: Microscope image of mesh layers of perforated laminates

4 Conclusions

The investigation has shown some interesting results in the attempt to improve the impact behaviour of polymer composites through reinforcement with metal mesh layers. The conclusions may be summarised as follows:

- The presence of the mesh does not greatly affect the absorbed energy, nor the damage area, at lower impact energies.
- A minimum volume fraction of metal fibres is needed to fully contribute to the impact behaviour.
- The energy absorption mechanism is mainly due to global mechanisms rather than local straining of the metal fibres.
- Surface treatment of the mesh allows more of the laminate to contribute to bending resulting in a larger damage area.
- For the placements investigated a maximum increase in perforation energy of 21%, corresponding to a weight increase of 5.3%, was found when mesh is placed in the bottom ply compared to the Plain laminate. A lower damage area was also found for the bottom configuration compared to the Plain laminates.

Acknowledgements

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