IMPROVEMENT OF INTRUSION AND CRASH BEHAVIOUR OF ALUMINIUM BEAMS BY CARBON COMPOSITE PATCHES

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Abstract
This study investigates the intrusion and crash performance of hybrid fibre-metal laminates based on aluminium and carbon or glass reinforced polymers, as compared to reference aluminium parts, made from AA6451 or 7075 automotive grade alloys. A first set of experimental and numerical cases of hybrid structures were correlated to validate and refine the model. Then, a range of configurations was numerically modelled to determine the optimum aluminium-composite lay-up architectures and the ideal locations of the patches leading to the best absorbed energy/weight ratio for given load cases. Several configurations and parameters were investigated and will be discussed: aluminium thickness (0.9, 1.5 and 2.5 mm) and aluminium type (AA 6451 and 7075), the number of layers of composite (2 or 3), the type of patch (5HS carbon/Glass) and the area of composite coverage, patch or stripes. Results demonstrate that localized composite patches improve the crash and intrusion properties of tubes without penalizing the overall part weight.

1. Introduction

Carbon fibre reinforced polymers (CFRP) have been widely used in many fields such as automotive and aeronautics owing to their high strength-to-weight and stiffness-to-weight ratio, and often compete with high-end aluminium alloys. These two materials can be combined into a hybrid design, to form an emerging solution to reach unique material characteristics [1]. Alternate layers of composite and metal have been shown to provide structures with high bending rigidity and minimal increase in structural weight [2]. In this context, different tubes are processed by varying the type and the thickness of the components. Then, the tubes are tested by intrusion and crash tests and the properties of the tubes are evaluated and compared. Finally, a numerical study is developed to optimize the location of composite patches as well as the mechanical properties/mass ratio.

2. Materials and method

Test samples contained Satin 5HS carbon or woven glass fiber reinforced epoxy (Epon 828) resin, combined with an aluminium layer, with either full or partial coverage. All hybrid composites were cured in an autoclave for 20 minutes at 140°C in a vacuum bag. An adhesive film LF-503 provided by LandL products was applied between the composite plies and the aluminium, as illustrated in Figure 1.

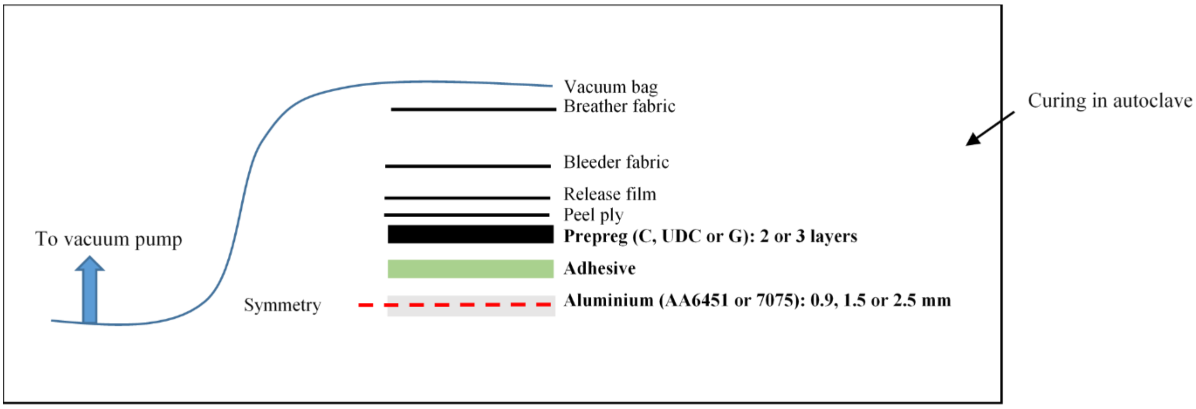

Figure 1. Processing of the hybrid composite by autoclave.

Two types of tubes, each consisting of a hat shape (HS) and a back plate (BP), were tested. In the hybrid configurations, the aluminium BP and HS were symmetrically covered by composite on each side. BP (185*500mm in intrusion tests and 140*300mm in crash tests) and HS were bonded together with structural adhesive in intrusion tests and were assembled by screws in crash tests. Three samples were tested for each configuration. Figure 2 shows the configurations of the two types of tests, before and after testing. The intrusion tests are 3-point bending tests where a cylindrical upper punch deforms the tube until the BP deformation reaches 30 mm so as to compare the various configurations. During the crash tests, a plate crushes the tube along its longitudinal direction. Force-displacement curves were recorded and both absolute and specific stiffness and energy absorption (from the area under the force/displacement curve) were evaluated for each test. The fracture mode was also analysed for each beam.

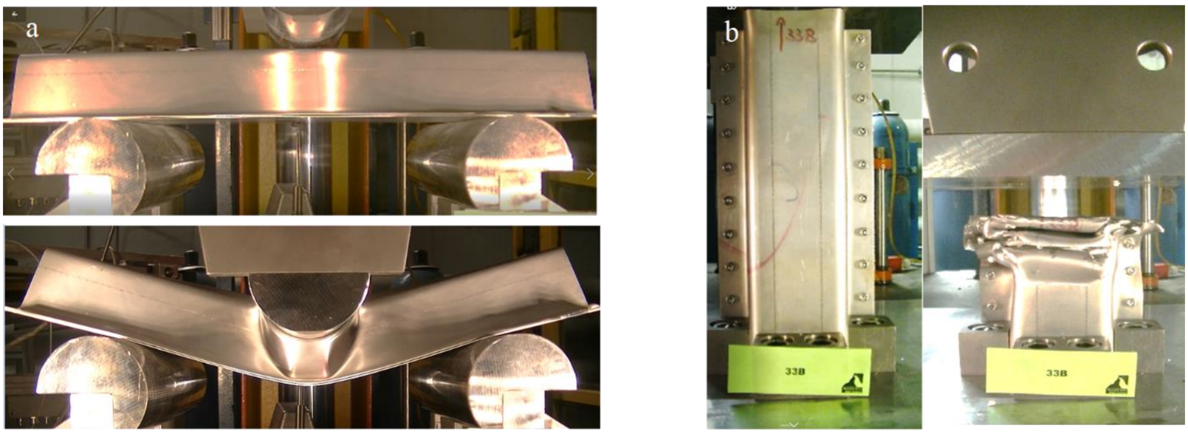

Figure 2. Intrusion tests (a) and vertical crash tests (b).

In parallel, a Finite Element Model of the intrusion test, taking into account the elasto-plastic deformation of the aluminium materials, the elastic deformation of the composite patch and adhesive was set-up. Constitutive laws used in the model were established from tensile tests on coupons of the individual materials. A first set of experimental and numerical cases of hybrid structures were correlated to validate and refine the model. Then, a range of numerical configurations was modelled to determine the optimum aluminium-composite combinations and the ideal locations of the patches leading to the best absorbed energy/weight ratio for given load cases.

3. Results

3.1 Crash tests

Figure 5 presents the absorbed energies of the various configurations. These configurations are either full aluminium tubes (*1,5 AA6451*, *1,5 7075* and *2,5 AA6451* where 1,5 and 2,5 are the plate thicknesses) or hybrid composite with 2 or 3 plies of carbon and one layer of adhesive (denoted as *CCA* or *CCCA* for 2 and 3 layers respectively) or glass (denoted as *GGA* for 2 layers). The crash curves of 1,5 AA6451 and CCA-1,5 AA6451 tubes are presented in figure 3.

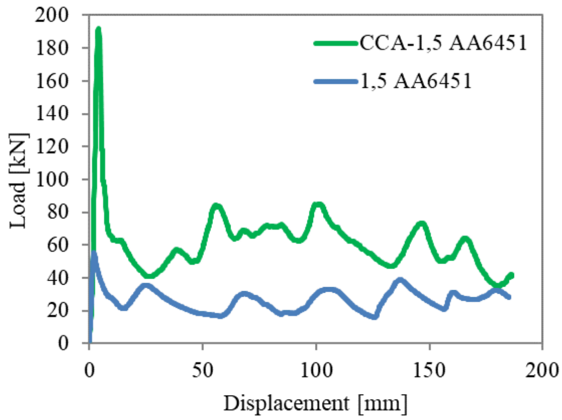

Figure 3. Crash curves for 1,5 AA6451 and CCA-1,5 AA6451 tubes.

Addition of two layers of carbon fibres (*CCA-1,5 AA6451*) or glass fibres (*GGA-1,5 AA6451*) to *1,5 AA6451* tubes increases the absorbed energy by 50% and 60% respectively, the latter being slightly higher due to the higher intrinsic energy absorption capability of glass fibre reinforced polymers. These hybrid tubes also surpass the energy absorption capability of a stronger grade aluminium (*1,5 7075*). The hybrid tube of the same aluminium (*CCA-1.5 7075*) outperforms the other hybrid configurations. Finally, the substitution of full coverage by stripes (Figure 4) which were placed symetrically on the top of the hat shape, on the sides and on the back plate, can be assessed by comparison of the configurations *2.5 AA6451* and *Stripes CCCA-2.5 AA6451*.

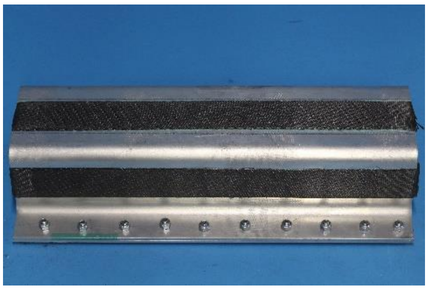

Figure 4. Crash tube with stripes.

In that case, the gain in absorbed energy is limited to around 5%. Figure 5b shows the specific energy absorption per mass of the tested tubes. *CCCA-0,9AA6451* outperforms all other configurations thanks to the 3 layers of carbon which improved the energy absorption capability without significantly compromising the weight. Interestingly, the configuration with the stripes has a lower Energy/Mass value than its reference aluminium; in the case of partial coverage the load was transferred to the uncovered regions which deformed rapidly, so finally the stiffening role of carbon was reduced.

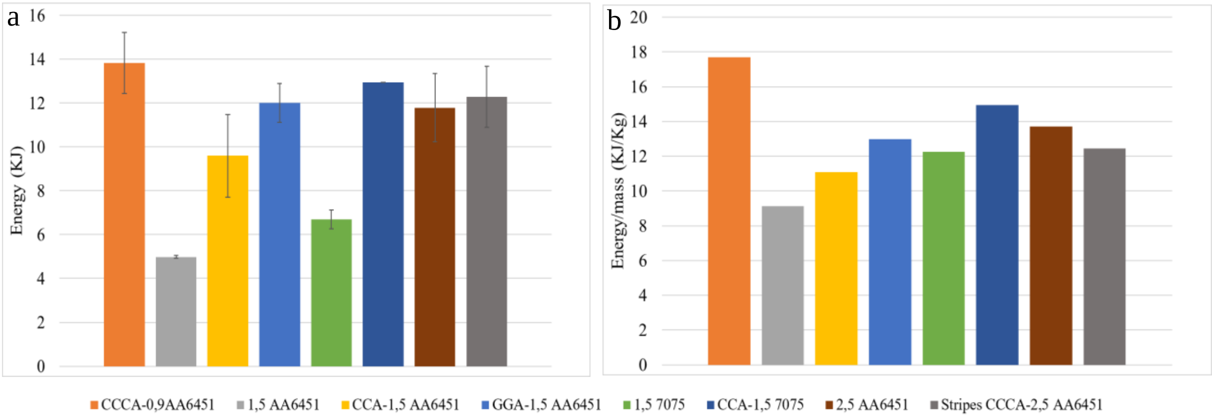

Figure 5. (a) Absorbed Energy and (b) absorbed energy/mass of the tubes tested in crash tests.

In summary, addition of the composites, either carbon fibre or glass fibre reinforced polymer, on aluminium crash tubes has a relatively minor effect on the Energy/Mass properties. A full coverage with 3 layers of composites is a priori of interest, but the cost of the hybrid tube becomes an issue. The placement of the composite stripes was not ideal and resulted in minimal improvement of the crash behaviour.

3.2 Intrusion tests

Intrusion tests were performed, in which the stiffness and absorbed energy were measured. The resulting performance is presented in the Figure 7a and 7b. The same configurations as in the previous section, except the additional *0,9AA6451*, were tested during the intrusion tests. The intrusion curves of 1,5 AA6451 and CCA-1,5 AA6451 tubes are presented in figure 6.

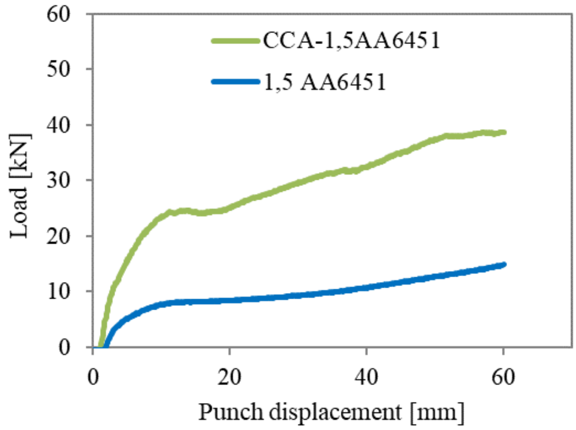

Figure 6. Intrusion curves for 1,5 AA6451 and CCA-1,5 AA6451 Tubes.

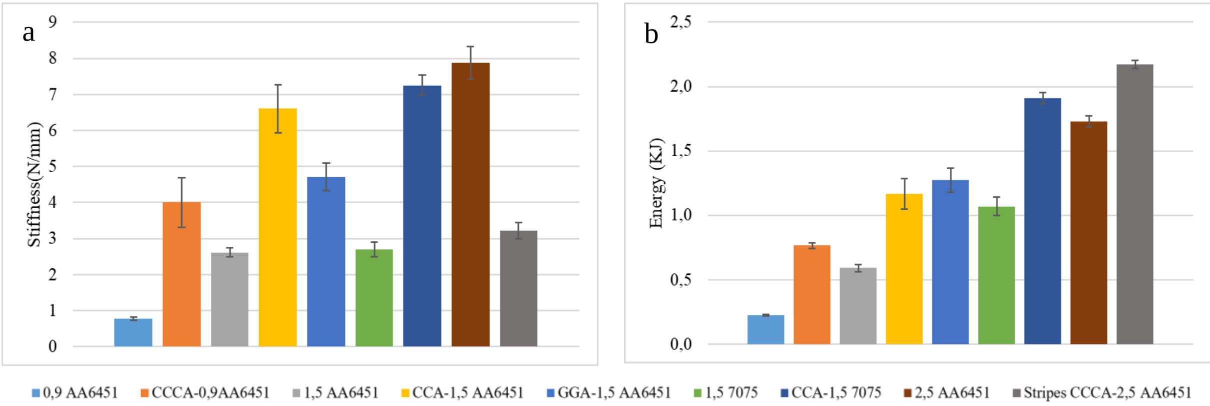

Figure 7. Stiffness and Energy of the tubes tested by intrusion tests.

Stiffness and absorbed energy were all increased by the addition of the composite patches. *CCA-1,5 AA6451* hybrid has a higher stiffness than its equivalent with the glass fibres (*GGA-1,5 AA6451*) and the absorbed energy is comparable for these two configurations. As expected, the hybrid with a stronger grade aluminium (*CCA-1,5 7075*) shows higher stiffness and energy values than the other two hybrids. By introduction of stripes on the sample *2.5 AA6451* the stiffness decreased due to the crushing effect of plies at the top of the hat shape, but the absorbed energy was increased in the presence of stripes.

These results are normalized with the mass of the tubes and presented in Figure 8a and 8b.

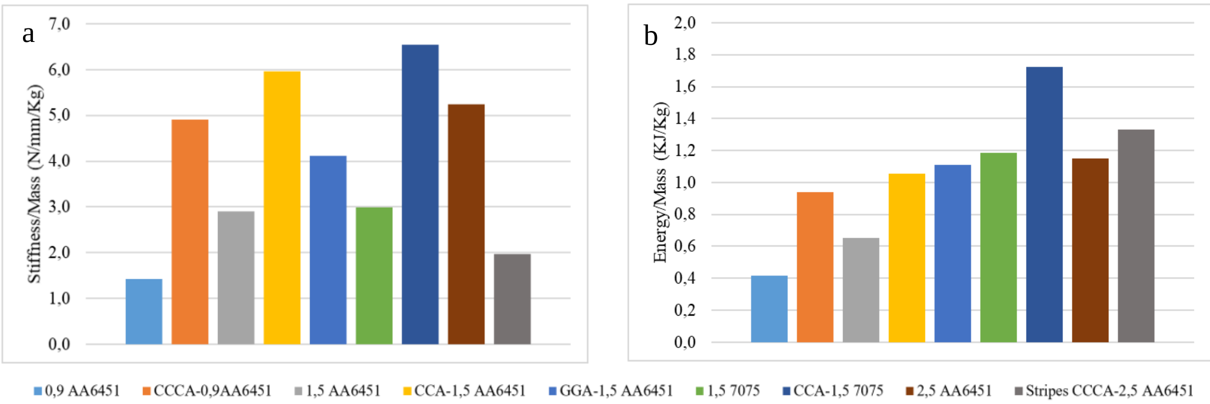

Figure 8. (a) Stiffness/Mass and (b) Energy/Mass of the tubes tested by intrusion tests.

Regarding the specific stiffness, *CCA-1,5 7075* and *CCA-1,5 AA6451* configurations have the best properties, underlining the efficiency of carbon patches. Contrary to the findings in the previous section, addition of stripes improves Energy/Mass value and indicates the link between the patch location/orientation and the load case.

3.3 Design optimization

Sections 3.1 and 3.2 pointed out that a good compromise between the added weight and the performance of hybrids with stripes necessitates an optimization step. We thus analyzed several other stripe configurations with the aim of improving the stiffness and energy while limiting the added weight.
Figure 9 shows four examples of the thirty simulated configurations. The modelling was carried out on quarters of hat shape. Comparison between configuration 9a and 9b showed that adding composite on the backplate did not improve the intrusion characteristics. The design in Figure 9a was improved by extending the patch to the top of HS and the flange of BP as shown in Figure 9c. This design was then further optimized by dividing the patches into smaller stripes as shown in Figure 9d. To validate the modeling, we produced a part with the configuration in Figure 9d (see Figure 10), performed intrusion tests and reported the results in Table 1 along with two full coverage patch configurations, namely CCA-1,5 AA6451 and CCA-1,5 7075.

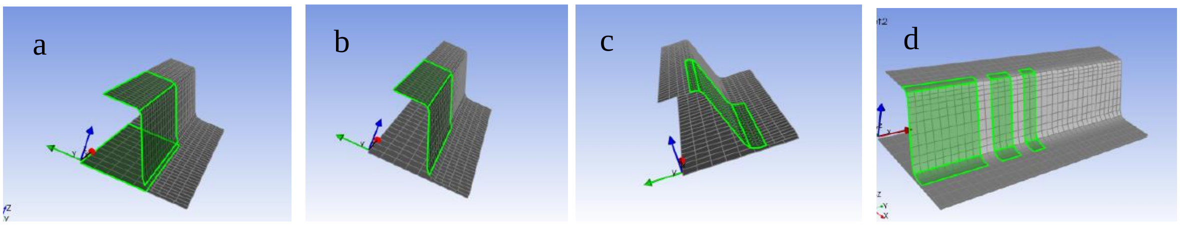

Figure 9. Methodology for the patch location.

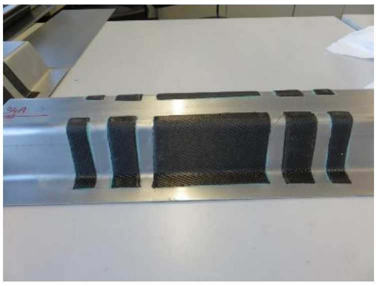

Figure 10. Composite Aluminium hybrid tube with patches optimization.

Table 1 shows that the optimized composite has 22% higher specific stiffness and 8% higher specific energy than *CCA-1,5 AA6451*. We also observed that the small patches near the fixtures of the three point bending test reinforced this region and the collapse of aluminium tube was thus avoided during the intrusion test. The difference between experimental and numerical results of absorbed energy is due to neglecting the damage in the simulations. The simulation requires further refinement to incorporate the damage and eliminate the difference in stiffness values; and these tasks will be considered in the future.

Table 1. Mechanical properties of composites.

Specimen Type	Stiffness (N/mm)	Specific Stiffness (N/mm/Kg)	Energy (KJ)	Specific Energy (KJ/Kg)
CCA-1,5 AA6451	6,6/**4,0**	5,9	1,2/**1,7**	1,1
CCA-1,5 7075	7,2/**4,2**	6,4	1,9/**2,1**	1,7
Optimized composite (CCA-1,5 AA6451)	8,1/**6,1**	7,5	1,3/**2,0**	1,2

Experimental/**Modelling**

4. Conclusion

This study investigated the intrusion and crash performance of hybrid fibre-metal laminates based on aluminium and CFRPs, as compared to reference aluminium parts. We observed that full coverage of the surface was a prerequisite for an improvement of energy absorption characteristics in crash. On the other hand, analysis of intrusion behavior indicated that patches and stripes improve the energy absorption. A Finite Element optimization study led to a new design of combining patches and stripes with a smaller area coverage than the original design (and thus less material requirement), that not only improved the low stiffness in hybrids with stripes but also surpassed the performance of the hybrids with full patches. This study will continue by investigating the benefit of carbon patches on Aluminium 7075 and integrating damage in the model to better predict performance in order to serve as design guideline for real automotive parts.

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