CARBON/DYNEEMA® INTRALAMINAR HYBRIDS: NEW STRATEGY TO INCREASE IMPACT RESISTANCE OR DECREASE MASS OF CARBON FIBER COMPOSITES

J. G. H. Bouwmeester*, R. Marissen#@, O. K. Bergsma@
*** DSM Composite Resins, The Netherlands**
 # DSM Dyneema, The Netherlands,
@ Delft University of Technology, Faculty of Aerospace Engineering, The Netherlands

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Abstract

The primary mechanical properties of hybrid composites made of Carbon fibers and High strength gel-spun polyethylene fibers (Dyneema®) are investigated. It was observed that the impact resistance of the hybrid composites is considerably increased due to replacement of carbon fibers by polyethylene fibers. The polyethylene fibers have high tensile strength, but negligible compressive strength. Thus the flexural stress at failure of the hybrid composites is reduced. However, due to the low density of polyethylene, the thickness of the hybrid composites increases with increasing polyethylene content at the same weight. Flexural strength and stiffness increase progressively with increasing thickness. Thus, the flexural strength and stiffness of hybrid composite sheets are hardly reduced at constant weight of the composite and increasing polyethylene fiber content. Yet, the improved impact resistance is completely conserved. Consequently, it is concluded that Carbon Dyneema® hybrid composites may be attractive for structures where impact resistance is the limiting load case and flexural resistance is important as well.

1 Introduction

Composites made from carbon fibers are extremely strong, stiff and lightweight structural materials. Therefore, such composites are very suitable for application as aircraft skin material. However, sheets from carbon composite skins are somewhat sensitive to the out of plane loads caused by impact. Hybridizing with strong polymer fibers like aramid fibers, or gel-spun polyethylene fibers is a well-known way to improve the resistance against impact. Various publications e.g. [1-3] describe such hybrid composites. However, the impact resistance is often measured on samples like “Sharpy specimens” that do not represent realistic loading situations for actual structures. The hybrid composites with gel-spun polyethylene fibers are often made with older generation fibers and not with improved grades that are presently available. Therefore, an investigation has been performed on hybrid composites made with high strength carbon fibers and the very strong modern Dyneema® SK75 fibers from DSM. The DSM Turane resin is used as a matrix. Various tests have been performed that are relevant for actual load systems on sheet material. The test results are discussed from the point of view of aerospace structures, i.e. load bearing skins.

2 Materials, specimens and tests

The primary properties of the base materials are listed in table 1. It can be observed that both fibers have a high tensile strength. The modulus of the carbon fiber is very high. The density of Dyneema® fibers is very low for such high strength fibers. Dyneema® fiber is a typical tension material, the axial compressive strength is almost negligible. The density of the resin is slightly lower than that of conventional epoxy resins. This is a real advantage for aerospace application in view of weight saving. The resin is a newly developed aerospace quality product with good adhesion, good mechanical properties, low density, and low viscosity and thus easy processing using resin transfer molding techniques.

Material	Tensile strength [MPa]	Young's Modulus [GPa]	Density [g/cm^3]
Carbon fiber Toray T300JB	4200	230	1.78
Dyneema® fiber 1760 SK75	3400 #	115	0.975
Turane Daron® XP6148 resin	70	3	1.1
# estimated axial compressive strength 100 MPa			

Table 1. Ingredient properties

Dyneema® fibers are produced by Gel spinning of ultra high molecular weight polyethylene; see e.g. [4, 5]. The low compressive strength makes it unsuitable for structural aerospace composites as a sole fiber ingredient. Compression resistant fibers like glass or carbon are needed for such applications. However, Dyneema® fibers are excellent for armor applications, see e.g. [6]. This is due to the combination of high tensile strength, low density and intrinsic fiber toughness. This fiber toughness is illustrated in the Figures 1 and 2. Figure 1 shows a knotted filament. The curvatures in the knot and the transverse deformation are impossible for other high strength fiber types like glass, carbon or aramid fibers. Figure 2 shows filaments that are tensioned over the edge of a sharp razor blade. Again, a sharp curvature and extensive transverse deformation occur, allowing pressure re-distribution over a larger distance along the blade edge. Thus the excellent cutting resistance is explained. Both pictures illustrate the damage tolerance of Dyneema® on micro-scale. Hybridization with a carbon fiber composite may add damage tolerance to the composite on macro scale.

The hybrid composites were made by dry winding of both fiber types on a plywood plate, covered with release agent. The winding plate was mounted in a filament winder along a diagonal axis, such that a suitable winding program provides alternating cross ply windings. The winding procedure is illustrated in figure 3.

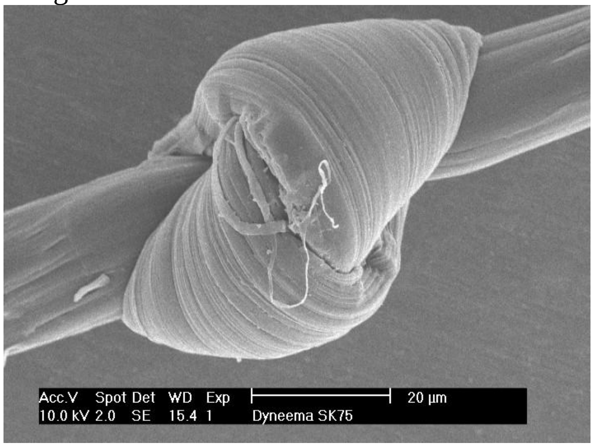

Figure 1. Knot in a Dyneema® filament

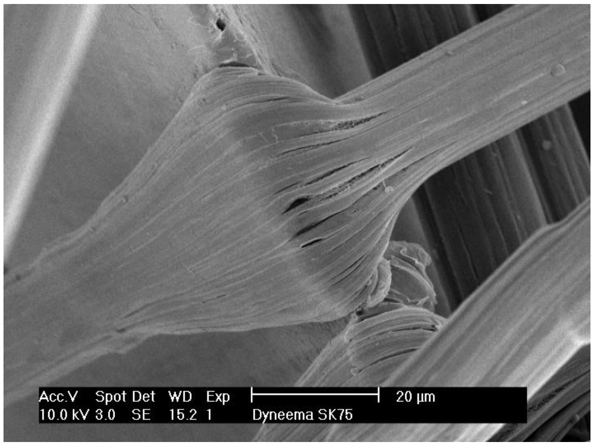

Figure 2. Dyneema® filaments tensioned over the edge of a razorblade

Up to four fiber bobbins were unwound simultaneously. Because Dyneema® has a different density than carbon and the yield of the bobbins used is different, the fiber percentage is neither the weight nor the volume percentage. However, by choosing the total number of bobbins as well as the ratio of the different bobbins, and adjustment of the winding pattern to the fiber yield per winding, a wide range of Dyneema®/carbon ratios could be established. The dry wound preform was then infused with DSM Turane resin, cured and post cured at 100°C. Two plates were then harvested, one from the top and one from the bottom side of the plywood plate. The required specimens were cut from the composite plates with a diamond saw.

Specimens for the following tests were made:

- Tensile tests according to ASTM D3039
- Flexural tests according to ASTM D790 (3pt. bending with L/t=40)
- Short beam flexural (ILSS) tests according to ASTM D 2344
- Compression tests according to ASTM D6641
- Impact falling dart tests are preformed with a hemispherical dart with a diameter of 15mm, and a mass of 2.13kg. Square specimens of 11x11cm are used. They are clamped in the support in such a way that an area with a circular diameter of 8cm is free to deform out of plane during impact. The thickness of the sheets was 1.5mm. Time-acceleration diagrams are provided by the equipment. These can be recalculated to load displacement diagrams that allow determination of the perforation energy.

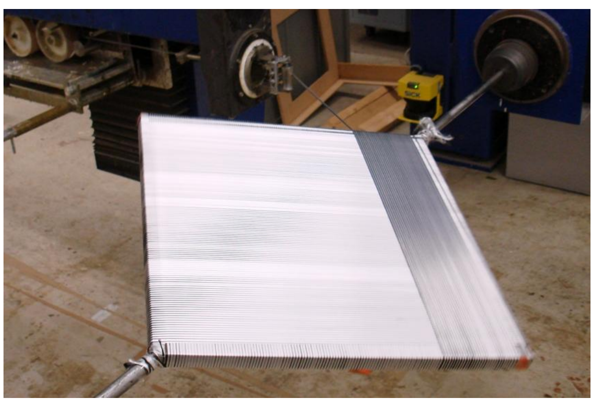

Figure 3. The winding specimen, here with Dyneema® fibers only

3 Test results

Figure 4 shows the test results at different fiber ratios, normalized against the values measured for composites with 100% of the fibers being carbon fibers. Table 2 presents the actual values at 100% carbon fibers. It can be seen in figure 4, that the properties related to fiber-matrix adhesion and compression strength decrease with increasing amount of Dyneema®. However, the impact performance increases considerably, as expected and intended. Figure 4 does not account for the effect of density reduction at increasing amounts of Dyneema (see densities in table 1). The structural mass of an aircraft is directly related to the density of the construction material, so judgment of structural performance should account for the density effect. A common way of accounting for this effect is by comparing specific properties, so by comparing properties divided by density. This way of comparing is relevant for in-plane loading and impact loading. This comparison is presented in Figure 5. Still this comparison is not adequate for all loading cases. Ashby [7] presented dimensional analysis for all kinds of material applications. The situation of flexural loading is typically relevant for the present case. Low density materials show larger sheet thickness at the same weight. This larger thickness causes additional bending resistance for two reasons: First, the increased volume of load carrying material. This effect would be accounted for by considering specific properties. Secondly, the distance from the internal stresses from the neutral axis is increased. This provides an additional resistance to flexural loads. The overall effect is that at the same weight, the flexural strength of a sheet is proportional to S/ρ^2, where S is the material strength and ρ is the density. For the flexural stiffness at the same weight, the proportionality is written as E/ρ^3, where E is Young's modulus. At the same thickness, the structural performance parameters are proportional to: $S^{(1/2)}/\rho$, for strength, and $E^{(1/3)}/\rho$ for flexural stiffness. It is obvious from these Ashby-considerations that low density is even more important than mechanical properties for sheets under bending loading.

Bending stiffness is also important for compression loaded structures if stability against buckling is the limiting condition. Indeed, aerospace structures are often limited by buckling rather than by the in plane compression strength. Local buckling is a frequently occurring limiting case, for which the flexural stiffness as well as the in plane compressive strength is important. Anyhow, the parameters E/ρ^3, and S/ρ^2 are relevant, at least for composite aircraft skins under compressive loading. Figure 6 presents these parameters as a function of the percentage of Dyneema® and compares them to plain non-corrected flexural stiffness and strength values. It can now be observed that the flexural performance of the hybrid composites does not decrease much with increasing amount of Dyneema® fibers. Especially the density corrected stiffness remains at about the 100% carbon level (apart from some experimental scatter), up to about 50% of the fibers being Dyneema®. Larger amounts of Dyneema® fibers cause a reduction of the bending resistance of the hybrid composites.

Property	value
Tensile strength	952 MPa
Tensile modulus	64 GPa
Compression strength	462 MPa
Flexural strength	1563 MPa
Flexural modulus	91 GPa
ILSS	65 MPa
Impact perforation energy per unit of thickness (for 1.5mm thickness)	11 J/mm

Table 2. Properties of pure carbon composite (reference value for hybrids in the Figures 4 and 5)

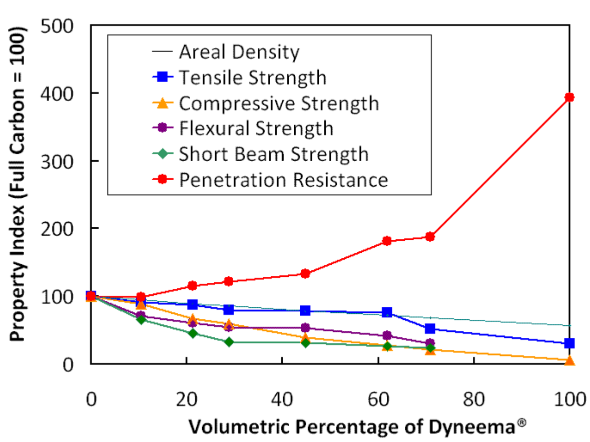

Figure 4. Properties of composites, with different amounts of Dyneema® fibers, varying between 0 and 100% of the fiber content, normalized against full carbon composite (0% Dyneema®)

4 Discussion

Aerospace structures are designed for various load cases. On a local level in the structure, this is reflected in the occurrence of different stress systems. Load carrying skins are typical for aerospace structures. For the skins these stress systems are preferably in plane, but out of plane stresses can not be avoided completely. The in plane stresses are tensile stress, compressive stress and shear stress. Carbon fiber reinforced polymers are excellent for this kind of loading. Probably, carbon epoxy composites are the most effective available materials for such loadings. Out of plane stresses are due to flexural loading and due to impact loading, more or less perpendicular to the skin. In fact impact loading also causes flexural stresses, but due to geometrical and inertia reasons the stresses due to impact occur very local, that means that only a small part of the total amount of structural material is available for resisting impact loading. This, together with the small fracture strain of carbon fibers limits the impact resistance of carbon fiber composites. The peak stresses under an impactor can be relieved due to delaminations and splitting along fibers, thus causing some stress redistribution, but in spite of this, carbon composites still have limited resistance to impact.

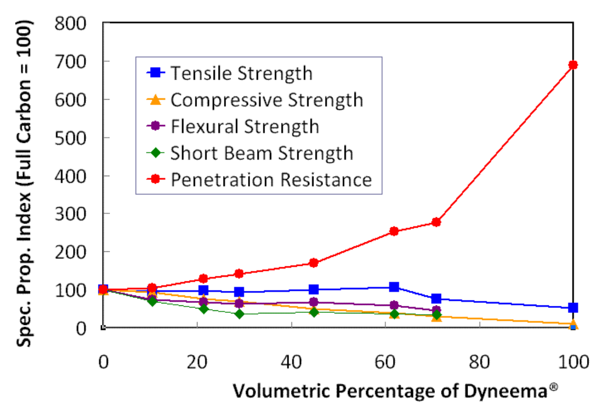

Figure 5. Specific of composites, with different amounts of Dyneema® varying between 0 and 100% of the fiber content, normalized against full carbon composite (0% Dyneema®)

The present results show that hybridizing the carbon composite with Dyneema® fibers improves the resistance to impact considerably. The impact resistance increases with increasing amount of Dyneema® fibers. Figure 7 shows a Scanning Electron Microscope (SEM) picture indicating deformed, but unbroken Dyneema® fibers together with broken carbon fibers, thus illustrating the contribution of the damage tolerant Dyneema® fibers to the impact resistance of the hybrid composite. However, other properties decrease, due to the almost negligible axial compressive strength of Dyneema® fibers. Figure 4 and 5 illustrate this. The compression strength decreases about linear with increasing amount of Dyneema® fibers, to a negligible value at 100% Dyneema® fibers. Also adhesion related properties decrease with increasing amount of Dyneema® fibers. Indeed, these fibers are chemically inert, so they cannot form chemical bonds with the resin. The decreasing ILSS with increasing amount of Dyneema® fibers is caused by this low level of adhesion. All this indicates that there is no real optimal material for all aerospace structures. The specific structural requirements for each component or location determine which material properties would be optimal. Composites already allow the choice of the amounts of fibers per orientation as an optimizing tool. Tension and compression stiffness and strength can be traded against shear stiffness and strength by choosing the relative amounts of 0^o or $\pm 45^o$ fibers. Hybridizing composites by exchanging carbon fibers by Dyneema® fibers allows trading of compression- and adhesion related properties against impact resistance. Most locations in aerospace structures will never suffer from impact, and carbon reinforced polymer composites will be a very good choice for such structures. However, for exposed locations, the impact resistance may be the critical design case. In such a case, hybridizing with Dyneema® fibers can be useful. The amount of Dyneema® fibers necessary will be dependent on the severity of the expected impact. The minimum amount necessary should be chosen in view of the reduction of some other properties.

A generalized consideration on the type of situations where the hybridizing is useful is presented below. Some basic observations and considerations are:

- The impact resistance is increased with increasing amount of Dyneema® fibers
- The compression strength decreases about linear with increasing amount of Dyneema® fibers
- It can be argued that compression strength is only relevant for structures with relatively thick skins. For thin skins (local) buckling will be the limiting loading case.
- The ILSS decreases considerably with increasing amount of Dyneema® fibers
- Interlaminar shear stresses in composites can become significant in thick composite skins. Thin slender skins will hardly build up interlaminar stresses, so fracture due to low ILSS is not to be expected for thin skins
- The reduction of flexural strength and stiffness as such is not relevant in view of the density effect according to Ashby-type considerations. Especially the “Ashby stiffness” remains at about the 100% level up to about 50% Dyneema® fibers. The “Ashby stiffness” is also governing the resistance of the structure against buckling.

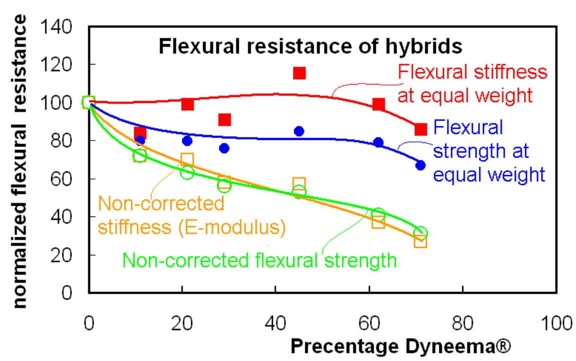

Figure 6. Flexural performance of hybrid Dyneema® carbon composites, according to Ashby type considerations as compared to plain non-corrected values

Combination of the arguing above yields the conclusion that application of carbon Dyneema® hybrid composites can be considered as an improvement option over pure carbon composites if the situations below apply:

1. The structure is critical on impact resistance
2. The structure is mainly designed for tension load, and/or
3. The structure is a thin skin

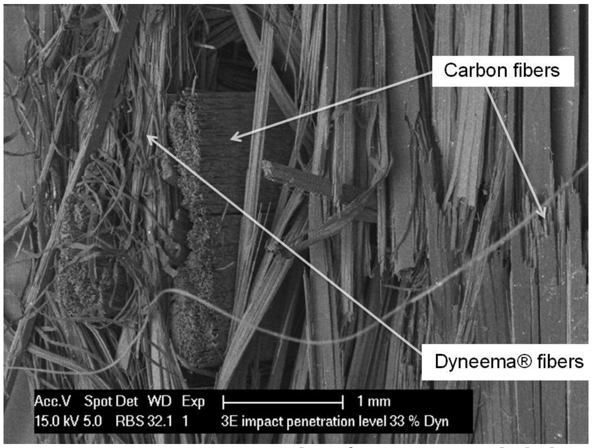

Figure 7. SEM micrograph of an impacted hybric composite

In general, the amount of Dyneema® fibers will not be higher than 50%, usually even lower. Very high amounts of Dyneema® fibers are reserved for composites with armor functionality only. Such composites utilize the tensile strength and damage resistance of Dyneema® fibers to a full extent, but exhibit hardly the balance of properties of structural materials. Combination with carbon fibers provides more balanced structural properties.

Composites allow trading of property directions by choosing relative amounts of fibers in different orientations. The amounts of choices are increased, considering that replacing carbon fibers by Dyneema® fibers allow trading of compression strength and ILSS against impact resistance.

It is beyond the scope of the present investigation to suggest specific structural applications for such hybrid composites. A check on local design criteria of composite skins against the three points (impact, mainly tension, thin skins) mentioned above might be worthwhile.

5 Conclusions

1. Hybrid composites with carbon fibers and Dyneema® fibers show considerably improved impact resistance over composites with carbon fibers only.
2. The ILSS and compression strength decreases with increasing amount of Dyneema® fibers.
3. The flexural strength and stiffness decrease with increasing amount of Dyneema® fibers. However, if the density reduction is considered as well, including its geometrical consequences on flexural resistance, the flexural performance remains about the same up to about 50% of Dyneema® fibers.

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