TOWARD AEROSPACE GRADE THIN-PLY COMPOSITES

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Abstract
The advantages of thin-ply composites such as increased onset of damage, much improved fatigue life and hot-wet resistance have been shown in several recent studies. The decreased inter- and translaminar toughness and the lack of a highly toughened thin-ply system constituted drawbacks limiting their potential application to damage-tolerance driven designs. The aim of this study is therefore to develop a new thin-ply pre-preg system to meet the ever increasing aerospace needs, with additional solutions to increase translaminar toughness where needed. The resulting system has exceptional performance in quasi-isotropic unnotched tension with an onset of damage above 900MPa and an ultimate failure above 1'100MPa, using the full potential of the fibers. The interlayer toughening strategy used enables it to reach compression after impact (CAI) values that are within the aerospace 3rd generation composites range. Finally, two fiber hybridization strategies have been developed. Both yield a large increase in translaminar toughness, and one of them generates a predictable and reproducible pseudo-plastic behavior.

1. Introduction

The effect of ply thickness in a laminate – or size-effect – has raised an increasing interest in recent years. It has been demonstrated [1, 2] that the stress at the onset of damage increases dramatically when decreasing the ply thickness, which implies higher allowable stress in a first ply failure driven design, but also an improved fatigue life. Bolted bearing tests in hot-wet conditions have also revealed that thin-ply composites are less affected by those conditions, suggesting an influence of the size-effect on matrix-dominated properties [2]. By taking advantage of the size-effect and the broader design space offered by thin-ply composites [3], composite designers can achieve much lighter structures, which is a key factor in a high-value market such as aerospace.

Unfortunately, the fracture toughness of the thin-ply systems studied so far remained relatively limited due to a limited toughening of the matrix. The observed reduction of the translaminar toughness [4] when decreasing the ply thickness could also hinder their use in damage tolerance dominated designs. The aim of the present research is therefore to develop a new highly toughened thin-ply prepreg

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system that matches the performance of the latest aerospace systems in terms of toughness and damage tolerance, while retaining the benefits of the thin-ply size-effect. The screening phase of this study is presented in this short paper. At first, the understanding of matrix and fiber properties on the size-effect are studied. A new aerospace-oriented matrix is then developed and optimized. Finally, advanced solutions such as interlayer toughening and fiber hybridization are developed and tested.

2. Materials and methods

2.1. Materials

Several matrix formulations and fibers are used in this study as described in Table 1 and 2, and their combinations for testing are shown in Table 3. Toray T800 fibres are retained as an ideal candidate for aeronautical applications due to their good balance of modulus and strength. M40JB [2] and AS4 fibres offer contrasting properties, which are used to evaluate the influence of a wide range of fiber moduli on the size-effect. HR40 and Twaron fibres are used to produce hybrid composites. The laminates presented in this paper are all quasi-isotropic.

Table 1. Matrix systems

Name	Description
TP80ep	80°C curing epoxy system
TP120ep	120°C curing epoxy system
Standard 180°C epoxy	180°C curing epoxy system
Aero 1	180°C curing highly toughened epoxy system
Aero 2	180°C curing highly toughened epoxy system - optimized

Table 2. Fibre properties

Type	Modulus (GPa)	Ultimate tensile strain (%)
M40JB	377	1.2
AS4	231	1.7
T800	292	1.9
HR40	393	1.12
Twaron	105	2.7

The interlayer toughening is performed by adding a controlled amount of thermoplastic toughener at chosen interfaces. The T800 / Aero 2 system is taken as a reference and tested against configurations with interlayer tougheners added every 7th , 3rd as well as every single layer.

In a bid to increase the energy dissipation in translaminar fracture, two different hybridation strategies are implemented:

- Increasing the energy dissipated by fragmentation and pull-out by adding low ultimate strain fibers along the T800 base fibers in the form of ply-level hybridization (groups of two plies made of different fibres)
- Increasing the energy dissipated by crack bridging by adding high toughness fibers along the T800 base fibers in the form of a tow-level hybridization (two different fibre types in one ply)

For the fragmentation/pull-out strategy, the low strain fibres must fragment before the high strain (T800) ones, their failure should not precipitate the failure of the whole laminate (stress transfer), and the fragmentation length should be optimized towards the promotion of pull-out [4]. A typical fragmentation length, calculated with a simple shear-lag model as presented in [5], comprised between

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100 and 1000µm is deemed suitable. This small fragmentation length requires the production of very thin plies to be achieved. The combination of 67µm thick T800 and 20µm thick HR40 plies is found to be satisfactory with a fragmentation length comprised between 500 and 1000µm.
Three configurations of the plies are identified as potentially interesting in a quasi-isotropic laminate, $[0°_{T800}/0°_{HR40}]$, $[0°_{T800}/90°_{HR40}]$, and $[0°_{T800}/22.5°_{HR40}]$ forming "improved basic laminae" of the same quasi-isotropic laminate (Fig. 1). Only the first two are considered in the present study.

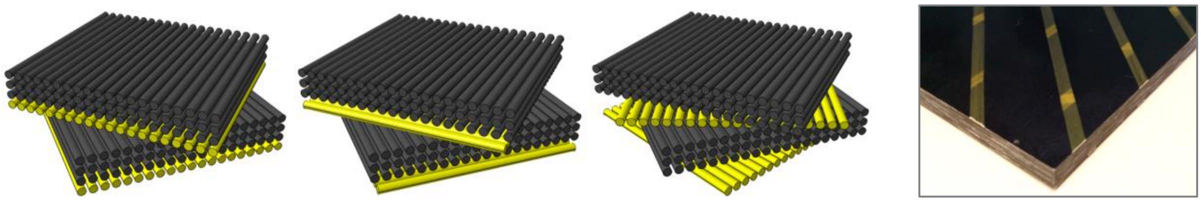

Figure 1. First three sketches: schematic representation of the T800/HR40 ply-level hybrid. 0°/0°, 0°/90°, and 0°/22.5° configurations with the T800 67µm ply in black and the HR40 20µm ply in yellow (only two "improved basic laminae" of the quasi-isotropic stacking are shown). Picture on the right: tow-level hybridized T800/Twaron quasi-istoropic laminate.

For the bridging strategy, Twaron fibres (aramid fiber from Teijin) are chosen for their high toughness and ultimate strain. Ply-level hybridization is not an option due to the large difference of moduli which would cause early delamination. To avoid this issue, tow-level hybridization is selected, in which both fiber types are integrated within a single ply (ply thickness = 70µm), which leads to a finely comingled configuration (Fig. 1).

Table 3. Test matrix. UNT = unnotched tension, CAI = impact and compression after impact, CT = compact tension

	M40JB	AS4	T800	T800 /HR40 hybrid	T800/ Twaron hybrid
TP80ep	UNT/CAI		UNT		
TP120ep	UNT				
Standard 180°C epoxy		UNT	UNT		
Aero 1			UNT/CAI		
Aero 2			UNT/CAI/CT	UNT/CAI/CT	UNT/CAI/CT
Aero 2, 1/n tough. interlayer, n=7			CAI		
Aero 2, 1/n tough. interlayer, n=3			CAI		
Aero 2, 1/n tough. interlayer, n=1			CAI		

2.2. Methods

2.2.1. Unnotched tension

Unnotched tension tests are carried out according to ASTM D3039/D3039M-08 on a MTS type 809 tensile test machine, with HBM 1-LY-41-6/120 and 1-XY31-3/120 strain gauges. Acoustic emission monitoring is used to determine the onset of damage trough a threshold set at 10^{-15}J on the cumulative acoustic energy [2]. The acoustic acquisition is performed with a Mistras-2001 system from Physical Acoustics Corporation, with two NANO-30 S/N749 probes.

2.2.2. Impact and compression after impact (CAI)

Impact and compression after impact tests are performed as stated in the ASTM D 7136/D 7136M-07 and ASTM D 7137/D 7137M-07 standard respectively, with HBM 1-LY-41-6/120 strain gages on one specimen per batch to control alignment and buckling for the latter. The specimen thickness of all laminates tested is between 3.97 and 4.48mm. All the impacts reported here carry an energy of 30.2 J.

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2.2.3. Compact tension

Compact tension tests [6] were done on a MTS type 809 tensile test machine, with an extensometer to measure the opening and 2 cameras to monitor both the crack propagation and the displacement fields. (scale on a white background on one side, speckle for DIC on the other side). The specimens are rectangles of 60 x 65mm with a thickness comprised between 9 and 10mm, with holes machined for the insertion of loading pins and a recess machined to receive the extensometer. The pre-crack is cut at the end of the recess with a diamond wire saw (130µm thick cut). The distance between its tips and the loading line is comprised between 24 and 25mm.

3. Results and discussion

3.1. Size-effect

The onset of damage and ultimate strength values in unnotched tension on quasi-isotropic specimens for various matrix-fiber combinations and ply thicknesses are presented in Fig. 2. Two different trends can be identified: systems with the "standard 180°C epoxy" matrix for which there is no size-effect, and all the others for which a very important size-effect is clearly present. In the former, the brittleness of the "standard 180°C epoxy" matrix or the weakness of its interface with the carbon fibers is considered to be responsible for the poor results as the onset of damage is always close to 0.8% strain independently of the fiber (AS4 or T800) and ply thickness. For the second group,very significant increases of both onset of damage and ultimate strength are observed when decreasing their ply thicknesses. To compare the performance achieved with different types of fibers, it is possible to normalize the strains at the onset of damage and ultimate strength by the ultimate strains of the fibers provided by the suppliers (Fig. 2 on the right).

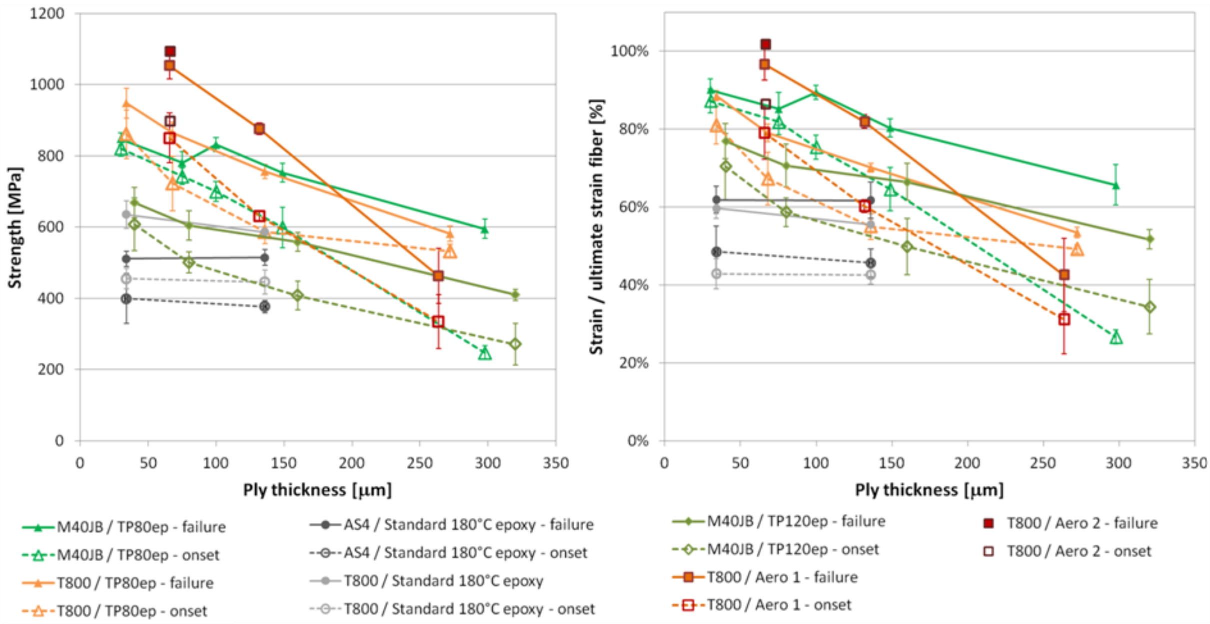

Figure 2. Left: onset of damage and ultimate failure strengths as a function of the ply thickness for various fiber/matrix combinations. Right: onset of damage and ultimate failure relative strain (normalization by their respective fibre ultimate strain) as a function of the ply thickness for the same systems.

Classical composites with ply thicknesses above 200µm exhibit onset of damage and failure in the range of 25-50% , respectively 41- 66%, of the ultimate strain of the fibers. However, for the laminates

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with plies thinner than 100µm, those two ranges are found to be significantly higher, with 58-89%, respectively 70-100%, of their fiber ultimate strain for onset and failure. This study therefore demonstrates that by using very thin plies and an appropriate resin formulation, it is possible to obtain a quasi-isotropic laminate that uses the full potential of the fibers in unnotched tension. These results also show that while the type of fiber used determines the ultimate level of performance achievable for very thin ply composites, the matrix and matrix-fiber interface seem to be responsible for the range and magnitude of the observed size-effect.

3.2. Hybrid laminates

Stress-strain curves in unnotched tension for the three hybrid configurations are shown in Fig. 3 and compared to classical thick- and thin-ply laminates (T800/Aero1 with a ply thickness of 268µm, and T800/Aero2 with a ply thickness of 67µm respectively). Both ply-level T800/HR40 hybrid laminates show an interesting pseudo-plastic behavior, with a smooth transition and about 0.47% of pseudo-plastic strain at failure. Their initial modulus corresponds to the law of mixtures and is thus 5% higher than the modulus of the T800 only laminate. The 0°/0° configuration exhibits a slightly higher onset of damage than the 0°/90° configuration, which for the former corresponds to the ultimate strain of the HR40 fibers. The ultimate strain corresponds to the ultimate strain of the T800 fibers, and the ultimate strength can be predicted by assuming that the 0° HR40 fibers are not carrying load anymore: a new modulus disregarding the HR40 plies is easily calculated with the classical laminate theory, and multiplying it by the ultimate strain of the T800 fiber yields an excellent estimation of the achieved ultimate tensile stress.

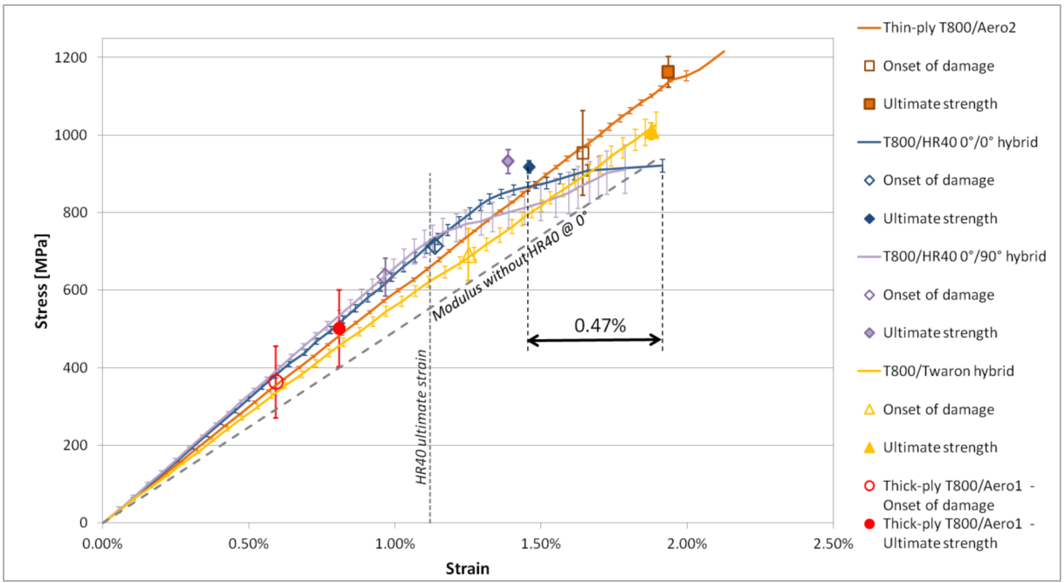

Figure 3. 0°/0° and 0°/90° ply-level T800/HR40 and tow-level T800/Twaron hybrids compared to non-hybrids thick- (T800/Aero1, ply thickness = 268µm) and thin-ply (T800/Aero2, ply thickness = 67µm) in unnotched tension on quasi-isotropic laminates. All curves and values are averages. The horizontal value for the ultimate strengths dots correspond to the elastic part of the strain.

The tow-level T800/Twaron hybrid exhibits a linear stress-strain behavior. Its initial modulus is 11% lower than for the reference, as expected from the law of mixtures. The onset is lower than for the thin-ply reference, and comparable to the onset of the other hybrids. The ultimate strain is very close to the ultimate strain of the T800 fibers. It is interesting to note that while the onset of damage and ultimate strength of the hybrids are lower than those of a classical thick-ply laminate, they remain much higher than those of a classical thick-ply laminate. In a sense, fiber hybridization in thin-ply laminates provides an interesting compromise in terms of pseudo-ductility, improved strength and first ply failure.

The preliminary results of the compact tension tests show both a higher maximum load and a slower crack progression for the hybrid laminates compared to non-hybrid thin-ply ones using the same constituents (Fig. 4). It was observed that after a certain crack extension, which depends on the laminate, the specimens tend to fail in compression at the opposite side to the crack. As a first comparison, the average dissipated work per unit area (Table 3) has been estimated from the crack length (the maximum crack extension visible in the outer 90° ply) before compressive failure and the dissipative work until that point (assuming a linear unloading to zero). Compared to the reference (T800/Aero2 with a ply thickness of 67μm), the tow-level T800/Twaron hybrid shows a doubling of the aerial dissipated energy, whereas the ply-level T800/HR40 hybrid in the 0°/0° configuration is quadrupling it. The ply-level T800/HR40 hybrid in the 0°/90° configuration shows an improvement as well, but it is very limited compared to the other T800/HR40 hybrid. The lower performance of the 0°/90° configuration of the T800/HR40 hybrid compared to the 0°/0° configuration in unnotched tension (onset) and compact tension is probably due to the higher interlaminar shear stresses generated by the large ply angle mismatch found in this configuration. A more detailed analysis of those results using DIC is in progress.

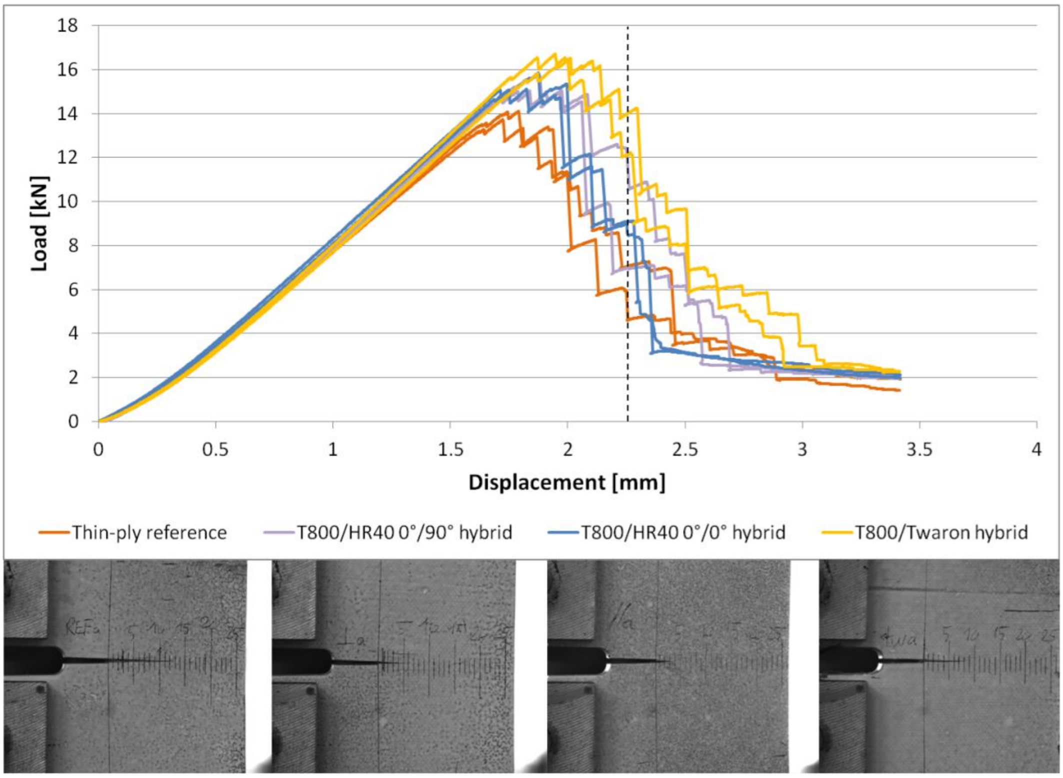

Figure 4. Ply-level T800/HR40 and tow-level T800/Twaron hybrids compared to thin-ply T800/Aero 2 non-hybrid (reference) in compact tension on quasi-isotropic laminates. The pictures at the bottom show the crack extension for a displacement of 2.25mm (dotted vertical line on the graph).

Table 3. Compact tension preliminary results

Material	Max. crack extension before failure in compression (mm)	Dissipated energy / crack apparent area (kJ/m^2)
Thin-ply reference	19	92’493
T800/HR40 0°/90° hybrid	12	137’205

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T800/HR40 0°/0° hybrid	4	367’062
T800/Twaron hybrid	10	184’225

3.3. Compression after impact (CAI)

Residual strength values in compression after a 30.2 J impact are shown in Figure 5. It should be noted that those results were obtained on specimens of about 4mm thickness (except for the Twaron hybrid) corresponding to a relative impact energy of about 1700 inch lbf / inch^2. As the ASTM standard recommends 5mm thick specimens and an impact relative energy of 1500 inch lbf / inch^2, the obtained values are conservative compared to other published values and can be considered as a lower bound.
The TP80ep matrix studied in [2] with high modulus M40JB fibers can be seen as a rather brittle first generation thin-ply composite with a CAI strength of only 150 MPa. The “Aero 1” system already shows a substantial increase in CAI strength while the optimized “Aero 2” formulation reaches CAI strength values of about 200 MPa, which is comparable to the second generation of aerospace composites. Overall, the CAI strength of the hybrid laminates considered here was found to be approximatively 10% lower than the reference T800/Aero2 system. The 0°/0° version of the T800/HR40 hybrid is once again performing better than its 0°/90° counterpart. The Twaron/T800 hybrid exhibited a relatively good CAI but the direct comparison with the other systems is slightly biased as its thickness is about 10% larger than other ones (4.5mm instead of ~4mm).
As shown in Figure 5, interlayer toughening is clearly needed to reach CAI values comparable to the third generation of aerospace composite (about 300 MPa). The interlayer toughened system with only one toughened interlayer every seven interfaces (n = 7) showed signs of delamination after impact, but already improved marginally the CAI strength (+6.5%) with respect to “Aero 2” formulation witouhout toughened interlayers. With every third interface toughened the improvement is more obvious (+18%). With all interfaces toughened (n = 1), an impressive increase of +43% is achieved with a CAI strength of 285 MPa. Based on our estimates, this system is expected to reach CAI values of about 300 MPa for a 1500 inch lbf/ inch^2 relative impact energy.

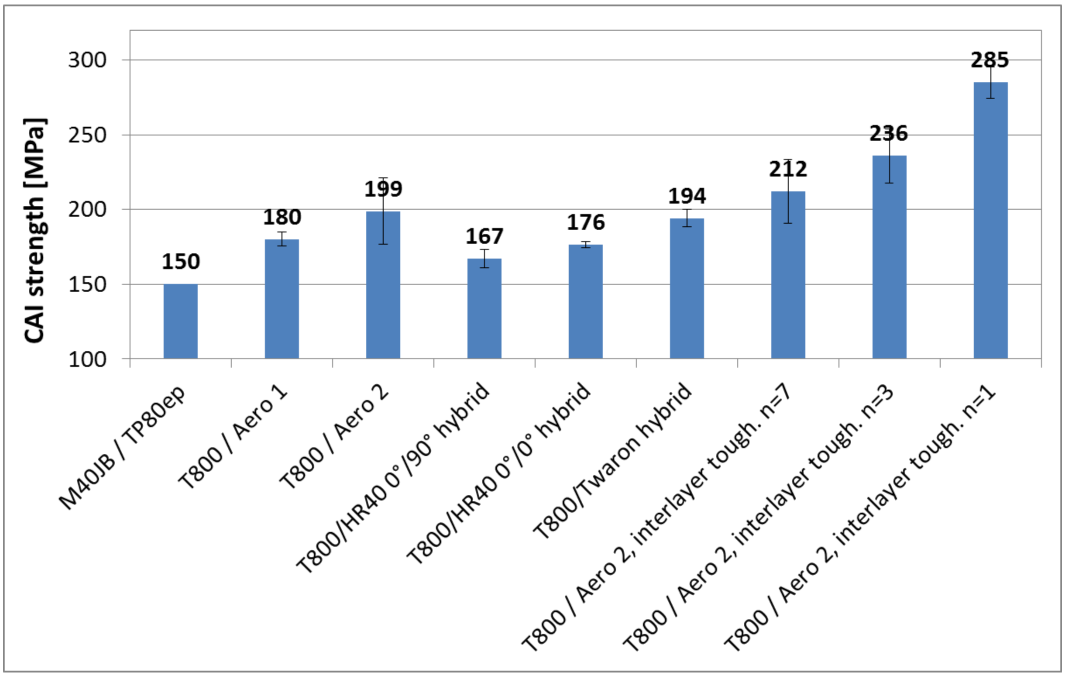

Figure 5. Compression after impact (30,2J) residual strength for various constituents and hybridization strategies. Except for the T800/Twaron hybrid, the specimen thickness is close to 4mm and the obtained value therefore at the lower bound of the standard.

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4. Conclusions

In the present work, the thin-ply size-effect in quasi-isotropic laminates under unnotched tension is confirmed for different types of fibers ranging from high strength to intermediate and high modulus. The matrix has shown an important role as its performance determines the range and magnitude of the size effect. It is observed that a weak matrix or fiber-matrix interface can potentially hinder the ply-thickness effects.

Compared to classical thick-ply composites which experience damage as early as about 35% of the ultimate strain of the fiber and fail around 50%, all working thin-ply composites tested so far remain undamaged below 60% and fail above 75% of the ultimate strain of their fibers. Remarkably, the latest generation resins developed in this project combined with T800 fibres in a quasi-isotropic laminate have an onset of damage above 900MPa and fail above 1'100MPa. These results show that optimized thin-ply composite, such as the T800/Aero2 system at 67μm ply thickness, can actually use the full potential of the fibres with a failure at 100% of fibre ultimate strain and an onset of damage up to 85% of this value.

For applications for which translaminar toughness and stress concentrators are an issue, new hybrid solutions have been developed. The HR40/T800 carbon-carbon ply-level hybrid composite offers a much improved translaminar toughness along with a marked pseudo-ductile behavior. The carbon-Twaron tow-level hybrid pre-preg shows a much improved translaminar toughness while retaining a linear behavior and a good CAI performance. The latter is very tough to machine, but could most likely be very interesting for high energy impact resistance.

Damage tolerance is greatly improved through matrix optimization (+30% with respect to TP80ep) and interlayer toughening (+43% with respect to non-interlayer toughened). Compression after impact values in the range of 300 MPa corresponding to the state-of-the-art of aerospace composites can be achieved with thin-ply composites, thus combining the advantages of the latter in terms of increased onset of damage, fatigue and hot-wet performance with the very high toughness and damage tolerance needed for aeronautical applications.

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