TRANSLAMINAR FRACTURE OF REGULAR AND HYBRID THIN PLY COMPOSITES: EXPERIMENTAL CHARACTERIZATION AND MODELING

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Abstract

Thin-ply composites have been shown to drastically increase the onset of damage and unnotched strength of composite laminates but exhibit a fragile fracture. Strategies to potentially improve translaminar toughness of thin ply composite should thus be developed. In this work, compact tension tests are performed using digital image correlation (DIC) and J-integral to measure the translaminar crack resistance curve of regular and hybrid fiber thin-ply composites. It is observed that the translaminar toughness decreases nearly proportionally with ply thickness, which relates to a linear decrease of the fiber pullout length. Hybrid thin-ply laminates made of T800 & HR40 fibers are designed to generate sub-critical fiber fragmentation lengths of 1 mm to promote fiber pullout. Ply-level hybrid quasi isotropic laminates made of T800-TP175@68µm & HR40-TP175@20µm plies are produced and characterized in unnotched, open hole and compact tension tests. The hybrid laminates exhibit a pseudo ductility of 0.6% and show up to 13% improvement in translaminar toughness. Fracture surface analysis shows that the pull out length is increased by the hybridization strategy. However, the additional energy dissipated by this mechanism is in part counter balanced by the substitution of 22%vol of high modulus/low toughness plies which limits the effective toughness increase.

1. Introduction

In recent studies, thin ply composites with ply thickness in the range of 30 to 100 µm have been shown to exhibit significantly improved laminate performance through the delay or suppression of delamination and intralaminar transverse cracking. As shown in [1, 2, 3], when ply thickness is reduced from 300 to ~30µm in a quasi-isotropic laminate, a clear transition of failure mode in unnotched tension is observed: thick ply laminates exhibit the traditional multimode fracture with a sequence of early transverse cracking and delamination before final failure of the 0° plies, while a fiber dominated quasi-brittle fracture is observed for the laminates with thinnest plies. Thin-ply laminates can thus reach very high tensile strength up to the fiber ultimate strain but the near suppression of other damage mechanisms prevent the development of a large process zone close to stress concentrators which leads to a reduction of their notched tensile strength and an increased notch sensitivity. Recent studies have shown that the translaminar toughness of a laminate decreases with ply thickness [4]. This reduction raises concern for the use of thin-ply composites in damage tolerant design. In parallel with these findings, strategies to produce pseudo ductile UD composites have been recently developed in order to re-introduce an apparent ductility into normally brittle composites. One of the methods developed makes use of fiber hybridization in the form of two different types of thin UD plies [5], one with fibers having a low ultimate strain (usually with higher modulus) and the other with high ultimate strain (usually lower modulus). Significant pseudo ductility could be achieved by carefully selecting the fiber types and ply thicknesses to promote stable fiber fragmentation without overloading the high strain fiber plies whilst avoiding delamination by using sufficiently thin plies. Another strategy to improve translaminar fracture is to promote long distance fiber bridging by incorporating high energy dissipation fibers such as Aramid into a carbon laminate.

In this work,regular and hybrid quasi isotropic laminates are designed and tested in unnotched tension (UNT), open hole tension (OHT) and compact tension (CT) to study their plain strength, notched strength and translaminar toughness. Damage mechanisms are studied by quantitative analysis of the fracture morphology from X-ray tomographies and are linked to ply thickness and fiber hybridization effects. Cohesive zone modeling translaminar fracture of regular and hybrid thin-ply laminates will be presented during the conference.

2. Materials and methods

Two types of thin-ply composites are used as baseline in this study. To evaluate the ply thickness effects on translaminar toughness of thin-ply composites, cross ply and quasi isotropic laminates are firstly produced using of NTPT M40JB-TP80ep prepreg with a range of ply thickness from 30 μm to 150 μm [2]. Secondly, a high performance thin-ply T800-TP175 quasi-isotropic composite with a ply thickness of 67 μm [3] is used as a basis for comparison of the potential of fiber hybridization in aerospace grade composites. NTPT M40JB-TP80ep UD prepreg is a low temperature curing system (80°C) with a relatively high modulus of 210 GPa and elongation to fracture of 1% in the fiber direction [2] while NTPT T800-TP175 system is a high temperature composite (180°C curing) with an intermediate modulus of 161 GPa and an elongation to failure of 1.9% [3].

Two hybridization strategies are implemented with the aim of improving translaminar toughness and OHT of thin ply laminates: (a) a carbon-carbon hybrid laminate (ply by ply hybrid laminate) with controlled fiber fragmentation to promote longer pullout length, (b) large scale fiber bridging with the addition of high elongation / high energy absorption fibers by incorporating Aramid fiber tows in carbon fiber UD prepreg.

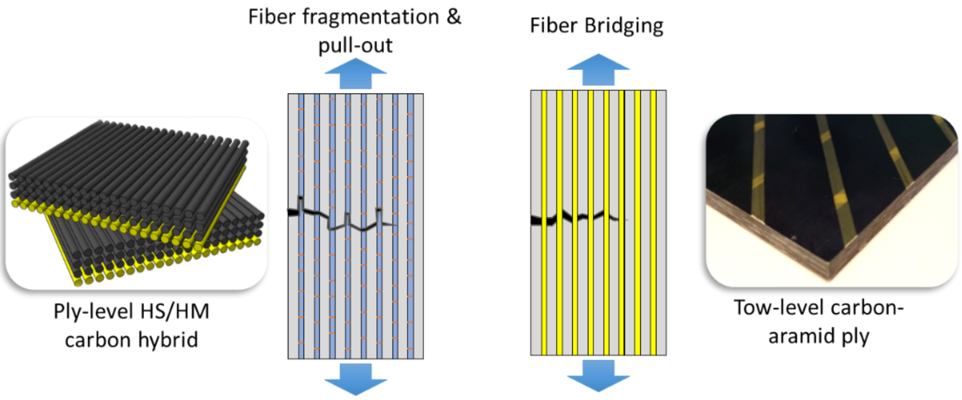


Figure 1. Strategies for translaminar toughness control and corresponding hybrid composite designs

2.1 Ply by Ply carbon-carbon hybrid laminate

Hybrid high strain (HS) - high modulus (HM) carbon fiber laminates are designed using the same equations as developed by Jalalvand et al. [5] for pseudo ductile composites but following a slightly different set of objectivesConsidering that translaminar fracture toughness was shown to be correlated to the length of pull-out developed in the process zone, the main goal pursued in this work is to try to extend the pull out length in thin-ply composites by introducing distributed micro crack precursors by controlled fiber fragmentation in the stress concentration regions. Quasi-isotropic layups $[45/90/-45/0]_{ns}$ are considered in which each layer is constituted by an hybrid ply. The hybrid ply, shown on Fig. 1, consists of two thin plies of HM and HS fibers stacked together with parallel [0/0] or perpendicular [0/90] fiber orientations. The design of the hybrid ply sub laminate is based on the following principles:

1) The target critical fiber fragmentation length l_c is set to about 1 mm and estimated using the plastic shear lag model $l_c = \sigma_{HM}^{u} t_{HM} / \tau^{y}$ [5] where σ_{HM}^{u} , t_{HM} and τ^{y} denote respectively the ultimate tensile strength and thickness of the HM ply and the shear yield stress of the matrix.
2) The strength and thickness of the HS plies must be sufficient to sustain the total load after fragmentation of the HM plies: $\sigma_{HS}^{u} \geq \sigma_{L}^{f} (t_{HM} + t_{HS}) / t_{HS}$. The laminate strength at onset of fragmentation is estimated as $\sigma_{L}^{f} = E_L \varepsilon_{HM}^{u}$ where E_L is the elastic modulus of the laminate and ε_{HM}^{u} denotes the ultimate strain of the HM fibers.
3) Delamination should not occur between HM and HS plies until the failure of the sub laminate. This condition is evaluated using the expressions in [5].
4) The laminate stress at onset of damage by fiber fragmentation σ_{L}^{f} should be sufficiently higher than the strength of an equivalent thick-ply laminate in order to retain the thin-ply advantages.

Based on those criteria, an optimal combination was found by grouping one 20 μm ply of high modulus HR40-TP175 (elongation to failure ε_{HM}^{u} = 1.1%, E_{HM} = ~217 GPa) with the baseline 68 μm ply of T800-TP175, which corresponds to a fiber ratio of 22% HR40 and 78% T800. The hybrid thin-ply prepreg were produced by North Thin Ply Technology using an automated tape layup system to produce hybrid fiber prepreg rolls for either 0/0 or 0/90 fiber orientations which could then be processed normally as a single prepreg to form the final isotropic laminate.

2.2 Carbon-Aramid hybrid ply

Due to the high contrast of fiber moduli, a ply-by-ply hybridization of carbon and aramid fibers would be prone to early delamination and thus another type of hybridization strategy has to be developed. Benefitting from the fact that the UD thin-ply prepregs are produced by spreading parallel fiber tows, some of the carbon fiber tows can be substituted by low K Aramid fiber tows to produce a tow-by-tow hybrid fiber UD prepreg. In the selected configuration for this work, Twaron aramid fiber tows of ~2.5mm width are inserted every 16.5mm, which corresponds to a fiber area ratio of 15% Twaron Aramid fiber and 85% T800 carbon fibers.

2.3 Unnotched and open hole tensile tests

For each baseline and hybrid laminates considered in this study, composite plates are produced by manually stacking prepreg tapes with intermediate debulk steps every 4 plies before curing in an autoclave at 80°C for 8h at 3bar for M40Jb-TP80ep and 180°C for 6h at 6bar for T800-TP175 and hybrids. The baseline hybrid composites are first compared to the baseline T800-TP175 composite in unnotched tensile tests (UNT) on quasi-isotropic laminates following ASTM D3039 (gauge length 240mm, width 24mm, thickness 2mm, tapered glass-epoxy tabs). The tensile tests are performed at a loading rate of 2mm/min on an MTS 809 hydraulic testing machine equipped with a 100kN load cell. The specimens are equipped with HBM 1-LY-41-6/120 and 1-XY31-3/120 strain gauges and the onset of damage of the composite is monitored by acoustic emission similarly to [2] using a Mistras-2001 system from Physical Acoustics Corporation, with two NANO-30 probes. The open hole notched strength (OHT) and onset of damage is also evaluated on quasi-isotropic specimens with a hole diameter of 6 mm and a sample width of 36 mm using the same test setup as for UNT.

2.4 Compact tension tests

Quasi isotropic plates of 10mm thickness are produced as described above for T800-TP175 and the hybrid laminates. Standard compact tension (CT) specimens of length 65 mm and height 60 mm are CNC machined, and a thin precrack is finally cut using a diamond wire saw (wire diameter 0.13mm) to generate an effective precrack length comprised between 20 and 27 mm. To visually monitor the crack extension, the front side of the specimen is marked with a 1mm step grid, while the back of the specimen is spray painted to generate a fine speckle pattern used for digital image correlation (DIC) displacement field measurement.

(a) (b)

Figure 2: (a) Representative vertical displacement fields obtained by DIC; (b) Three zones selected for the fitting of the displacements fields and contour selected for the *J*-integral (blue, red and superposed green).

The CT tests are performed on a hydraulic MTS 809 testing system under displacement control at a loading rate of 0.5 mm/min. The crack opening displacement (COD) is measured using a crack opening clip gauge while the two cameras (1.3MPixels, 10fps, 25mm lens) are used to monitor crack extension (front face) and DIC pattern (back). The crack extension is evaluated visually from the front facing images. Correlated Solutions Vic 2D DIC software is then used to reconstruct the displacement field around the crack during the test and the displacement fields calculated at different crack propagation states are exported to Mathworks Matlab for direct computation of the J-Integral (Eq. 1) over each segment of the contour shown in Fig 2b.

$$J = \int_{\Gamma} w \, dx_2 - \int_{\Gamma} \sigma_{ij} n_j \frac{\partial u_i}{\partial x_1} \, ds \,, \quad i, j = 1, 2 \tag{1}$$

The DIC displacement fields calculated by the software (Fig. 2a) are first fitted with a piecewise cubic smoothing spline over three regions in order to compute accurate displacement gradients and strains on the contour. Stresses and strain energy are then computed from the calculated strain tensor and the stiffness matrix of the laminate. The integration over each segment is computed by trapezoidal integration rule.

2.5. Fracture analysis

After testing, selected specimens are scanned by X-Ray computed tomography at AMADE / University of Girona to analyze the 3D crack patterns generated during crack propagation. The main crack profile is then manually traced on transverse section at different distance from the crack front. The reconstructed crack height profiles are processed by wavelet decomposition to isolate the local crack height oscillation that corresponds to fiber pullout as shown on Fig. 3. The RMS pull-out length is finally compared for the different systems as a function of the distance to the crack front in order to highlight the evolution of the fracture process zone.

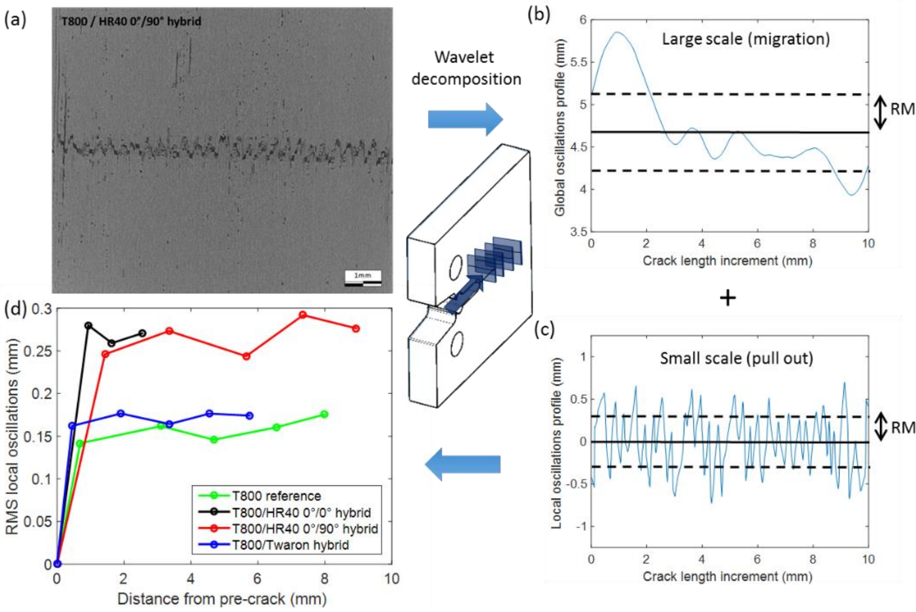


Figure 3: Crack profile analysis in CT specimens from X-Ray tomography images (a) by wavelet decomposition of large scale crack migration (b) and local pull out (c). RMS pull-out amplitude is reported for the different hybrid materials tested as a function of distance from the crack front in (d).

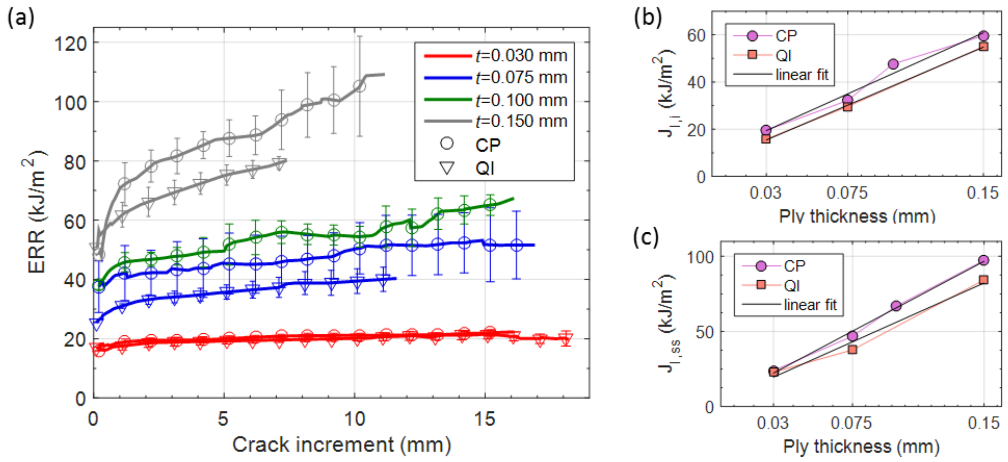


Figure 4: (a) average R-curves for different ply thicknesses in TP80ep-M40Jb CP and QI laminates; Critical translaminar ERR at initiation (b) and steady state (c)vs ply thickness

3. Results

3.1 Effect of ply thickness

The translaminar R-curves of M40Jb-TP80ep quasi-isotropic (QI) and cross-ply (CP) laminates are compared in Figure 4a. It can be clearly seen that the translaminar crack resistance is significantly reduced when reducing ply thickness, both at initiation and during propagation. As expected, the QI laminates exhibit a consistently lower translaminar strength compared to CP because of their lower fraction of 0° plies. As shown in Figure 4b&c, both initiation and propagation critical ERR show a nearly proportional decrease with ply thickness which might raise concerns for damage tolerance for the thinnest plies. However, despite the adverse size effects, it should be noted that the lowest value of translaminar toughness, recorded for the 30µm plies quasi-isotropic laminate, remains slightly higher than the one of high performance aluminum alloys used in aeronautics. Nevertheless, it appears clearly that, when selecting an optimal ply thickness, a compromise has to be found between the strength and toughness. In that regard, the optimal ply thickness is usually found in the range of 100 to 60 μm [2,3].

3.2 Hybrid composites

As shown in the UNT test results in Fig.5, due to the 22% fraction of high modulus HR40 fiber, the T800-HR40 hybrid laminates show a significantly higher elastic modulus in UNT tests while the T800-Twaron hybrid is more compliant due to the lower modulus of aramid fiber.

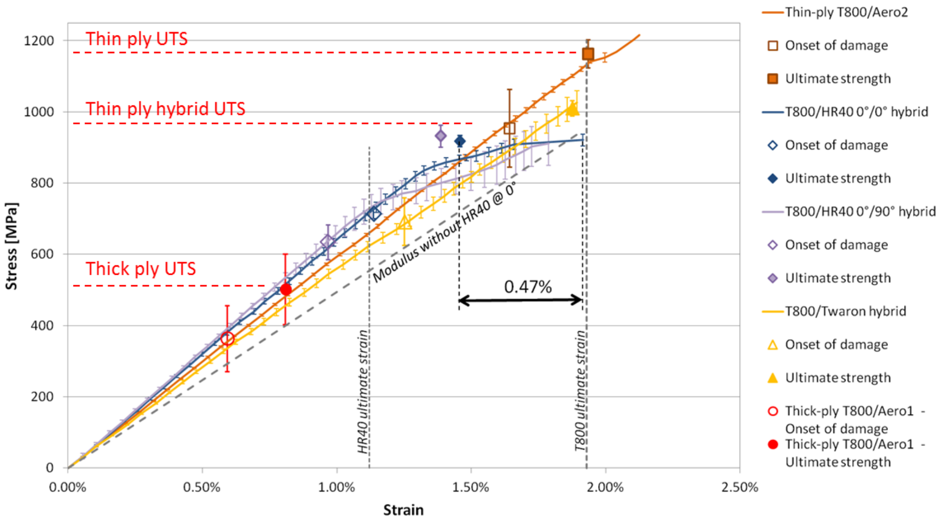
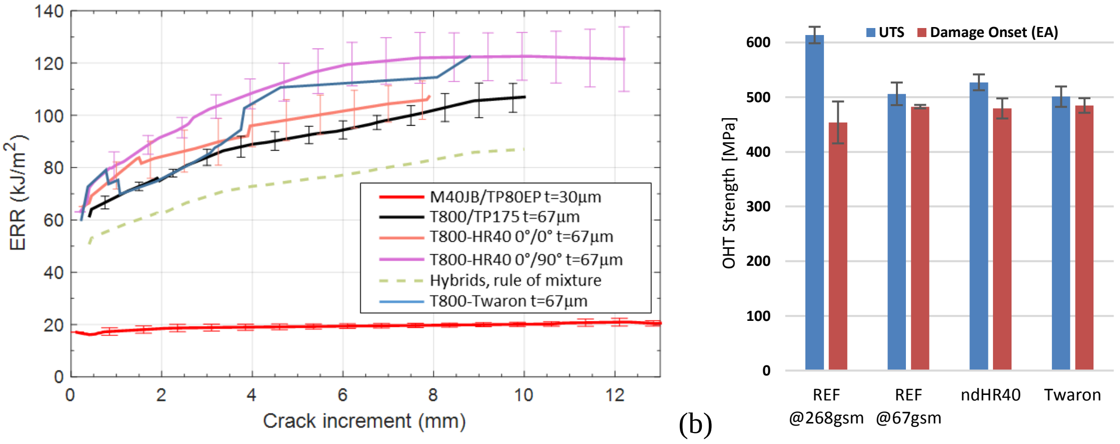


Figure 5. Unnotched tensile response of quasi-isotropic T800-HR40 and T800-Twaron hybrid laminates compared to the T800-TP175 baseline material at 67μm ply thickness.

Significant pseudo ductility of 0.47% is observed for the T800-HR40 hybrid composite laminates (both 0/0 and 0/90) with a deviation from linearity due to fiber fragmentation at a strain corresponding to the ultimate strain of the HR40 fiber. However, the T800-Twaron hybrid behaves quasi linearly until failure which is to be expected as the Twaron fibers have a higher ultimate strain compared to T800 and thus do not fragment before failure. Both T800-HR40 and T800-Twaron hybrids fail at a strain corresponding to the ultimate strain of the high strength T800 fiber (1.9%) which demonstrates that despite fiber fragmentation, no delamination develops until final failure. Thanks to the suppression of delamination related to the low ply thickness, both the onset of damage and strength of the hybrid quasi-isotropic laminates are Noticeably improved compared to traditional thick ply laminates with the first damages occurring at about 700 MPa and a final failure above 900 MPa for both T800-HR40 and T800-Twaron. Finally, the observed UNT onset of damage and strength successfully validate the selected design hypotheses and it was thus verified that the performance of all the thin-ply laminates tested here can be accurately predicted by using simple classical laminate theory. The translaminar R-curve of the baseline and hybrid laminates are compared in Fig. 6a. Overall, both regular and hybrid composites have a comparable translaminar toughness at initiation, but that the hybrid laminates exhibit an improved crack resistance as crack propagates (gain of up to 18% for T800-HR40 0/90). Interestingly the 0/90 ply configuration in the T800-HR40 hybrids is significantly tougher than the 0/0 configuration as it seems to promote a larger process zone. It should also be noted that due to the limited stable crack propagation before compressive failure develops in CT specimens, some of the R-curve have not yet reached a steady state (such as T800-Twaron hybrid) and thus larger contrast might have been observed if longer crack extension could have been monitored. Finally, the reference high strength T800-TP175 67μm thin-ply QI laminate has a comparable translaminar toughness to other known aerospace grade composites and thus does not seem to be affected too seriously by adverse ply thickness effects as compared to the high modulus M40JB-TP80ep laminates.



(a) (b)

Figure 6: (a) Translaminar R-curve of quasi-isotropic T800/HR40 hybrid composites compared to corresponding non-hybrid laminates (b) OHT strength and onset of damage

As shown in Fig. 6b, only the 0/0 HR40 hybrid (ndHR40) shows a slight improvement of OHT strength compared to the baseline T800-TP175 laminate (527 MPa vs 506 MPa, +4%) but the hybridization effect is not sufficient to reach the OHT strength level of the thick-ply T800-TP175 268µm (614 MPa). Indeed, compared to the thick ply composites, the observed failure mode of the hybrid thin-ply T800-HR40 laminate does not show signs of delamination before failure, which would help reducing the stress concentration at the apex of the hole. However, in all cases, the thin-ply composites exhibit a higher onset of damage compared to their thick ply counterparts.

3.3 Fracture morphology analysis

The analysis of the fracture profiles obtained by X-Ray tomography (Fig. 3d) highlights the fact that the length of the pulled out fiber bundles is effectivelly increased in T800-HR40 hybrid laminates, which tends to support the initial hypothesis stating that controlled fiber fragmentation can be used as a mean to control pull-out length in translaminar fracture. Moreover, the average RMS pull-out amplitude of ±0.3mm (~0.6 to 1mm peak to peak) measured in T800-HR40 X-Ray scans correlates reasonably well with the predicted fragmentation length of ~1 mm. In contrast, the T800-Twaron hybrid composite does not promote longer pull-out length of the carbon fiber bundles, but as can be seen in Figure 7, the Aramid fibers extend much further away from the crack plane than the carbon fiber. Combined with the lack of steady state in the R-curves measured, this could suggest that the Aramid fibers continue to bridge the crack at much larger opening than in the baseline laminate. However, tests with longer stable crack growth would be required to verify this hypothesis and determine if the aramid fibers significantly improve translaminar toughness for large scale cracks. Finally, the reconstructed fracture surfaces shown in Fig. 7 clearly highlight the large contrast in pull-out length between the high modulus M40JB-TP80ep,the high strength T800-TP175 baseline and the hybrids composites. This differences in pull out length and fracture topology could at least in part explain the higher toughness of the latter. However, in terms of toughness, this effect remains comparatively small compared to the potential reduction induced by ply thickness reduction, and thus further optimizationof that hybrid composite concept is needed to achieve both high strength and high toughness.

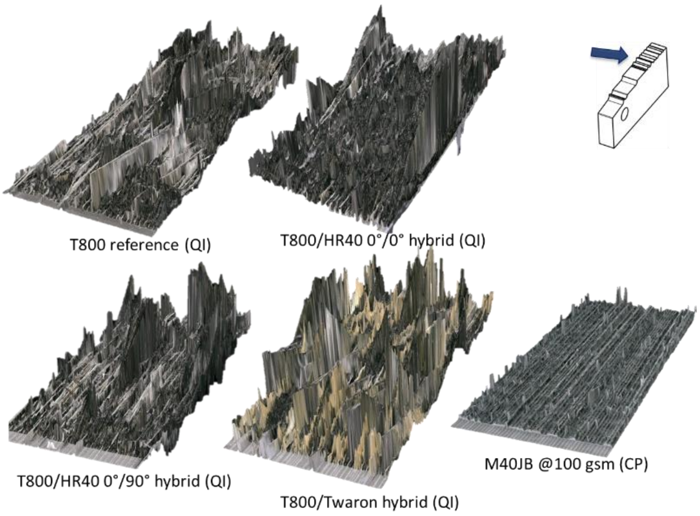


Figure 7. CT fracture surfaces for the QI high strength T800-TP175 @67μm and hybrid laminates compared to high modulus M40JB-TP80ep CP laminate of comparable ply thickness.

3. Conclusions

In conclusion, this study has shown that:

1) Reduction of ply thickness induces a directly proportional decrease in translaminar toughness for both QI and CP laminates in high modulus thin-ply composites. This reduction correlates with the decrease of fiber pull-out length of the 0° plies. However, the translaminar toughness of high strength T800-TP175 composite with an intermediate ply thickness of 67μm remains perfectly acceptable with values in the range of 60 to 100 kJ/m^2 in a quasi isotropic layup.
2) Two hybridization strategies have been proposed and demonstrated to improve translaminar toughness, (a) by increasing pull-out length using controlled fiber-fragmentation and pull-out in HM/HS carbon – carbon hybrid plies and (b) by increasing energy dissipation through large scale fiber bridging in hybrid carbon - aramid plies.
3) The observed damage mechanisms and UNT strength correlate well with calculations and both hybrid laminate exhibit excellent strength and toughness properties.

Acknowledgments

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