EFFECTS OF HYBRIDIZATION OF LAMINATES WITH RANDOMLY ORIENTED STRANDS AT COUPON AND PART LEVELS

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Keywords: *Randomly oriented strands, Compression moulding, Hybrid effect, T-stiffeners*

ABSTRACT

Hybridization of randomly oriented strands (ROS or R) and laminate groups are necessary to obtain the trade-off solutions of formability and performance in complex parts fabricated with composites. The current work summarizes two experimental studies (at the coupon and part levels) carried out on hybrid architectures of randomly oriented strands and laminate groups. At the coupon level, the tensile behaviour of co-moulded hybrid fibre architectures of randomly oriented strands combined with cross-ply laminates is studied. The mechanical effects of hybridization such as changes in stiffness and strength, failure characteristics, and the variability of results are explained and compared with Aluminum 7075. Significant improvements in the mechanical and processing quality of randomly oriented strands are observed with small proportions of laminate groups in the specimen. A positive synergy or a positive hybrid deviation from the rule of mixtures exists between the architectures when stacked in specific configurations (about 15% in longitudinal stiffness and 20% in longitudinal strength). At the part level, two critical manufacturing issues namely the strand waviness and the swirling of strands at intersecting junctions of geometric features hinder the extensive use of ROS. The part level study aims at mitigating these flow-induced defects through the hybridization of ROS with continuous fibres, with an emphasis on the ease of manufacturing, and repeatability. Two hybridization strategies are proposed for T-stiffeners as they represent the generalized intersecting junctions of stiffened panels. They include: flow-control element (FCE) and flange reinforcements (FR). A quantitative assessment of pull-out strengths of three T-stiffener configurations is made and compared with conservative estimates of pull-out strengths of T-stiffeners made of laminates. FCE improves the strand flow at the junction, reduces variability and enhances the pull-out B-basis design allowable by about 24%. A quasi-isotropic laminate with FR along with an FCE produces 12.5% pull-out strength improvement. Further, the work bolsters the idea of using hybridized ROS composites on load bearing complex shaped aerospace parts as efficient replacements of metallic structures.

1 INTRODUCTION

Continuous fibre (CF) preforms exhibiting excellent mechanical performance are limited in use due to the low formability characteristics and are confined to simple shell-like geometries with minimal curvature and thickness variations. On the other hand, long discontinuous fibre preforms such as randomly oriented strands (ROS) (Figure 1.a) offer high processability and formability but exhibit lower mechanical performance [1]. A trade-off solution, as suggested by various authors [2-9], is to use a 'hybrid architecture' that integrates the formability of ROS and performance of CF (Figure 1.b). By controlling the contents, position and arrangement of the individual phases, adequate formability and better mechanical performance can be achieved. Thermosets and thermoplastics are extensively used as matrix systems. Thermoplastics form crystals that are thermally reversible upon melting [10] allowing re-moulding, reparability, ease of joining by welding, and recyclability. Conversely, thermoplastics are difficult to process owing to high melting temperatures, high viscosities, and the need for high temperature and pressure for consolidation and crystallization. Compression moulding that involves preheating a composite preform above its melting temperature, then placing it in the tool and consolidating by the direct action of the mould has been recognized as a versatile and low cost manufacturing method for ROS thermoplastics [1].

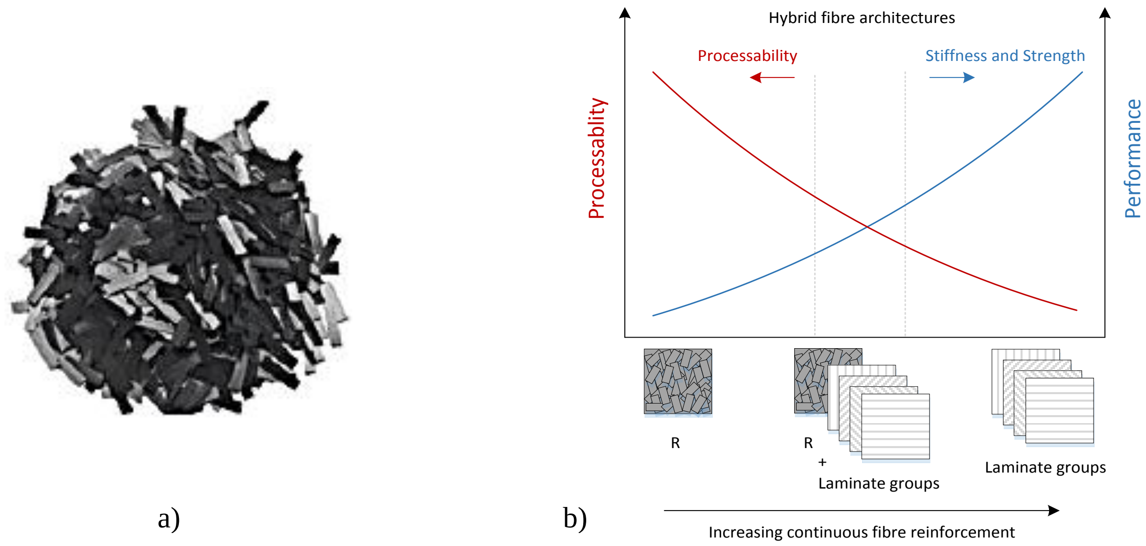


Figure 1: a) Randomly oriented strands or chips of prepreg tapes; b) Performance vs. processing [11]

In the literature, several authors have studied the mechanical behaviour of randomly oriented strands of prepreg-based unidirectional tapes, in thermoset and thermoplastic matrix systems [12-15] at coupon and part levels. The results of their work indicated that the ROS based coupons exhibited similar stiffness as quasi-isotropic laminates while their strengths were much lower and are accompanied by a huge variability. The variability was mainly attributed to the heterogeneous microstructure and the strand waviness (Figure 2.a). Most of the studies on hybrid fibre architectures deal with the use of randomly oriented fibres and continuous tapes. Selmy et al. [16] examined hybrid configurations that consisted of unidirectional (U) and random glass fibres and epoxy. The tensile behavior of hybrids was improved when U-fibres are placed in the middle vs. the surface of the composite. Han et al. [17] studied the bearing failure behaviour of bolted joints in hybrid architecture with ROS and fabric reinforcements. Bourban et al. [4] optimized the interfacial properties of glass mat thermoplastics. Lee et al. [18] worked with CF reinforced by interlayers of short random fibre mat and found that hybrids exhibited less scatter of the strength properties and higher transverse strength than CF specimens. Brooks et al. [19] focused on monitoring and modelling of damage development in hybrid fabric/glass mat thermoplastic composites produced by compression moulding. Hybrid material showed an increase of 53% in modulus and about 30% in maximum load over the monolithic glass mat. While the overall performance of low load bearing or non-structural ROS parts have been studied minimally [15, 20, 21] at the part level, none of the studies deal with ROS hybrids for load bearing applications. Strand waviness and swirling at the junctions of intersecting geometric features (Figure 2.b) are the two critical manufacturing issues that increase the variability of properties, thus causing a reduction in the design allowables. In the general context, hybridization refers to the use of two distinct materials whose characteristics complement each other to produce synergistic effects or the hybrid effect [22]. The effect is assessed either as positive or negative based on the deviation of the material property from that of the rule of mixtures (RoM) behaviour. Hybridization is usually carried out at the fibre level to increase the ductility of a low-elongation material such as carbon fibres by intermingling glass or polypropylene fibres that exhibit higher elongations. The problem investigated here is that of hybridization of fibre architectures, typically a low elongation-low strength material (i.e. ROS) hybridized with a higher strength-higher elongation material (i.e. continuous fibre laminates) of the same fibre type and matrix system.

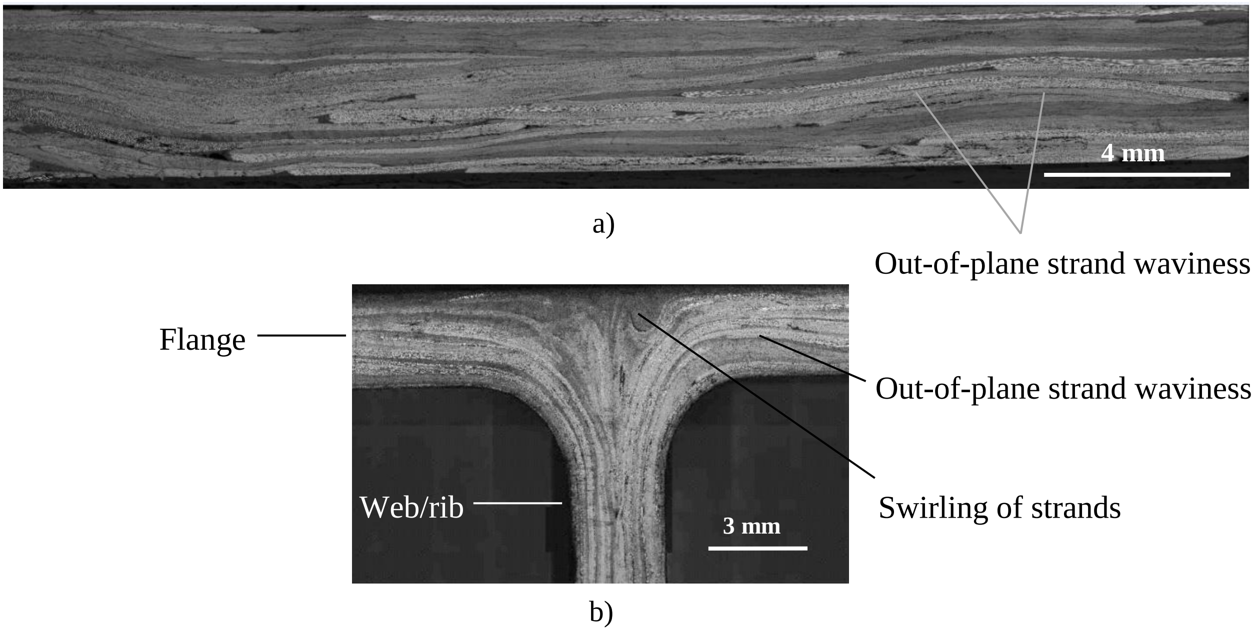


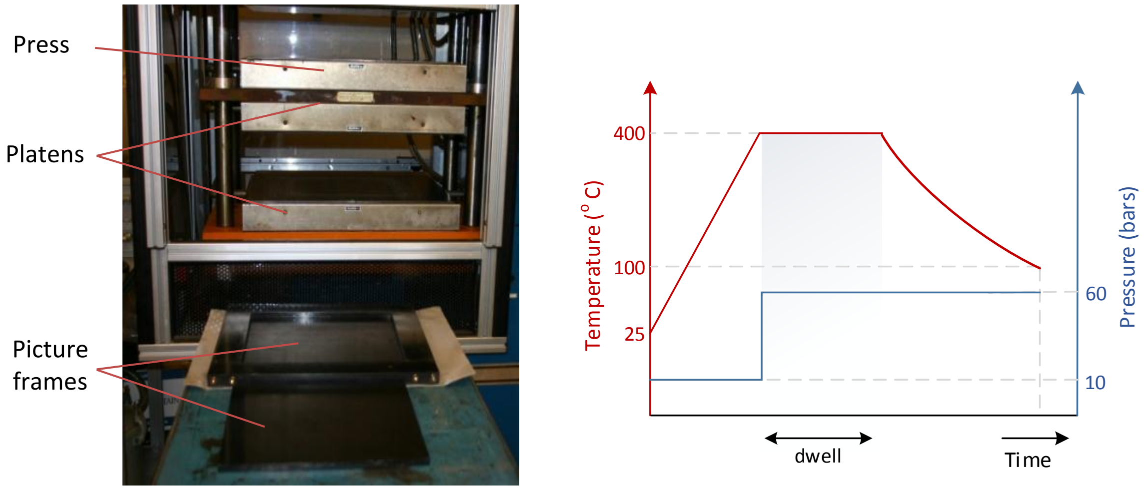
Figure 2: a) Micrograph of ROS flat specimen fabricated with 25.4mm x 12.7mm carbon/PEEK strands showing out-of-plane strand waviness; b) Micrograph of ROS T-stiffener with swirling and out-of-plane strand waviness at the junction of web and flange [23]

At the coupon level, the current work explores the tensile behaviour, quantifies the hybrid effect and assesses the extent of synergy in co-moulded hybrid fibre architectures of ROS and cross-ply (CP) laminate groups of carbon/PEEK. At the part level, two hybridization strategies are proposed to address the critical manufacturing issues (strand waviness and strand swirling at intersecting junctions) in ROS based parts, and to improve the mechanical performance while reducing the variability. The strategies are implemented and validated with experimental testing of T-stiffeners. The effects of these strategies on the stiffness, strength, failure modes and variability are quantified. The pull-out strength test results are compared with conservative estimates of the pull-out strength of quasi-isotropic L-stiffeners using analytical formula and experimental data from literature.

2 Experimental Studies – Tensile behaviour at Coupon level

2.1 Processing

Carbon/PEEK strands of 25 mm x 12 mm were chosen and placed in small batches into a steel mould and shuffled back-and-forth each time to minimize their out-of-plane orientation. The picture frame mould was placed into a press (Figure 3.a) and minimal pressure was applied to close it. The processing pressures and temperatures were fixed at 60 bars and 400°C, respectively, based on processing studies [24]. Once the processing temperature of 400°C was reached, full pressure of 60 bars was applied (Figure 3.b). Following a 20-min dwell, the mould was cooled down at an average cooling rate of 10°C/min. The panel was then de-moulded and trimmed into test specimens for the tensile tests. For the hybrid configurations, all the preforms were placed in the mould at the same time, consolidated and co-moulded without using any pre-consolidated panels. The quality assessment using several micrographs indicated about 2.5% resin rich areas, about 0.1% voids. The warpage assessments were made and quantified in [11].



a) b)

Figure 3 : a) Compression moulding set-up; b) Processing parameters (Time, temperature, and pressure)

2.2 Test matrix and Mechanical testing

A thickness ratio of 15/85 (t_{tape}/t_{ROS}) and a cross-ply laminate is chosen for hybridization. Three hybrid stacking positions/configurations have been chosen: T-R-T, R-T-R and T-R (Figure 4). The positions of the reinforcements have an influence on the failure initiation and propagation [16]. The thickness ratio was chosen based on the potential applications, load sharing, individual thicknesses, material availability and processability. Pure ROS and Cross-ply (CP) laminates have been fabricated and tested for benchmarking the results. Table 2 lists the test configurations fabricated for the tensile testing using ASTM D3039 [25]. Digital image correlation technique was used to measure the strain field.

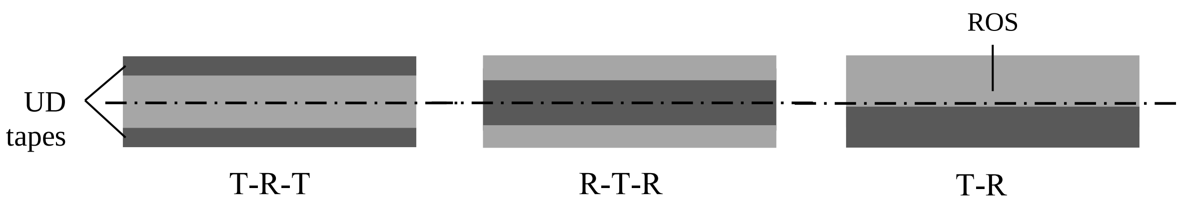


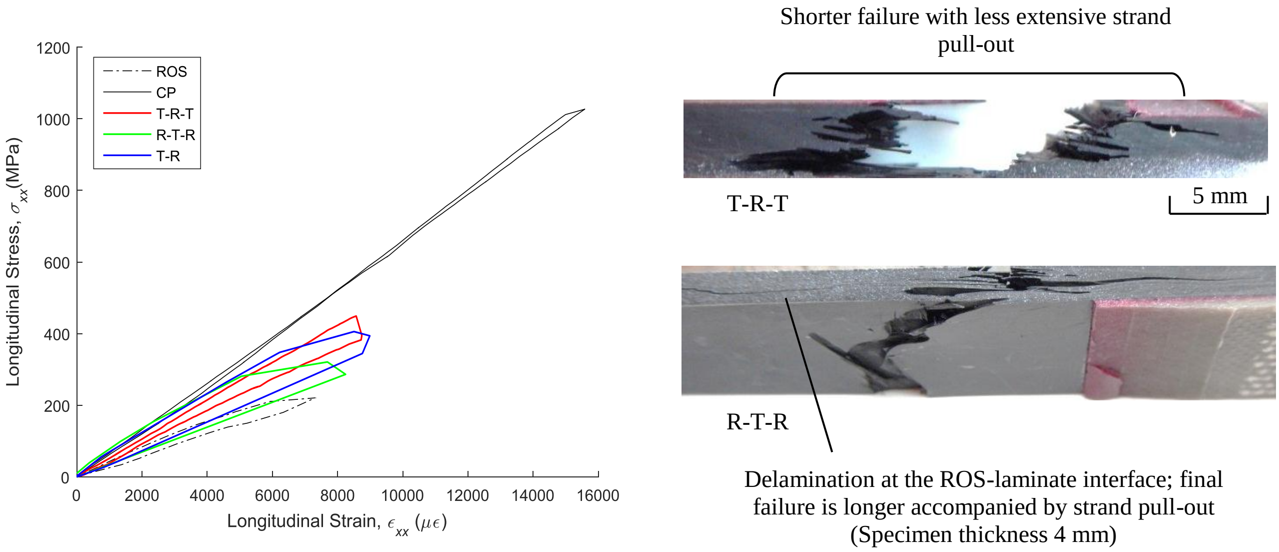
Figure 4 : Hybrid stacking configurations

Configuration	UD Tape t_{tapes} %	ROS t_{ROS} %	Specimens for ASTM D3039
ROS		100	5
T-R-T	15	85	5
R-T-R	15	85	5
T-R	15	85	5
CP	100		5

Table 1: Test configurations

2.3 Results – Coupon level

Envelopes representing the bounding regions of stress vs. strain curves for ROS, cross-ply and their hybrids are depicted for various hybrid stacking configurations (Figure 5.a), to provide qualitative estimates of the variability. Among the base configurations, ROS has the highest variability and its strength is the least. The typical behaviour of the stress-strain curve for ROS is mostly linear except for the last 10% of the strain when the curves usually tend to be non-linear. This is attributable to the rapid progression of failure due to sliding or pull-out of strands. Among the base laminate groups, cross-ply has the highest stiffness and strength and determines the upper bound. All the envelopes of the hybrids lie between these bounds indicating that stiffness is additive with the reinforcement type.



a) b)

Figure 5 : a) Envelopes of stress-strain behaviour of the test configurations; b) Typical failure characteristics of T-R-T with shorter failure paths and R-T-R with long delaminations accompanied by extensive failures

The axial load is distributed in the architectures proportional to their extensional stiffness. With the failure of one of the phases in a hybrid specimen, the load is transferred to the other remaining material until the complete specimen failure. Based on the strain-to-failure, ROS is a low elongation material that fails first before the laminate group (high elongation). In the chosen hybrid configuration, (i.e. 15/85), the extensional stiffness of ROS was higher than the extensional stiffness of the laminate group. Thus, ROS shares higher axial load. With the failure of ROS, the load in the laminate group increases. The laminate group, existing in a small percentage, fails almost instantly due to the high load due to the static stress concentration factors demonstrating shorter lengths of failures, without extensive fibre pull-outs as shown in Figure 5.b. R-T-R configurations exhibit more fibre pull-out and long failure paths or extensive damages (Figure 5.b) compared to T-R-T and T-R. The out-of-plane waviness of the laminate group reduces the overall properties. As ROS phase fails at low strains, the phase redistributes the load to the adjacent tapes gradually, resulting in the stretching of tapes. Since, some parts of ROS are still in contact with the tapes, the interface starts delaminating thus causing extensive failures. For T-R configurations (15/85 configuration) four specimens showed long failure paths with fibre pull-out of the strands and significant delamination at the interface. T-R configuration demonstrated a mix of the failure characteristics of T-R-T and R-T-R.

The normalized tensile properties (longitudinal stiffness, longitudinal strength and strain-to-failure) of all the test configurations are quantified with their variabilities in Figure 6. ROS and CP laminate represent the upper and lower bounds of properties for the hybrid materials, as they constitute the parent material architectures. A 15% laminate group acts as reinforcement to the ROS phase, and improves the stiffness, strength, and strain-to-failure as expected. However, when the hybrid stacking configurations are considered, T-R-T demonstrates the highest properties among the hybrids, despite all the configurations possessing similar axial properties theoretically. The high properties in T-R-T can be attributed to the reduction in the strand waviness in the specimen due to the outer laminate groups, and bridging of the ROS phase by the tape layers during failure. T-R configuration exhibits the better properties than R-T-R. The R-T-R configuration demonstrates the least properties among all the hybrids. Micrographs of R-T-R specimens reveal strand waviness on either side of a centrally placed laminate group forcing the waviness on the laminate group. Waviness or undulations result in interlaminar normal and shear stresses [26] in the out-of-plane directions causing pre-mature failure of the specimens. A possible means of minimizing such waviness is to use pre-moulded panels of ROS and laminate groups. Further, the tensile properties of Aluminum 7075 are highlighted to show that comparable properties can be obtained by the hybridization or ROS with a small proportion of CP laminates. While the absolute properties for the hybrids are lower than aluminum, the specific stiffness and specific strengths are much higher, as discussed in [11].

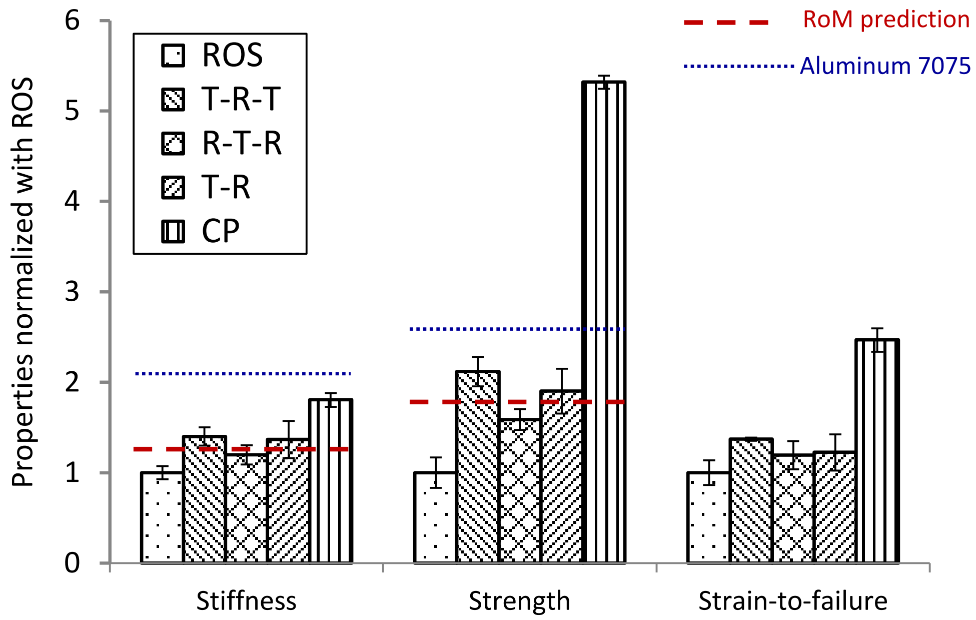


Figure 6 : Tensile properties (Stiffness, Strength, and Strain-to-failure) normalized with ROS properties

While the laminate groups reinforce the ROS architecture and boost the properties, the most important of all the results is the synergistic effect that is observed. The T-R-T configuration exhibits a positive synergy or positive deviations (16% in the stiffness and 20% in the strength behaviours) from the rule of mixtures behaviour (Figure 6). A small positive improvement of about 5-8% in stiffness behaviour and about 5-8% in strength is observed for the T-R configuration with a higher variability than T-R-T. The R-T-R exhibits a negative synergy, although the properties are higher than the baseline ROS. ANOVA [27] analysis of the results indicate that there is no substantial evidence to accept the null hypothesis thus rendering the quantitative comparisons valid. Elaborate explanations about the process quality, the extent of synergies, the failure characteristics, specific stiffness and specific strengths and the tensile behaviour with other thickness ratios and hybrids of ROS and quasi-isotropic and angle-ply laminates are discussed greater detail in [11].

3 Experimental Studies – Pull-out behaviour at Part level

3.1 Hybridization strategies and test configurations

Two hybridization strategies are proposed: Flow-control element (FCE) and the Flange Reinforcement (FR) (Figure 7). A pyramidal stack of unidirectional tapes (with fibres in the rib length direction) constitutes the FCE. The flow-control element facilitates the strand flow inside the rib cavity and around the junction as the 90o tapes within the FCE provide an accommodative sliding interface to the flow direction. The presence of 0° plies in the flow-control element enhances the axial stiffness in the depth direction of the junction, which could be regarded as a secondary benefit. While, elements analogous to an FCE have been used in industry in T-stiffeners fabricated with continuous fibre composites, known as a ‘Radius Filler’ or a ‘Noodle’ [28, 29], the application of the FCE to ROS or to short fibre composites is novel. Flange reinforcement added in the form of a lamina or a laminate, is a hybridization strategy that can be regarded as a stiffening feature for the top surface of the T-shape flange. FR could also be regarded as a parent continuous fibre structure on which a stiffening ROS rib is ‘grown’ by compression moulding.

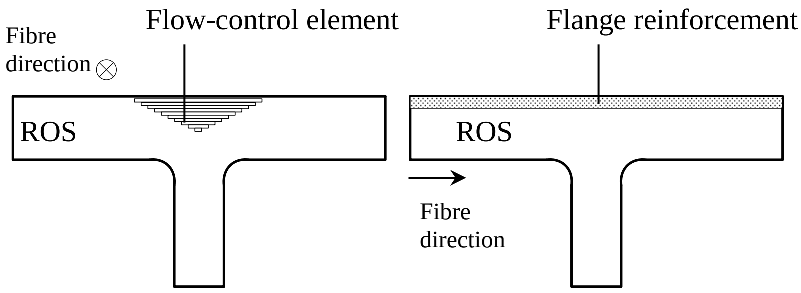


Figure 7: Hybridization strategies

Three test configurations (Table 2) (six coupons each) are chosen to examine the effect of the hybridization strategies. Configuration A comprises of pure ROS specimens for benchmarking of the results. In configuration B, a flow-control element (FCE) is added. Configuration C explores the benefits of adding a quasi-isotropic layup as flange reinforcement (FR) together with a flow-control element. This configuration also examines the extent of ply waviness in the flange induced by the strand flow. It is to be noted that the flow-control element in configuration C is smaller than in configuration B due to the presence of the flange reinforcement laminate.

Configuration	FCE	FR
A		
B	x	
C	x	x

Table 2: Test configurations and hybridization strategies (‘x’ represents inclusion of the strategy)

3.2 Processing and Mechanical testing

The tooling and the procedure used for the compression moulding of T-stiffeners is described in [23] (Figure 8.a). The flow-control element at the junction of two intersecting flow-fronts channelizes the strand flow into the rib cavity while changing its own shape to facilitate filling of the swirling prone region. For the hybrid configurations, all the preforms are placed in the mould at the same time, consolidated and co-moulded. The T-stiffeners obtained are trimmed into 25 mm wide specimens for pull-out strength tests. Pull-out strength tests determine the resistance of a structure to the out-of-plane loadings such as interlaminar tension and shear loads. In real applications, the boundary conditions determine the actual loading scenario and are complex to replicate. A custom pull-out test fixture with roller supports is developed and used along with a tensile testing machine (Figure 8.b). The T-stiffener rib is pulled in displacement control until an overall displacement of 4 mm is achieved. The maximum load capacity of the stiffener and the load-displacement curves are measured.

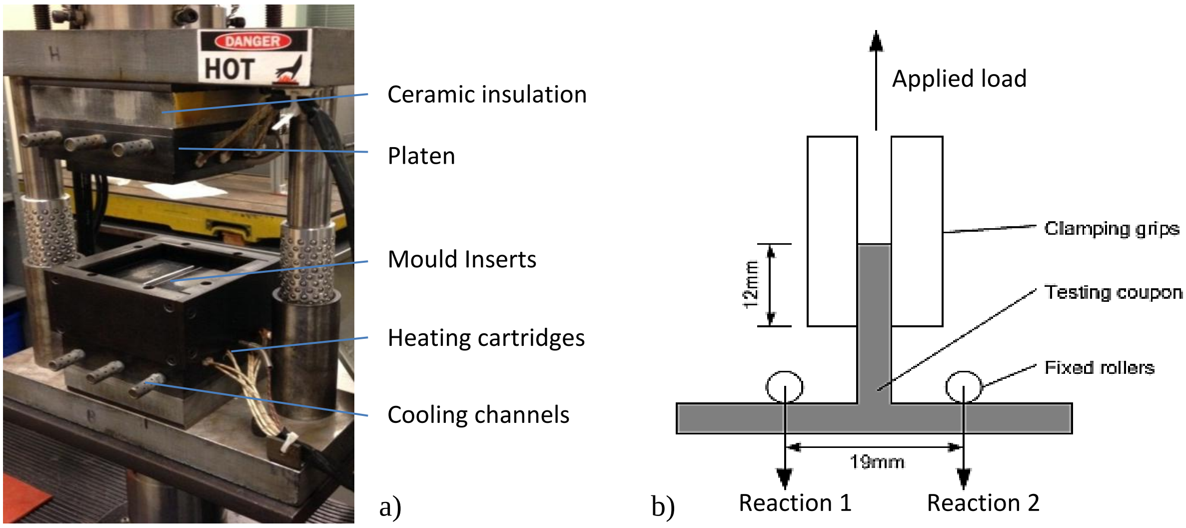


Figure 8: a) Compression moulding set-up for T-stiffeners; b) Pull-out strength test fixture

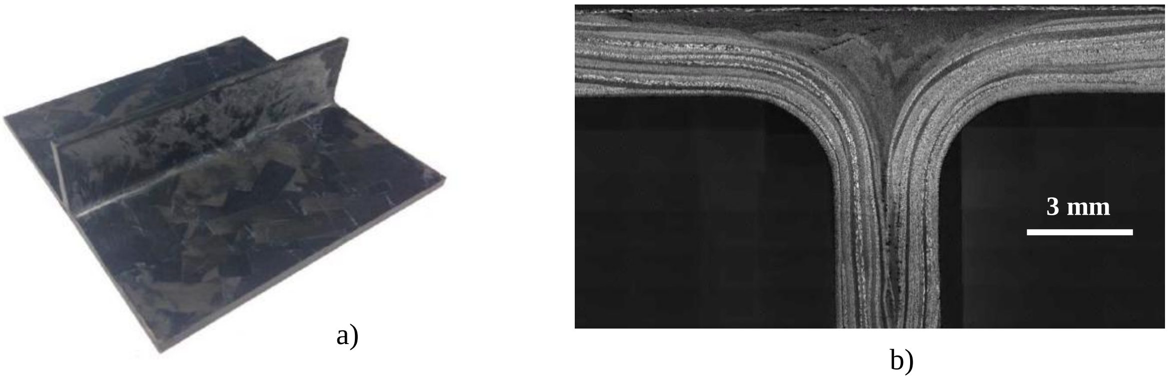


Figure 9: a) Compression moulded T-stiffener; b) Strand flow improvements with FCE [23]

3.3 Results – Part level

A T-stiffener (Figure 9.a) and its micrograph at the junctions reveal swirling-free regions and minimized strand waviness (Figure 9.b). The 90° fibres of the flow-control element accommodated its shape to the strand flow with consistency across all the configurations proving the robustness of the flow-control strategy. FCE eliminates the knit lines at the junction and was accurately co-moulded with minimal preparation. Figure 10.a quantifies the pull-out load and stiffness behaviour of all the test configurations represented through box-plots. Pull-out load comparisons of configurations A and B indicate the effect of the flow-control element. A significant improvement of 24% on the B-basis load allowable is observed in configuration B that incorporates an FCE. Configuration B coupons have the lowest scatter in loads compared to A and C. Adding 8-layers of a quasi-isotropic laminate on the flange increases the load capacity by 8-10% compared to configuration B, and 12-13% compared to configuration A, when considering the median of the results. Configuration C exhibits a stiffness increase of 18% compared to B and 25% compared to A.

Figure 10.b illustrates the sequence of failures observed by interrupted tests in each of the configurations. The laminate group is loaded in compression before failure, and exhibits higher compression strength, which explains the higher global strength of T-stiffeners in configuration C. The B-basis allowables of configuration B are higher than configuration C due to the variability of results and discussed in detail in [23]. Configurations B and C exhibit comparable pull-out strengths as that of the T-stiffeners fabricated with quasi-isotropic laminates.

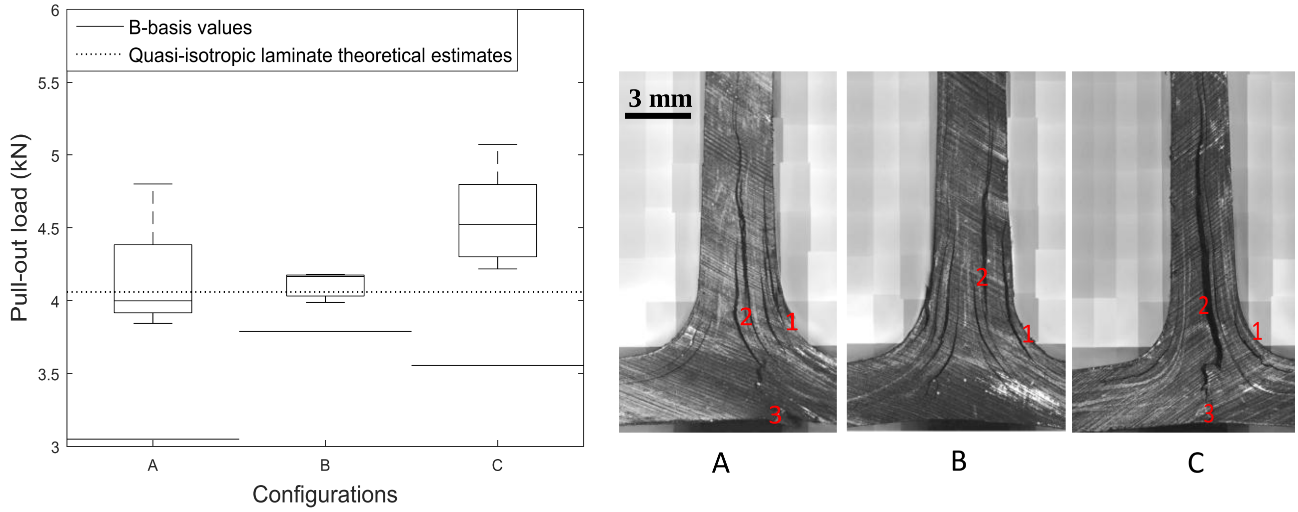


Figure 10: a) Flow-control element; b) Failure images for the configurations (with failure sequence as appeared)

4 Conclusions

The hybrid architecture is a trade-off solution between two conflicting objectives namely structural performance and processability. In this work, the weaker architecture (i.e. randomly oriented strands) is reinforced with a stronger architecture (i.e. laminates) to improve the tensile properties and processing aspects at the coupon level. The tensile behaviour (tensile stiffness, tensile strength, tensile strain-to-failure) of a 15/85 thickness ratio of laminates to ROS (t_{tapes}/t_{ROS}) is studied under three hybrid stacking sequences. The results are compared with that randomly oriented strands, cross-ply laminate and Aluminum 7075. In addition to the significant improvements in the tensile properties that can be achieved using the laminate reinforcements, a synergistic effect is observed. A positive deviation of 16% in the stiffness and 20% in the strength behaviours is observed when laminate group is stacked on either sides of a centrally placed ROS group. A negative synergy is observed when the laminate group is placed centrally between two ROS groups.

At the part level, two hybridization strategies (flow-control element and flange reinforcements) are proposed for generalized T-stiffeners to mitigate the manufacturing issues such as strand waviness and strand swirling. Pull-out strength tests are performed on three T-stiffener configurations. The flow-control element improves the strand flow at the junction, reduces variability and enhances the pull-out B-basis design allowable by about 24%. A quasi-isotropic laminate as a flange reinforcement along with an FCE produces 12.5% pull-out strength improvement. The two hybridization strategies elevate the pull-out strength capability of ROS composites to a comparable value with that of quasi-isotropic laminates. Further, the research promotes the use of ROS composites on load bearing complex shaped aerospace parts to serve as replacements for metallic structures.

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