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Hybrid composites with integrated metallic connectors: the effects of insert geometry on the mechanical performance of composite structures

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Carbon fibre reinforced thermoplastic composites provide excellent specific mechanical properties, rapid processing solutions and recyclability, which are highly suitable for manufacturing lightweight automotive and aircraft components. In practical applications of the composites, there is a requirement for joining composite parts with metal parts or composite parts together. This is commonly conducted via mechanical fasteners or adhesive bonding. Our study proposes hybrid composite solutions in which metallic load introduction inserts are embedded into composite laminates during composite manufacturing process. Design of inserts and optimization of the inserts' geometry are carried out to understand their effects on pull-out strength of the insert in the hybrid structure. Pull-out testing is performed on hybrid structures with variation of insert parameters including base-plate diameter, insert position and insert materials.Failure progression of the composites under pull-out loading is also investigated. The results of the study suggest optimal insert geometries and provide a deep understanding on failure behavior of the hybrid system under loading.

1. Introduction

Carbon fibre reinforced thermoplastic composites (CFRTPs) provide excellent specific mechanical properties, rapid processing solutions and recyclability, which are highly suitable for manufacturing lightweight automotive and aircraft components. In practical applications of the composites, there is a requirement for joining composite parts with metal parts or composite parts together. This is commonly conducted via mechanical fasteners or adhesive bonding. The joints with mechanical fasteners involve drilling holes in composites which weaken the composite and the overall structural performance. For the adhesive bonding, there are challenges to achieve high bonding strength with thermoplastic substrates due to lack of chemical bonds.

A more promising approach is the structural integration of metallic load introduction elements (so-called 'inserts') in thick-walled CFRTP. Contrary to mechanical fasteners, which are drilled and assembled during post-processing, the inserts can be introduced during the manufacturing process with minimal interruption of fibre continuity and are hence assumed to reduce stress concentrations and extend structural life under thermo-mechanical fatigue loading conditions. In general, the metal insert consists of a base plate with an attached joining element, such as a threaded bolt. During the fabrication process of the CFRTP, the base plate is placed between the plies of the CFRTP laminate. The load introduction into the laminate is then carried out over the area of the base plate.

Ferret et al. [1] investigated two different types of bigHead® inserts under tensile (pull-out), compressive (push-in) and bending loads. The inserts were embedded in a composite laminate using an epoxy matrix. The insertswith a smaller base plate resisted higher forces than those with a bigger base plate in tensile tests, as well as in compressive and during bending tests. This was attributed to the fact that fibre distortions and cut-outs wereminimized with smaller inserts.Gebhardt et al. investigated the performance of inserts embedded in composites under pull-out and bending loads [2-3]. The inserts were made of stainless steel and the base plate had a thickness of 0.6 mm to 1 mm and diameters ranging from 30 mm to 50 mm, in combination with 2-6 composite plies above the inserts. It was found that the introduction of additively manufactured pins on the insert surface could increase the ultimate tensile and bending loads by 142% and 127%, respectively. In the same work, the influence of adding a bead pattern to the insert plate was also investigated, which resulted in an average increase in bending strength of 38% but no improvement in tensile strength.Hopmann et al. [4] compared the pull-out performance of inserts and bonded fasteners, both made of aluminium.The results showed that the performance of inserts was up to 37% higher than that of fasteners.

Most of studies focus on thermoset matrix systems manufactured via Resin Transfer Molding (RTM) process.Research studies investigating embedded inserts in fibre reinforced thermoplastic composites are limited. Our study proposes hybrid composite solutions in which metallic load introduction inserts are embedded into composite laminates during composite manufacturing process. Design of inserts and optimization of the inserts' geometry are carried out to understand their effects on pull-out strength of the insert in the hybrid structure. Pull-out testing is performed on hybrid structures with variation of insert parameters including base-plate diameter, insert position and insert materials. Failure progression of the composites under pull-out loading is also investigated.

2. Hybrid composites and pull-out test

There are no standard test methods to determine the performance of hybrid connections. Therefore, an in-house testing methodology for embedded inserts was developed. The samples were designed which comprised a composite laminate and an embedded insert withlocalized introduction of through-thickness loads as part of the assembly loading requirements. The insert performance is investigated via pull-out test.

2.1. Composite processing

Flat composite laminates with an embedded metallic insert were designed for the study, which were constructed using plain weave carbon fibres and Polycarbonate (PC) thermoplastic matrix (Figure 1a). The insert was designed as a screw thread connected to a base plate, which was embedded in the composite laminate (Figure 1b). The inserts were made of stainless steel and Titanium. The geometry (mainly cone and flat shape) of the base plate was varied to study its effects on the final pull out strength, while the screw thread dimensions were kept constant.

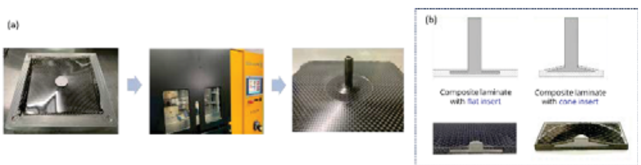


Figure 1. (a) hybrid composite samples are processed using compression moulding, (b) metallic inserts with cone and flat base plates

Compression moulding process was used to produce the insert-embedded composites as shown in Figure 1(a). The processing was carried out under the Collin hot press, in which optimal processing conditions were established to achieve high quality composites. A designated compression mould was designed with mould inserts for holding the metallic pin at the correct location. The mould insert is interchangeable to cater for different metallic inserts in the composites.

2.2. Pull-out test

In order to investigate the strength of the embedded insert in composites, an pull-out testing was designed and set up on the Instron Universal Testing machine with a 100 kN load cell, as seen in Figure 2. The pull-out tests were conducted with a cross-head velocity of 5 mm/min. The sample was clamped between two clamping plates, and the pin of the metal insert was attached to the upper test fixture using

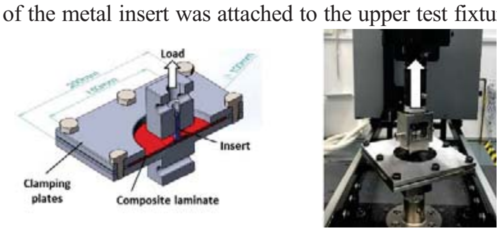


Figure 2. Pull-out test set up on Instron testing machine

a screw thread. Load-displacement curve and maximum load at failure were recorded.

3. Effects of insert geometry on pull-out performance

Experimental study was conducted to understand effects of insert geometry, especially main changes in geometry of the base plate, on final pull-out performance. Two types of inserts were used, namely cone and flat inserts. Geometry parameters of the base plate such as diameter, height and slant angle were characterized.

3.1. Insert with cone and flat base plates

Stainless steel inserts having a cone and flat base plate with the same base plate diameter of 30 mm were used in this study. The inserts were embedded in a 4mm thick composite laminate, with insert depth (vertical position within composite) of 1mm. The composite samples

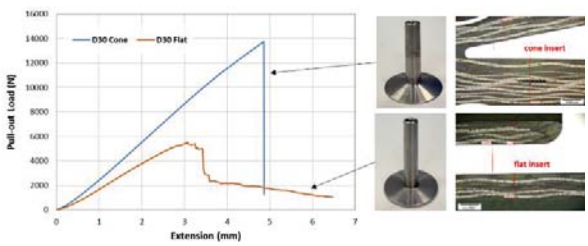


Figure 3. Typical pull-out test load-extension curves of composites with cone and flat inserts

were then characterized under pull-out test.

The hybrid composites were tested under pull-out loading and typical pull-out load-extension curves for a comparison between the composite with cone and flat inserts are presented in Figure3. The cone insert system has a significantly higher stiffness and strength, in which the pull-out strength is more than double that of the flat insert system. With the cone insert, the load could reach approximately 14000 N, while it was only in the range of 5500kN for the system with flat insert. Given the same composite thickness (1mm) on top of

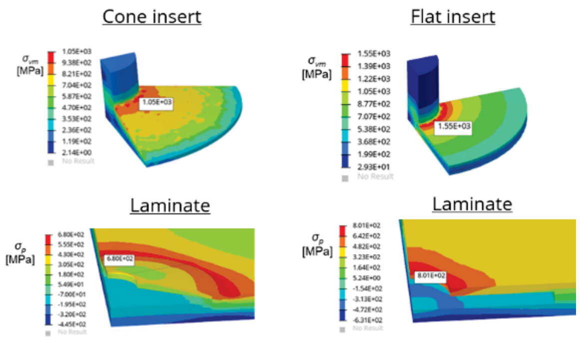


Figure 4. FE stress analysis for flat and cone inserts under pull-out loading

the two inserts, the base plate profile has a significant influence on final pull-out performance. It can be explained that the stress concentration in the composite laminate created around the insert profile was different for the cone and flat inserts as it can be seen in simulation results in Figure 4. Higher local stress concentration in the case of flat insert system could lead to premature failure of composite under pull-out loading. This shows that the insert geometry strongly determines the stress concentration in the surrounding composite and the final pull-out strength of the hybrid composite systems.

3.2. Effects of cone insert geometry

Investigation on the effects of insert geometry was conducted with both steel and titanium cone inserts, considering variation of insert diameter, cone height and vertical position within the composite laminate (Figure 5).The base plate diameter was varied between 20 mm, 30 mm and 40 mm. The cone height was fixed at 3 mm for one set of inserts with different plate diameters (FH – fixed height), and the slant angle was fixed for another set of inserts (FA – fixed angle) at 12.6°, with the depth kept constant at 1 mm in both cases. For the 30 mm diameter samples, three insert placement depths of 1 mm, 2 mm and 3 mm were also investigated.

Figure 5. Variation of cone insert geometry

Figure 6 shows a comparison of pull-out load values among the composite systems with different insert geometries. Pull-out load increases with increasing base plate diameter, in which the highest strength of 1960 N was achieved for the D40_FA steel samples. Thepull-out strength increased by an average of 123% by increasing the diameter from 20 mm to 40 mm in the FH and FA inserts.For the

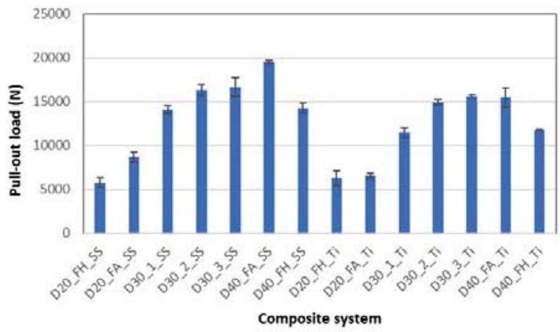
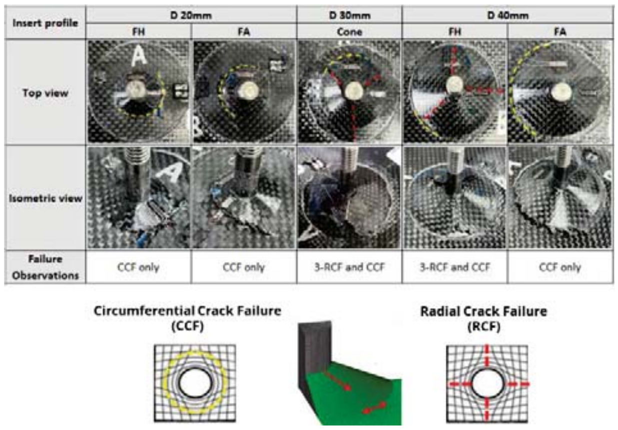


Figure 6. Pull-out strength of composites with different cone inserts' geometries

same base plate diameter, the fixed angle inserts (FA samples) are shown to have improved pull-out strengths compared to those geometries with fixed heights.

Besides the variation of insert geometry, increasing the depth of the inserts inside the composite laminate (d) also plays an important role



to increase pull-out loading. For both steel and titanium inserts, an insert placed at a deeper layer position carried a significantly higher pull-out load. The pull-out strength increased by an average of 27%

Figure 7. Failure modes observed in pull-out tested samples

by increasing the depth from 1 mm to 3 mm in the 30 mm diameter inserts.

The failure modes of pull-out tested composite systems were experimentally characterized. It was observed that the composite was fractured with fibre breakage and there were two common failure modes, including (i) radial crack failure (RCF) which was initiated from the area around the insert pin, (ii) circumferential crack failure (CCF) developed around the edges of the insert base plate with involved composite delamination. Figure 7 shows the failure modes of composites with different cone insert profiles. The CCF mode appeared more with the inserts having smaller base plate diameters, whilethe CCF and RCF mixed modes were observed when the base plate diameter increases.

3.3. Optimization of insert geometry for high performance and lightweight

Optimization of pull-out strength design of the cone inserts considering a wide range of insert parameters was conducted. The experimental results were used to validate a finite element model,

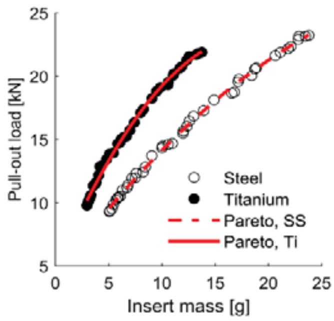


Figure 8. Insert design chart for pull-out strength and insert mass

which was then used for multi-objective optimization and the generation of design charts, considering both maximum strength and minimum weight multi-objective design requirements. For each insert material, a Pareto front was determined, which defines the set of optimal inserts' geometries related to its vertical position.

As seen from the experimental results,larger inserts are likely to be stronger, but will occupy more space in the composite laminate and the stronger steel inserts will have higher density, hence resulting in increased weight for the whole structure. Therefore, a multi-objective parametric optimization considered both insert mass and pull-out strength. The resultant Pareto fronts for both steel and titanium inserts are presented in Figure 8. It can be observed that for a given insert mass increase, titanium is the superior insert material. Even though titanium's density and stiffness are both reduced by a factor of approximately 1.8 compared to steel, this result implies that the reduction in density is the most important material characteristic for the insert.

The experimental results were superimposed onto the design charts as presented in Figure 9. It can be seen that the 30 mm diameter inserts at a depth of either 2 mm or 3 mm have the best performance given their same mass. This result indicates that increasing the insert depth is an effective means of moving towards the Pareto frontier without increasing insert mass or volume. Some of the 2 mm and 3 mm depth inserts slightly exceed the Pareto frontier; this is due to small discrepancies in pull-out load prediction between the experimental results and the modelling predictions.

4. Conclusions

Hybrid composites with embedded metallic inserts provide high load

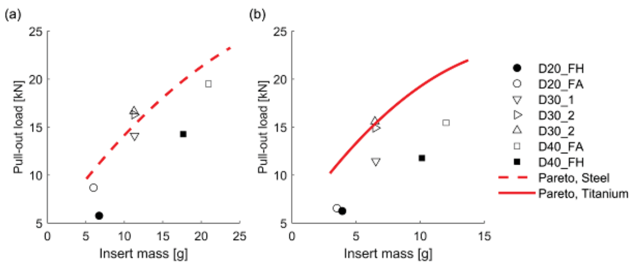


Figure 9. Comparison of Pareto fronts with experimental test results; (a) steel and (b) titanium.

capacity in combination with potential for the lightweight design. Optimization of the insert geometries could enhance the load distribution over a large surface of the base plate while maintaining high performance of continuous fibre compositesaround the insert. The developed hybrid composites have high potentials for applications in lightweight composites which are connected to other components.

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