THE ECONOMICS OF THROUGH-THICKNESS FIBRE REINFORCEMENT USING SINGLE SIDED ROBOTIC TUFTING

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Abstract

The drive to reduce cost in both the initial production and through life maintenance phases of composite structures has led the aerospace industry to examine alternatives to expensive prepreg options. Liquid resin infusion techniques, in conjunction with dry fibre preforms, offer the possibility of using low cost fabrication methods, but the possible weight penalty associated with meeting performance criteria can often negate this cost saving in terms of increased fuel consumption. The use of through-thickness reinforcement has the potential to not only bring the performance in line with toughened prepreg solutions, but to improve on it. To investigate the economics of tufting for 3D composite components, a series of metrics including manufacturing cost, performance and weight are studied for tufted and non-tufted NCF and a prepreg using a generic T-post case study. Based on the through-life cost benefit of a lower mass solution, the tufted T-post offers superior economy, with a weighted cost per part estimated to be almost 17% lower than the current prepreg solution. The generic T-shaped component has only been considered as a bolt-on solution; however the results could be applicable to many more multi-component, fastener-free preform applications and offer further cost saving potential for other aircraft.

1. Introduction

The increasing use of composite materials in commercial aircraft has ultimately been driven by the prospect of reductions in fuel consumption. This has been an area of profound interest for many years, with notable efforts beginning with the Aircraft Energy Efficiency (ACEE) program led by the National Aeronautics and Space Administration (NASA) [1]. More recently the ability of composite materials to reduce structural weight and subsequently fuel consumption has been demonstrated by their use in the Airbus A380, where they account for approximately 16% of the weight of the airframe. Fuel burn calculations have shown the A380's approximate life time fuel saving as a result of the incorporation of composite materials equates to approximately €30 M [2]. Current passenger aircraft now incorporate around 50% by weight of non-metallic components.

A long-recognised drawback of advanced composite materials, lessening the appeal to the aircraft operator, is their high manufacturing cost [3]. With the market leaders of the commercial aircraft industry aiming to achieve high volume production with future aircraft [4, 5, 6], there is a strong driving force behind the development of time and cost reduction strategies for the manufacture of advanced composites.

Tufting is one of many technologies used to assemble fibre preforms for resin transfer moulding (RTM) [6]. A robotic stitching head passes a suitable thread through the thickness of a stack of multiaxial reinforcement, leaving a tuft head on the rear face (Figure 1). As well as partially automating the preforming process, through-thickness fibres are expected to enhance certain mechanical properties, such as inter-laminar shear and impact resistance [7, 8]. The benefits of these property enhancements must be evaluated in the context of changes in manufacturing costs: initially robotic tufting requires additional capital expenditure, and, depending on the component selected, may either increase or decrease the overall preform assembly time when compared to prepreg layup and consolidation. Additionally, the presence of tufting threads can, if not properly optimised, disrupt the reinforcement architecture, affecting not only in-plane mechanical properties, but also permeability during the mould-filling phase of RTM. The technique therefore requires a high level of skill in design and manufacture to prevent this.

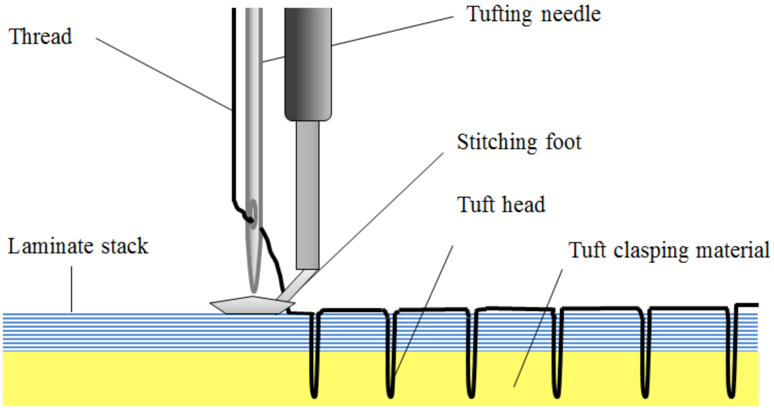

Figure 1. Diagram demonstrating the arrangement of the thread in the tufted preform

2. Methodology

This study is concerned with a composite T-post component (Fig. 2). Detailed analyses of the RTM manufacturing route using (a) tufted and (b) non-tufted preforms were compared to (c) a benchmark prepreg/autoclave process, concurrently considering all stages of the processes, material properties and cost/performance modelling. As far as possible, the work was based on *in situ* observations and measurements; however, these were performed in a research laboratory, rather than a production environment, and some extrapolation of the data is required. In particular the tufting process was assessed on a flat panel geometry rather than the assembled 'T' as this provided a larger database of information. This was deemed valid in terms of assessing the tufting process itself as the configuration is still a fairly simple geometry. The time to tuft the horizontal and vertical planes was easily extrapolated but an estimate of the time to tuft through the noodle region was estimated based on anecdotal experience of the operator.

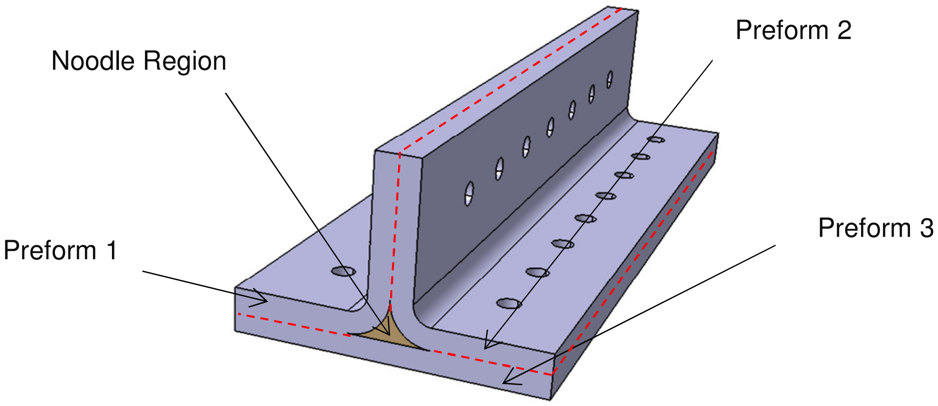

Figure 2. Schematic of a composite 'T' post.

2.1 Cost analysis

As the basis of a cost model, each of the activities carried out within the manufacturing processes was recorded and analysed. To estimate labour costs the model uses the framework of the ABC approach [9], separating the manufacturing process into its main sub processes: fabric cutting and lay-up, robotic tufting, preform de-moulding, resin injection, resin cure and de-moulding. These sub-processes are then divided into their constituent activities, each of which is related to production quantity and labour rate (assumed to be £50/h). Where it was impractical to capture complete activities, their durations were accounted for using the feature-based method, where activity times were calculated as a function of the component's dimensions and material characteristics. Examples of sub-process activities making use of this technique are the robotic tufting and the RTM mould fill time, each depending on the arrangement of the inserted tufts. Here a liquid permeability study and process modelling facilitated estimates of the labour times. To calculate the total labour costs, the activity times of the sub-processes were summed and then multiplied by the labour rate. For an appreciation of the uncertainty in the recorded values, variation was simulated using the Monte Carlo method.

As tufting represented an additional step in the overall process, the cost of the non-tufted component was estimated by removing the associated costs and comparing the permeability of the non-tufted preform (therefore no account was taken of any possible reductions in tool loading times associated with a pre-shaped preform). The manufacturing cost of the equivalent prepreg component (with the same in plane fibre content as the tufted component) was estimated using the commercial cost model SEER-DFM [10]. In addition to labour costs, the material, energy, tooling and equipment costs (including capital expenditure) were also considered. Material cost estimates were based upon the amount of raw material in the final component and the amount of material scrapped during its manufacture, including consumables. Energy costs were determined using calculations of equipment usage time and the documented equipment power ratings, and the contributions of tooling and equipment were established with information provided by the manufacturers.

2.2 Performance analysis

Structural modelling using FEA compared the performance of the tufted composite material with a non-tufted composite consisting of the same fabric, lay-up and resin, and an equivalent prepreg laminate made with the same lay-up and fibre volume fraction. Performance is considered in terms of the maximum strain during a simple pull-off load case. These simulations emulate physical tests completed during the component's testing program to determine the strength and stiffness of the structure's noodle region (Fig. 2) and its delamination behavior.

Due to the complex geometry of the tufted composite's fibre reinforcement, homogenous material properties were assumed. In the absence of validated mechanical property data, the elastic properties of the material were estimated using the design and analysis program CoDA [11]. Using the fibre-related terms of the rule of mixtures for longitudinal tensile modulus, the synthesized properties of the non-tufted composite could then be adjusted to account for the additional fibre volume fraction of the tuft thread in the tufted composite.

To model the pull-off test, half of the symmetric inverted T-shaped specimen was represented (Fig. 3). A fixed boundary condition was also applied to a section of the upper face of the rib post's flange, emulating the fixtures of the pull-off test arrangement. The pull-off load was applied normal to the upper surface of the web.

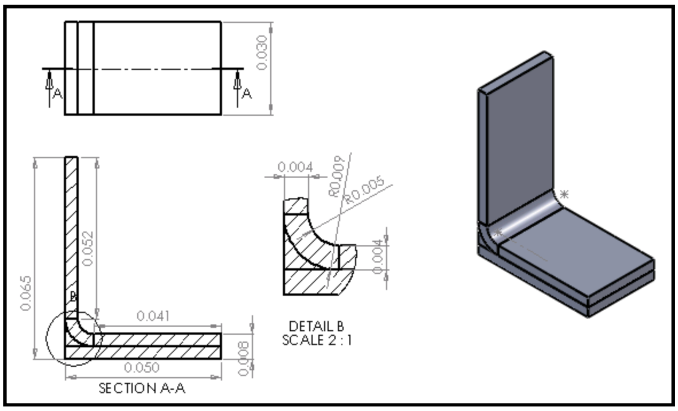

Figure 3. The geometry and dimensions (m) of the pull off test specimen, reproduced in Solidworks.

3. Results and Discussion

3.1 Manufacturing cost estimates

The estimated costs/part of the tufted, non-tufted and prepreg composite T-posts, each with a production quantity of 1000 parts (representing that likely experienced in commercial aircraft production), are shown in Table 1.

Comparing the values purely in terms of manufacturing costs, it can be seen that the NCF components offer significant cost reductions over the prepreg solution. The non-tufted component requires little expensive equipment and is therefore, for small production runs, significantly cheaper than the other options. Once equipment costs are removed (as would be the case where the equipment is amortised over more than one component type), the cost of the tufting process becomes clearer. It is important to emphasise that the cost of tufting is based on a lab scale environment. In production, with a fully automated stitching cell, the costs are likely to be further reduced. The tufting process at the time of this study, and for the small component geometry, was heavily dominated by factors such as the thread cut sequence and the need to have an operator present. In production it is likely that larger components would be tufted and then sectioned in order to provide economies of scale, and that the operator may be running up to three cells in a fully automated mode. However, in order to ensure that the analysis was based on existing data, these factors have not yet been considered.

Component	**Cost/part (£)**	**Cost/part excl. Equip (£)**
Prepreg	620 ± 19	477 ± 19
Tufted (Industrial extrapolation)	592 ± 3	349 ± 2
Non-tufted (Industrial extrapolation)	232 ± 3	207 ± 2

Table 1. Example Costs/part of the prepreg, tufted, and non-tufted composite T-posts

The high prepreg costs result from labour, raw materials and consumables. The non-tufted solution was costed on the basis that the same material content would lead to a viable structural solution; at this stage no account was made of any performance shortfalls that may result. The advantages of the lower cost RTM solution are decreased when tufting is added, due to the additional labour costs, but this will need to be balanced and assessed against the performance enhancements and ensuing weight reduction.

3.2 Structural modelling results

Linear static FEA of the pull off test was modelled in Solidworks Simulation. The maximum strain results are provided in Table 2.

Principal strain	Prepreg	Non-Tufted	Tufted
Max ε_1	1982	2128	1957
Max ε_2	-260	-279	197
Max ε_3	-1347	1437	-1336
Max ε_{12}	1661	-1920	-1627
Max ε_{23}	324	351	343
Max ε_{13}	-470	-514	-487

Table 2. Maximum strains (microstrain) of the T-post obtained from FEA. The error resulting from the estimation of elastic moduli are considered insignificant.

In all cases, the maximum strain is generated through the thickness of the material (modelled as the first principal strain direction), at the surface of the component's radius (Fig. 4), rather than in the noodle region.

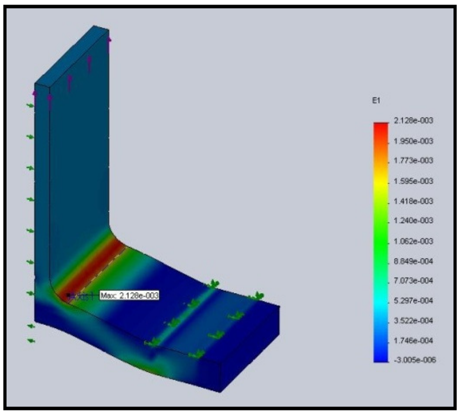

Figure 4. The first principal strain results of the non-tufted T-post pull-off test simulation, indicating the maximum strain.

Table 2 indicates that in this load case, the tufted material provides the best performance as far as stiffness is concerned, resulting from its enhanced through-thickness elastic modulus (E_3). Comparing the results of the tufted and non-tufted materials, strain is reduced by about 170 με. Compared to the prepreg, strain is also lower (25 με). Even with these modest reductions to the maximum strain, there may be scope for reducing material volume and therefore weight, using lighter fabrics or altering the layup, with positive implications for both the cost reduction and life cycle costs.

Normalising the weights of the model components, and in doing so altering their performance, a simple comparison of the materials in terms of their performance/weight in the investigated load case can be made. This comparison provides an indication of the relative weight efficiencies of the composite materials in this application.

3.3 T-post performance/weight

Using an estimate of the weight of each component, a performance index was calculated. Due to the fact that both low weight and low strain are desirable, the performance index is calculated as the inverse of (component mass multiplied by its maximum strain): $(M\varepsilon)^{-1}$. The component providing the best weight efficiency is therefore indicated by the highest performance index value. Table 3 documents the mass of the component when made with each of the composite materials, and the calculated performance index (PI).

Material	Mass (kg)	Performance index $(kg.\varepsilon)^{-1}$
Non-tufted composite	0.029	16189
Tufted composite	0.030	17007
Prepreg composite	0.030	16835

Table 3. The weight and performance index of the T-post test element with each simulated material

The results indicate that with a PI of 17007 $(kg.\varepsilon)^{-1}$, the tufted composite is the most weight efficient material for this load case.

3.4 Relative component economy

Using the PI, it is possible to define how the weights of the complete components vary when normalised to achieve the same maximum strain, and hence to calculate the variation in the estimated manufacturing cost by altering the material and labour costs directly associated with the quantity of material. The economy of each component is thus established in terms of its trade-off between manufacturing cost and lifetime aircraft fuel consumption resulting from its weight in a similar calculation to that of DOC (Direct Operating Cost) [12]. Table 4 shows the modified costs/part considering lifetime fuel consumption (based on the lifetime fuel burn/kg of the Airbus A380, estimated to be €2000 or £1620 [2]) and weight of the tufted, non-tufted and prepreg T-posts normalised for the maximum through-thickness strain of the tufted component.

Component	Weight (kg)	Cost/part (£)	Cost/part excl. Equip (£)
Prepreg	0.187	923 ± 19	781 ± 19
Tufted (Industrial extrapolation)	0.185	892 ± 3	649 ± 3
Non-tufted (Industrial extrapolation)	0.188	539 ± 2	514 ± 2

Table 4. The costs/part and weights of the various T-posts when normalised to achieve the same maximum through-thickness strain as the tufted T-post, at a production quantity of 1000 parts.

The final cost/part estimates of the three T-posts, considering lifetime fuel consumption and manufacturing cost (Table 4) highlight that the dry preform / liquid resin infusion options provide better economy than the baseline prepreg solution. The non-tufted solution offers the potential for a 34% cost saving but this assumes the performance, in terms of other loading conditions, can be met. In the likelihood that the performance advancements of the tufted solution are required, it can be seen that tufting provides an economic advantage over the prepreg component, facilitating a reduction in manufacturing cost as well as lifetime fuel cost, due mainly to reduced labour and consumable materials. The overall lifetime cost/part reduction achieved by the tufted composite rib post is £132 (a 16.9% saving), which in a single aircraft would generate a saving of £5808 assuming the use of 44 identical wing rib posts per aircraft. These cost differences are significant, although it is again emphasized that only the pull-off load case has been considered.

4. Conclusions

The use of the non-tufted RTM composite for this application produces the lowest combination of manufacturing cost and lifetime fuel cost (at the current fuel price). However, without examining the full range of structural load cases it is not proven that the non-tufted component could meet the impact and out of plane load requirements. The tufted component provides the likely required performance improvements and a cost advantage over the prepreg/autoclave manufacturing route.

The conclusions made here are limited to the direct pull-off load case. A complete appreciation of the economy of the materials considered within the mixed load case of this application requires more detailed structural analysis. This should include failure modes as well as elastic deformation, since tufting is expected to enhance the out-of-plane strength and delamination resistance of the laminate. It is also important to consider the wider structure when looking at the benefits of tufting. The T-post on its own has been shown to be cost effective when comparing to conventional prepreg options, but both have been considered only as bolt-on solutions. The possibility of using tufting to produce larger multi-component assemblies, thus reducing the need for fasteners and in turn reducing both weight and life-cycle costs, promise further cost reductions.

5. Acknowledgements

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