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INVITED PAPER

MAKING AUTOMATION PAY - COST & THROUGHPUT TRADE-OFFS IN THE MANUFACTURE OF LARGE COMPOSITE COMPONENTS

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ABSTRACT

The automation of complex manufacturing operations can provide significant savings over manual processes, and there remains much scope for increasing automation in the production of large scale structural composites. However the relationships between driving variables are complex, and the achievable throughput rate and corresponding cost for a given design are often not apparent. The deposition rate, number of machines required and unit production rates needed are interrelated and consequently the optimum unit cost is difficult to predict. A detailed study of the costs involved for a series of composite wing cover panels with different manufacturing requirements was undertaken. Panels were sized to account for manufacturing requirements and structural load requirements allowing both manual and automated lay-up procedures to influence design. It was discovered that the introduction of automated tape lay-up can significantly reduce material unit cost, and improve material utilisation, however higher production rates are needed to see this benefit.

Keywords: Composites, Cost, Automation, Trade-offs.

1 INTRODUCTION

The introduction of automation to the production of large scale composite structures has mostly been applied to individual manufacturing stages to aid processing time and cost, and improve quality and consistency. For example, current standard practice in aerospace is to trim raw ply materials using computer numerical controlled (CNC) cutting equipment, and inspect components using robotic non destructive testing (NDT) systems. Lay-up processes are however lagging behind other aspects of composite manufacture. This is partially due to the very significant capital costs associated with the equipment needed, and typically higher recurring costs. However, these automated machines can be operated with minimal labour and can yield better consistency and precision than the equivalent manual processes.

But the picture is complicated, and the headline figure of kilograms per hour as the deposition rate depends on both the capability of the equipment and the size of the component. Consider for example Automated Tape Laying (ATL). The more capable machines allow deposition at higher advancing speeds, and larger components provide longer deposition paths, allowing greater distance which in turn permits the machine to achieve its maximum deposition rate. This technology is still developing, hence the maximum rates are still behind what is needed for true high volume throughput.

The question then is: *"When needing to go into production how does the design of the panel (i.e. the volume and geometry of material) and the manufacturing process proposed interact, and therefore what resource produces the maximum output for that design?"*

Using a single carbon-fibre epoxy material this question is addressed by studying the design and manufacture of a typical wing cover. Both manual and automated lay-up processes are studied with each design cognisant of production process. Non-recurring and recurring costs are also obtained.

The following sections give some basic background and context on the material, design, and manufacturing processes as well as the implications on cost, before moving on to the methodology and results obtained.

2 BACKGROUND AND CONTEXT

Before elucidating on the actual design and costing methods, it is useful to identify key aspects for consideration in the choice and usage of the material systems, the key design considerations (which should include manufacture) and the general process considerations (which also link to design).

2.1 Material Considerations

Composite material systems come in several formats from individual fibre and resins to more sophisticated pre-impregnated fabrics (pre-preg). Typically processed material systems such as pre-pregs or woven fabric are used for large components to reduce manufacturing time, but this brings with it additional cost. The other trade-off with such woven fabrics is that fibre crimping and reduced fibre volume fraction tend to reduce in-plane strength and stiffness. Non-crimp fabrics are structurally superior, consisting of several consolidated uni-directional layers. They also carry additional cost. Woven fabric, non-crimp fabric and unidirectional tape are all provided in roll form and are well suited to manual lay-up. However, in the case of ATL only unidirectional tape is usable.

Research into the costing costing of raw composite materials has been limited. A few publications of note including Goss 1986; Cinquin 2001, clearly identify that the material itself, and the precursor are the main drivers. In industry this is recognised and the best avenue for price reduction is through long term contracts and competitive tendering. As this is the key element, contract pricing is used in these studies, although it is non-dimensionalised.

2.2 Design Considerations

Typical wing structures consist of stiffened panels, that is an external skin stiffened by longitudinal (spanwise) and lateral (chordwise) stiffeners. These panels are subject to impact damage, and as they are thin they may exhibit instability which must be checked for during design. Since the panels are typically designed and analysed in small sections, neighbouring elements may have differing thicknesses. In manufacturing ply continuity must therefore be carefully maintained across these boundaries. Such structures may also require a repair at some point so, panel repairs which include mechanical fasteners must also be accounted for. Interestingly, the thickness of the repaired panel drives the size of the fastener, which can constrain the width of the structural element.

The design of panels in this way can also cause stress concentrations due to different thicknesses across boundaries (Saresta et al 2007) which require methods to blend adjacent segments (Yamazaki 1996; Kristinsdottir 2001). These can both improve ply continuity and reduce stress concentrations. Genetic algorithms are often used to help here (Kristinsdottir 2001; Seresta et al 2007), but the most common industrial method, and the one used herein is the use of a pre-defined library of compatible stacking sequences. This approach has been demonstrated to keep mass down but maintain ply continuity (Niazi 2006).

2.3 Manufacturing Process Considerations

There are many processing options available in the steps to produce a composite part, from preparing raw material through to curing the final part shape. Autoclave production is most common for aircraft primary structure manufacture. Thus the studied wing cover is assumed to be autoclave cured using invar tooling.

Costing of such processes and the range of approaches available is wide, and unlike the material itself, there are many studies on costing for composite component manufacture (Curran 2004; Kauffman 2011; Bader 2002; Schubel 2012; Kendalla 1998). Manufacturing costs in most studies do not model production volume as a variable, but all noted that material utilisation was a key driver. Schubel (2012) examined wind turbine blades and production volume, identifying that costs do fall rapidly up to 400 parts, but level off above 1000 parts per year. In this case automated processing takes twice the production volume before reaching a plateau, due to large initial capital cost. It is outside aerospace that the true advantages of automation are seen, as per Kermo (2000) and Kandella (1998). These give some indication that perhaps the same savings through automation may not be achievable in aerospace with lower production volumes.

3 CONFIGURATION DESIGN, ANALYSIS AND STUDY METHODOLOGY

As indicated above design and manufacturing are tightly linked and therefore a combined methodology is required. Each structure must be redesigned to suit the manufacturing process used, so that the appropriate constraints are imposed and the wing structure designed correctly.

3.1 Structural Configuration, Constraints and Materials

The chosen configuration is an upper wing cover for a single aisle aircraft. It has 118 individual skin-stringer units with a fixed rib pitch of 700mm and variable stringer pitch (165-300mm). The loading is idealised into 19 zones as per Figure 1 (Quinn 2012, Mullan 2012). Compression buckling is not permitted at less than 130% limit load. The stacking sequences are all balanced and symmetric. Skin ramp rates are kept at 1:10 chordwise, and 1:20 spanwise.

A laminate material library was generated using ply properties, the Tsai-Hill failure criterion and a simple empirical knockdown factor of 40% (Renieri 1981) to obtain damaged and part allowables.

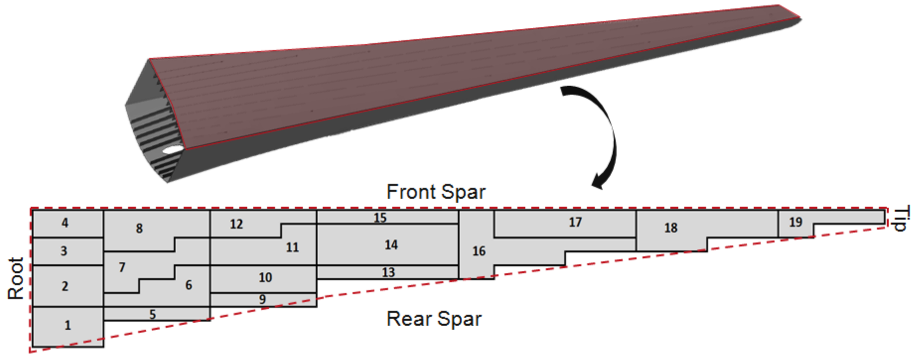

Figure 1 – Upper wing cover loading zones.

3.2 Structural Design

The structure is further idealised as a series of plate and column elements, and sized using standard aerospace check stress methods including;

- Static strength of skin and stiffener sections under compression and tension loading.
- Static strength of skin sections under shear and combined tension and shear loading.
- Uniaxial and biaxial compressive skin buckling, skin shear buckling and combined compression and shear buckling.
- Stiffener cross sectional buckling and crippling.
- Stiffener compressive Euler buckling and combined flexure and local crippling using both Secant and Johnson-Euler methods.
- Combined stiffener axial compression and lateral pressure using beam-column analysis methods.

An automated sizing tool developed in-house was used for all design and analysis work. The basic process is to generate a design space from all combinations of geometry and material; and the component design satisfying the appropriate constraints for the chosen manufacturing process.

3.3 Manufacture & Manufacturing Costs

For the studies it was assumed that the lay-ups would consist of pre-preg unidirectional plies (0,90,+45,-45) and non-crimp fabrics (±45 & 0,90), and for ATL unidirectional tape. With manual lay-up it is assumed that de-bulking occurs after the first ply, and every three subsequently. After lay-up the component is sealed in a vacuum bag and cured in the autoclave at ~180ºC for 8 hours. The skin is cured before co-curing the stiffeners to create the final component.

An activity based costing approach is used to obtain costs for this manufacturing process, in conjunction with contract pricing and industrial labour data (Mullan 2012). It is assumed that all ATL equipment is solely for manufacture of the wing cover. Amortisation is based on utilisation factors estimated from real production data and is calculated over the life of the production run. The production route using manual layup is shown in Figure 2 (using ALT the cutting and layup operations are replaced with a single ALT layup process).

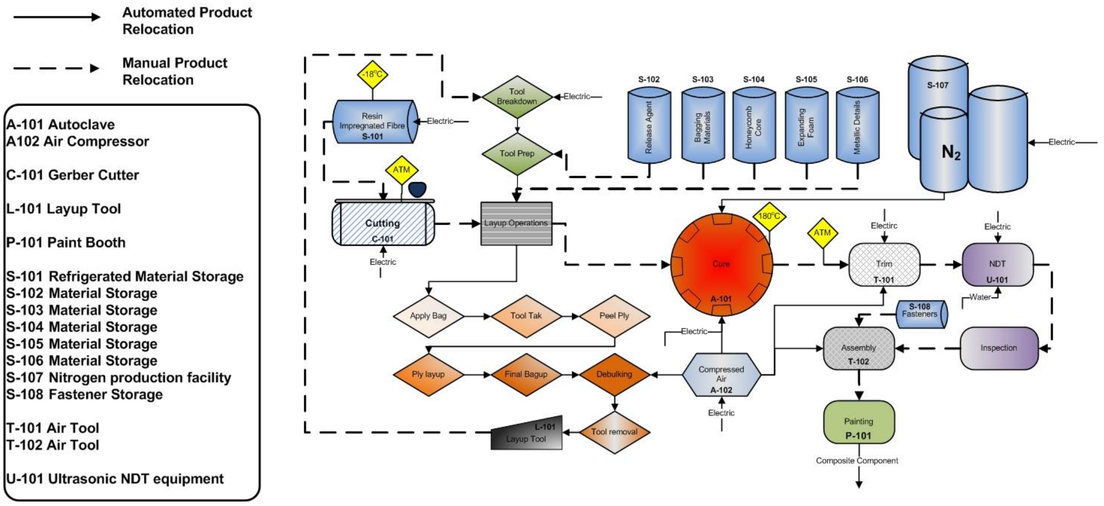

Figure 2 – Composite component production using the hand layup (HLU) process.

4 RESULTS AND DISCUSSION

In order to compare the two manufacturing processes two different designs were produced to match the freedoms and constraints of the layup processes, the key characteristics of which are summarised in Table 1. For the cost analysis of each design the production was based on a three shift pattern with a two year return on investment period for the ATL equipment. Deposition rates were varied from 3 kg/hr (standard HLU rate) to 30 kg/hr (current limit of ATL commercial technology). The target was for a maximum of 140 wing sets per anum.

Table 1: Trade-study design spaces.

	ATL-0.50	HLU-0.50
	Skin	
Materials	Uniaxial tape	Uniaxial and Biaxial NCF fabric
Composition	40/40/20 ±10%	40/40/20 ±10%
Guide laminate	$[[+45/-45/0/90/0]_9]_s$	$[[\pm45/0,90/0]_9]_s$
No. of laminates	39	39
Thickness increment	0.5mm	0.5mm
	Stiffener	
Materials	Uniaxial and Biaxial NCF fabric	Uniaxial and Biaxial NCF fabric
Composition	50/40/10 ± 10%	50/40/10 ± 10%
Guide laminate	$[[90[0_2/\pm45/0]_2]_3]_s$	$[[90[0_2/\pm45/0]_2]_3]_s$
No. of laminates	13	13
Thickness increment	0.5mm	0.5mm

4.1 Results for Component Designs

The key design results are shown in Table 2. There is very limited difference in the weight of the optimised ATL and HLU designs (0.25% based on the lighter ATL solution). As would be expected the ATL solution features a greater number of plies and ply drops.

Table 2: Component designs.

	ATL-0.50	HLU-0.50
	Skin	
Mass (kg)	367.5	368.3
No. of plies*	316	77
No. of ply drops	54	34
	Stiffeners (12 off)	
Mass (kg)	204.7	205.3
No. of plies*	792	792
No. of ply drops	217	215
	Wing cover	
Mass (kg)	572.2	573.6

** The total number of physical plies including for HLU splicing due to material roll width limitations.*

4.2 Results for Costs

The key cost results are shown in Table 3. Three key results emerge:

- the ATL solution has a lower unit cost (13.8%).
- the material costs are lower for the ATL solution (due to lower raw material prices and higher material utilisation).
- the overall plant cost are a factor of 1.63 higher for the ATL solution.

Table 3: Component unit cost breakdown.

	ATL-0.50	HLU-0.50
Optimum maximum equipment deposition rate	23 kg/hr	---
Number of ATL machines	1	---
	Skin	
Material	0.377	0.583
Labour	0.013	0.026
	Stiffeners (12 off)	
Material	0.316	0.317
Labour	0.066	0.066
	Wing cover	
Energy	0.012	0.012
Plant	0.218	0.134
Total	1.000	1.138

Figure 3 illustrates the results of the cost study when production rates are increased and additional ATL machines are brought online to increase throughput. This interesting result illustrates that lower overall cost may be achievable with fewer ATL machines but the deposition and production rates need to be much higher to see the benefits.

5 CONCLUSIONS

The study focused on comparing the costs for large composite panels manufactured using hand lay up or automated tape layup methods and compared the resulting designs and costs for both. Analysis of the results have shown that the optimum cost is a function of the minimum deposition rate and the minimum number of ATL machines needed to meet the production rate. The costs have step changes at points and hence are highly sensitive at these junctures to small changes in either the design, the production rate, or the deposition rate. Good understanding of these boundaries and the interaction of the chosen production method with the final design of the product, is therefore clearly needed to achieve the benefits promised by automation technology, or equally importantly, simply to understand the costs being incurred by design or production decisions.

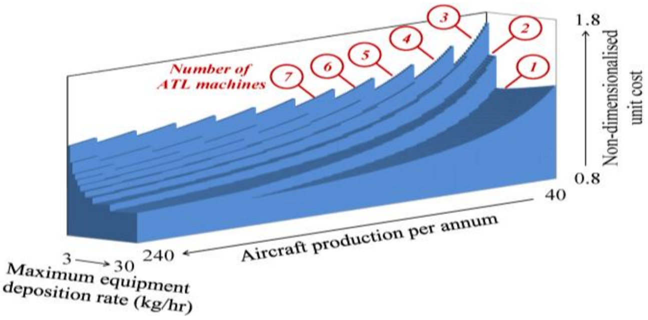

Figure 3: Unit cost analysis results with varying production and deposition rate.

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