AUTOMATING THE MANUFACTURE OF VERY COMPLEX COMPOSITE STRUCTURES

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ABSTRACT

Since the earliest developments of advanced composite materials and structures, and certainly within 10 years of the commercialisation of carbon fibres [1], there has been a realisation that automation of the manufacturing processes would be a necessary prerequisite for the widespread application of the technology outside of the highest value applications, where manual processing was cost-effective for the small production numbers that were initially needed. As production volumes have risen the industrial response in the aerospace supply chain has largely been to seek lower and lower cost labour by moving production offshore, often severing the critical link between design and manufacturing teams as a result. More than 40 years after the recognition of the need for automation there has been only a very limited use of automated processing, at least for high performance structures of complex geometry. This paper is an exploration of why it has proven so difficult to automate the manufacture of complex geometry, minimum mass, high performance composite structures, and aims to shed light on possible routes forward in different application areas of composite structures

1 INTRODUCTION

If we consider the process chain for a typical complex geometry composite aerospace secondary structure - an autoclave moulded, honeycomb cored, wing panel, made using preimpregnated woven reinforcements - we can define a set of process steps to the end of the moulding stage. A significant number of additional steps are needed to get to a finished flying component, but we are only considering moulding here.

1. Tool cleaning
2. Tool release agent application
3. Defrosting of prepreg and paperwork preparation
4. Ply cutting and kitting
5. Honeycomb cutting and machining
6. Manual lay-up of prepreg ply by ply onto the tool, possibly including a film adhesive
7. Prepare a vacuum bag and debulk the lay-up
8. Emplace the honeycomb core(s), possibly adding a syntactic foam edge fillet or splicing adhesive
9. Repeat step 6
10. Repeat step 7
11. Prepare a vacuum bag and cure consumables
12. Place tool in autoclave, connecting up vac bag and thermocouples
13. Cure part in autoclave
14. Remove tool from autoclave
15. Demould part
16. Deflash part
17. Complete paperwork and route to inspection and NDE

Of these 17 process steps only aspects of steps 4 and 5 are routinely automated. Even for structures largely manufactured using automated fibre placement (AFP) it is unusual not to have some requirement for additional manual lay-up - e.g., for local pad-ups, lightning strike protection or to apply glass insulating plies. Even if all the lay-up is by AFP, only one process step is removed in most cases, so that even then there are 14 process steps out of 16 that are essentially manual in nature. Equally, changing to an out of autoclave, vacuum-only process has almost no impact on the overall process chain.

2. THE CURRENT STATE OF THE ART.

The great bulk of research on automating composites manufacture has focused on automation of lay-up, so to a first approximation we should not talk about automated manufacture of this sort of composite structure, but about automated lay-up or automated reinforcement collation.

There are a number of very negative aspects to the manual lay-up processes using woven reinforcement, so potentially large gains can be made by adopting alternatives, especially automated alternatives.

1. Despite laminators usually being described as unskilled or semi-skilled workers; anyone with practical experience of lay-up on complex surfaces will readily accept that it can be a very skilled job.
2. No standardised and graduated skill training schemes for laminators are known to the author, so skill levels in the workforce can be very variable and often essentially uncontrolled - leading to variable quality in the manufactured parts, and to difficulties in growing a workforce and ramping up production.
3. Manual lay-up can be a slow process, and attempts to speed it up tend to impact badly on quality.
4. The details of how to translate the design intent into a specific series of actions to be carried out by the laminator are seldom clearly and unambiguously captured in Manufacturing Instructions. Laminators are often, in effect, required to complete the detailed design process in early prototyping
5. The process of Manual lay-up has not been extensively studied and the outputs of the studies that have been made [2,3] have yet to be incorporated into design guidelines and design and production practices, although they do promise the potential for very significant improvement, without eliminating manual processing.
6. At the ply cutting stage there is generally a very significant material wastage, which added to cured part trim waste can mean almost half of the costly reinforcement ending in landfill rather than the final moulding.

To date, the main focus of automated lay-up research for primary aircraft structures has been on automated tape laying (ATL using wide tapes) and automated fibre placement (AFP using a number of individually controlled narrow slit tapes), which has a major impact on the amount of in-process waste (it has much less impact on materials cost as slit tape is much more costly than wide UD prepreg). This research has led to the development of an industry to supply these machines and the specialist reinforcement forms that they require and they have become widely used in the primary structures of modern commercial aircraft such as the Boeing 787 and Airbus A350. However, these developments have certainly not been without difficulties and the structures being made are essentially rather simple geometrically.

The limitations on geometrical complexity come from three sources inherent in part geometry and the basic function and design of the AFP/ATL machines. The first is that even for the AFP machines the width of the band of tapes is substantial (>50mm to maximise lay-up rate) and the rollers that are used to deliver the tapes have very limited lateral compliance, so that internal corner features such as that shown in fig 1 cannot be accommodated unless the features are extremely shallow. Even for single curvature ramps there will be a limit to the ramp rate due to the limited radial compliance of the delivery rollers, as shown in fig 2.

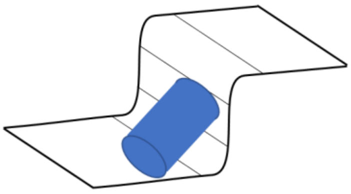

Fig 1. Delivery rollers cannot conform to many of the geometries that we need to produce

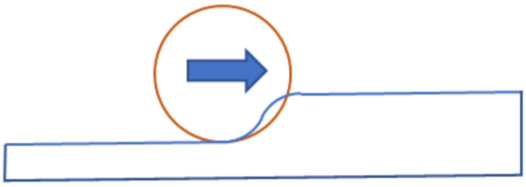

Fig 2. Even simple single curvature geometries may prove difficult to manufacture by AFP

The second is that the AFP reinforcement delivery heads are very complex pieces of equipment as they must be able to deliver a number of tapes, each under individual control of tension, backing paper removal, and cutting and placement at the start and end of each tape delivery. This level of complexity means that the heads are very significantly larger than the delivery rollers and part geometrical complexity is limited by clashes between tool and the delivery head fig 3.

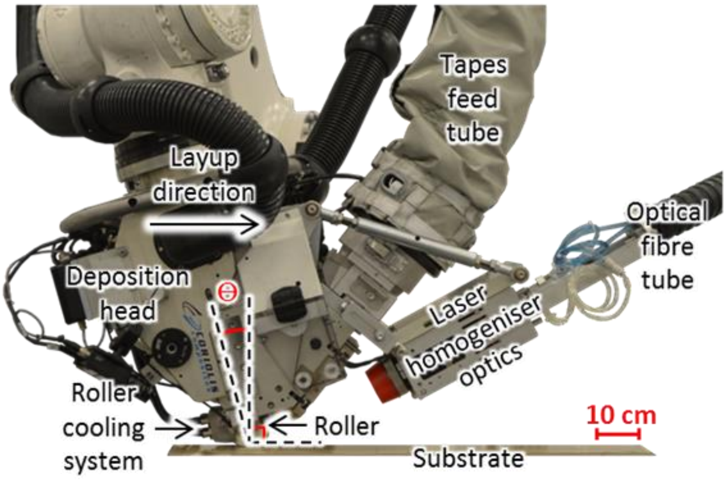

Fig 3. Typical AFP delivery head

Additionally limitations from the systems manipulating the delivery heads, generally robots or gantries can limit the geometrical envelope possible, as shown in fig 4. Fig 5 shows some cross-sections through a moulding made for a structural automotive application currently in production, compared to the cross-section of a typical robot mounted AFP head, there is clearly no way that these sorts of components can be manufactured with the current AFP technology, even if the machines could hit the necessary takt times.

Lastly, there are limitations arising from interactions between the machinery and the part geometry. The simplest of these is that for small external radii the limited roller compliance means that even if 10 or more tapes are available only a much smaller number of tapes can be used in practice for some ply directions, as shown in fig 6. This clearly impacts strongly on the productivity of the equipment even if it does not necessarily impact on the potential to manufacture the geometry. The productivity depends on factors such as the maximum speed of lay-up, the acceleration rate to that speed and the length of each ply, as well as the number of tapes that can be laid in each pass.

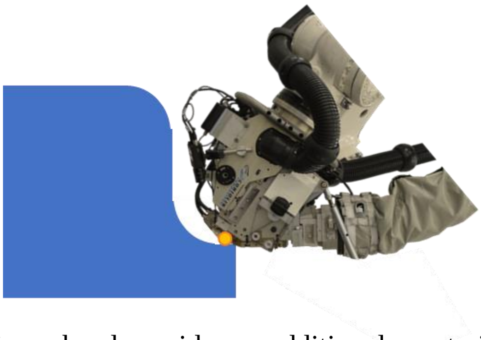

Fig 4. The size of the delivery head provides an additional constraint on possible geometries

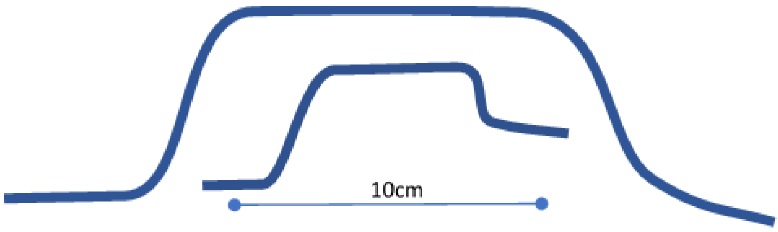

Fig 5. Typical cross-sections through a production component for an automotive application.

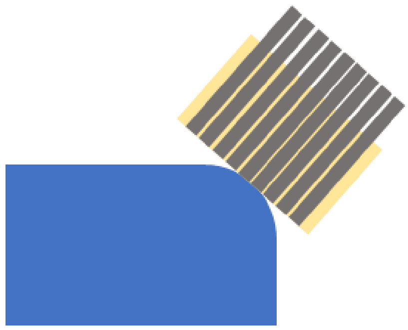

Fig 6. Although the system can deliver 8 tapes, only two can be laid here due to the geometry

In practice the speed at which the plies can be laid down is very geometry dependent, being much slower over any corner features than in flat areas. In addition, for any area of double curvature there are difficulties in matching the geometry with an array of tapes, see fig 7. An attempt can be made to have the tapes follow a geodesic path, essentially keeping them straight in a local frame of reference (but not necessarily in the global frame of reference defined by the ply rosette), but this will tend to generate significant gaps and overlaps between adjacent tapes. The alternative is to steer the tapes in the plane to maintain a set of tapes that are locally parallel to each other but not straight in either the local or global frame of reference. Tapes can only be steered to a very limited extent (minimum radius of curvature is often in the region of 1000mm) to avoid tapes becoming wrinkled and deformed. Either gaps and laps or wrinkled fibres will significantly impact on the structural performance. All these factors combine to dramatically limit the level of complexity available via the AFP process.

For the typical aerospace component described earlier very significant changes to the design would be needed to deliver a component that could be laid-up by AFP, and for the more geometrically complex mouldings needed in automotive applications there is simply no realistic possibility of achieving cost, rate and geometry targets by this route.

Fig 7. Mapping tapes to doubly curved surfaces. Left hand image each tape follows a geodesic path across the surface. Right hand image each tape is steered to stay at a constant distance from the previous tape becoming increasingly wrinkled (the first tape was applied along a geodesic).

3. MOVING BEYOND THE STATE OF THE ART IN AEROSPACE COMPOSITES.

Some of the limitations of AFP have been addressed by the development of lay-up heads that shear the tapes rather than steering by a simple rotation of the roller [4.5]. These can achieve an order of magnitude improvement in the minimum steering radius on flat surfaces, but have yet to be demonstrated to be better able to comply to curved surfaces requiring tape steering. Another approach intended to broaden the geometry range of AFP & ATL is to lay up a flat preform and transform it into a complex double curvature geometry by hot drape forming approaches using single or double diaphragm forming. Despite a significant amount of high quality research [6,7] the current ability to generate defect free formed geometry by hot drape forming is limited to very simple geometries.

Research in this area is now looking at linking tape shearing or tow placement (using equipment developed from embroidery machines to generate a very complex fibre preform, see fig 8) to generate a preform that can be successfully formed into more complex, defect free preforms by hot drape forming [8]. This work is at a very early stage of research and to date it is unclear whether it will prove to be successful.

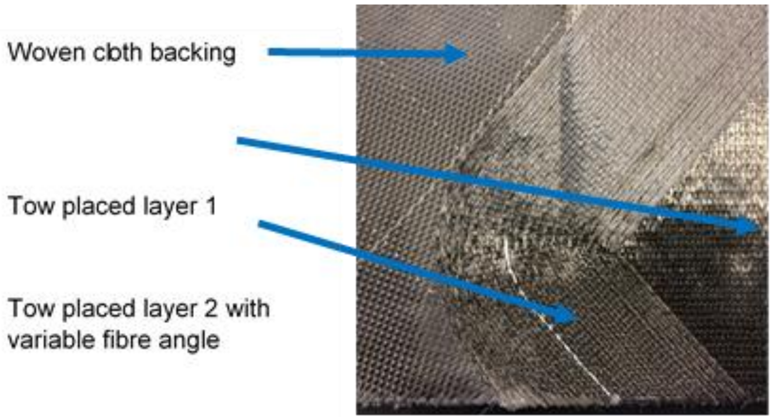

Fig 8. Tow placement can be used to generate very complex preforms

An alternative to the use of AFP and the many variants on fibre placement, is to return to the reinforcement form currently used for the manual lay-up of complex composite geometries - woven or non-crimp fabric prepregs and attempt to directly automate the lay-up of these materials. This research has progressed along two paths. Firstly, attempting to use press forming or drape forming to form the required geometry, and secondly using robots to replace the human laminators. Whilst significant progress has been made in simulating the deformation processes in software [9,10,11], this has not led to widespread use of automated forming of prepreg as part of a lay-up strategy for complex composite components, as it seems not to be possible to replicate the required complex surface geometries without severe, strength-limiting, defects in complete plies shaped by this route.

Secondly; using robots to directly replace human laminators [12,13] has been a focus of research for 20 years with little progress being made. It is at least arguable that the lack of progress is related to the definition of manual lay-up as an unskilled process. How hard can it be to apply brains and robots to the automation of an unskilled task? The answer, of course is that it's very hard if you don't have a workably complete understanding of manual lay-up, and most attempts at robotic automation have not been founded on that understanding. Even the apparently simple task of removing the protective backing films from the tacky prepreg has yet to be reliably automated for cut plies of either UD or woven prepreg.

Recent work [14] into understanding manual lay-up has delivered at least a partial route to robotic lay-up via a two step, press forming and robotic smoothing process. This process probably represents the state of the art in robotic lay-up, but it should be very clearly noted that it does not actually replicate the processes used by a skilled laminator, even if it is strongly informed by an understanding of those processes. It would certainly not be unreasonable to state that this work demonstrates that a direct replacement of skilled laminator by robots using the same techniques as the laminators will probably not be possible. There have been some early stage proof of concept or feasibility studies of other approaches such as the use of active tools [15] to form the reinforcement, but nothing to date has developed past the medium TRL range.

4. OTHER ROUTES FOR PROGRESS.

If the state of the art in robotic automation seems to indicate that skilled laminators cannot directly be replaced by robots, and the best AFP machines (including all current variants) are even less able to deliver defect free complex components, then there is clearly a need for a root and branch reappraisal of composites manufacturing options.

Fig 9 illustrates the essential difference between forming metal sheet and forming a woven reinforcement via a forming limit diagram. For the metal there are regions where any combination of minor and major forming strains within that region would be expected to be tolerable without failure. It is still necessary to hold and control the blank properly during stamping or other forming to prevent local buckling and surface waviness, but there can be a substantial range of major and minor strains which are acceptable. This means that when we move away from the simplicities of hemispherical or elliptical surfaces to surfaces with many regions of different local curvatures there is no inevitable breakdown in forming quality.

By contrast the forming limit diagram for a bias cut woven cloth can be expressed as a single line, as there is to a first approximation a fixed kinematic link between warp and weft. Imposing major and minor strains that do not follow this fixed relationship inevitably result in tearing, wrinkling and similar defects being generated. For complex surfaces with many regions of different curvatures there are likely to be a very limited number of ways of mapping this fixed kinematic link across multiple regions, whilst ensuring that adjacent regions have matching fibre directions across the region to region boundaries to eliminate defects. There may also be additional constraints on maximum fibre distortion, or a requirement to start the forming process at some datum edge.

A very significant research effort has been expended on this reinforcement drape problem over very many years, both in academia and by software houses [9,10,11], but it is still quite straightforward to define a surface geometry that can't be solved automatically by the available software. Of course, this is exactly the challenge that we are expecting our "unskilled" laminators to solve on a day to day basis by an experience-based problem solving process. So one route forward is clearly to develop reinforcements that "behave more like sheet metal". Simply replacing woven prepreg with a stack of crossplied UD prepreg is a step in the right direction [16] and adding a lubricating layer between plies helps a bit more by allowing the fibre directions to deform more independently. There are other approaches that can be used that additionally permit the deformation in the fibre direction that is not normally possible in UD or woven prepreg. These include slitting or laser cutting the prepreg into shorter lengths, stretch-breaking tows prior to prepregging and the alignment of short fibres. [17,18,19,20], needless to say in all those cases there is some impact on maximum mechanical performance, at least for flat laminates - although the impact on strength is often less than the impact on the strength of a continuous fibre laminate due to a wrinkling defect. All of these approaches have been suggested, researched and developed; to date none have had any widespread industrial adoption.

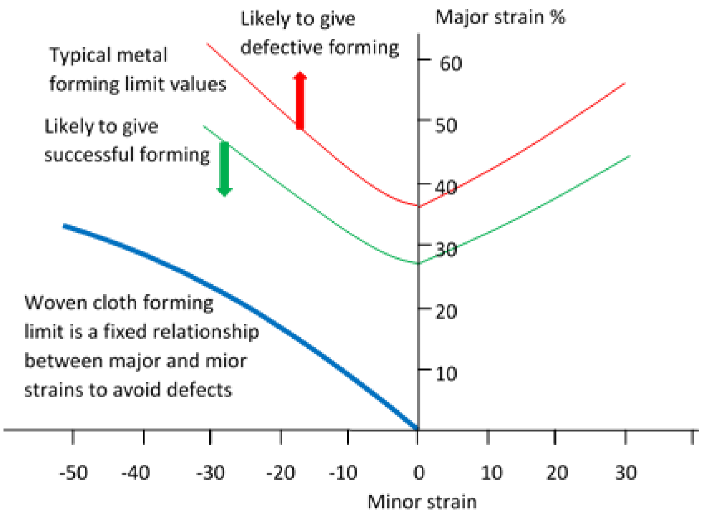

Fig 9. Forming limit diagrams for sheet metal and woven cloth

In practice the ideal target would be to lay up a fully detailed discontinuous preform in the flat state by pick and place methods or ATL/AFP and simply form it into the tool by single diaphragm forming, or possibly in a stepwise fashion using a sequential approach using pressure pads or robotic end effectors. This would deliver a very great reduction in lay-up time and largely eliminate the need for skilled laminators. It has to be stressed that there is a gulf between the concept and a practical and proven process, but all the separate elements have recently been demonstrated.

Another approach is to redefine the deformation task. If, rather than forming a complex set of connected surfaces with a large ply of reinforcement we take a small patch of reinforcement and form it to the locally simple surface we can eliminate most of the large scale defects. We are then replacing them with a much larger number of small scale and local defects. The bulk of these defects are related to the ply drops at the end of each prepreg patch. The impact on mechanical properties of the ply drop reduces to manageable levels for thin plies of prepreg, so it's possible to define a process that can cope with relatively complex geometry surfaces and effectively steer the fibre paths by rotation between sequential patches [21]. It should also be noted that adopting the use of thin plies would also improve the performance of those processes cutting fibres to enhance formability. Robotic application of thin preform patches in a controlled array, or forming of thin (locally or globally) discontinuous plies, certainly has the potential to meet the technical requirements for automated lay-up; whether it has the potential to meet the commercial requirements for quality, reproducibility and productivity only time will tell. The key message here is that fibres don't have to be continuous - just well aligned - and that some of our difficulties in forming complex geometries in an automated way arise because we have continuous fibre.

4. BROADER ISSUES.

Returning to the basic process steps identified at the start of this paper it should be noted that these steps are essentially fully serial, we move from one step to the next in a linear progression. There would for example be a significant improvement in overall productivity if we did not have the cure tool captive in the lay-up process, as the lay-up process can currently take significantly longer than the cure cycle. A detailed examination of manual lay-up has shown that the prepreg tack has a major impact on the speed and quality of lay-up [2]. The right level of tack is critical to achieving a good capture of the tool surface geometry, and to the ease with which laminators match the reinforcement to the surface. One downside of the use of tacky reinforcements is that the mould tool is generally tied up for the lay-up cycle as well as the cure cycle, increasing the tool cost/moulding. Another limitation is that in general we cannot easily remove a complex laid up stack of tacky prepreg from a tool surface without any damage, so that even if we move over to the use of formable discontinuous prepreg we cannot easily separate out the forming and curing stages.

It can very reasonably be argued that the simple answer is to stop using prepreg and instead use dry fibre and resin infusion. This is reasonable in some respects, but whilst dry fibre is very easy to form to shape it simply doesn't stay formed when the forming forces are removed whether these be manual or automated. So to directly replace manual lay-up with woven prepreg with dry woven cloth only works if a tackifying agent is applied to the tool surface for the first ply, and to each subsequent ply surface. This seems unlikely to be an acceptable practice for critical structures as the tackifier is incorporated into and forms part of the matrix in an essentially uncontrolled way. Equally, this is simply moving from manual prepreg lay-up to manual dry cloth lay-up so fails to impact on automation.

Because Resin Transfer Moulding (RTM) is a fully tooled process the process chain that we started with can be shortened and more steps are amenable to automation, such as mould loading and unloading, and the use of net shape tooling potentially eliminates trimming. Variants of RTM would normally be regarded as the starting point for moulding complex automotive parts such as that from which the cross - sections seen in fig 5 were extracted, and this part was indeed made by RTM. The part was made from a number of stamped preforms, each made and trimmed to size in an automated stamping press. The reinforcement was coated with a powder binder that can be softened and released by heat and which resets on cooling to hold multiple formed plies together.

At first glance this seems to meet the requirements laid out earlier, there are however some very significant limitations. Firstly, we know that ply drops limit performance and that processes such as prepreg ply patch placement need to use thin plies to avoid significant drops in performance. For a press formed, or stamped, preform to be stable it needs to have at least two plies of reinforcement, and it is very common in automotive RTM for the preforms to be significantly greater than 1mm thick. Preform thicknesses in this range would lead to a major knockdown in performance in structures using assemblies of multiple preforms; and although through thickness reinforcement at preform edges should improve matters mechanically it imposes an additional cost. The use of 3D weaving and other complex weaving processes have been suggested as alternatives to assemblages of pressed preforms to alleviate some of these issues, but have yet to be demonstrated as a cost-effective alternative. The automotive body in white structures carry very low strains in normal operations, essentially being designed on crash cases. For these structures thick preforms and simple overlaps between adjacent preforms to build up a complex structure can be acceptable. For aerospace structures with higher operational strains, higher cure temperatures and thermal strains, longer lifetimes, more stringent safety requirements, more challenging weight targets and a zero damage growth design criterion a thick preform approach would not be acceptable.

Secondly, the automotive reinforcements are still continuous fibre reinforcements, so the ability to stamp them into complex shapes is rather limited, which is why a number of preforms might be needed to form a shape that could be a single pressing in steel. Equally, whilst aerospace structures are generally gap-free surfaces, automotive parts for a passenger cell have large open areas, again leading to the use of multiple preforms to control waste levels. As noted earlier, it is very hard to avoid all wrinkles in a pressed preform of woven cloth or NCF. In an automotive environment the standards for wrinkling quality can be lower than in aerospace. If a wrinkle is seen in every part made, but the structure performs well in test then that part quality can be defined as "good". In principle this approach could also be used in aerospace, although it is much less likely to be. For simpler structures that can be made from a single pressed preform the trend in automotive composites is in part away from RTM to a simpler process of wet compression moulding which eliminates much of the tooling complexity of RTM to reduce manufacturing costs.

Lastly, the material wastage for this approach of the assembly of stamped preforms from woven or NCF Reinforcements will be even greater than for ply by ply lay-up in aerospace due to the need to control the forming of the blanks via blank holders and subsequent trimming. Even with the potential for recycling of the in-process wastes this adds significant cost as, with the greater automation in automotive composites the material costs become more of an issue than the labour costs. Other processes such as directed fibre placement using robotic air laying techniques [22] may offer a more appropriate balance of reduced fibre wastage, avoidance of sectionalised preforms when the preforms have large open areas, and potentially weak joint regions in automotive preforms albeit at lower absolute baseline fibre volume fractions and mechanical performance. It might be better to retain the final forming process in the tool to be able to maximise the fibre laydown rate in a flat format and avoid tying up the tool fibre for any longer than absolutely necessary.

5. CONCLUSIONS

A few conclusions emerge from this consideration of options for automating the manufacture of geometrically complex composite components in aerospace and automotive environments. The first is that the optimum solution is likely to be different in the two cases, if only because the geometry of the components is actually very different. They both give rise to complex geometry - but in very different ways. The second is that the answer may lie as much in modifying the reinforcement to suit the processing and rate targets as in trying to automate the lay-up of current materials. Lastly, that making current approaches a little better by incremental improvements to each process step will not be good enough. We need to redesign the complete system of manufacturing composites from the ground up. This will always be challenging in the aerospace environment. In that environment, in the short term, focusing on really understanding manual lay-up, building that understanding into Design for Manufacturing and skills training and support tools will probably pay the strongest dividends for the very large numbers of secondary structures needed.

Acknowledgements

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