

Forming Complex Shaped Components Using Drape Simulation Software: Informing Manual and Automated Production Needs

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ABSTRACT

When forming components using composite materials, manual lay-up techniques remain unrivalled, despite shortcomings that limit geometrical complexity. As a result efforts towards automation of the manufacturing process can be desirable. These can be through more automated builds, or via better informing the manual lay-up through simulation. Automation of more complex components is however difficult to achieve due to some technological barriers. Some progress in simulation tools to predict formable shapes has been made, but little in tools to predetermine the manual operations required. The work herein describes a concept to link component design and manufacture using an in-house simulation tool developed at the University of Bristol, UK, called Virtual Fabric Placement.

INTRODUCTION

In the manufacture of components using composite material, manual lay-up using typically carbon fiber-epoxy resin prepregged fabric remains unrivalled in terms of versatility. This does however come with significant shortcomings which include amongst others the time to lay-up a component, and the need for a highly skilled workforce to undertake the tasks in forming. Governing costs of a composite component are also often cited in terms of the overall efficiency possible in forming the reinforcement to a required shape [1]; which for manual forming with highly skilled operators is said to significantly increase the associated costs, especially if inefficiencies in the lay-up are allowed.

However, in the aerospace industry there are also strict certification & tolerance requirements, which have realistically been transplanted from metallic products, without necessarily considering the characteristics of composites. These certification and tolerance limits do restrict the available geometrical complexity of producible components, often making highly complex shapes beyond present production capability. But these limits also extend build times of the current practically producible components. As a result, efforts to automate the manufacturing process can be desirable. This can be

through more automated builds, or via better informing the manual lay-up process.

For composites, methods to automate the manufacturing process were identified & reported in 1980 [2], although reference to composites automation can be found as early as 1967 [3]. These automated cells were revisited in intervening years, with [4-6] of special interest. The cells utilized robotics, approaching automation through pick-&-place technology of plies cut from broad-good cloth. The methods are interesting, but more important is the fact that these cells were being identified at the advent of simulated design methodologies, showing that interpretation of design and automation was an early desire. It is also worth noting that these early cells also identified the complexity in composite manufacture; with [4] especially referencing to the need for a reject region to be incorporated to the cell. However the cells of [2, 4-6] were unsuccessful, for a mixture of low parts count at the time, and also significant technology barriers.

These barriers included efficient and reliable pick-&-place end effectors, despite some research on gripping mediums [7]. Indeed it is arguable whether any of these technology barriers (film peeling, pick & place, gripping & end effectors) have yet to be demonstrated successfully, approximately 15 years later. However at the same time dominance in composites automation through direct placement of unidirectional materials in bands or courses (where necessary) onto tooling became prominent and has really dominated the composites industry since. Automated processes utilising direct material placement are largely limited to Automated Tape Laying (ATL), Automated Fiber Placement (AFP) [8], although some RTM preforming techniques & Filament Winding can also be described as automated processes. These are said to improve manufacturing efficiency and thus off-set the costs through (although not limited by):

- Reduction in labor hours - per component automation can provide a significant reduction in the labor hour content required to fabricate composite parts. The reduction is suggested as high as 90% [9] although 25% appears to be the average [10] (component dependant);

- Increased material utilization factors of 1.05-1.20 (95-80%) & so reduced wastage rates, compared to manual processes with utilization factors of only 2.25 (40%) [10];
- Reduced need for in-process inspection through computer controlled machines laying up the material, it is not necessary to have a quality operator verifying ply completion & orientations (if necessary) [8], and;
- Higher quality & repeatable parts are possible which can contribute to the overall cost reduction. Indeed component cost reductions of 25-60% compared to manual forming are often cited [11-12].

However there are some concerns as to these suggested improvements & especially the cost reduction benefits. These reductions not only include projections for broad-good cloth automation [2], but also for material & processing substitution from the traditional processing routes to dry fibers/ infusion [11-12]. The cost projections also often assume 100% material use, despite course/ band overrun necessary in ATL/ AFP, as well as the cured component trim that will be lost. The cost outputs also tend to ignore the fact that material costs for automation are higher, with ATL tape for example 5-15% more expensive than the more traditional prepreg used for manual forming [9-10]. Tooling costs can increase as compaction pressure increases relative to manual operations [9], although consolidation steps are still required at regular intervals [13]. Equally, Non-Destructive Evaluation will still be necessary after curing operations. It is hard to ignore that overall, 30-80% of a given component's cost is material related [11-12], depending proportionally to preform mass but inverse proportionally to complexity (although it is also suggested that half a components costs are in lay-up, cure and assembly [9]). It is in fact very difficult to tease out the claims for cost reduction due to different level of automation for different parts.

Perhaps the largest concern should be that the capital investment required for an ATL/ AFP or similar is large & the process overheads increase as a result. If each element of a build is not properly accounted for then a case could be made where labor costs are simply substituted for various overheads when introducing an automation machine. A machine is bought to only really serve 1-2 components during its lifetime, which limits the flexibility of a shop-floor for agile throughput. Indeed, while much of the industry is concerned with increasing the deposition rates of automated machinery, it is perhaps more apt to consider the throughput per unit area of a shop floor for manual labor comparison. For example, it is often the case that labor, consumables, processing etc are entwined in a burdened process per hour cost making it very difficult to generate a true cost for a component build breakdown.

The only known major cost study, comparing both manual & automated techniques, was undertaken in 1986 [14]. Interestingly, it suggested that automation may not be cost effective due to low parts volume, the capital investment required, and the marginal gains in scrap; while material costs would continue to dominate.

Labor costs were suggested to be a minimal contribution and were as such marginal. Overall the main disadvantage was that no design for automation was in place, and that much of the equipment used was not necessarily designed for composites. It is debatable whether a sufficient change in the industry has occurred since; despite the expected airframe numbers required in the upcoming years [15-16] (including an industry in transition from metallic to composites use [17]). For example, Table 1 attempts to show the number of components required for a wing-set (excluding the centre wing box) over increasing ship-set requirements. The numbers are very high, especially if we consider ship-sets similar to the expected rates of [17] for the new single aisle replacements that are likely to be near-all composite. If we consider them as primary or secondary structures, we find that on average secondary structures are dominant (at approximately 85% of the total). If we further consider which components are currently automated, then we find that it is a mere 12% of the total, but importantly it is clear that ATL/ AFP is concentrated on & mainly applicable to, those larger geometries that are relatively simple. Here lies the major disadvantage in composites automation: at current technology levels and under the limits & tolerances of the industry, automation cannot manufacture these more complex geometries with confidence. For these more complex structures it is better to develop methodologies to inform the manual lay-up techniques, and also investigate the geometries to enable more rapid manual forming that could perhaps later on lead to automation.

Manual forming techniques allow highly complex shaped components to be produced, but the practical operations required to do so are often counter intuitive [18-19]. Some progress has been made in developing numerical simulation tools to predict draping effects through tow re-orientation on formable geometries, but little progress has been shown in developing tools that predetermine the manual operations & potential difficulties associated with component geometry. The difficulty in simulation is matching assumptions made in virtual space with what is possible manually. Further complexities involve the facts that any drape simulation tool must sit in the concept and detailed design stages of Figure 1, assisting in design & returning information ready for Design for Manufacture stages of a geometry. While the tool must be modular allowing design feedback, the hierarchal position in the design system is relatively low [1], as Table 2 shows.

AN OVERVIEW OF CAE DRAPE SOFTWARE

Computer modeling of how fiber reinforcement fits to a mould surface has developed in 2 ways, distinguishable by the outputs intended use. For high production volume industries, significant investment must be made in detailed design of tooling equipment and analysis of the resulting process. Much work has thus been done to develop finite element based simulations, to accurately predict the results of mechanical forming operations. In contrast, low production volume industries such as aerospace, dictate that large investment in expensive

tooling is not economically viable. As a result of manual forming dominance, it is also more appropriate to design & directly specify manipulations required of the operator. Thus geometric/ kinematic simulation aids are preferred. These solutions simulate drape through making the assumption that the reinforcement material deforms as a simple mechanism, although some initial assumptions must be made about how the mechanism will be formed to the tool. The simulation output can be used directly as a representation of the required lay-up, but importantly the simulation costs are reasonable. It is this type of drape simulation that we will concentrate on.

STATE OF THE ART IN GEOMETRIC/ KINEMATIC CAE DRAPE SOFTWARE

The most popular model for simulating the mechanics of woven fabric reinforcement is the pin jointed net model first proposed by [20] to understand textile drape, and then used by [21] to model drape of composite fabric. The model is based on the assumption that a fabric's deformation mechanism can be represented by a rectangular array of originally square cells, each represented by four pin jointed rigid elements. The rigid elements represent the warp and weft tows; the pin joints represent the way that the fabric weave or stitch links the warp and weft tows together (as a mechanism). As a piece of fabric is draped over a 3D surface it must deform through a combination of 5 modes of deformation [22]: Fiber bending, Fiber straightening, In-plane shear, Fiber slip and; Fiber stretching. The pin jointed net only takes bending and in-plane shear into account. A deformation limit is specified as the minimum angle between the warp & weft tows. At this limit the tows lock together preventing any further in-plane shear. To predict the alignment pattern on a 3D shape, a pin jointed net is mapped onto the surface as far as it can be without reaching the specified locking limit.

In order to generate a draped pattern for a specific geometry, a start point and the initial warp & weft tow directions need to be specified. One of a number of different mapping algorithms can then be selected, each of which generate a draped pattern for the surface according to different criteria (loosely associated with assumptions about the real lay-up sequence), but previously shown to be impractical or non-intuitive as lay-up strategies [19]. Figure 2 for example shows 3 different drape pattern results for the same simple shape where, the start point is specified at different points on the base. In the case of Pattern 1, the mapping algorithm is based on Geodesic control tows while Patterns 2 & 3 apply the same algorithm but from different start points, producing completely different solutions. Other algorithms include:

- Planar control tows: A planar warp & weft control line is generated from the start point over the surface initially to constrain the generation of the net.
- User defined control curve: A user defined control curve is specified manually on the surface geometry (e.g. the component edge) so that sufficient constraint is achieved to generate the net over the surface. This

option assumes that a single warp &/ or weft tow of the ply is placed on the surface to match the generated control line; but is difficult to achieve practically.

- Energy Optimization: Cells are generated in concentric sets around a start point to minimize the overall shear deformation in each set through iterative processing.
- Maximum/ Minimum Optimization: Cells are generated in concentric sets around a start point so that the maximum positive shear angle is equal to the maximum negative shear angle in each set. These optimization routines are usually based only on kinematics where shear stiffness is assumed to be zero, and if the max-min optimization is only set for the local concentric cell then only the local optima will ever be found.
- Draped Surface Order: The user is provided with options to subdivide the surface & specify the order in which each sub-surface is draped. This is the nearest simulation to manual lay-up, as the draped pattern in each sub-surface forms the constraint to the next sub-surface in the drape sequence.

These various mapping algorithms evolved from work in [23-24] where limits of the simple pin jointed net were explored. The model is a useful guide in determining whether or not a shape is formable, but because it only simulates in-plane shear deformation & does not account for additional deformation modes from fiber mechanical properties, it can neither take effects arising from the forming environment conditions into account. This impacts on the deformation extent possible but can also influence fiber trajectories. For this reason, the simple net model alone is not able to give accurate indication of where defects such as wrinkles may be generated.

Commercially there are 2 main suppliers of kinematic drape simulation tools. Simulayt [25] have developed lay-up simulation technology incorporating an initial condition specification based on geometric optimization & some manufacturing operations, which is used by several companies. Vistagy [26] via FiberSim is the only major competitor & uses a similar strategy for the simulation. The outputs from existing commercial drape simulations include a 3D pattern of tow trajectories and a flat pattern for the given solution which allows a surface to be defined as either formable or not. The primary requirement for any commercial drape simulation software is a simple, quick and intuitive user interface for specification of the initial conditions. A final interesting example of this can be found in work by [27-28] that investigated such methods. It is of particular interest as the methods would appear intuitive to someone skilled in draping, & outlined a methodology for allowing tailoring & dart insertion in simulation (as available commercially).

THE FUTURE OF LAY-UP SIMULATION

The impact of fiber re-orientation, induced by drape, on structural performance is becoming recognised. But risks in overestimating the capabilities of presently available commercial kinematic drape tools exist by overlooking the fact that operators have substantial control over the forming process. Because of this, lay-up simulation is

unlikely to accurately mimic practical lay-up & cannot be used as a prediction tool [29]. Commercially available kinematic modeling tools can predict whether or not a mould shape is formable with some certainty, and thus they will generate a tow alignment pattern (for specified conditions). But they can not predict the most intuitive or practical tow pattern for lay-up. For complex shapes, often the pattern desirable from a design point of view is very difficult to achieve in practice by being unintuitive [18]. Any extra information the tool can provide as to the practical difficulties in achieving a chosen pattern would be invaluable.

INTERACTIVE DRAPING AND MANUAL LAY-UP CHARACTERISATION

In developing new software for forming, the University of Bristol departed from simulation; developing an interactive draping strategy [1]. This involves the software representing a ply in virtual CAE environments & providing the user with controls to place the ply in real time in a manner that mimics lay-up. Instead of supplying initial conditions and requesting a simulated solution, the draping strategy will make no prior assumption to how drape should happen. By doing this, the user approaches the lay-up design in the same way as would be done manually. This allows designers freedom to experiment with the virtual ply in real time, and make decisions about the component lay-up during design. The decisions can then be recorded as lay-up instructions, or provide information on the difficulties associated with the lay-up.

In order to mimic practical lay-up in the virtual CAE environment, some assumptions must be made about the dominant forming operations used by the operators. Characterization of manual lay-up processes is complex, as operators essentially have complete control over the material deformation. But it is possible to limit the operator to some basic operations, without limiting the forming process versatility. To do this, some specific vocabulary has been identified, along with Figure 3 [1]:

1. Stuck material - is the portion of the ply deformed and tacked to the tool surface.
2. Free constrained - is the portion of the ply free in space but contains warp and weft tows which are stuck at some point along their length.
3. Free unconstrained - part of the ply that is completely unconstrained or only contains either a warp or a weft tow stuck at some point on its length.

During the forming process any point on the ply being formed will start as free & unconstrained and become either stuck or constrained via placement operations. A smoothing operation is then required to deform all free constrained material to the tool surface. From this simple characterisation, any logical manual lay-up process can be resolved into sequences of placement and smoothing operation pairs. The stick points are points on the ply which are forced onto the tool and define the route taken by the lay-up sequence over the surface. It is this route that must be defined control the lay-up process [1].

VIRTUAL FABRIC PLACEMENT

Thus University of Bristol has developed Virtual Fabric Placement (VFP). The underlying principle is to provide the user with a tool to carry out virtual forming operations the way it would be done manually. The intention is by designing the lay-up operation virtually, the formability of a geometry becomes self evident at the design stage providing feedback between design & manufacture. An interactive forming tool must graphically represent all main features as observed in reality. Importantly the reinforcement being formed must be fully displayed, compared to other drape simulation tools that generate tow trajectories contacting over tool surfaces, regardless of the effects of the ply as a whole. In reality this free material has a controlling effect on the forming process & is used as a handle to impose manipulations on the ply, Figure 3. To represent the process graphically, the free portion of the virtual ply should be displayed and used as a means of governing forming processes. Inverse drape simulation allows a tow pattern to be generated in free space from pre-specified trajectories regardless of any forming surface [30]. This principle is employed in VFP to represent the free region of the net during the virtual forming operation [1, 19].

The operation to impose in-plane shear deformation on the material is separate from the operation used to stick free material to the surface (tacky prepreg cannot be dragged easily over surfaces). In practical terms, the VFP sticking operation involves selecting a node on the free ply or net and forcing it to the tool surface. Figure 4 shows the node placement algorithm [1]. It assumes that the selected node on the free net rotates in a plane defined by 2 vectors. When sticking a new portion of free material to a surface 2 forces are applied to the free material: 1 to hold the free material in space away from the tool (vector 'V') & the other at a selected point, forcing it to the surface (vector 'Normal'), against the constraint of the stuck material. The node to be stuck & the sticking force direction must then be specified to complete the mapping algorithm input. The direction of the sticking force can in theory be applied in any direction but can be assumed to act in a parallel direction to the net surface normal at adjacent constrained nodes. Applying a sticking force at any other angle to the net normal will induce additional in-plane shear. So by definition, the act of placing a single free net node in contact with the surface will constrain all free nodes along the edge of the stuck region in the row containing the newly stuck node. These constrained nodes can be automatically mapped to the surface as a depiction of the practical smoothing operation by an algorithm similar to that used in traditional kinematic drape simulation [27].

Figure 5 shows the VFP user interface consisting of an initially rectangular net representing the ply to be formed, and a cursor controlled by the user's mouse movement. As the cursor moves over the net it will select each node it passes over, mapping it to the surface before using the smoothing algorithm on all local constrained nodes & moving on to the next position. The cursor is in effect the