The generic 'moulded sail' has come a long way since the first 3DL headsails appeared on fragile inshore IOR50s in the early 1990s. Now it is common to see 3DL going round the world – both in the Volvo Ocean Race (*below*) and on tougher (for sails) solo events like the Vendée Globe. *Right*: the famous 'garbage bag', as rivals nicknamed Lowell North's famous green Mylar/Dacron 12 Metre genoa back in 1977

BILLY BLACK

From textiles to composites – Part 1

Or how the 'sailmaking' industry moved from weaving natural fibre to providing manufacturing materials for the aerospace industry. Bill Pearson takes us on a fascinating journey that is still very much underway

It has become increasingly rare for any structure built for a performance sport application to be constructed from anything other than composites. And at the high end that means carbon fibre pre-preg composites.

The reason for this is that in performance sporting applications there is an insatiable demand for both stiffer structures and lighter weight. Today the word 'composite' implies fibre and resin matrix structures built from material laid up in a mould, and thermo-formed under heat and pressure. Sailmaking has been evolving in this direction for two decades, and as we now stand on the precipice of another paradigm shift in sail fabrication technology, referencing sails more generally as performance composite structures makes the coming revolution seem both desirable and inevitable.

In this first part of three articles I review the past 25 years of performance sailmaking to remind us of the path we have travelled down to the present. In Part 2, I will look forward to what the next generation of sails will look like, and in Part 3 I will discuss some of the other performance manufacturing applications that are beginning to take advantage of lessons originally learnt in the sailmaking arena.

The history of performance sailmaking is the story of the pursuit of modulus, the measure of a material's ability to resist stretch (stiffness). The greater the effective modulus of a sail the more energy created by wind pressure is translated into driving force to power a boat forward through the waves. Stretch in the sails, mast or rigging acts as a shock absorber and dissipates – in other words, wastes – some of the available power that the wind produces from getting turned into drive force.

The ramifications of this fact extend a lot further back in our sport and in performance sailmaking than is generally realised. Assembling panels of woven material to make sails dates back thousands of years, but we will define the history of 'performance' sailmaking as starting with that famous race around the Isle of Wight in 1851.

In the mid-1840s the secretary of the US Navy was becoming concerned about the supply of sailcloth for his ships. Up to that time most of the sailcloth used in the US was flax, imported from Europe. In the event of another war, that supply would surely be cut off. A small domestic sailcloth industry had been growing for about 30 years, but it was based on cotton fibre rather than flax. Cotton was new to sailcloth, and hence largely unproven, at least in the eyes of the Navy.

The secretary polled his captains for their opinions and got back conflicting reports. Some claimed flax was stronger and more reliable, while others said that cotton stretched less and held more wind. Embrace the new technology or stick with the old, it was a tough choice, the anecdotal evidence from the field was conflicting. In the end, the Navy chose cotton, partly due to the results of a yacht race…

In 1851 the visiting yacht *America* had sails made from Egyptian cotton, as opposed to the flax sails on the 14 local UK vessels. The difference in the sails on the boats was obvious enough for *The Times* to report the next morning that the challenger's sails were 'flat as a sheet of paper', and thus allowed the boat to sail closer to the wind.

Those sails were flatter at least in part because they were made from a superior material. Although not as strong as flax, cotton has a higher modulus, or better resistance to stretch. The *America*'s sails thus held their aerodynamic shape better, because they stretched less. In days when boats sailed at maybe 55-60° to the wind, *America* could reputedly sail 5° or 6° higher than her competitors.

As it turned out, what the Navy secretary heard from his fleet was correct: flax was stronger, but cotton 'held more wind' or stretched less. Thus began modern performance sailmaking, when someone realised that for performance, resistance to stretch (modulus) is more important than strength[1].

This story resonates with me, because as we bring on the next generation of sailmaking technology (3Di), we are fighting these same battles. Scepticism about the new technology, conflicting reports from the field, and finding the balance between modulus and strength.

The age of material replacement

In the sailmaking business and the sport, cotton fibre ushered in what I refer to as the 'Age of Material Replacement'. As new and better materials became available they replaced the existing material but they were employed in the same manner. Hence more modulus was achieved by substituting a superior material, but the manufacturing process for making the sailcloth, and for using the sailcloth to assemble a sail, remained unchanged.

This process to improve sails solely through material replacement lasted from the 1850s up to the late 1970s, when the first laminated sailcloth appeared. Lowell North used a Mylar/Dacron laminated fabric on his 12 Metre *Enterprise* in 1977.

Laminated sailcloth improved the bias stretch characteristics of woven fabric, which provided a more stable aerofoil shape, if not more modulus overall. But this lamination process also allowed usage of the higher-tech fibres, which were harder to weave, to be used in sailcloth. Just three years later a woven Kevlar/Mylar laminate was used on *Freedom* to win the 1980 America's Cup. However, from here material replacement just continued apace, albeit in a slightly more sophisticated laminate configuration. All sails were still crosscut (horizontal) assembled panels at this point.

The next two innovations appeared more or less simultaneously at the dawn of the computer age, and they informed one and other. Innovative Kiwi Tom Schnackenberg figured out how to shape panel sections using a computer routine, and then define mathematically how much curvature (broadseaming) to put into each panel to yield a finished 'flying shape'. At roughly the same time Peter Mahr, who started North Sails Cloth, noticed that loosely woven polyester fabrics underwent a shift in the orientation of mechanical properties during the fabric finishing stage.

In textile manufacture the fibre in the fill direction (transverse) is straighter than the fibre in the warp (machine direction), and hence has better effective modulus. The shrinkage during the finishing stage in certain constructions improved the warp enough to change the balance of properties. Mahr then developed the idea to produce warp-oriented sailcloth.

This development dovetailed perfectly with Schnack's nascent development of the first sailmaking digital platform. The computer didn't care if the panels were horizontal or vertical, it could provide the correct edge shaping for either typology. While vertically cut panels in sails were not unique, vertically shaped panels were a significant innovation. Schnackenberg went on to design 'leech cut' vertically panelled and shaped sails, using the new warp-oriented laminates for *Australia I* in 1980[2].

About this time the computer ceased being used solely for computation and data management and started to drive the design process itself. In 1983 Schnackenberg took panelled sailmaking to its logical conclusion by creating the first tri-radial sails for *Australia II*. Specific panel typologies arose with ever more sophisticated schemes. Next were panel schemes radiating out of all three corners, in an effort to better align the straighter warp threads to the sailing loads as mapped by Schnackenberg. This emphasised a new paradigm of design, but not of construction. Fabrics by now were Kevlar laminates, and hence much stiffer and able to carry the ever increasing sailing loads on these more highly developed yachts.

This strategy reached its absurd end game 10 years later when panelled sails for the 1992 America's Cup had 100 or more individually shaped and assembled panels in each sail. It was time for some forward thinking. Enter JP Baudet and Luc Dubois.

The age of process (better use of existing materials)

All the fibres in use today have been in existence for 30 years, and many are approaching 50 years old (or more). The approximate dates when various synthetic fibres came into use are: Dacron (1945), Carbon (1960), Aramid (1970), UHMWPE (1980), PBO (late 1980s), Vectran (1990).

Despite the fast pace of evolution in the electronic technology world it would appear that the lead time from conception of a new fibre on the chemical drawing board to full commercialisation can still be over 10 years. Evidence of this is the infamous fibre M5 which was patented in the early 1990s, has been announced and hyped a few times since then, but is still not for sale or even being produced in small quantities. The hold-up here is possibly the same issue that blighted PBO: the inability to fully flush residual solvent from the spun fibre at the end of the process, creating an unstable material that can be of inconsistent quality.

If and when the next new fibre/material does arrive there is no guarantee that it will move the state of the art forward. UHMWPE, while used widely in generic sailmaking, has had little impact at the performance end of the sport (at least until 3Di). In 1998 North Sails were the first to adopt the wildly hyped PBO, and first to ditch it one year later.

That turned out to be prescient as this environmentally unstable material would go on to cause lots of grief in the body armour industry, and is now again flirting with controversy in the rigging business. Vectran, while still the fibre of choice for textile applications in the aerospace industry, has also had little impact on sailing because of its relatively low modulus.

All the R&D departments of the big fibre producers have been working on a 'Super Fibre' for years, with apparently nothing even remotely close to coming to market. Therefore, it would appear that nothing is imminent in terms of new fibrous materials that are likely to change the game in performance sailmaking.

This puts a premium on what we call ▷

‘process’, or the way a fibre is employed in the manufacture of a sail or structure.

In the absence of new materials, he who makes the best use of available materials makes the fastest sails. Hence our mantra at North is ‘better use of existing materials’. This philosophy was the driver behind the creation of North Cloth 30 years ago, of 3DL in the early 1990s, and very specifically is the impetus behind the current 3Di project.

There is nowhere else to go to make big improvements, to continue to increase the effective modulus of the membranes, than to realise better performance out of the existing base materials.

3DL (three-dimensional laminate)

Without question 3DL was the seminal development in sailmaking since the change from wovens to laminates. It led to a sail that was better in every regard. It has both more modulus and more strength than what came before, and at the same time was lighter. As is often the case in a technological revolution the metamorphosis is accompanied by, or driven by, a new approach to the medium.

In the case of this fundamental change from panel assembly to monolith structure, the whole approach changed at once instead of in evolutionary steps. It was a giant leap out of the textile paradigm into the modern world of composite fabrication. Now by carefully choosing the constitution of the membrane sailmakers can prescribe exactly the mechanical properties of the resulting product.

If you type ‘composites’ into Wikipedia this is what comes up: ‘Composites are made up of individual materials referred to as constituent materials. There are two categories of constituent materials: matrix and reinforcement. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent materials.

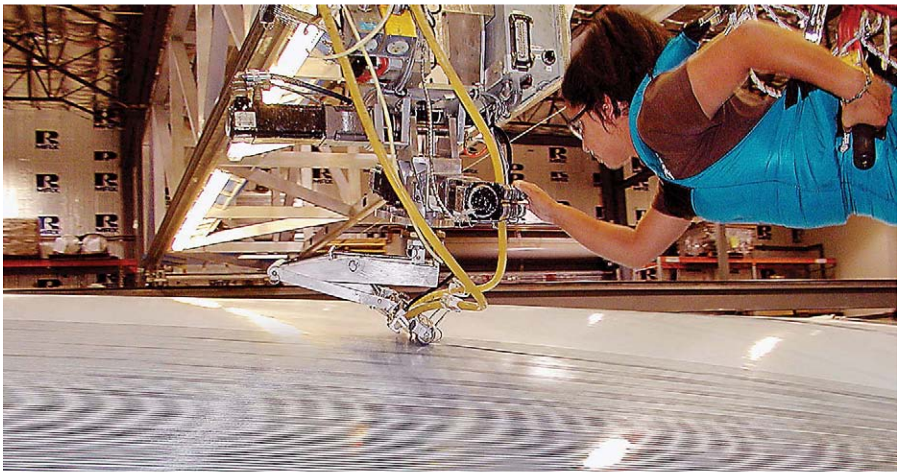
‘*Engineered composite materials must be formed to shape* [my italics]. The matrix material experiences a melding event, after which *the part shape is essentially set*.’

These are conditions that define composite structures, and set them in opposition to traditional structures where sections or panels are mechanically assembled. It does not matter if you are talking about buildings, boats or sails.

These particular characteristics are, therefore, what set apart a modern high-performance sail from a more traditional construction. It is:

(**1**) moulded like any other composite.
(**2**) has bespoke fibre orientations and density clusters.
(**3**) is a unitary monolithic structure (in other words, not assembled mechanically).

Now we can look at each of these aspects in turn…



At North’s 3DL plant in Minden, Nevada the operators monitor the fibre-laying process while suspended from gantries above the adjustable moulds in a hang-gliding harness

Bespoke fibre placement

The placement of fibres in modern sails reflects anticipated wind loads and variations in the stress field as the boat moves through the waves. The variation in fibre density and orientation allows us to optimise locally for strength and stiffness. The greatest fibre densities are clustered in the corners, from where on a sailboat the loads are reacted.

This requires fibre orientations in a modern sail to be asymmetric, as opposed to the formal symmetrical micro structure of a textile. In traditional textile manufacture the symmetry of the 0-90 grid (warp and weft) requires that fibre be positioned evenly throughout any structure, not because of the requirements of the structure or product, but because of the requirements of the textile manufacturing process. By placing fibre only where it is required this new world allows for better material economy, and better material economy allows for lower weight for the finished part. Our process allows us to put fibre only where it is required, on an as needed basis, and thus make the lightest structure possible for a given application.

These membranes are built as a unitary, monolithic structure. Sails are built full size, in one piece, on large articulating reconfigurable male tools (moulds). The sails are built in 3D space, with complex curvatures, in the shape they will assume when they are flying on the boat and pressurised. Fibre runs corner to corner, uninterrupted by seams or joins.

Most importantly, and often overlooked, is that the fibre itself is laid in 3D space, in the spatial location it will inhabit when the sail is inflated. It is impossible to overstate the importance of this in the performance of the finished product.

In this process there is no longer any distinction between the sailcloth and the sail. The two are fabricated simultaneously. They are indistinguishable and inseparable. The surface and structure are integrated, as these two are also created together. In this way, even though it is still laminated to a film substrate, the finished product becomes a composite.

Even though there is a visible distinction between surface and structure (which will disappear in the next-generation 3Di technology), it is nearly monocoque. In non-moulded sail manufacture you still make the sailcloth sections individually and then assemble the component parts mechanically.

In this new paradigm chemistry replaces mechanical assembly. Covalent bonds and van der Waals forces are the new seams, gluing and stitching.

3D moulding

This bespoke fibre placement being executed on a large scale is still unique, the product being preformed on highly unconventional equipment at North Sails Nevada. The heart of the process is an articulating mould that can be adjusted in three dimensions to match the complex curvature of a custom sail configuration.

The surface contour of the mould is achieved with dual pneumatic actuators controlling up to 350 pantograph armatures driven by an attached vertical screw, one-quarter turn at a time, adjusting its lifter 1mm per turn. This in turn adjusts a segmented surface structure made up of parallel pultruded battens and supporting cross bars, covered by closed-cell neoprene foam that provides an insulating base layer for the layup. The foam toolbed is covered with a loosely fitted, metalised nylon sheet that reflects through the part during infrared heating/curing.

This is a push-button operation, with the actuators firing in rotation. A surface area up to 500m^2 completely readjusts in around five minutes, sail to sail on a bespoke basis.

A number of overhead gantries run the length of the building, serving nine individual moulds of varying sizes and geometries. A robotic arm descends from the gantry and a number of different tools for varying stages of manufacture can be plugged in. An automated fibre placement system with a PLC-controlled six-axis head is suspended from the gantry, which lays down the fibre architecture. For the structure of a sail the head precisely follows the 3D curve of the mould surface, the fibre head ‘drawing’ a pattern in yarn that matches anticipated loads in the sail in

Dennis Conner's *Liberty* to windward of training partner *Freedom* in 1983. *Liberty* is by now trialling some leech cut sails but Conner's 1983 America's Cup defence always lagged the Australia II sailmaking programme led by Tom Schnackenberg

the correct 3D spatial location. Fibres that run continuously from one corner to another provide the backbone to carry the specified primary structural loads.

After the structural fibre is in place a secondary film is applied, then a vacuum bag is built around the laid-up sail before lamination begins. In a similar process to that used in the manufacture of rigid composite parts, the lamination system involves pulling vacuum between two layers of thin film that encase the fibre structure and resin matrix. This forces the components together consolidating the laminate, drawing out any air that would create voids in the finished product, and locking individual fibre tows into 3D spatial locations.

Automation and mass customisation

This process broke through a technology wall many thousands of years old, where individual sections of symmetrical woven material had to be joined together mechanically with stitching or later gluing. An underlying theme that runs throughout this area of technical textiles and flexible composites is a second manufacturing revolution, which would move beyond the Industrial Revolution's idea of mass production, and toward realities of individualised production or rapid customisation[3].

The process is the same in each production cycle, but each sail is unique in terms of geometry, structure and aerodynamics. With this process the visualisation of aerodynamic ideas developed within the computer are fluidly exported as information to control fabrication robotics such as fibre placement and tool paths for lamination systems. This will become an even bigger component of the next generation of technology… in sails and elsewhere.

Twenty years on from the genesis of the idea by JP and Luc the specificity of the design and manufacturing technique is still representative of the most radical advances in the fields of textiles and composites today. In short, no one else is doing anything like it, anywhere, in any industry. The process and the product remain unique even in their maturity.

Today, for better or worse, the formal visual language of asymmetrical fibre architecture and load path structures is the defining features of a modern sail. The visual language has almost become more important than the technology that gave birth to that language, as this visual component is what defines a string sail as 'modern' in the eyes of many.

But almost all string sails are still created through fabrication strategies that employ panelisation and a mechanical assembly process that is little different from the manner in which sails have been produced for centuries. Many practitioners have figured out how to employ the visual language of modern sails without deploying the technology that created the advancement and gave rise to this 'look'. Indeed, in many cases you see the moulding technology and the monolithic nature of the 3D membranes attacked as frivolous and inconsequential to the end result, therefore implying that the image of modern is more important than the technology. It would be hard to imagine this situation existing in Formula One, but for some reason in our sport we allow, if not encourage, fashion to be confused with technology.

Towards the composite future

Late in the last decade 3DL had worked its way up the fibre replacement food chain; pentex, aramid, Vectran, UHMWPE, PBO, SM Carbon Fibre and then IM Carbon Fibre. By the end of the Valencia Cup cycle an enormous amount of design and engineering time was being spent on optimising 3DL fibre architecture for tiny gains in sail stiffness, while demanding ever more sophisticated use of CFD and FEA and the associated spiralling computational times.

Truth be told, most of the performance had been wrung out of the 3DL structure in the preceding 20 years – the technology had run its course. This is not to imply that load path sails are no longer good sails, but rather to state explicitly that significant advances in effective sail modulus would no longer be forthcoming without another radical innovation.

Once again it was high time for some forward thinking. The search for the next big improvement in 'process' that would yield more modulus from the base materials was on. In Part 2 of the series we meet Gerard Gautier and Edouard Kessi, two more Swiss guys with bright ideas and new thinking – who also wanted to change the world.

Bill Pearson started with North Sails in 1990 at the North UK office. He has since held a number of positions at the 3DL facility, most recently overseeing the 3Di development programme. He is now head of materials technology and development globally for the North Technology Group. He is a frequent lecturer at conferences and universities on fibrous systems, flexible composites and the shrinking space between textiles and composites

1 The Art and Science of Sails, Michael Levitt and Tom Whidden
2 The North Sails Story, Michael Levitt
3 Extreme Textiles, Matilda McQuaid, Susan Brown on 3DL ❑