Mirabella V: Modern Sail Design & Construction Challenges for the World's Largest Sloop

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SUMMARY

This paper will address the four distinct challenges that the *Mirabella V* project presents to the sailmaker:

- To develop a material that can withstand enormous loads and resist breakdown from abrasion, flogging, flex, mildew and delamination in both design and non-design loading scenarios
- To design sails resistant to wear from battens, lazy jacks, and routine handling
- To build sails that can be manufactured with available equipment and space
- To support the mainsail with the strongest lightest batten solution

Each challenge will be detailed, the manner in which Doyle Sailmakers approached the challenge will be presented and the development and final design of each solution will be described.

1. INTRODUCTION

Mirabella V, the latest of Joe Vittoria's Mirabella Yachts, is pushing the boundaries of modern boat building and sail construction. At 75 m, *Mirabella V* will be the world's largest sloop and with a reacher measuring 1,600 m^2, Doyle Sailmakers will be building the world's largest sail. The inventory consists of a mainsail, staysail, working jib and UPS, or reacher. All told, the inventory weighs in at 3,535kg including battens and excluding hardware.

The scale of *Mirabella V*'s sails requires novel engineering that will take full advantage of Doyle's extensive superyacht experience, from material development to novel construction techniques.

2. UNDERSTANDING THE SCALE OF *MIRABELLA V*

2.1 SIZE COMPARISON

Over time, boats have become larger as the technology to support them has advanced. Doyle Sailmakers' experience with superyachts dates back to 1985, when they were asked to build sails for the 125' S&S designed *Freedom*. *Mirabella V* is over twice the length and has almost four times the sail area. The largest sails that Doyle Sailmakers has built to date are those for the Perini 64 meter *Felicita West*, whose mainsail and reacher measure 531m^2 and 779m^2, respectively. By comparison, J-Class *Shamrock*'s mainsail measures 417m^2. *Mirabella V*'s mainsail and reacher measure 1300m^2 and 1614 m^2, respectively, more than double the size of *Felicita West*'s.

2.2 LOAD ANALYSIS

2.2 (a) Load & Required DPI Analysis

The first step taken to analyze the enormous loads on the sails is to run a Load and Required Denier per Inch Analysis. This calculation, based on sail area, aspect ratio and wind speed, returns a recommended minimum fiber density (denier per inch) over a range of wind speeds (Figure 1). It also returns the estimated loads on the three sail corners of the sail (Figure 2).

From this information, the required material strength is determined. The corner loading information is also used to estimate running rigging and hardware requirements.

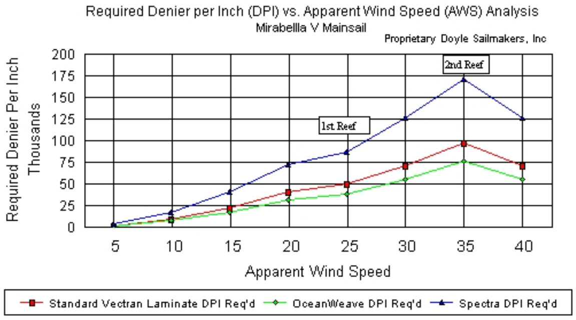


Figure 1: Doyle Sailmakers' proprietary Load and Required Denier per Inch Analysis graph showing the recommended minimum fiber density for *Mirabella V*'s mainsail.

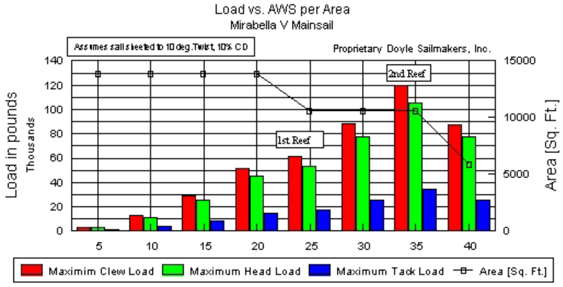
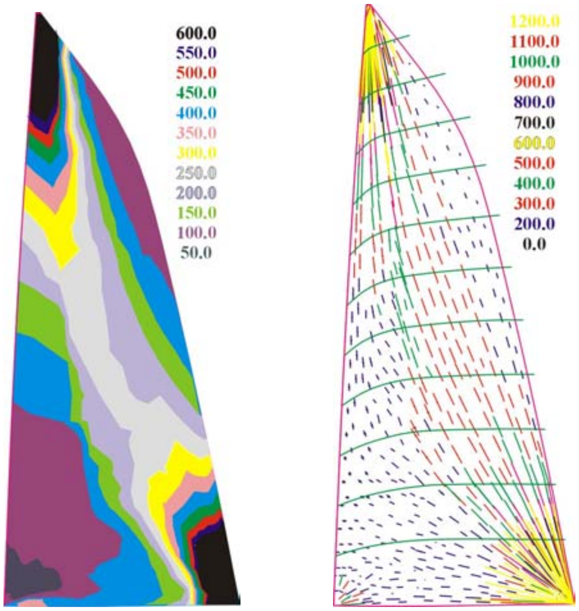


Figure 2: Doyle Sailmakers' proprietary Load and Required Denier per Inch Analysis graph showing the loads on the corners of *Mirabella V*'s mainsail.

2.2 (b) RELAX plots

Following the Required Load and Denier per Inch Analysis, a preliminary design was run to more fully define the sail geometries, including roach profile and batten layout for the mainsail, leech hollow and foot round for the genoas, and overall surface shaping of all four sails. A RELAX simulation was then run at the maximum expected AWS and expected AWA for each sail. The most important output data for the sailmaker are the Principal Stress and Stress Flow maps. These load maps reveal areas of similar load (Figure 3) as well as magnitude and direction of the load (Figure 4, a vector map).

This information assists in determining fabric distribution throughout the sail, reinforcing patch sizes and panel orientation. Running two different load analysis programs provides an in-house check of the calculations as well as a more comprehensive understanding of the loads on the sail in various configurations and wind speeds.



Figures 3 & 4: RELAX plots showing areas of similar load (Principal Stress, Figure 3, left) and magnitude and direction of the load (Stress Flow, Figure 4, right).

3. OCEANWEAVE®: THE *MIRABELLA V* SAILCLOTH

The load analyses reveal that the *Mirabella V* sails will see loads never before realized on a sailing yacht and that the sails require a material not commercially available in the sailcloth market. One of the earliest decisions made on the *Mirabella V* project was to not simply scale up an existing product, but to develop a different, better solution.

A primary goal was to achieve a more durable product with a longer lifespan, similar to a tightly woven Dacron. Dacron, however, does not have the modulus to withstand the loads of *Mirabella V*. Although new high modulus fibers have replaced Dacron for higher load applications, they unfortunately do not have comparable heat shrinkage properties. Thus, they cannot be woven tightly enough to have acceptable diagonal stability. Currently, high modulus fabrics are typically laminated to films. These laminates have excellent instantaneous properties but suffer from durability issues when flexed, crunched, flogged and exposed to UV radiation.

Although lower strength materials exist that could be scaled up to meet the load requirements of *Mirabella V*, one side effect is the thickness and weight of the final product. Common laminate constructions require up to three separate layers of high modulus fibers to create a 46,000 dpi fabric. The high modulus base layers are laminated with up to four layers of film and two external taffetas, for a total of nine layers. Thus, although the fibers themselves are configured efficiently, a great deal of weight is added in film, glue and taffeta. Also, when flexed, thicker materials stretch on the tensioned side and pucker on the compressed side, lifting away from the film and creating small areas of delamination that can trap water and foster mildew growth.

Some laminate styles combine woven material with scrims or inserted yarns, or combine yarns of radically differing properties. Testing shows, however, that the strength and stretch resistance of such fabrics are primarily determined by the lowest stretch members and the stretchier components do not share the load equally. In a high quality woven material, every yarn works for the material, readjusting to shifting loads and sharing both designed and unexpected loads.

To solve this challenge, Doyle Sailmakers partnered with Warwick Mills, a special applications fabric mill in New England, to develop OceanWeave®, a rugged woven Vectran x Vectran sailcloth. Warwick Mills, whose customers include NASA, Boeing and DuPont, specializes in high-performance composite materials for the aerospace, industrial and recreational markets. They are responsible for the landing bags for the Mars Pathfinder and the development of new materials for high altitude (21,000m) airships for surveillance and telecommunications. It was this experience that formed the starting point for the development of OceanWeave.

3.1 DEVELOPMENT GOALS

Drawing on Warwick Mill's extensive experience in woven Vectran x Vectran applications, the specifications and requirements of the *Mirabella V* sailcloth were detailed and discussed. The goal was to create a sailcloth that could handle the enormous loads that would stand up to the abuse that sails routinely endure and more effectively resist the five basic causes of premature aging and failure of sails:

- UV degradation
- Delamination
- Mildew
- Tearing
- Strength loss and ultimate failure due to the above causes.

The material also had to exhibit the following properties:

- Strength of at least 500 kg/cm in the warp direction
- High abrasion and tear resistance
- Aesthetically pleasing
- Consistent high quality
- Soft hand
- Weight efficiency

3.2 DEVELOPMENT ACHIEVEMENTS/IMPROVEMENTS

The following steps were taken to meet this challenge and differentiate OceanWeave from the existing commercially available alternatives:

Improved Delamination Resistance

- Removal of the film layer common to all laminate sailcloth
- Creation of a core fabric with high mechanical integrity even without taffetas covers
- Elimination of the scrim-to-scrim bond found in higher DPI, multi-layer products
- Elimination of the glued scrim core, which has no mechanical integrity when delamination of the scrim-to-scrim bond occurs
- Removal of the voids and openings in the core-taffeta bonds

Increased Mildew Resistance

- Control and consistency of the top coat process
- Switch to a mildew resistant resin
- Addition of a fungicide to the resin
- Elimination of the voids in the structure (As proven by a 10-wash cycle, the water infiltration to the core of the product is very low.

Increased UV Resistance

- Use of an intrinsically UV resistant topcoat resin

The result of this design brief is OceanWeave: a tightly woven 100% Vectran x Vectran core with a woven taffeta applied at a 45 degree angle for bias stability (Figure 5). This material does not rely on film in any manner, and can have as high as 70,000 deniers per inch of Vectran running in the same direction in a single core layer. OceanWeave represents a synergy of durable woven sailcloth with the most cutting edge synthetic fiber and textile technology available today. Additionally, a film-less woven material handles flexing, crunching, and flogging much more effectively than a traditional laminate. The first run of OceanWeave was delivered in May 2001. Fourteen months later, the OceanWeave product line consisted of five styles in full-scale production.

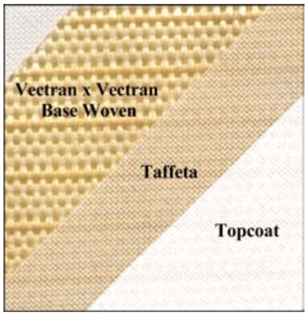


Figure 5: OceanWeave's woven Vectran x Vectran foundation is surrounded by polyester taffetas (upper left corner and middle) for bias stability and a UV and mildew resistant topcoat (lower right).

3.3 TEST RESULTS

To assess the relative performance of the material, a battery of tests were conducted on the OceanWeave product line and compared to three competing materials on the sailcloth market: a heavier weight Vectran laminate made for Doyle Sailmakers, a Spectra/Carbon laminate from a competing sailmaker and a commercially available carbon fiber-reinforced Spectra sheet laminate.

3.3 (a) Fiber Content, Weight & Thickness

As fiber density increases, so too does material thickness and weight. Combining multiple layers of lower count base materials to provide the required fiber density adds thickness and weight in the form of film and glue.

The most comparable fabric to OceanWeave 2000 in terms of material and fiber count consists of three structural fiber layers, four film layers and two external taffetas. OceanWeave 2000 has no film layers and contains all of the structural fibers in one woven layer. The result is a 17% reduction in thickness and a 19% reduction in weight. Spectra sheet laminates, as expected, are considerably thinner and lighter than all competing materials, but lack the durability and toughness of OceanWeave.

3.3 (b) Warp, Fill & Bias Stretch

Warp, fill and bias stretch tests are conducted to assess the shape retention properties of the cloth and are used to select a cloth that can maintain minimal stretch under the design loads. The results are also indicative of material stability, weave design and crimp.

Warp fibers run the length of the cloth roll and are the primary load-bearing members in OceanWeave. The warp stretch test results demonstrate the effectiveness of proper warp tensioning of a woven product. Although the warp yarns cross over and under one another in the weave, proper tensioning of the warp results in straight fibers whose stretch performance is competitive with and even exceeds that of film-based materials with perfectly straight scrim fibers. Although Carbon fiber film-based products exceed Vectran in terms of stretch resistance, they are subject to the weaknesses of all film-based laminates.

Fill fibers run perpendicular to the warp (across the roll of cloth) and travel over and under the straight warp fibers, creating crimp. The fill stretch of woven OceanWeave is higher than that of film-based laminates due to this crimp. However, it also creates a forgiving structure, in which recoverable stretch helps to prevent material failure in non-design loading scenarios, such as with loss of halyard tension when the sail is loaded horizontally from clew to luff cars.

Unlike the competing materials, OceanWeave does not rely on film for bias stability, but instead on a tight weave and polyester taffetas applied at a 45-degree angle to the base woven. Thus, although OceanWeave relies on polyester fibers and a tight base weave for bias stability, it demonstrates comparable bias performance versus film-based materials. OceanWeave 2000, with no film layers, follows a similar stretch line to the most comparable product that contains four film layers.

3.3 (c) Tensile Strength & Slit Tear

Tensile strength and slit tear tests gauge the material's ability to resist catastrophic failure under non-design loading. OceanWeave, whose components work together as a mechanically and chemically bonded woven, has a tensile strength ranging from 180 kg/cm (OceanWeave 1000) to 530 kg/cm (OceanWeave 3000).

Slit tear tests are a standard FAA test for high altitude airships. The tests are conducted by cutting a one-inch wide slit in a 12" x 8" sample perpendicular to the test direction and applying a load until the tear is propagated (Figure 6). This is among the most important damage tolerance tests for sailcloth, since it is a rating of the ability of the cloth to maintain its integrity and not propagate a tear caused by spreaders, battens, blocks, etc.

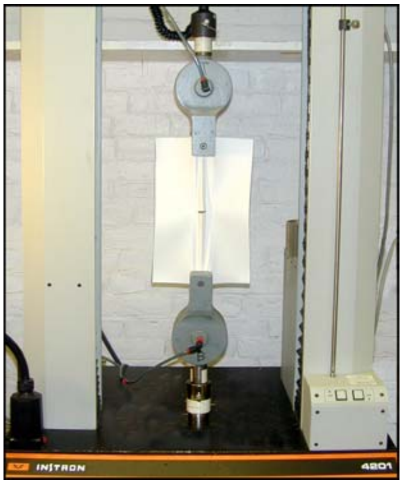


Figure 6: OceanWeave 2000 slit tear testing on an Instron materials tester.

These tests show the strength of OceanWeave and the most striking weakness and damage intolerance of certain film-based laminates. The crossing points of the base woven "lock up" and prevent the tear from growing, whereas the film-based materials rely on individual fibers held in place by glue to prevent tears.

3.3 (d) Peel Test

Peel tests are an indicator of the adhesion quality between adjacent layers in the sailcloth. Lower peel loads indicate a weaker interfacial bond and consistent peel loads indicate a uniform bond across the entire surface. OceanWeave's consistent high peel strength can be attributed to the quality of the woven-taffeta bond that relies on both mechanical and chemical bonding for strength. The bonding resin not only sticks to the taffeta, but also encapsulates the fibers creating more of a composite structure. The lower peel strength of commercially available laminate sailcloth demonstrates the weaker interfacial bond between the film and taffeta layers, which do not allow penetration of the resin through the film layer.

3.3 (e) UV Resistance Testing

Long term accelerated UV testing shows minimal degradation in OceanWeave strength over time. After 2,000 hrs of Xenon arc testing (the equivalent of over 6,000 hrs of full-time exposure), the OceanWeave samples showed only a 30% reduction in tensile strength. Visual inspection of cloth coupons after extended QUV testing (a combination of accelerated UV testing and water spray) showed negligible color change in the top coated OceanWeave samples, compared to non-top coated samples and other commercially available laminate sailcloth, demonstrating the effectiveness of the OceanWeave's UV inhibitors. 'Real-world' sunlight exposure tests revealed little to no visible degradation.

3.3 (f) Mildew Resistance Testing

Both informal in-lab mildew tests and "Barbados" tests (exposure to 'real world' heat and moisture) showed no appreciable mildew growth on any of the test samples. No appreciable mildew growth has been observed on any OceanWeave sail in service, the oldest of which has sailed for 2.5 seasons in New England and the Caribbean.

3.3 (g) Lamination/Bias Performance Testing

Bias performance is intimately linked to lamination quality. The critical factor in bias performance is not instantaneous stretch resistance, but the resistance to bias fatigue with repeated shear loading, as occurs when the sails go slack or flog. This repeated shearing action is what breaks down cross-linkers in glue and weakens film, eventually leading to delamination and possible failure. To simulate this, a testing apparatus was built that holds a small test coupon of cloth in between jaws. The jaws are then cycled back and forth in opposite directions, to shift the cloth along its bias. At each shift, the strain on the jaws is recorded, tracking the decrease in bias stiffness with increasing cycles. Film-based laminates perform extremely poorly in this test, while OceanWeave's woven structure holds together very well, shifting as necessary with the shifting load. Each stage of OceanWeave bonding development has seen marked improvement in this performance test, which Doyle Sailmakers feels is the most indicative of ultimate material longevity.

3.3 (h) On Water Testing

Critical to the improvement and product quality is an understanding of how the material behaves in the field and how it fares with age, real world environmental exposure and handling. The first OceanWeave sail is in its third season on-board the Little Harbor 75 *Palawan.* Fourteen months ago, *Borkumriff IV* took delivery of a 400m^2 mainsail. More recently, a full inventory of sails was installed on *Felicita West*, a 64 m Holland-designed Perini Navi ketch.

3.3 (i) Quality Assurance

Knowledge of and confidence in the product quality is a key to successful product development. To ensure that the material meets the standards that the Doyle Sailmakers/Warwick Mills partnership has set, the following controls have been established:

- Operation under ISO (International Standards Organization) 9001 design control and ISO 9000 manufacturing control
- Addition of Certificate of Conformance Testing and a Lot Tracking system
- Knowledge and control of the full history of the product, from the production of the taffetas to the topcoat process, using only raw fibers and chemicals from outside suppliers

4. SAIL DESIGN & CONSTRUCTION

With weight and shear size making construction a harrowing challenge, innovative thinking was required to develop construction methods to handle such large sails.

4.1 THE *MIRABELLA V* SEGMENTED MAINSAIL

To overcome this challenge for the mainsail, Doyle Sailmakers will be constructing a "Segmented Mainsail". The sail will be composed of separate, yet interdependent, sections with full-length battens joining the segments at the top and bottom edges to form the complete sail. Construction, handling, shipping and service are much easier with independent, smaller sections, as the largest will not exceed 360m^2 and 400kg. The segmented mainsail renders unnecessary specialty machinery, additional labor to move the sail around, and additional loft structural support.

4.1 (a) Prototype Testing

Initial on-water testing to determine the viability of the segmented mainsail was conducted in winter 2001 on a prototype 42 m^2 X-3/4 Ton mainsail. In this test, the segments were connected to the batten via boltrope grooves on the top and bottom of the batten, according to the original concept. In this design, the sail slid onto the batten instead of the batten sliding into the sail. Although the test proved generally successful, it was found that without properly securing the sail, the segments shifted along the length of the batten during tack and gybes and become misaligned. In addition, the boltrope groove design proved more technically complicated to build, heavier than other options, and relied on the strength of the grooves to keep the sail together, which suggests a greater likelihood of potential failure.

The second stage of testing took place at the Doyle Vela Superyacht Cup in Palma de Mallorca, Spain in early October 2002. A 150m^2 prototype OceanWeave segmented mainsail was built for the 22m *Golden Opus*. This sail contained two segmented battens, one that was connected with a continuous lashing system, as canvas work is connected to a frame, and another that was connected with mainsail "loops": loops of material on alternating segments that form a hinge joint along the batten. Although both methods ultimately proved successful, the mainsail loop method was considerably simpler to install and resulted in a smoother, more consistent sail shape.

4.1 (b) Design

Following the testing in October, a final design was detailed using the "mainsail loop" concept (Figure 7).

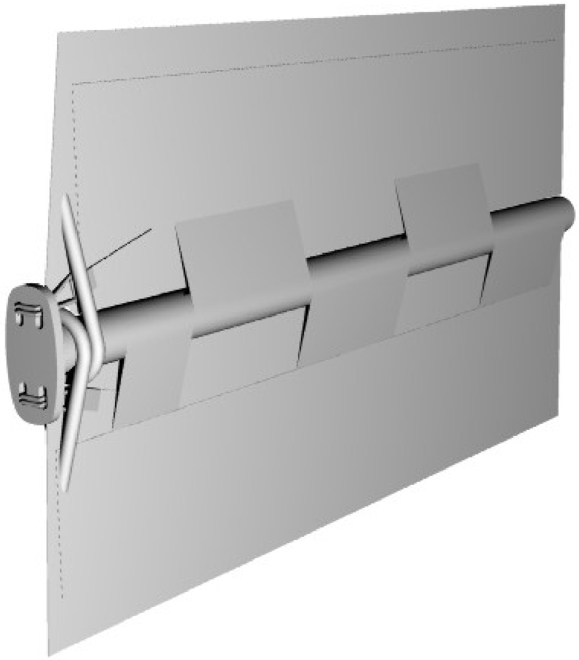


Figure 7: Mainsail loop geometry at the batten outboard end showing the loops and the capturing flap securing the loops to the sail.

In this design, the loops connecting the sail segment to the batten are set into the panel and extend around the batten and back to the other side of the sail. The loop dimensions were determined by assessing the stress and failure modes of sewn seams around a round pin. It was found that a loop length from the center of the batten to the junction with the sail of twice the batten diameter was ideal. Since this would result in open space at the battens, the sail itself extends to the very edge of the batten. Running horizontally along the sail is a capturing flap that secures the loops to the sail and acts as reef reinforcements at the first and second battens. Since the loops result in uneven loading along the tops and bottoms of the segments, finding a balance between performance and ease of construction was essential. A 400mm wide loop was chosen for its size and efficient use of cloth. This design also provides for easier construction, as the parts are identical for the top three battens and the bottom two battens.

4.2. HEADSAIL CONSTRUCTION

4.2 (a) Bonded Seam Technology

Similar to the mainsail, the sheer size of the UPS and working jib make one-piece construction impossible with existing machinery. However, unlike the mainsail there are no mechanical connections in the body of the headsails and all components must be flexible to furl properly.

To solve this problem, Doyle Sailmakers explored the possibility of bonded seams. Although the vast majority of sails are sewn together, many film-based laminate sails (particularly for racing) are glued together. Because OceanWeave relies on a strong bond between the taffeta and base woven, the bonded surface is carefully prepared during production using Vectran-specific bonding technology. Doyle will take advantage of this high quality bond for final assembly of the large sail sections.

Each sail will be built and finished in three to four separate sections, which will be joined as the last production step. To join the sections, the covering taffeta will be removed using heat. The surface is then prepped and hot glue is applied under pressure to the bonding area. Once the bond is set, capturing flaps are glued to the edges of the seam to prevent peeling of the primary bond (Figure 8).

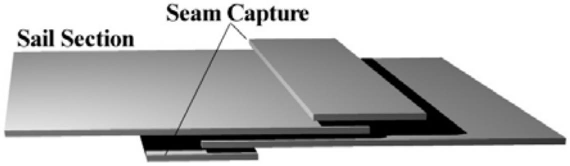


Figure 8: Captured seam showing the sail sections, the primary seam overlap, and the "capturing flaps" on either side of the primary seam that help prevent peeling at the bond.

This bonding technology was testing at both Yale Cordage and Warwick Mills to assess strength and failure mode. The testing at Yale focused on instantaneous, unabused samples, while the testing at Warwick Mills focused on long-term accelerated abuse and cyclical loading.

In unabused sample testing, it was found that the bonded seam samples failed at the material breaking strength, showing 100% material strength conversion. The manner of failure was fairly consistent among samples. At loads near the breaking strength, the material itself was stretching considerably, while the glue at the bonded seam was holding the woven fibers in place so tightly that they couldn't stretch with the rest of the material. This created a tension point where the material ultimately failed.

4.2 (b) Corner Construction

The peak working jib clew load is 37t, the equivalent of hanging one and a half IACC yachts from the corner of the sail [1]. At such loads, it is critical that the corner attachments be as light and flexible as possible since weight, chafe and safety are primary concerns. Thus, Doyle Sailmakers will be constructing the sail corners using soft corner technology. Each corner will consist of a length of rope, formed into a loop on the outside of the sail, passed through itself at the edge of the sail, and fanned out into the patch on either side. In this way, the corner becomes an integral structural component of sail and overall weight is reduced.

5. *MIRABELLA V* BATTEN TECHNOLOGY

For batten development and construction, Doyle Sailmakers turned to Ted van Dusen of Composite Engineering, a Concord, Massachusetts-based company. Ted's experience includes battens for *Team Adventure* and the mast and boom for Bruce Schwab's Open 60 *Ocean Planet*, a competitor in the Around Alone Race.

5.1 BATTEN MATERIAL

A high roach mainsail presents a challenge for almost any size sail; a superyacht mainsail with a roach as large as *Mirabella V*'s presents a very special challenge.
The batten development for *Mirabella V* was largely a question of optimization: at the required batten stiffness, what is the maximum toughness that could be achieved while minimizing weight aloft? To answer this question, Doyle Sailmakers and Composite Engineering surveyed the different material options available: standard pultruded fiberglass, S-glass and carbon fiber. Although carbon fiber is renowned for its stiffness and low weight, S-glass, a tri-axially woven fiberglass with a reinforcing carbon layer (~15% of fiber content), has a bending radius before break that is three times greater than carbon. It is for this reason that the top four battens, which will experience the most flogging, highest loads and least support, were specified as S-glass. The bottom two battens – the largest and heaviest – will be constructed of carbon fiber, providing the greatest weight savings for the battens that require the least toughness. The savings in weight from switching from all S-glass to an S-glass/carbon fiber combination is 145 kg.

5.2 BATTEN END FITTINGS

The inboard and outboard batten end fittings secure the sail segments and provide a means to tension the foot and head of each segment along the batten (see Figure 7). In keeping with the low-weight, soft construction concept of these sails, a high strength Vectran line will run along the luff and leech of each segment and form a loop at the top and bottom corners. The ropes will loop around the battens and provide vertical load transfer up the luff and leech. Webbing loops on the inboard and outboard ends will be lashed forward to the batten end fittings to provide horizontal tension.

5.3 COMPRESSION RELEASE BATTENS

The batten materials selected clearly demonstrate Doyle Sailmakers' commitment to durability and toughness. However, regardless of material selection, certain conditions will stress any batten to break. In particular, tacking and gybing often cause the sail to flog or "snap" across the centerline of the boat, loading the upper battens and cars significantly. In order to minimize the risk of breaking battens aboard *Mirabella V*, Doyle Sailmakers has developed the Compression Spring Batten. The CSB utilizes a spring integrated into the inboard batten end to relieve this compressive load. It will be implemented on *Mirabella*'s second and third battens down, which are located along the most aggressive curvature of the roach. These battens see the highest loads and are generally the most likely to fracture. With the implementation of the CSB, the batten will compress under high loads, reducing the overall length. This reduces the load on the batten, which minimizes the likelihood that the batten will break.

5.3 (a) Concept Testing

Compression Release Batten testing began on a local X-3/4 Ton in winter 2001. The first stage of testing involved a basic concept analysis. During these tests the breaking mode of small wooden battens was analyzed to determine which events were most likely to lead to breakage. The findings supported Doyle's previous experience as described above.

Second stage testing involved the introduction of a relatively low load gas spring on the inboard end of the batten. As with the wooden dowel battens, the compressive load was found to be highest when tacking. Sailing upwind did not compress the spring. However, as the sail crossed the centerline of the boat during a tack it tended to take on an S-shape to pass through the shorter distance between the straight mast and the leech, compressing the spring with the inboard end load. Interestingly, only the strongest of the various springs exerted enough force to re-extend after initial compression.

5.3 (b) Design

The working components of the Compression Spring Batten are located at the batten's inboard end, between the luff car and the standard batten. The dynamic portion of the CSB consists of a carbon/S-glass plunger that slides inside the batten. Housed inside of the plunger is a nitrogen-gas spring that allows the batten to respond to the extreme compression loads that could cause fracturing (Figures 9 & 10).

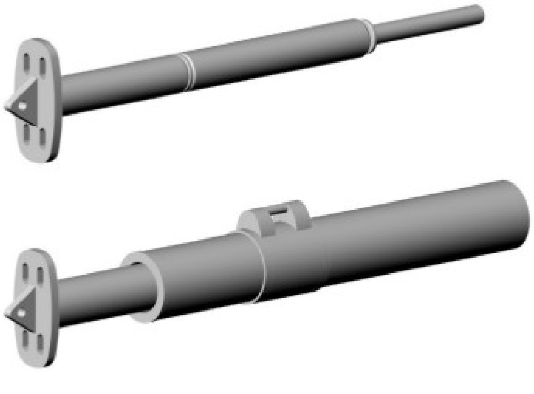


Figure 9: The upper rendering shows the interior components of the CSB (from left to right): the end fitting and its extension inside the plunger, a rubber shock absorber and the gas spring cylinder and rod. The lower rendering shows the exterior components of the CSB (from left to right): end fitting, plunger and batten (with a fitting to secure sail).

The interface between the plunger and the batten occurs through a nylatron bushing that is secured to the inner wall of the batten. This self-lubricating plastic allows the batten to slide along the outside of the plunger without the need for fragile bearings that are more susceptible to failure. The plunger acts as a rigid structural member that resists the torque in the batten, making sure that the batten remains rigid in the dynamic region of the CSB. By acting as a structural member, there is no transverse loading of the gas spring, which can lead to the failure of the spring's seals. By housing the spring inside the plunger, the spring is also protected from water and salt spray. The end of the plunger will have a hole from which the spring's rod will protrude. The other end of the rod will rest against a retaining wall in the batten that is protected by a stainless steel plate to resist wear. The back end of the spring is restrained in the plunger by the end fitting that attaches to the luff car and will slide inside the plunger. By enclosing the spring inside the plunger, the plunger unit can be easily separated from the batten, allowing for easy removal or replacement of the spring if necessary.

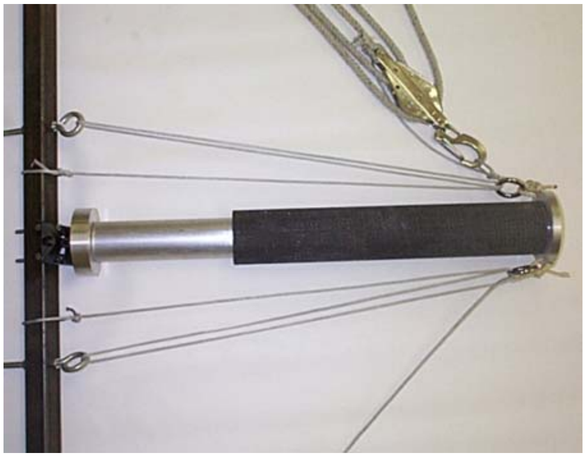


Figure 10: Scale model of the *Mirabella V* CSB with block and tackle rigging used to compress the spring while applying a side load.

5.3 (c) Spring Selection

After exploring mechanical and gas springs, a gas spring was chosen for the CSB. The reasons are three-fold: First, the gas spring provides a choice of initial load at which the spring will begin to compress. This allows the batten to behave normally until the end loads are equal to the initial load required to compress the spring. A mechanical spring does not share this behavior, instead deforming under much smaller loads, leading to a dynamic batten in all conditions. Second, the same amount of travel can be achieved at similar loads with a gas spring that is physically far smaller than a mechanical spring. The smaller size allows the gas spring to be housed inside the plunger portion of the batten instead of inside the batten itself (see Figure 9). By housing the spring in the plunger, the length of the batten that must remain rigid to keep the spring, batten, and plunger properly aligned is minimized, allowing as much of the batten to retain the designed characteristics as possible. Finally, the use of a gas spring allows for some fine adjustment of the loads that cause initial and maximum deflection. By varying the cylinder pressure the same spring can work over a range of loads.

The spring chosen for the *Mirabella V* project is a custom, stainless steel spring that is designed to begin compressing at approximately 8,000N and reach its maximum deflection of 200mm at 12,750N. Standard gas springs have a ratio between the initial load required to deflect the spring and the maximum load around 1.4. The *Mirabella V* project, however, requires a custom spring with a load ratio of almost 1.6 in order to achieve the desired behavior. The design loads for the spring were determined from the buckling loads of the battens. Batten designer Ted Van Dusen estimates the batten end loads to be three times the buckling loads of the batten column, which range from 2,250N – 4,500N, producing end loads over the range of 6,750N-13,500N. By allowing the batten to begin compression at an end load of 8,000N, it is anticipated that the loads will be reduced so that the end loads will not reach the upper end of the load range, where fracturing the battens becomes possible.

Doyle believes that the implementation of the Compression Spring Batten will greatly reduce the likelihood that battens will break aboard *Mirabella V*.

6. CONCLUSIONS

The scale of the *Mirabella V* project calls for an examination of both new materials and methods to overcome the size and load challenges of these enormous sails and a more careful examination of current construction techniques and design. Drawing on the expertise of members of the fabric and composite industries as well as its own history in superyacht sail construction, Doyle Sailmakers has created new and novel solutions to the challenges of high-load, low weight durable sailcloth and has developed novel solutions to construct large sails in limited space. Finally, with the Compression Spring Batten, Doyle has developed a potential solution to catastrophic batten failure.

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8. REFERENCES

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9. AUTHOR'S BIOGRAPHY

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