Aspects of yacht design
For
75M sloop Mirabella V

Ron Holland and John Stott
Of Ron Holland Design.

Abstract

Mirabella V is the largest single masted sailing vessel in the world. She is almost 60% longer and 2.6 times heavier than the next largest sloop. Her mast height is 35% taller than both the tallest and largest sail-training vessel, the Russian ship Sedov and the current tallest yacht the Ron Holland 64m SY Felicita West. Despite her size and interior appointments Mirabella V has been developed with sailing performance as a priority.

Super yacht design theory developed by the Ron Holland Design office over the years had to be reviewed and rewritten when in the early stages of Mirabella's design we began to realise that the numbers were "well off the scale" of existing knowledge.

This paper discusses the effects of scale on Mirabella's design and sailing characteristics and goes on to describe the development of the philosophy for the sail handling systems and operation under sail.

Secondly the paper describes the design of the lift keel system. Including the keels safe operation and structural design.

Overview (Ron Holland)

The Mirabella V project has pushed the existing experience for large performance masted sailing yachts to a new level. Not only is Mirabella V the largest single masted sailing yacht ever designed, but also the largest sailing vessel to be built using composite materials.

The design brief called for a yacht that fulfilled the clients' personal requirements for sailing performance and interior appointments without compromising high-end market charter potential. This aspect of the design was given great attention and Mirabella V will present to the fortunate few who are capable of chartering her, a unique sailing experience.

The technical challenges presented to the designers, builders and equipment suppliers required many groundbreaking efforts. Sailing loads with regard spars, rigging; sails and sail handling gear are in the order of 30% higher than any existing sailing yacht. All the related equipment was calculated, designed and manufactured on a one-off custom basis using both scaling of known load data and calculations based on first principals. Common sense also played a major role in deciding the factors safety with obvious input from regulatory bodies such as Germister Lloyde, Det Norske Veritas and the Maritime Coastguard Agency.

Design Philosophy

Mirabella V was conceived by the owners with performance very high on their list of priorities. The sloop rig, ballasted drop keel and relatively light displacement were all pre-requisite and never really questioned during the course of the initial design work.

The design and engineering was concerned with working around a fixed design concept. This fact combined with the extreme size has made Mirabella v a significant challenge.

The major advantage of scale effect at this size is that whereas righting moment rises as the fourth power of length heeling moment from the rig rises only as the cube. In effect a yacht gets more and more stable for similar designs in direct proportion to her length. Therefore at Mirabella V's size achieving good sailing stability through a high ballast ratio or low C of G is not so important as it is with smaller yachts of even half her length. Form stability becomes predominant.

However very large sailing yachts are managed in a very different way to smaller yachts. Due to the consequences of overloading the sailing systems and equipment, the general approach to operating yachts over 60m is extremely conservative. Sail is reduced much earlier and most passage making is with limited sail and often with some use of the engines.

Apart from the safety aspect and general risk of "hard Sailing" very large yachts, it is not practical for general comfort and mobility to allow yachts over 60m in length to heel much past 15°. For Mirabella V all sheet-handling winches will automatically release load at 22° heel. Maximum GZ is reached at about 40°. Thus while stability was indeed considerably reduced relative to smaller craft we did not reduced as far as similitude would have allowed for sailing heel angles.

Of course we could have put an even larger rig in and retained "normal" hull stability dimensions but the potential advantages to be had in enhanced performance would have been undermined by engineering problems and in any case the performance advantages to be gained by decreasing the stability dimensions, such as shallow draught and displacement were far more attractive. . In this regard the rig design weight/strength relationship would have been a case of diminishing (and possibly negative) return.

A yacht of Mirabella's size but proportioned as a contemporary performance cruiser with associated ballast ratio would have had excessive righting moment at normal sailing heel angles making the handling unnecessarily difficult and heavy, and possibly dangerous.

At this size the "light displacement" low load option is clearly favoured for structural reasons while maintaining enough sail area to insure excellent performance on such a light hull. Low freeboard also makes good aesthetic proportion easier to achieve.

Not withstanding the light displacement option being chosen, the disadvantages of the size are largely to do with loading and structural design. With Mirabella V's size and inherent form stability, keel size was no longer predominantly governed by ballast considerations; a check was made to make sure we were not going too small with the keel which would have caused excessive leeway. It is worth noting that acceleration will be relatively slow compared with "normal size " yachts and there would be a risk of the foils stalling when getting under way however she should carry her way well when tacking and manoeuvring. For Mirabella V the keel area/sail area ratio falls between Hyperion and an international Americas Cup class yacht. *(Hyperion is probably the closest yacht in size and form to Mirabella V currently afloat. She is 156ft (42.5m)*

Having ensured sailing stability fairly easily, the only concern was to maintain (with some margin) the MCA criteria at the opposite end of the righting moment curve (ie positive stability at 90°).

The light displacement and shallow canoe body ties in well with the fact that at this size the need for interior hull depth becomes much less of a concern due to the considerable divergence in the relative physical height of our clients and the freeboard of there new yacht. However freeboard was probably more critical to the MCA requirement for 90° positive stability.

Scaling Effects

1. **Performance optimisation and effect of scale**

For two geometrically similar yachts of different sizes, complete similarity cannot be achieved unless the wind speed also scales as $\sqrt{L}$ (where L is the linear dimension). This means that the larger boat would need stronger wind to perform similarly to the smaller one. Furthermore, heel angle is governed by a balance between power to carry sail (righting moment) and sail area.

Stability scales as L^4 and heeling moment as L^3, if the wind velocity is constant. Apparent wind effects only go some way to increasing the wind speed for larger vessels, and has less effect at higher or limiting true wind speeds.

The jump in size with Mirabella has made the effects of scale particularly apparent and allowed a viable departure from proportions normally seen on very large sailing yachts.
When these proportions were studied against other contemporary yachts it becomes apparent just how far the concept has pushed the boundaries.

		Flying Fifteen	GEORGIA	HYPERION	FELICITA WEST	**Mirabella V**
Effective waterline length	L	5.75	41.5	39.5	40.8	**68**
Displacement _ load	□	0.476	350	290	670	**750**
Sail area 100% FT	SA	14	1020	927	1320	**2137**
Length : displacement ratio	L/_□	7.36	5.9	5.95	4.66	**7.5**
Sail area : displacement ratio	SA/[_□]^2	23	20.5	21.2	17.24	**25.8**

(A Flying Fifteen is an international class of keel boat which will plane in 12 to 15 Kts of apparent wind, Georgia is currently the worlds largest sloop, Hyperion is the worlds second largest sloop, Felicita west is the largest ketch)

The above table shows that Mirabella is much more like a ”sports boat” than what we would conventionally describe as a super yacht.

A secondary advantage of light displacement is an easily driven hull, which leads to:

- Lighter machinery.
- Smaller stern gear_ lower parasitic drag under sail.
- Shorter engine room and/or better engine ratings.

2. Structure and effects of scale

Ron Holland design needed to be aware of the effects on scale on the structural design and how it would affect the overall concept.

A yacht structure is typically loaded by its own weight or a loading that will scale proportionally with weight and therefore is proportional to L^3 and it follows that bending moment is proportional to L^4. We see how stress scales as follows.
For tension, shear and local compression: □= load4area _ $L^3/ L^2=L$
For beams: □= M4I/y _ $L^4/ L^2=L$
For columns: Load _ EI4 L^2 or E_ [Load x L^2]/ I _ $L^5/ L^4=L$
Similar columns loose strength again in direct proportion to L. (ie. E would have to increase in proportion to L to maintain similarity, which clearly it cannot, since E is of course a constant)

3. Getting the proportions (numbers) right.

It is difficult to calculate the best proportions for length, displacement, beam, draught etc. There are so many other factors and influences, that achieving a good balance is an art with a healthy quantity of science. We use the scale effects as a guide to striking the right balance. Trying to blindly use the “numbers approach” alone tends to produce poor yacht design and is often unnecessarily time consuming and expensive.

Obviously at this size a method of reducing draft is required hence the lift keel and twin rudders which give a draught range from 4.2M (13.8FT) to 10.2 (33.5FT). Twin rudders maintain good efficiency at reduced draught. Secondary advantages include:

- Improved maneuverability with twin propellers
- Gives room to incorporate the launch ramp for the motor tender.

4. Stability regulations and safety

Little if any precedent has been set regarding safe stability for vessels of this specific type and size however a few general principals can be used to study safety aspects.

Characteristic	Positive aspects:	Negative aspects:
Large size	• Large roll moment of inertia (L^4) Relative reduction in breaking wave effect • High quality and professional manning. • Load monitoring on sailing systems. • Sailing manual of operation.	No undesirable effect
Low freeboard/ Superstructure	Negligible topside wave impact effect in extreme conditions	Satisfaction of code - positive stability to 90^o **more difficult** to achieve as size increases.
Relatively high Beam: hull draught Ratio	Good initial stability gust response and sail carrying ability	Satisfaction of code - positive stability to 90^o **more difficult** to achieve as size increases.
Tall bermudan sloop rig	• Fast gust response by single sheet adjustment. • High roll damping with deep fin keel. • High roll moment of inertia • Rapid reduction in projected sail area as yacht heels • Tall rig= lower than 1.4 (MCA) gust factor (see following texts)	No undesirable effect (Possible slight reduction in off wind performance with increased aspect ratio)

As we have seen to achieve perfect similitude between geometrically similar vessels of different sizes in an equivalent environment, wind speed would need to increase by L and this is not at our discretion. In general, this means that larger yachts are less susceptible to the gust being strong enough to cause problems. The stability "codes" have been written based on the statistical analysis of vessels (mostly sail training) from 20m to 41m and the requirement for a positive stability range of 90^o heel was chosen. We assume that statistically it is much less likely that a yacht will experience 90Kts squalls than 60Kts squal. The current code does not differentiate between vessels of size or rig type.

The code uses a gust of 1.4 times the ambient wind speed which gives a heeling moment of factor of two. This is based on what has been proven to happen at 10 meters above sea level. A gust is arises when faster air from higher up descends due to a disturbance caused by unstable air mass or large obstigals to the flow. However with Mirabella's rig at 90m high and her main boom approximately 10m off the water the average gust factor over the sail plan is probably much less than 1.4. We believe that gust factor should be varied with mast height.

Sail plan design

The key aims were efficiency and simplicity. The mainsail is to be as efficient as possible to insure the most area for a given mast height and so a large roach was introduced using a full batten system. The large roach contributes to good acceleration in light winds.

The three headsails will never be individually reefed as their furling units and sails cannot carry the huge loads associated with reefing, this is a fact of life at this size and is again a result of structural scale effect. The three sails will be progressively furled as the wind speed increases. This also has the effect of maintaining helm balance by moving the mainsail and headsail areas progressively nearer the mast as sail area is reduced.

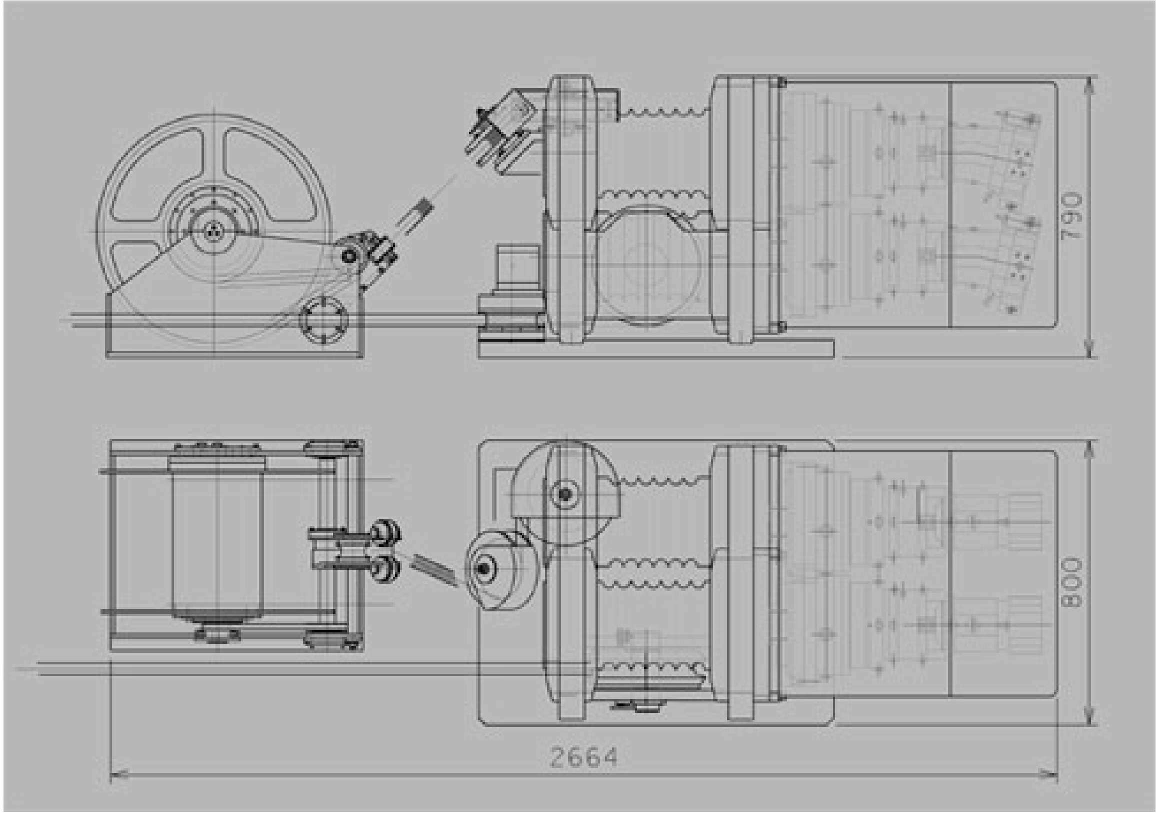
Sail handling systems

Keeping the displacement relatively low and so keeping the power of the yacht within reasonable limits has produced acceptable running rigging load (just!). It was important not to completely loose touch with the current technology in hardware.

In spite of the size of Mirabella V, the philosophy for handling and control was to keep things as simple as possible, in some ways a back to basics approach. This makes it much easier to manage the yacht in a seaman like way, allowing flexibility and versatility. It also takes out many of the unknowns associated with such a leap in size and reduces incalculable development cost for hardware.

Simplicity was achieved in various ways; by giving the crew plenty of options to move sheeting points using barber hauls and leads to various winches, both manual and captive. The mainsail reefing system is standard slab reefing as seen on modern race boats. The first reef can be put by using the captive main halyard winch and a single reef line to a second captive winch. Both these winches are operated from the helm stations allowing the mainsail roach to be dipped under the backstay when tacking with the full mainsail. The second reef is a separate two-line system for the tack and clew, which are pulled down using the manually operated winches and then secured using heavy strops to pad-eyes in the boom. Many of the ideas for the running rigging details have been adopted from the Maxi-catamarans, currently the most powerful performance racing yachts, built for ocean racing and records these vessels are designed to be sailed and crewed very efficiently.

The main halyard is a continuous system attached to the top and bottom of the headboard car. This reduces the amount of loose rope in the halyard winch room and the size of the winch itself. It has allowed the mainsail to be pulled down as well as up in a fully controlled manner.
For the sheet winches the loads and rope lengths dictated a separation of function between hauling and rope storage.



Sander sheet winch tested to 43T, SWL 38 T, WL 30T

The physical size of the winches dictated the use of a combined function for two of the four headsail sheet winches. The reacher and working headsail sheets can be disconnected and re-lead for changeover, or the UPS can be used on the large manually operated hydraulic winches on the aft deck for medium duty off the wind.

The overall setup of the boat will be dictated by the duty to which the boat is being put, weather for relaxed cruise mode or full performance mode and will be also governed by geographical location. This mode changing ability was foreseen by our client and fits well with the size factor.

The manual operated hydraulic utility winches are the largest ever made with up to 14T dynamic load capacity. These winches will handle the barber haulers and other utility functions from the winch room. The use of clutches or jammers is not possible on a yacht of this size and ropes must be secured on winches or conventional cleats. The barber haulers may be required to carry static loads as high as the sheet load when a 60° deflection is required at high apparent wind angles. To insure that overloading does not occur a manual of safe operation will be used on board, with load monitoring on the individual winches. Highest sheet load will occur when close hauled and when little or no barber hauling will be required for sheets. The sheets will then go directly to the 38T capacity captive reel winches.

The issue of sheet load is critical to the engineering of the deck hardware and associated local structure. Calculating the sheet load is very difficult and theoretical calculation using membrane theory was tempered with pre recorded data from other yachts. Coefficients were derived from wind tunnel test data for standard sloop sailplans.

As with any engineering system scale effect also plays its part in the philosophy of load management and controle. The table below demonstrates how scale effect imposes a different philosophy of load management on us:

Component	75m sloop	33.5m sloop
Rope working load @ 15° heel	30	4.5
Rope max peak working load @ 22° heel	38	6
Rope breaking load (durability governed)	110	15
90° turning block breaking load	60	15
Deck structure/ e-turnblock/ break out load	90	20
Projected load at max RM	51	8
Auto. winch payout load	38	**Not required**
RM at 15°	837.7	61.5

Load in Tonnes and Rm (righting Moment) in Tonne-meters

New design challenge for safe operation

Rhd and Doyle sails carried out studies of the running rigging loads, which were followed, by an independent study commissioned from the Wolfson unit. This was essential for the protection of sailing systems and the issue of safety for the crew and charter guests. The result of this study has been to insure that the loads are monitored and kept within safe levels.

To insure this several new safety features have been added to the sailing systems not previously seen on sailing yachts:

- Automatic payout of winches and vang at specified loads and heel angles.
- Lift keel always fully deployed under sail.
- Manuals of safe operation and seamanship, outlining, for example, sail reduction at certain wind conditions.

Keel design

The design brief was as follows:

- Low C of G fin and bulb
- Lift keel with 6m range of movement.
- 150T weight.
- Chord length of 3.9m
- Keel fin thickness to be minimum to reduce form and pressure drag.

Principal of operation

The keel is raised and lowered by way of a single 156 Tonne hydraulic ram pin jointed at the superstructure and the lower end of the fin keel cavity (fig 2). When the desired location is reached the keel is secured using short stroke hydraulic locking rams by driving the keel forward a short distance into a tapered bearing area, called the side pads (fig 3). To release the keel, for raising or lowering, there is a similar set of rams at the forward side of the keel box that will drive the keel aft.

Side pad clamp load is carefully adjusted on set-up using the differential load between the fore and aft locking rams. When the keel has been positively located in the clamped position tapered locking blocks are put in place to react fore and aft load directly into the keel box structure and avoiding overloading the horizontal locking rams. All the locking hydraulics operate on the dry side of the keel box structure. The locking rams operate through glands to bearing blocks against the keel leading and trailing edges. The lift ram however must operate in a free flood cavity within the keel fin, and has been specially designed to resist corrosion Hunger Hydraulics, who supply rams for the offshore industry.

Load analysis

We worked closely with DNV to produce suitable criteria. This was the subject of much debate between DNV, Hi-Modulus, Vosperthornycroft and Ron Holland Design. Longitudinal loading due to grounding or collision being the chief concern. Serious consideration was given to a long stroke aft locking ram as a buffer system in the case of collision but was deemed too complex and potentially unreliable.

1. **Collision /Grounding**

Clearly scale effect played a large part of the basis for discussions regarding the fore and aft loading upon grounding. A criteria of 3g commonly quoted by classification societies for yachts up to 18m was clearly not feasible at this size where reaction loads would be about 30 times greater. Collision with flotsam or whales was also considered, and although collision could not be blamed on crew error, grounding would give rise to the greatest loads.

Calculation of actual grounding loads would have been very complex and probably not all that accurate, as energy would be dissipated in many ways. We knew that even if this study had been thoroughly undertaken the loads would have been uncontainable for a dead stop collision of the fully extended keel into rock from any reasonable cruising speed.

A different approach to this problem was needed where it was surmised that grounding would be considered to be a whole lot more serious than it would be in a yacht of half Mirabella V's length.

As is now considered normal for large yachts, professional management and passage planning will be required by the crew. Grounding will be considered a very serious issue. The implications of grounding are similar for any large or high-speed vessels.
At the time of this discussion, the design team were also formulating a parallel philosophy with many aspects of the design particularly with the engineering of the running rigging systems. As is normal for

yachts with bulb lift keels, Mirabella V is not expected to take the ground without docking blocks being in place.

The idea in the case of a hard, high speed grounding is to contain flooding with the use of a cofferdam around the keel box and in the very extreme case we have single compartment flood-ability as required by under the MCA code.

It was agreed that the maximum longitudinal load that the keel should sustain is the mass of the canoe body under a de-acceleration of 0.3g. This equates to a stop in 1.14 seconds from ten knots, in a distance of 3m for the hull, and marginally less for the keel due to the tendency for the yacht to pitch forward. With the keel in the fully lowered position, resulting in impact 7.5M below the canoe body a reaction load of 9.3MN or 950T would result at the aft lower locking ram.

2. Transverse Load

The agreed criteria is a quasi-static heel angle of 90^o. The upper and lower bearing pads are designed to a load of 4MN or 414T and 5.5MN or 565T respectively.

Due to the method of clamping the keel by driving it forward (wedge like) into a tapered slot, the pad areas were limited to the tapered area at the forward portion of the fin although with the keel in the fully lowered location the lower side pad area could be extended aft without compromising the hydrodynamic shape of the fin outside the hull. To do this a portion of the fin plating in the lower pad area was milled from solid 100mm thick z property steel billet, instead of rolled from 40mm plate as was done for the majority of the fin. (Fig 1 section c).

3. Structural design

The initial decision was to use steel for the fabrication of the keel, bulb and keel box structure. A composite keel box was considered however it would have been extremely difficult to engineer load paths from the highly loaded bearing pads area into the transverse hull floor structure using composite material without isotropic properties. A mild steel box was simpler to construct and a much more engineering friendly material in this structurally complex area.

A steel fabrication was also chosen for the keel fin and bulb. A bronze cast fin would not have been as efficient in either minimizing the thickness of the fin while incorporating the lift ram within it or being as efficient at containing the required 36T of lead. Because the fin will be welded to the bulb (both fully ballasted), under the hull only the fin and bulb plating will form the weld joint. Vertical internal structure stops short of this welded joint and is capped with horizontal webs about 50mm short of the joint (fig 2).

Safety factors were applied as per normal rule requirement (3.33 over ultimate strength for the composite structure and 1.5 over yield for the steel work).

Finite element modeling was used in the design of the keel fin structure, with the study focusing on the highly loaded lower side pad area. This area was subject to a combination of global bending loads (axially compressive) and local membrane pressure loads from the side pads (fig 4).

There were plenty of issues thrown up in the course of the design work. The main considerations was the capability of the fabrication team to weld such heavy plating blindly to the internal structure the side plating in this local area is up to 95mm thick in places. Irons brothers the fabricators got to “practice” on the bulb fabrication first, as we were refining the fin design. There were issues of fatigue characteristics of slot welds highlighted by DNV who worked closely with Vosperthornycroft to find a suitable weld solution. There was also the issue of maintaining dimensional tolerance of the fin, to avoid the lift ram from contacting the side of the ram cavity within the fin.

The keel box extends from the hull bottom to the top of the superstructure, is open top and bottom and comprises two structural entities. (fig 2) The lower part transmits transverse and longitudinal loads directly into the composite structure consisting of the 2.5m high structural floors, longitudinals and hull shell. The upper part that extends from the lower deck or waterline up to the top of superstructure carries the fin and bulb weight through the lift ram pin joint into the hull structure. The upper box structure has been intentionally lightly fabricated to avoid over stressing and fatigue of the box structure due to the inevitable small movements of the yacht's hull and deck at sea. Access composite panels have been used in the side of the box for inspection and maintenance of the keel fin coatings during major refits.

The keel box structure

The obvious drawback of using steel is the issue of corrosion. However the keel and keel box are fabricated from relatively heavy plates and the coating system has been carefully researched by Vospers especially for the contact areas of the fin and pads where a high tenacity paint system will be used. The locking system has been designed to maintain a clamp on the keel in such a way as to avoid movement between the pads and the fin. Movement would not only cause ware of the pads and paint system but would likely be noisy and was considered an important issue. To investigate this the stiffness of the structure has been calculated and considered together with frictional properties of the side bearing pad materials.

The pad material was researched and an elastomeric material called Thordon has been chosen. This manufactures provided us with enthusiastic technical support and proof of the materials unusual "memory" properties in returning to its original shape following the application of high local loading, rather like a very dense sponge. This material will spread out local unevenness of load due to wear, marine growth or slight shape variations in the keel surface. "Bedding in" and bending of the keel foil will also cause slight unevenness of pressure distribution in the side pad areas.

Keel bulb and fin plating

Conclusion

This project has given us an opportunity to learn more and take a bigger step in the evolution of the sailing yacht. We all know how very fortunate to have been involved in such a fascinating project as this. This project should stand a mile stone for some time to come. We look forward to sailing her in the next few months and hope it all works as it is supposed to.