# DESIGN EVALUATION AND ALTERATION OF THE DARK HARBOR 17.5: CASE STUDY OF A MODERN REPLICA.

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**SUMMARY**

While there is still a strong passion and interest for traditional crafts, many of the designs now need to be adapted to comply with the contemporary rules and regulations, and additional modifications are required to meet modern expectations, in areas ranging from comfort to safety; hence the need for modern replicas. In order to ascertain the constraints on modern replicas, a redesign of a Dark Harbor 17.5 will be proposed. First, an initial design evaluation will be performed to assess the characteristic of the original yacht, regarding hydrostatics, hydrodynamics, structural arrangement and stability. Modifications in accordance with regulations and owner's requirements will then be implemented to create a modern replica suited to today's market. Finally, the new design will be compared to the original one, allowing to evaluate the challenges of design modernization and the impact of contemporary requirements on a traditional design.

## 1. INTRODUCTION

Designed in 1908 by B. B. Crowninshield, the Dark Harbor 17.5 is a classic example of a traditional day sailor. It is the particular lines of historic vessels that make them attractive and elegant and still lead a number of sailors to choose traditional boats. However, true replicas can prove to be unsuitable from a commercial point of view. Indeed, traditional designs were not conceived for contemporary rules and regulations. Plus, what used to be inexistent or a luxury feature, such as an engine on a small sailing vessel, has now become norm. There is, therefore, a call for modern replicas, complying with the relevant regulations and offering a similar standard of comfort as modern boats.

To investigate the challenges resulting from those modern replicas, the redesign of a contemporary Dark Harbor 17.5, currently being built at the IBTC Portsmouth, has been undertaken. The initial design has been assessed, to later allow a comparison with the modern version, with particular emphasis on the issues raised by regulatory compliance and the incorporation of modern comfort elements.

## 2. THE DARK HARBOR 17.5

### 2.1 ORIGINAL DESIGN

A number of documents relative to the original Dark Harbor 17.5 are still in existence [1] and include: a linesplan, table of offsets and scantlings, as well as a sail and construction plan, respectively presented in Figure 1 and Figure 2.

The main parameters for the Dark Harbor 17.5, derived from the original plans and documentation, are listed in Table 1.

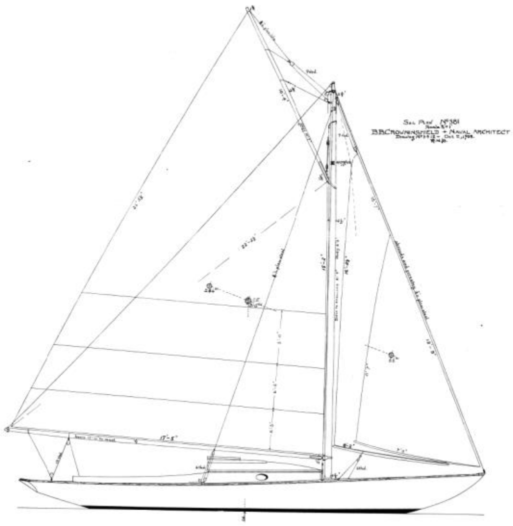

***Figure1:*** *Sail plan of the Dark Harbor 17.5 [1].*

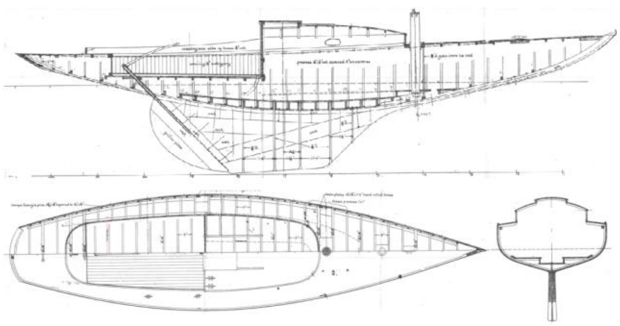

***Figure 2:*** *Structures of the Dark Harbor 17.5[1].*

| | | |
|---|---|---|
| LOA | 25' 10'' | 7.87 m |
| LWL | 17' 6'' | 5.33 m |
| BOA | 6' 3'' | 1.90 m |
| Draft | 4' 3'' | 1.29 m |
| Displacement | 3420 lbs | 1551 kg |
| Sail Area | 311 ft$^2$ | 28.89 m$^2$ |

***Table 1:*** *Original Dark Harbor 17.5 particulars.*

Finally, the original design philosophy of the craft is captured in the following short historical description of the design [2]:

*"In 1908 B.B. Crowninshield was asked to draw up a one-design class of knockabouts to be initially known as the Manchester 17½. The class was to become one of the most popular and long-lived of the knockabouts; about 200 boats were built in Maine, for example, where the name was altered to reflect yacht club affiliation. The most common name for the design is now the Dark Harbor17½, named after the summer colony at Islesboro that once had the largest number of these boats.*

*One still finds many a Dark Harbor 17½ "knocking about" New England waters. (a dozen or so reside at the Buck's Harbor Yacht Club in Brooksville, where they are still raced on Eggemoggin Reach.) The boats were built well and have lasted well, with cedar planking over oak frames, a lead ballast keel, copper and bronze fastenings, and simple deck construction – canvas-over-cedar-or-pine – to discourage freshwater leaks. Most were built with the self-bailing cockpit as shown on the drawings, although a few were given deep cockpits with seats for more comfort.*

*While intended primarily for afternoon sailing and racing, these boats have often been used for coastal cruising; the low cabin trunk has space for two transom berths."*

Based on all those information, a design assessment of the original craft was performed, as presented in Section 3.

## 2.2 MODERN DESIGN BRIEF

The Dark Harbor 17.5 was originally designed to sail in America, whereas the modern replica currently being built in the IBTC Portsmouth will be operated from Chichester with a sailing programme focussed on the Solent. Following this first modern build, it is expected that a small commercial production line will be set up.

The design brief, clearly established by the owner, is to build a classic boat with upgrades from the original to make the boat more comfortable and practical; the main requirements being:

- Increase the operational area, by making the keel shallower, and therefore be able to expand the sailing programme of the boat. This is also linked to the intention of making the boat trailerable.

- Modify the hull planking from carvel to strip planking with mahogany veneers. This is aimed at achieving a stronger and more modern construction while minimising the maintenance for the owner.

- Add an electric inboard engine to make the boat safer and practical. Indeed, very few owners would consider sailing into harbour nowadays.

- Add a portable toilet to enhance the level of comfort for the owner and his guests; this also extends the sailing programme and enables spend a night onboard.

- Add an anchor locker in a watertight compartment at the front of the boat.

- Change the material of the mast, boom, gaff and fore boom from wood to carbon fibre, making the boat lighter.

The impact of these requirements is significant, not only for the redesign but also regarding the type of replica that will be achieved.

## 2.3 MODERN REPLICAS

There is great importance in being able to state whether a vessel can be considered a replica or a reconstruction. A number of definitions have been laid out by the National Historic Ships UK [3]. For instance, the process of replication is given as: *"Replication means starting from scratch to build a copy of a vessel and can be defined at various levels of detail and accuracy".*

A true replica would be characterised as an exact reproduction of the original vessel in every detail, except some minor details such as the fender ropes.

Since the Dark Harbor will deviate from the original, the definition of an operational replica seems better suited, as it allows for some modifications to meet the operational needs, such as the safety equipment and some internal changes for specific functions.

However, the major changes to the keel design and radically different construction method make the modern Dark Harbor a representation. Indeed, the representation is defined as a vessel which was based on a particular craft but had its appearance modified, considering the overall impression but not the accuracy.

The vessel is to undergo some major changes, dictated by the owner in order to meet the contemporary standard of comfort expected, but the vessel is to retain the spirit of the original Dark Harbor, thus making it a representation project.

# 3. DESIGN ASSESSMENT

## 3.1 3D MODELLING

The hull surface was modelled with a computer aided design (CAD) software, following the instructions of the linesplan and the table of offsets, making the hull as close to the original design as possible. As the original design dates from 1908, there is some uncertainty regarding the accuracy of the lines and the measurements. Originally, lofting the boat full size would have ensured fairness; in this case, too, some corrections were necessary to make the hull lines smoother, leading to the model presented in Figure 3.

***Figure 3:*** *3D model of the original Dark Harbor 17.5.*

To check the accuracy of the designed model, the hydrostatics were calculated based on the linesplan using Simpson's rule and then compared with the hydrostatic analysis of the 3D model. This comparison is shown in Table 2.

| Particular | 3D Model | Simpson's Rule | Error |
|---|---|---|---|
| LOA (m) | 7.92 | 7.92 | 0% |
| Lwl (m) | 5.34 | 5.33 | 0.13% |
| BOA (m) | 1.91 | 1.91 | 0% |
| Bwl (m) | 1.84 | 1.82 | 0.85% |
| Tk (m) | 1.28 | 1.28 | 0.05% |
| Displ. (kg) | 1555 | 1542 | 0.86% |
| WSA ($m^2$) | 12.64 | 12.06 | 4.62% |
| WPA ($m^2$) | 6.61 | 6.78 | -2.60% |
| Cp | 0.47 | 0.50 | -5.56% |
| Cb | 0.12 | 0.12 | 0.13% |
| LCB % from AP | 45.41 | 45.18 | 0.49% |
| LCF % from AP | 44.28 | 45.97 | -3.81% |

***Table 2:*** *Modelling comparison.*

To use Simpson's rule the waterline was divided in ten sections, and this may have affected the accuracy of some calculations. To increase the accuracy, a greater number of sections may be required. However, the relatively small errors demonstrate a faithful representation of the original design.

A detailed weight estimation was also performed based on the original scantlings and allowed to validate the displacement of 1556 kg, with a vertical centre of gravity (VGC) 272mm below the design waterline, and a longitudinal centre of gravity (LCG) 210mm aft of amidships.

## 3.2 STABILITY

In order to evaluate the original design, its stability will be tested against modern regulation. This is critical to ensure that the new boat, despite the shallower keel, will have a stability at least equivalent to the original.

All the recreational crafts placed on the market within the European Economic Area (EEA) are to comply with Recreational Craft Directive (RCD) [4]. Part of the requirements to make the boat available on the market is to follow the guidelines of the ISO 12217 for stability to demonstrate compliance of the craft with one of the four design categories. In this case, the vessel being intended for coastal cruising, it will be designed for category C, inland, allowing sailing in wind speeds up to Beaufort 6, and significant wave heights up to 2m.

As a vessel of hull length greater than 6m, the vessel is to comply with the ISO 12217-2 [5]. This involves consideration for a range of parameters, such the downflooding angle (DFA), righting moment (RM), the angle of vanish stability (AVS) and wind stiffness (WS). These values were assessed separately and then compared in Section 4.8 with those obtained after all changes were implemented.

## 3.3 STRUCTURE

The original structure of the boat was made of ⅞ inches (22.22 mm) square oak frames, evenly spaced every 8 inches, and steamed onto the ¾ inches (19.05 mm) cedar carvel planks, fastened with copper rivets. An analysis of the structure against present regulation, namely the ISO 12215-5 [6], was realised, highlighting that a factor of safety of over 5 was applied for the frame spacing.

It is however critical to mention that this analysis was purely indicative and that the results cannot be considered fully accurate. Indeed, the ISO 12215-5 idealises the panels and stiffeners as built-in beams. Although unknown, the end fixity of a plank riveted to timbers cannot be 100%, thus introducing a significant uncertainty on the results. Furthermore, the ISO 12215-5 is not meant to be applied to traditional wooden construction. While only a limited structural assessment was possible for the original vessel, the new structure designed and built using modern construction techniques fall within the scope of the standard and the assumptions made in the underpinning theory will be valid, thus providing a much more relevant analysis.

## 3.4 PERFORMANCE

An important aspect of the performance evaluation was the resistance model, based on the Delft Systematic Yacht Hull Series (DSYHS) [7]. The total hydrodynamic resistance of the boat is given by the sum of the resistances of the hull and the appendages and will be compared to the new design in Section 4.9.

## 4. REDESIGN

### 4.1 MOTIVATIONS

The design was modified according to the client's requirements presented in Section 2.2, with the objective of retaining a classic sailboat, with however some modernization to improve the level of comfort and comply with the rules and regulations.

The addition of a propulsion system, toilet, modern electronic equipment, etc. will result in an increase in weight. This is the motivation behind a modern construction and carbon rig: trying to save weight to balance the addition of the equipment onboard and keep the vessel on its original waterline.

### 4.2 KEEL DESIGN

The new keel aims to keep the performance and stability of the original boat. As a result, a number of parameters were kept the same, such as the centre of lateral resistance (CLR), the planform area and the sweep angle. For rudder, the shape had to be changed as a consequence of the shallower keel, but the area was conserved, thus keeping the original manoeuvrability of the boat.

The challenge on the keel design was to reduce the draft with the lesser impact on the VCG as possible. Indeed, the weight added in the hull and a shallower keel, imply a higher VCG, and therefore a reduction in stability which should be avoided.

As a consequence of reducing the draft, the chord length will be increased to conserve a similar planform area. The longitudinal position of the keel must also be modified in order for the CLR to be kept in the same location. Finally, the longer root chord leads to a longer lead section at the bottom, thus allowing to reduce its height for a given volume and lower the VCG for the given span of the keel.

Different types of keel were designed and the stability was checked for all to ensure compliance with the ISO 12217-2. The final design was selected by the owner based on aesthetical considerations, as well as the ability to save weight. Indeed, to retain a given righting moment, either a larger mass must be provided acting at a smaller lever, or vice versa. In this case, three options were proposed:

- A 1.00m deep keel with a 750kg ballast (50kg heavier than the original).
- A 1.05m deep keel with a 700kg ballast (same as the original).
- A 1.10m deep keel with a 630kg ballast (70kg lighter than the original).

The latter option, depicted in Figure 4, was adopted, thus giving a 7.5 inches draft reduction compared to the original, and now allowing the structural arrangement to be tackled.

***Figure 4:*** *New shallower keel.*

### 4.3 STRUCTURE

A modern wooden hull construction method has been selected, composed of 12mm thick western red cedar strip planking, then covered by two layers of 2.4mm mahogany veneers, placed at +/- 45 degrees; hence a total hull thickness of 16.8mm.

As the pressures acting on the hull decrease further aft, the frame spacing took advantage of this. Consequently, the 350mm spacing applied forward of station 7.5 is increased to 450mm aft. One of the originalities of construction is to retain square stream-bent oak frames, to minimise the labour and cost associated with laminated frames.

The new structure was checked against the ISO 12215-5 requirements for category C, thus ensuring compliance with the regulation.

### 4.4 PROPULSION SYSTEM

To be more manageable in marinas, add safety in emergency situations and be able to operate against the strong tidal currents found in the Solent, an engine must be fitted. As the vessel is aimed at inshore operation, only a limited range is required. This, associated with the will to achieve a sustainable design and ensure quiet motoring, lead to the choice of a fully electric propulsion.

Based on the resistance of the new Dark Harbor 17.5, the power required to achieve a given speed was ascertained, and is shown in Figure 5. Note that an efficiency of 0.69 was considered for the chosen FeatherStream propeller [8], established based on the Wageningen B-Series Propellers method [9].

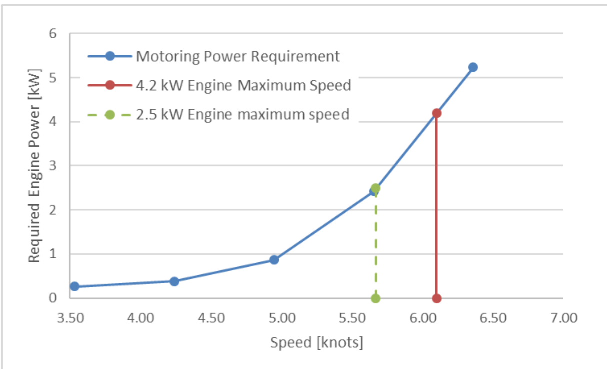


***Figure 5:*** *New design power curve.*

The considered Bellmarine electric engine [10] being available in 2.5kW or 4.2kW versions would result in top speeds of 5.6 and 6.1 knots respectively (neglecting the air drag and added resistance due to waves at this stage). Eventually, the 4.2kW engine was chosen.

This then allowed to assess the number of batteries needed and associated range. With a capacity of 138 Ah, each Valence battery [11] would provide a range of 8.2 nautical miles at maximum speed for a weight of 19.5 kg. A total of 4 batteries were selected, thus providing a range of 32.7 nautical miles when motoring at full speed. However, the range is significantly increased at lower speeds, as presented in Figure 6.

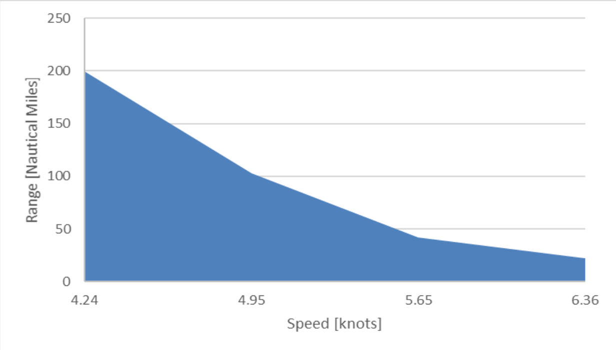


***Figure 6:*** *Motoring range for different speeds.*

It is to be noted that this range does not include considerations for the use of navigation equipment and navigation lights at night, but it considers the recommended maximum discharge of 80% of the battery capacity to maximise its lifespan.

## 4.5 AESTHETICS AND EQUIPMENT

To make the boat more visually attractive, the option of teak decking was adopted. Indeed, with a low freeboard, a teak deck enhances the aesthetical appeal of the design. This represents an increase in cost, but also weight; 20kg in this case.

An anchor locker was added at the bow of the boat in a watertight compartment. This fit with the operation philosophy of the boat, and enables not compromising the appearance of the vessel.

A portable chemical toilet was added, chosen for its minimum volume as the available space in the boat is very restricted. This addition makes the sailing experience more comfortable, especially when sailing with guests.

As per the engine location, the installation of the toilet highlighted a major challenge of modern replicas: the extremely limited space available to implement all the required modifications to meet the standard of comfort expected nowadays. Indeed, no spare volume was allocated to fit an engine or a toilet in the original design, making the modernisation particularly complex.

## 4.6 CARBON FIBRE RIGGING

The original rigging was composed of wooden spares, namely the mast, boom, gaff, and foresail boom, as depicted earlier in Figure 1. Having raised the centre of gravity because of the shallower keel and additional equipment installed, moving to carbon fibre spars appears particularly attractive, as saving weight very high will significantly lower the overall VCG of the boat.

Firstly, the foresail was modified, and the use of a furling system implies that no foresail boom will be required.

Then, the original keel-stepped mast (coming through the deck and resting on the backbone) was replaced by a deck-stepped mast, supported by a mast pillar inside the hull. From a structural point of view, this means that a stronger and therefore heavier mast section will be required, due to the difference in end-fixity between a keel-stepped and a deck-stepped masts. This decision is however dictated by the necessity for the owner to be able to take the mast down; also ensuring a better watertight integrity of the deck, critical on a wooden boat.

In order to evaluate the weight savings of a carbon mast, boom and gaff, a rig design based on the Nordic Boat Standard [12] was undertaken, and allowed to calculate the reduction in the weight of the rig thanks to the use of carbon fibre. Furthermore, the sails will be replaced by a high-quality polyester sailcloth, Dacron, which has greater resistance and durability compared to the canvas. Other sources of weight savings include new shrouds and stays as well as deck fittings and ropes.

Overall, the new rigging will allow saving an estimated total of 23kg, now allowing to perform a weights and centres calculations for the new boat.

## 4.7 WEIGHTS AND CENTRES

While the weight change is critical in the design process, so is the location of the centre of gravity. Hence the need to update those parameters for the new vessel. The balance between the weight gained and the weight saved compared to the original is presented in Table 3.

| Weight change | Mass (Kg) |
|---|---|
| ***Gained*** | 143 |
| ***Saved*** | |
| **Structure** | 25 |
| **Rigging** | 23 |
| **Ballast** | 70 |
| **Total:** | **25** |

***Table 3:*** *Weight changes*

Despite the addition of several new elements to the boat to fit with contemporary standards, which includes engine, batteries and a toilet, savings in other locations brought the overall weight to 1595kg, i.e. a 40kg increase, with no alteration to the location of the VCG.

This allows the vessel to float on its original waterline, and not to impact the original stability.

## 4.8 STABILITY

The results of the stability assessment are summarized in Table 4, and compared to the requirement for category C under the ISO 12217-2.

| Parameter | Original | New | Requirement |
|---|---|---|---|
| DFA (°) | 58.1 | 56.3 | >35 |
| AVS (°) | 137.7 | 137.4 | >90 |
| WS (°) | 38.0 | 38.5 | <45 |
| Max. Gz (m) | 0.50 | 0.50 | - |
| Max. Gz (°) | 79.0 | 78.0 | - |

***Table 4:*** *Stability Comparison.*

Despite the shallower draft and heavy modifications, the overall hydrostatics and stability of the boat were retained, ensuring the original qualities of the vessel are conserved, while meeting the regulatory requirements.

## 4.9 IMPACT ON PERFORMANCE

With only a negligible increase in displacement and a constant wetted surface area despite the shallower draft, as the keel area was kept constant, the overall resistance increase is 2.7%.

Furthermore, as there is no significant change in the stability and the sail plan will remain the same, it can therefore be concluded that the speed of the boat will not suffer any significant alterations, as validated by a velocity prediction programme.

As a result, the general appearance and performance of the original boat were conserved.

## 4.10 CONCLUSIONS

The modifications implemented to the Dark Harbor 17.5 design made the vessel more in line with today's customer expectations. The addition of an engine, shallower keel and toilet offer greater comfort, while the modern construction technique and carbon fibre rig provide an attractive commercial argument, coupled with a minimum maintenance required. Furthermore, compliance with the RCD category C was demonstrated. All of these did not actually impact the behaviour and performance of the boat, and the aesthetical qualities of the original have been conserved.

# 5. CONCLUSIONS

Thanks to the availability of historical designs, modern replicas can now be built with great accuracy, with however contemporary requirements for a more comfortable and safer design, complying with the appropriate rules and regulations.

The design of a modern Dark Harbor 17.5 replica, or rather representation, was undertaken to significantly modify the engineering of the vessel, while retaining the original aesthetical attraction inherent to classical designs. A shallower keel allowed to increase the area of operation and make the boat trailerable. The electric propulsion system allows for a more practical use of the vessel, while acknowledging the modern environmental concerns. The addition of comfort such as a toilet also makes the vessel more commercially attractive. Furthermore, the modern wooden construction, with strip planking covered with veneers makes for a strong and durable hull, requiring minimum maintenance; while the carbon rigging allows for weight savings and easier handling of the craft. Finally, the design was proven to comply with the RCD and relevant ISO standards for category C.

The design assessment of the original craft allowed to ensure the modern representation would perform and behave the same; this was achieved with a virtually identical stability and resistance, an untouched sail plan, and a keel and rudder arrangement conserving the characteristics of the original.

However, significant challenges were highlighted in the design process. The additional components to be retrofitted to the original design are of significant volume of mass, particularly on a vessel as small as the Dark Harbor 17.5. Physically positioning those such as the engine, for instance, can be particularly challenging. Furthermore, it is very easy to make the boat heavier, and new means of saving weight in other areas must be found, for instance looking at a lighter structure, more efficient use of the ballast, or modern carbon fibre rig. Finally, modern regulations, particularly for structure, are not suited to analyse traditional construction methods such as carvel.

Nevertheless, those challenges can be overcome to provide modern replicas and representations, commercially attractive and compliant with the present regulatory framework, while capturing the essence of the original design and therefore supporting the conservation of historic crafts and classic designs.

## 6. ACKNOWLEDGEMENTS

The principal author would like express special thankfulness, warmth and appreciation to the persons and organisations below for their support in the realisation of this project.

The professors of the EMShip Master programme for their vital support and assistance.

The professors of Southampton Solent University for all their patience in sharing their knowledge and expertise.

The owner of the Dark Harbor replica and the IBTC Portsmouth, where the built is under way, for the opportunity to be involved with the redesign and the fascinating discussions.

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