HIGH SPEED MONOHULL – CONCEPT OPTIMISATION AND VERIFICATION

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SUMMARY

The paper details the design, methods, building, testing and legislation process of a new high-speed craft concept rendered possible due to development of new production techniques utilizing extended use of carbon fibre reinforced sandwich in combination with vacuum infusion moulding technique. The use of carbon fibre materials has opened for concepts that in general only have been available for non-commercial projects due to high material cost. The project visualised by the construction of a high-speed ambulance/SAR vessel operating in the Norwegian coastal areas. In addition, experience from operation is described and a discussion is made with respect to HSC, Norwegian regulations, IMO- and EU-regulations.

AUTHORS BIOGRAPHY

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1. INTRODUCTION

The Brødrene Aa 20 m, 45knot monohull is an ambulance craft, however, the design, methods and technology developed through this project can be utilized for many types of craft and different concepts using the same mould. I.e. patrol, rescue, passenger, workboat landing craft to mention a few.

L_{OA}, Length overall	[m]	19.0
Length between perp., L_{PP}	[m]	15.5
Breath, B	[m]	4.7
Trim, T_{AP}-T_{FP}	[m]	0.23
Displacement, Δ	[t]	25.7
Speed (max)	[kn]	44
Operational speed	[kn]	36-38
Passenger capacity	No	12
Crew	No	2
Service area		R4
Waterjet propulsion, Kamewa		2 x FF 450 s
Main engines 2xMAN D2842LE413	[kW]	2 x 735

Table 1: *Principal particulars 'M/V "Rygerdoktoren "'*

Figure 1: *Picture from full-scale trial for 'M/V "Rygerdoktoren "'*

2. HULL FORM OPTIMISATION

2.1. CONSEPT – LIMITATIONS AND ADVANTAGES

The idea of this carbon-fibre-concept is to make a monohull design that can be used in the L_{PP}-range 15.5-20 meter at speeds up to 45 knots. The long version (i.e. L_{PP}=20m) hull has a parallel aft ship from the vertical stern and 5 m forward. As a result of this only one mould is adequate to make different versions with lengths between 15.5 and 20 meter (L_{PP}). Inserting a bulkhead where the vertical stern is to be placed can simply do this.

When the length of the ship is to be adjusted by adjusting the length of the parallel aft-ship the idea was to optimize the hull form with respect to the medium length, i.e. for the 18m (L_{PP}) design.

Keeping control on the LCG is a main issue for this kind of concept. LCG-position will initially move towards stern the longer the boat. The position will influence manoeuvrability and initial trim that is important for calm water characteristics.

Carbon fibre is one of the most solid materials in relation to its density. Compared to similar ships built in another lightweight material – aluminium, a reduction in lightship hull- weight in the range 20-40% can be achieved. This weight-reduction will of course be a great advantage compared to similar ships built in heavier materials with respect to resistance characteristics.

For short, the consequence of the weight reduction effect is less required power to achieve same speed -> smaller engine -> lighter ship -> less required power… I.e. the opposite of the usual weight/power spiral.

2.2. RESISTANCE

Three different versions of a model in scale 1:8.5 were tested for resistance in calm water. One initial version (A, L_{OA}=19.45m), one modified/optimised version (B, L_{OA}=19.45m) and finally a shorter version of (B), (C, L_{OA}=18.00m). All versions were trim optimised. In addition C-version was tested for dynamic stability in high speed.

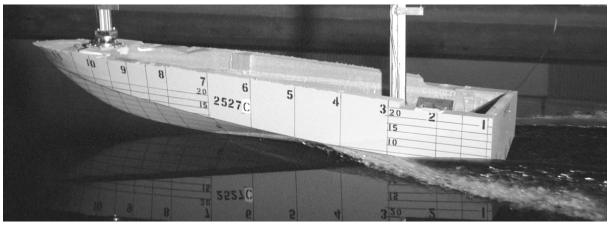

Figure 2: *Picture from calm water resistance tests. C – version, 18 tonnes, 0.5deg initial aft trim, speed: 40 knots*

A lot of spray from fore hull for A-version was observed during resistance tests. This showed clearly on the streamline paint test at 40 knots (20 tonnes) as cross-flow streamlines. Based upon this, a modification of the forehull was performed by slimming the fore-hull by reducing the concavity of the cross-sectional stations. The streamlines on the aft hull showed very stable flow, i.e. straight, longitudinal lines. A small modification was also done there reducing the concavity to improve seakeeping-characteristics.

Further, a modified hull model was made – B-version. The effective power curves, P_E, together with running trim are found in Figure 3. As seen from the figure, the C-model (short version of B) has a hump in the running trim curve (‘*Run. Tr. C-18t’*) at 20 knots ($F_N \sim 1.0$). The hump is present in the power-curve too, resulting in higher resistance for C-model than B-model despite the 2 tonnes lighter displacement. This is a consequence of justifying the ship length only by cutting of the parallel aft body. A more optimal power- and trim curve is obtainable if the hull could be modified for the actual length.

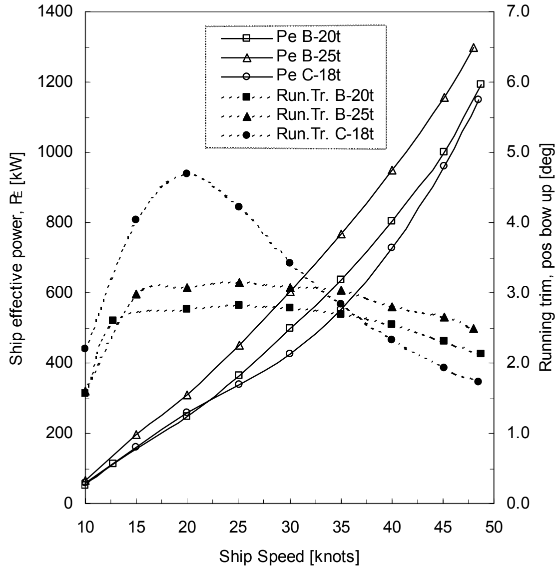

Figure 3: *Ship effective power and running trim*

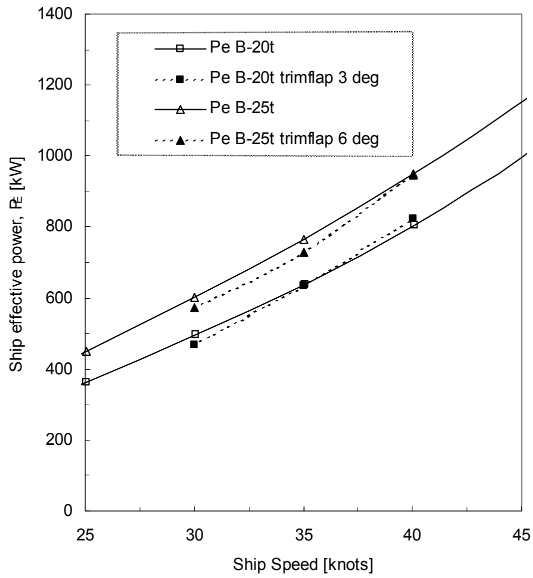

Figure 4: *Ship effective power and effect of trimflap*

Nevertheless, this hump in the resistance curve can be reduced considerably by applying for instance interceptors or trim flaps. A test was done for B-version, as shown in Figure 4. By experience the resistance-curves using trimflap is lower than without in the speed-range close to the ‘problem-area’ of C-model. The potential resistance- and running trim reduction for C-version is expected to be higher due to the high hump in running trim compared to B-version. As indicated in Figure 4, the favourable effect of using trimflap is mainly a function of ship speed and displacement. The effective trimflap area (with respect to speed and resistance) has to be found for each displacement. Of course, trimflap angle and -shape influences the result too. Anyway, the hull lines of a comparable aluminium-boat with the same deadweight could in this case be a bit more optimal with respect to resistance characteristics. The total weight would also be higher due to lower strength/weight ratio than carbon fibre. Of course, aluminium boats can also be optimised using trimflap (or something of the sort). Though, this boat will not have the same resistance (and trim) reduction potential as the corresponding C-version. I.e. the total-weight reduction (at same deadweight as for the aluminium boat) and the potential of resistance reduction using trimflap/interceptors would probably be a better concept than an optimised aluminium boat.

A positive effect of using trim-adjustment in speed was confirmed for full-scale test of M/V ”Rygerdoktoren ” that has a L_{PP} of 15.5m (C-version has L_{PP} 16m). The waterjets mounted on this ship has integrated interceptors. Looking at Figure 5, a clear advantage of using interceptors is shown, especially near ‘hump’-speed for C-version around 20 knots as seen in Figure 3.

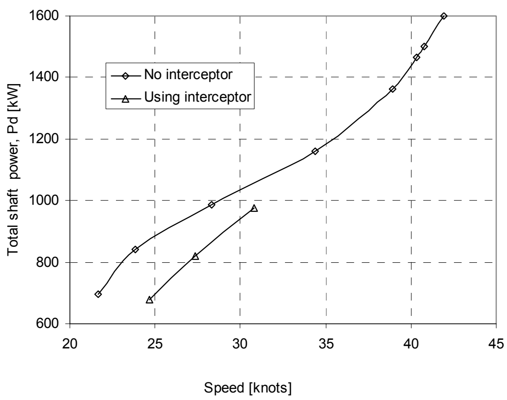

Figure 5: *Total shaft power for M/V ”Rygerdoktoren ” with and without interceptors. Displacement ~ 25 tonnes*

2.3. MANOEUVRING

The weight reduction is achieved in periphery areas when considered the ships built in other materials. The radius of gyration has an important influence on the manoeuvrability and the sea keeping performance. With a small radius of gyration, this opens for use of ballasting weights in order to adjusting this so as to achieve the optimum performance in relation to the sea condition.

In model tests (B-version with L_{PP}=17.5m) the waterjets were mounted horizontally. I.e. the scope could only be adjusted horizontally (for turning) and in the vertical plane only (for stopping/backing). In full-scale the waterjets were mounted in an angle flush to the V-shaped aft hull, see Figure 6. Consequently, when performing a turn in full-scale, a vertical jet-component is present (as opposed to in model-scale). In a starboard turn the effect is a force working upwards on port side waterjet and downwards on starboard waterjet resulting in a heeling-moment towards starboard and a more sudden turn compared to a horizontally mounted waterjet. As a result a comparison between model-scale and full-scale manoeuvring measurements could not be accomplished.

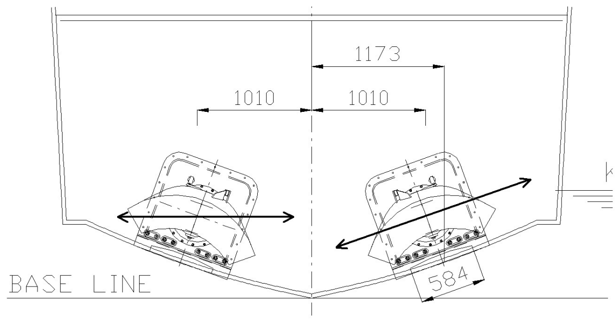

Figure 6: *Waterjet placement and rotation direction of scope when turning. Model to the left and full-scale (M/V ”Rygerdoktoren ”) to the right.*

Nevertheless, the manoeuvring characteristics found from model tests showed good manoeuvre characteristics. In a turn the ship heeled towards the centre of the turn and the model showed fast and precise manoeuvring capabilities. This was also confirmed in the full-scale trial of M/V ”Rygerdoktoren ”. The ship showed remarkable turning capabilities. At 25 knots the tactical diameter in a 28° starboard (angle on waterjets) turn was estimated to 38 m, i.e. a dimensionless L_{OA}/D = 2, see Figure 7. This extreme low number is mainly a consequence of the small radii of gyration.

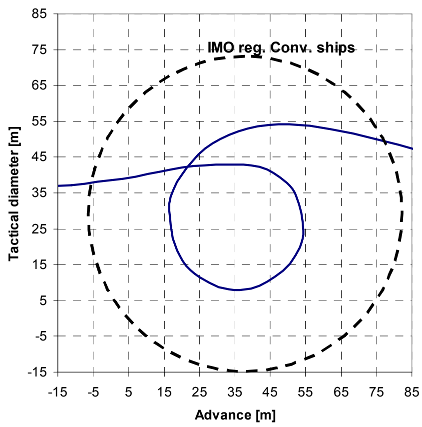

Figure 7: *Turning circle (StB) at 25 knots, M/V ”Rygerdoktoren ”*

As mentioned, the waterjets mounted on M/V ”Rygerdoktoren ” had integrated interceptors. Results from trial showed that the boat was fully able to make turns (not very sudden) only using one interceptor. A great advantage with this kind of turn is that the heeling angle and speed loss is low compared to using waterjets. Using max immersion on the interceptors at 35 knots equals the same turning-rate (~ 6°/s = turning diameter of ~250m) as using the waterjets at an angle of ~7° at the same speed. The (stable) heel angle using interceptor is only ~ 4° compared to ~ 8° using waterjets. Speed loss using interceptors is only 1 knot from 35- to 34 knots. The corresponding speed loss when using waterjets only is 5 knots.

2.4. SEAKEEPING

Regarding calm water performance characteristics, all trim optimisation tests showed that an initial aft trim of ~ 0.5° was optimum. With respect to seakeeping characteristics, aft trim is not preferable. This concept boat has a ‘solution’ to this problem. When heading into rough waters, a trim tank in the bow region is available for filling up with water or fuel. When this tank is filling up the low radii of gyration (longitudinally) increases and the aft trim will decrease. Both are propitious for seakeeping characteristics. The effect was measured in model tests, see **Figure 8**, and confirmed by full-scale trial for M/V ”Rygerdoktoren ”.

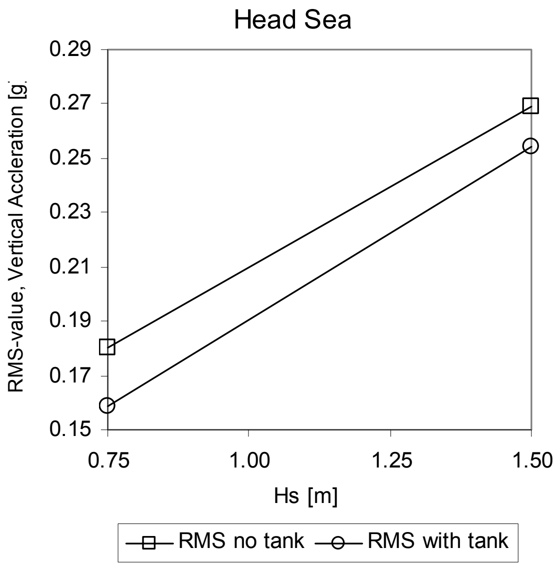

Figure 8*: Vertical acceleration level in CoG in head sea from model seakeeping tests, with and without trim tank. Hs/Vs = 0.75m/35kn and 1.50m/25kn*

A comparison between model- and full-scale is done in Figure 9.

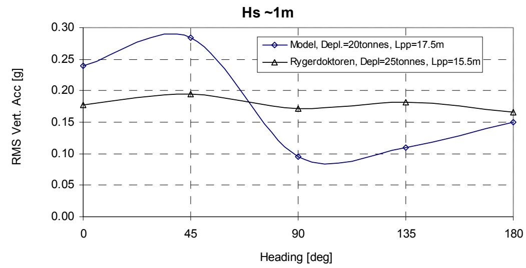

Figure 9: *Comparing RMS vertical acc. in CoG for (B)model- and full-scale. No interceptors and no trim-tank at speed ~ 30 knots. 0.5°aft trim for model- and 0.7° fwd trim full-scale.*

The full-scale ship (M/V ”Rygerdoktoren ”) is by crew experienced as a very precise ship to operate in rough seas. The ship had no problems with steering and broaching on a long trip with following seas, heading from Oslo towards Stavanger (in Norway) SS5-6.
Dough the displacement is higher in full- scale

Figure 10: *Picture from seakeeping tests in ocean basing with B-version*

3. PROJECT CONFIGURATION

The goal of the project was to develop a platform concept that is of such flexibility that it may be adapted to a variety of missions. The essential of this was the cost that is associated with the building of moulds for the hull and superstructure.
Due to that there was a definite requirement that the platform would handle the criteria:

1. Hydrodynamic performance to be able to handle a length envelope of Lpp between 15,5 and 20m.
2. The Arrangement to be divided into commercial areas and to technical areas.
3. Engine room to be divided into a compartment for electrical components and one for mechanical.
4. The platform to be prepared for common used engine types ranging from 500-1500 kW as well as propulsions systems such as water jet, FP and CP propellers.

5. Technical systems to be designed to handle most type of concepts in order to reduce the amount of engineering.
6. The aesthetic design to be of such a quality that most operators may accept it.

In order to comply with the goals of the project a project group were created as given in Figure 11

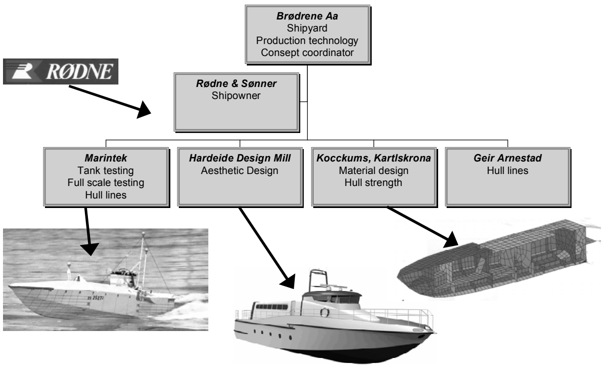

Figure 11: *Project group working with concept development*

4. MATERIALS AND STRENGTH

4.1. HISTORICAL REVIEW

Historical milestones in the naval architecture have shown that ship design have been linked up to production and material technology. As examples are when welding were introduced, to ship construction about 60 years ago.
During the last 20 years, in general it is optimization of production techniques and of materials that have taken place. The materials used for high-speed crafts are mainly aluminium although composite materials were used in some projects up to the mid nineties. When considering the fact that the outfitting of a vessel is the same independent of the construction material, the main area of which weight reduction may be achieved will be to consider alternatives of the construction material if a significant step forward is to be achieved.

4.2. CARBONFIBER AND COST

The essential of this project have been the falling prices of carbon fibre and in parallel the development of low cost moulds and effective production methods.
Carbon fibre has in general been associated with high performance racing cars, expensive sports equipment and products of high cost (high tech weapons). The price have the last 5 years decreased almost to the half, now being around €50 pr. Kg. Compared to aluminium and steel this price is extremely high, but as the amount of material are reduced and the use of high cost labour is lower, this equals the higher price.
The Swedish navy have done the same reflection and they are currently in a program of the construction of STEALTH type corvettes (VISBY).
It is assumed that this development is about the same as experienced with aluminium in the 60'ties.

4.3. CARBONFIBER AS A CONSTRUCTION MATERIAL

Carbon fibre is known as a material with one of the highest weight/strength/stiffness materials available. Still in compression the performance is only marginal higher than glass fibre concerning breaking strength.
On the other hand the specific weight of carbon fibre is less than glass fibre.
Considering concentrated loads the carbon fibre reinforced sandwich is about 4 times better than glass fibre.
In general the dimensioning criteria of hull structures are based upon the material breaking strength or the yield strength.
Stiffness criteria are often only related to a vibration matter, associated with i.e. comfort class notation etc. In order to reduce vibration or to ensure a stiffer structure, more material is added to the structure i.e. in aft ship or in the area around slender bulbous bows.
When using carbon fibre, the stiffness is already present as the breaking strength is related to the compression.

Considering the weight of a bottom panel in the slamming zone, the weight is 12 kg/sqm. This equals an aluminium plating of about 5mm. It must be noted that according to the DNV HSLC, the minimum plating thickness of shell plating below loaded water line is appr. 4mm. A composite panel do not have stiffeners, which is a necessity of an aluminium panel. In the high load areas the weight reduction is about 40% compared to aluminium, for the areas with low load factor such as the superstructure, the weight reduction varies between 20% and 30%. For a total ship, this may give a light ship reduction of 20%-30%. Considering a typical 40m catamaran with a light ship weight of about 130 tonnes, the weight reduction may be in the area of 20-30 tonnes.
In such a case the required engine capacity may be reduced with 10%-20% without influencing the operational speed of the vessel. A typical engine installation such as MTU 396/16V used in the aluminium version, the composite version may be considering the 12V type. With an annual total of 3000 running hours, the fuel reduction will be in the area of 700.000 litres of fuel.

5. PRODUCTION AND PRODUCTION METHODS

The use of moulding techniques in production of pleasure crafts have and will still be the dominating production method.
Concerning the project, the use of moulding is only a part of the production process. The main features are

the use of a vacuum infusion process in combination with a mould.
This allows for a sandwich type material where the matrix is used as core glue, and that the inner and outer laminate are all infused simultaneously ref. Fig.10.
The production process is divided into following main sequences:

1. Manufacturing of moulds
2. Application of inner/outer laminate and core
3. Infusion of matrix (vinylester)

Figure 10 shows the final part of the production process as the matrix are infused to the hull.

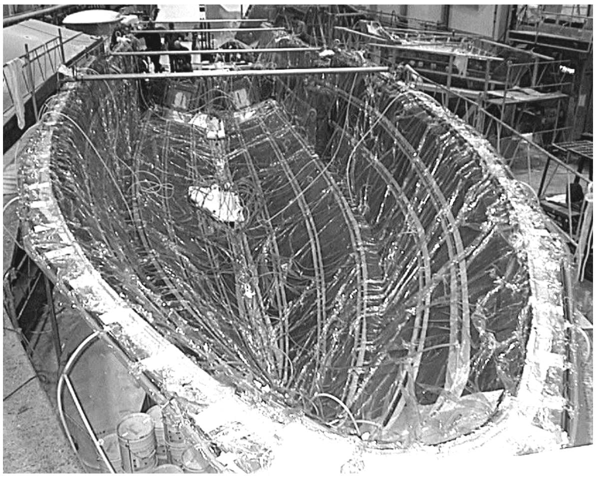

Figure 12: The hull during the vacum infusion process.

The main features of this production technique are:

- Application of laminates and core material are carried out without the use of glue/matrix. This is a dry process, and makes the production environment better.
- The quality control is better as the distribution laminates and core may easily be inspected before application of the matrix.
- The infusion is carried out through night time, only a minimum of 2 persons are required.
- Infusion gives a high degree of fiber content (70%).
- By vacum infusion the clued joints have a higher quality, delamination problems as reckognized by sandwich materials som 10-15 years ago are reduced significant.
- Use of moulding hav open for a underwater bottom finish that have a roughness of better than 75μ, friction is therefore better than most other materials used in construction.

By the use of moulds, an exact geometry input ensures that section building is accurate and with low risk. Figure 11 illustrates the sections used for the concept.
The figure 11 also shows the area of were the lengthening are carried out.

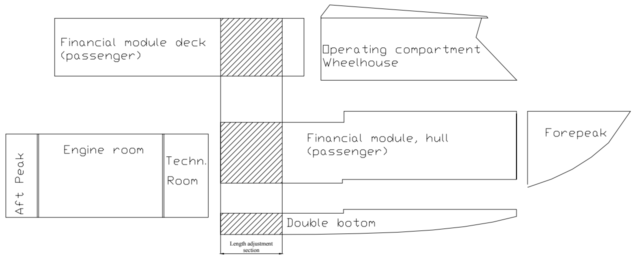

Figure 13: Module concept

6. EXPERIENCE AND REGULATIONS

6.1. EXPERIENCE FROM OPERATION IN DIFFERENT CONDITIONS

The vessel have been in operation in one year, and have a total of 1800 running hours which is about 45.000 NM.
The vessel replaced an ambulance boat built in the mid 80'ties. The Norwegian health department were some years ago considering to shut down the service and replacing the boat with helicopter and cars. The only way for the operator to answer this treat was to look for a tonnage that could compete and make the service attractive to the health department. After the introduction of the M/V "Rygerdoktoren", the experiences are in summary:

- Response time from scramble to arrival at site is about the same as helicopter, better than cars.
- The engine size is the same as the replaced boat, but the service speed is close to 10 knots higher.
- Small radius of gyration have given a concept with extremely high sea keeping performance in rough seas (SS4-SS6), compared to helicopter there are almost a negligible number of weather cancellations.
- The vessel are more equipped than a car or helicopter. When an injured have arrived on board, this is identified as being a part of the hospital, and the time elapsed from the pick site to the hospital have becoming less important (due to present doctor and nurse).
- In May 2003 a milestone was achieved as the vessel was preferred prior to a conventional ambulance car to assist in a traffic accident! The boat was at site before the car and had higher capacity.
- Efforts in creating good ergonomic operating compartments including the engine room have shown that the boat is attractive to crew members as well as health personnel.

The ship-owner states that the investment has been according to expectations, and that the introduction of carbon fibre reinforced sandwich have reduced

operational costs and open new market segments which before were not available.
The ship-owner shortly after the hand-over of the M/V "Rygerdoktoren" ordered a catamaran commuter ferry delivered May 2003, produces along the same methods.

6.2. HIGH SPEED CODE - COMPLIANCE

The first prototype vessel of this concept does not comply with the HSC Code. The prototype have been a R&D project, were the main goal have been to provide a boat that in concept was according to the HSC Code, but not with regards to requirements for components and equipment as it was important to have a realistic ambition of accomplishment. The concept though is fully compliant to the HSC both in construction and equipment, if required by the administration.
Considering the HSC, the 2000 edition is the one chosen as this is more flexible in relation to vessels less than 30m/150grt.
Still the HSC should by the next revision adjust in a higher degree to vessels in the range of 15-25m with respect to equipment and construction.
As the concept only allows for a single engine room compartment, the category A is the only possible alternative.
The concept may also be adapted to paramilitary versions, and by that the DNV PATROL notification is relevant.

7. CONCLUSIONS

The project has shown that when introducing new hull materials, this must also be associated with a new design concept. It is when a total concept design is performed that the benefit of a new material reveals.
The introduction of carbon fibres in the commercial market will basically benefit constructions where combination of stiffness and weight savings are of importance. Apart from complete hull or superstructures, it is also possible to introduce this in modules were i.e. material fatigue have been a problem such as slender bulbous bows, stern section etc.
Concerning aesthetical design, due to the weight/stiffness, new expressions may be introduced for components such as mast, bulwarks etc.
Although a high material cost, the man-hours consumed during the production is less than for metal constructions, and it is expected that the break even cost will be at 1,5.

The disadvantages with respect to resistance and trim by using the same mould for different lengths can be reduced significantly by using for instance interceptors. Further, building a boat in carbon fibre is weight saving in itself compared to for instance aluminium. This is of course also an advantage with respect to resistance level, comparing same deadweight at same speed.

Seakeeping characteristics can be improved by filling a trim tank in bow both increasing the initially low radii of gyration and increase bow down trim.

8. REFERENCES

1. MARINTEK reports 601869.00.01-03, reports from model tests, 2001

2. MARINTEK report 601869.00.04, 'FULL SCALE MEASUREMENTS', 2002