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Further Optimisation of the Enlarged Ship Concept, Applied to Ro-Ro Cargo/Passenger Vessels

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Abstract

The "Enlarged Ship Concept" (ESC) was successfully applied to a freighter in the form of a Ro-Ro Cargo/Passenger vessel by Journée, Pinkster and Tan (1998). Their results showed a performance improvement both in a technical and economical sense. However recommendations were made for further improvement of the enlarged designs in order to produce even better results.
These recommendations include the following design work:

- optimisation of the vertical position of the upper deck of the enlarged vessels in order to reduce the vessel's mass, while, at the same time satisfying the requirements regarding allowable stress values due to longitudinal bending moments,
- optimisation of the mass of the enlarged vessels by utilisation of high tensile steel,
- optimisation of the vessel form with regard to vessel resistance and propulsion and
- optimisation of the vessel's turn around time by not utilising the lower deck for the carriage of trailers.

In this paper, these recommendations are carried out and lead to an even more promising performance improvement, both in a technical and economical sense. It is shown that the ESC certainly has a good viability for these types of vessels, creating even more income possibilities for the ship owners and a much safer vessel, even though it produces a more expensive ship to buy and exploit.

1. Introduction

Keuning and Pinkster (1995) explored the so-called "Enlarged Ship Concept" (ESC) by applying this to a fast 25 knot, semi-planing, 26 m. patrol boat. The Froude number was, based on vessel length, equal to 0.81. The main driver behind this application was the fact that a mono-hull sailing at high forward speed in head waves may incur unacceptably high vertical accelerations that may hamper the safe operability of the craft. Their work concerned three design concepts, namely a base boat with two enlarged ship configurations. The key to the ESC is that

deadweight, i.e. payload, fuel and stores as well as vessel speed remain constant and equal to that of the base boat. In essence, they improved the seakeeping behaviour and decreased the resistance of the fast patrol vessel by increasing the length in steps of 25% and 50% and so increased also the length to beam ratio, reduced the running trim under speed and improved the general layout of the ship. The most important results from this study showed that the best design alternative was that with a 50% increase in length. On the one hand, a 68% marked improvement regarding a decrease in vertical acceleration in the wheelhouse in head seas and a 40% decrease in required propulsion power in calm water at a speed of 25 knots were obtained. On the other hand, the maximum purchasing price of the largest design alternative was estimated to be only 6% higher than that of the basic 26 m. patrol boat and the exploitation costs for a given mission profile were relatively reduced by 7%.
Keuning and Pinkster (1997) presented further research on the ESC topic. Extensive model testing related to vessel resistance and motions were carried out and subsequent results were described in detail. This second study confirmed the results of the first study and favoured, once again, the Enlarged Ship Concept. In the meantime, the results from these studies have been applied to a number of new buildings of fast patrol boats in The Netherlands.
A logical question at this stage was then as follows: “Can the ESC also be successfully applied to the common work horse of the seas, the ordinary marine freighter?”. Journée, Pinkster and Tan (1998) answered this question by applying the same ESC to a full time “freight carrying” vessel being a Ro-Ro/Passenger vessel representative for present services in the UK-West Europe route.

2 Base Ship and Enlarged Designs

The base vessel of 157 m. length was lengthened by respectively 25% and 50%, while deadweight and speed remained constant, see Figure 1 and Table 1.

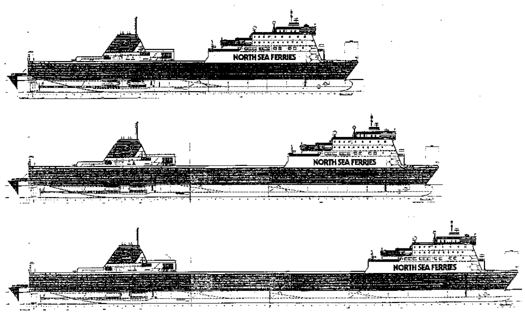

Figure 1 Base Vessel and Lengthened Ships

Parameter	ESC-0	ESC-1	ESC-2
Increase in Length (%L)	0	25	50
Loa (m)	166.77	206.18	244.97
Lpp (m)	157.65	197.06	235.85
Bmld (m)	23.40	23.40	23.40
T (m)	5.80	4.97	4.50
KB (m)	3.26	2.69	2.36
BM (m)	9.01	10.25	11.35
KG (m)	10.42	10.83	10.87
MG (m)	1.85	2.11	2.84
Cb (-)	0.61	0.64	0.66
Depth to main deck (m)	8.60	8.60	8.60
Depth to upperdeck (m)	14.40	14.40	14.40
Lightshipweight (t)	7417	9126	11176
Deadweight (t)	6020	6020	6020
Displacement (t)	13437	15146	17196
Speed (kn)	22	22	22
Propulsion power (kW)	24480	25700	33500
Passengers (-)	120	120	120
Lane length upperdeck (m)	930	1190	1450
Lane length maindeck (m)	910	1170	1430
Lane length hold (m)	200	0	0
Trailer capacity 40 t (-)	156	165	165
Water ballast (t)	234	0	0
Gross tonnage (GT)	17464	21452	25396
Net tonnage (NT)	5239	6436	7619
k_{xx}/B (-)	0.43	0.43	0.43
k_{yy}/Lpp (-)	0.29	0.29	0.29
k_{zz}/Lpp	0.29	0.29	0.29

Table 1 Main Particulars of Base Ship and Alternative ESC Designs

The consequences with regard to vessel mass, stability and trim, cargo-hold configuration, propulsion power, freeboard, net tonnage and building costs were evaluated. On the operability side, seakeeping performance as well as operability were also assessed. Finally, costs were determined for the base ship as well as for the two ESC alternatives. The most important results are shown in Table 1 from this recent study for the best design alternative. A 25% increase in length showed, on the one hand, a small and insignificant improvement regarding a decrease in vertical acceleration in the wheelhouse in head seas and a 5% increase in required propulsion power in calm water at a speed of 22 knots. On the other hand the maximum purchasing price of the largest design alternative was estimated to be 10% higher than that of the basic 157 m. Ro-Ro/Passenger vessel. The exploitation costs for a given mission profile were relatively increased by 8%.

All in all, when comparing these results to those related to the 26 m. patrol boat, the Ro-Ro/Passenger vessel at a first glance appears to give a less satisfactory result when enlarged. However, a definitive advantage of the ESC is the provision of space for the accommodation of lighter cargoes - if available - which consequently significantly increase the earning capacity pro rata and transport efficiency as may be seen from Table 2.

Index	ESC-0	ESC-1	ESC-2
Increase in length (%L)	0	25	50
Building costs	1.00	1.10	1.28
Power at 22 knots	1.00	1.05	1.32
Operational costs	1.00	1.08	1.18
Transport efficiency [1)]	1.00	1.01	0.80
Transport efficiency [2)]	1.00	1.17	1.13
Trailer capacity [1)]	1.00	1.06	1.06
Trailer capacity [2)]	1.00	1.22	1.49

[1)] 12.2 m. trailers total all in load of 40 tons each (6020 dwt)
[2)] idem, with all in load of less than 40 tons each (6020 dwt)

Table 2 Results of Economical Calculations for Ro-Ro/Passenger Vessel

With regard to safety, applying ESC to a Ro-Ro vessel also renders an improvement in concept design due to a significant increase in survival capability after having suffered the ingress of water into the hull. The condition that the lowest hold remains empty and optimally subdivided for this purpose must be respected.

Furthermore, Journée, Pinkster and Tan (1998) thought that further optimisation of the enlarged designs of the Ro-Ro Freighter/Passenger ferry may well lead to more promising results. Therefore, it was recommended that the vertical position of the upper deck of the enlarged vessels be optimised to reduce the vessel mass. The utilisation of high tensile steel be looked into as this will surely reduce the vessel mass, while at the same time being able to withstand the higher longitudinal bending stresses. Further, optimise the vessel form with regard to vessel resistance and propulsion and optimise the vessels turn around time by not utilising the lower F-deck for the carriage of trailers.

In the present paper a number of these recommendations are investigated with regard to their implications and merits and the subsequent results regarding the final design outcome are discussed.

3 Further Optimisation

The ESC-1 produced overall the best results from the investigations carried out by Journée, Pinkster and Tan (1998). In order to make a quick estimate of what the effect on the design would be by altering specific design parameters within the given concept, the depth of ESC-2 was altered in steps of 0.6, 1.0 and 1.4 m., respectively. The depth to main deck was thereby varied from 8.80, 9.2, 9.6, and 10.0 m. The weather-deck, situated at 14.40 m. above the base line for the base ship, was also changed by the same amount. In essence, the effect of these changes will result in a change in - amongst others - vertical centre of gravity, lightship weight, vessel draft and initial metacentric height. These changes have been estimated to be within a certain range. For example, due to the changes in vessel depth, the vertical centre of gravity of the loaded vessel has been varied from 10.83, 11.50, 12.00 to 12.50 meter, respectively and the draft from 4.00, 4.50, 4.97 to 5.50 meter. This variation accounts for a possible (later to be determined) decrease in lightship weight due to the effect that an increase in depth may have on required section modulus from a viewpoint of bending moments and/or torsional moments. The main fixed values for these calculations are given in Table 3.

Parameter	ESC-1	ESC-1 0.60	ESC-1 1.00	ESC-1 1.40
Incr. in length (%L)	25	25	25	25
Loa (m)	206.18	206.18	206.18	206.18
Lpp (m)	197.06	197.06	197.06	197.06
Bmld (m)	23.40	23.40	23.40	23.40
Incr. in Depth (m)	0.00	0.60	1.00	1.40
Incr. in Depth (m) [1)]	0	0.07	0.10	0.16
Depth to main deck (m)	8.60	9.20	9.60	10.00
Depth to upperdeck (m)	14.40	15.00	15.40	15.80
Deadweight (t)	6020	6020	6020	6020
Speed (kn)	22	22	22	22
Prop. power (kW)	25700	25700	25700	25700
Passengers (-)	120	120	120	120
Lane length upperdeck (m)	1190	1190	1190	1190
Lane length maindeck (m)	1170	1170	1170	1170
Lane length hold (m)	0	0	0	0
Trailer cap. 40 t	165	165	156	156
Trailer cap. 40 t	191	191	191	191

[1)] to main deck

Table 3 Main Particulars of ESC-1 and Alternative Designs with Increase of Depth

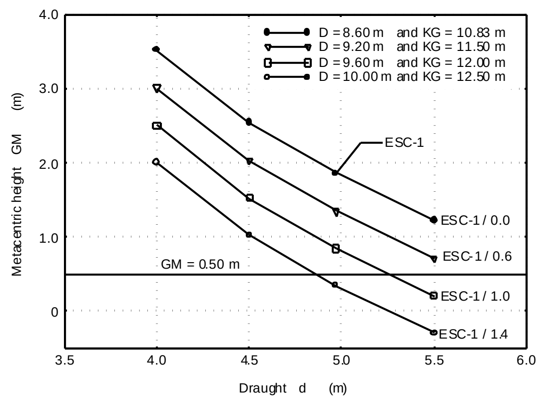

Figure 2 Metacentric Heights of ESC Series

In view of the added freedom of the designer to place decks and cargo according to his own (best suited) requirements, it was decided to make the subsequent motion calculations for 4 values of the following three design parameters: depth to main deck, vertical centre of gravity and vessel draft. These combinations are also shown together in Figure 2.

4 Ship Motions

The vessel motions were calculated using the linear strip theory program SEAWAY of the Delft Ship Hydromechanics Laboratory, as described by Journée (1992). These calculations were carried out in Beaufort 7 to 11, at wave directions ranging from head to following seas. The energy distribution of the irregular waves in the considered coastal areas was described by uni-directional JONSWAP wave spectra. According to Hasselmann (1973), this wave energy distribution is a favourable choice for fetch limited seas. Figure 3 shows a commonly used relationship between wave period, wave height and Beaufort number.

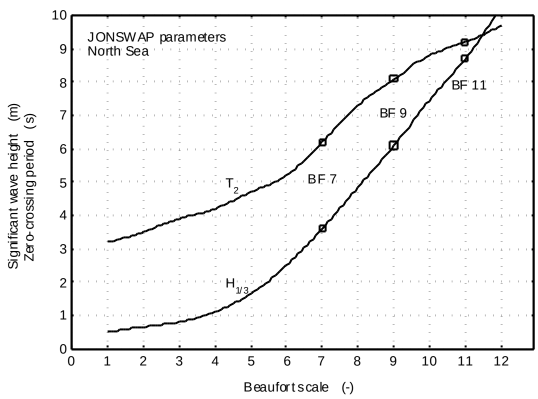

Figure 3 JONSWAP Wave Spectra Parameters

The long-term probability on exceeding a certain sea state was obtained from Global Wave Statistics whereas the limiting criteria of ship motions were obtained from Karppinen (1987). Since the topic investigated in this paper deals with large seagoing vessels, ship motions are calculated at 20 and 15 knots instead of at a service speed in calm water of 22 knots. When assuming that the still water resistance is proportional to at least the square of the ship speed and using calculated data on added resistance in seaway, a sustained sea speed in rough weather dropped from 22 to 15 knots would expect to be an acceptable average.

Journée, Pinkster and Tan (1998) gave the vertical significant acceleration amplitude at the bridge in head seas as a function of the Beaufort scale with an acceleration criterion of $0.3 \cdot g$. At both speeds course can be maintained by ESC-0 in sea states up to Beaufort 8, which will be exceeded during about 2% of the year. As expected, the two enlarged ships ESC-1 and ESC-2 can maintain their course up to Beaufort 9 and 10, respectively. Also shown by Journée, Pinkster and Tan (1998) was the probability on slamming in head waves, defined by a relative vertical velocity criterion at the bow. Using a slamming criterion of 2 per cent, all ESC ships can maintain their course up to Beaufort 8. The effect of ship size and forward speed on slamming appears to be relatively small. In the light of these results no more effort will be put into investigation of these phenomena for the design alternatives of ESC-1 as presented in the present paper. However, effort will be put into the more critical aspects of these larger vessel which are the strength related phenomena, such as vertical bending moments and tosional moments due to ship motions in a seaway.

5 Vertical Bending Moments

As may be seen in Figure 4, the largest significant amplitude of the vertical bending moment is met in head seas (180^0) for all Beaufort numbers.

The magnitude of the corresponding vertical bending moments in a BF 11 is in the order of magnitude of the still water bending moment. The difference in vessel speed of 20 or 15 knots in a seaway does not have any meaningful influence on these results.

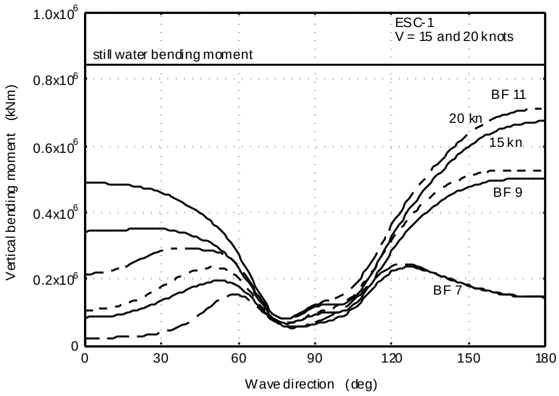

Figure 4 Effect of Speed and Wave Direction on Vertical Bending Moment of ESC-1

Figure 5 shows that increasing the vessel depth for ESC-1 does not appear to cause any significant changes in the vertical bending moments in a seaway.

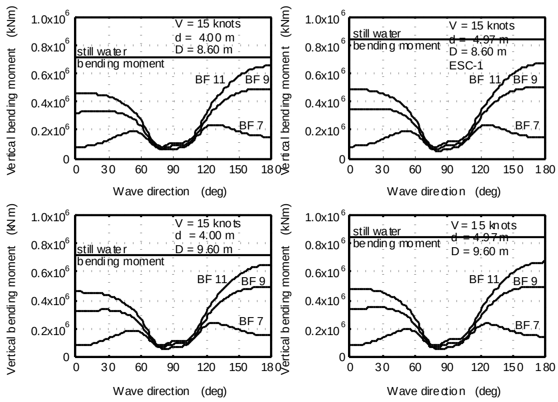

Figure 5 Effect of Wave direction on Vertical Bending Moments of ESC-1 Alternatives at a Speed of 15 knots

The same level of safety factor for bending moment for all vessel alternatives relative to ESC-1 has been assumed and the simple elastic beam theory to the sides, bottom and topsides has been applied. This means that the scantlings of the vessel for a fixed bending moment value may be estimated using the following relationship between bending moments for the two designs under consideration:

$$\frac{t_{s2} \cdot D_2^{\ 2} + (B/D_2) \cdot t_{d2}^{\ 3} + 3B \cdot D_2 \cdot t_{d2}}{t_{s1} \cdot D_1^{\ 2} + (B/D_1) \cdot t_{d1}^{\ 3} + 3B \cdot D_1 \cdot t_{d1}} = \frac{M_{b2}}{M_{b1}}$$

Equation 1

The index 1 refers to the ESC-1 design and the index 2 to the alternative with the increased depth. The value t_s / t_d refers to the average thickness of the ship's side/deck (including plating and stiffeners etc.). B refers to the ship's breadth and D to the depth.

The basic formula used to derive Equation 1 is that giving the bending stress, s_b:

$$\left(\frac{M_b}{W_b}\right)_1 = s_b = \left(\frac{M_b}{W_b}\right)_2$$

Equation 2

The index 1 refers to the ESC-1 design and the index 2 to the alternative with the increased depth. The value M_b refers to bending moment, W_b to bending section modulus and t_s / t_d to the average thickness of the ship's side/deck (including plating and stiffeners etc.). B refers to the ship's breadth and D to the depth.

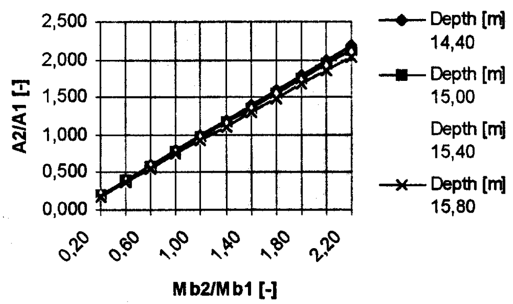

Figure 6 Effect of M_{b2}/M_{b1} on Ratio Cross Sectional Area of ESC-1 Alternatives

From Figure 6, the effect on cross sectional area may be estimated for a given vessel depth to the weather deck and given M_{b1}/M_{b2} values. Since $M_{b1}/M_{b2} \approx 1$ in the case under investigation in this paper, the reduction in steel weight is approximated as being 0.8%, 1.4% and 1.8%. This gives a decrease of respectively 50, 81 and 110 ton for D is 15.00, 15.40 and 15.80 meter. This in turn leads to a reduction in building costs with a maximum of approximately 1%.

Given A_1, t_{s1}, t_{d1} and ratio M_{b2}/M_{b1}, the average thickness t_{s2} may be calculated, using the assumption that $t_{s1}/t_{d1} = t_{s2}/t_{d2}$. With t_{s2}, t_{d2}, B and D_2, then A_2 may be determined.

The cross sectional areas A_1 and A_2 are defined as follows:

$$A_1 = 2 \cdot (t_{s1} \cdot D_1 + t_{d1} \cdot B)$$

Equation 3

and:

$$A_2 = 2 \cdot (t_{s2} \cdot D_2 + t_{d2} \cdot B)$$

Equation 4

6 Torsional Moments

As may be seen from Figure 7, the largest significant torsional moment amplitude occurs in and around stern quartering waves (70^0) for all Beaufort numbers.

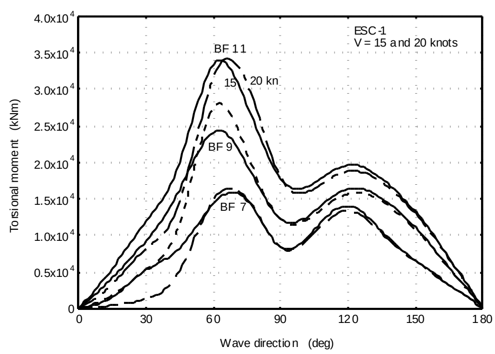

Figure 7 Effect of Wave Direction on Torsional Moments Amidships of ESC-1

The magnitude of the corresponding torsional bending moments in BF 11 is in the order of magnitude of twice that found in BF 7 conditions. The difference in vessel speed of 20 or 15 knots in a seaway does not have any meaningful influence on these results.

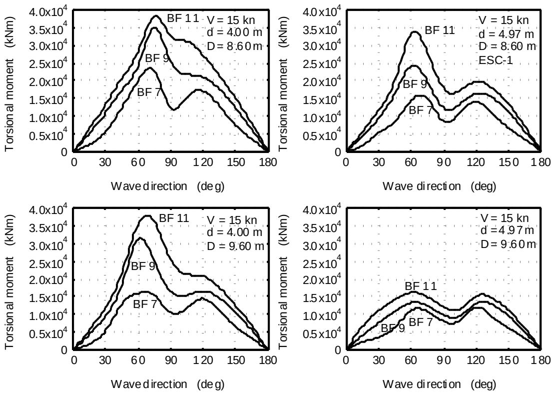

Figure 8 Effect of Wave Direction on Torsional Moments Amidships of ESC-1 Alternatives at a Speed of 15 Knots

Figure 8 shows that increasing the vessel depth for ESC-1 appear to cause significant changes in the torsional moment in a seaway.
Assuming the same level of safety factor for torsion for all vessel alternatives relative to ESC-1 and the application of the simple elastic torsional theory for a hollow (singular) rectangular thin walled structure applied to the sides, bottom and topsides. This means that the scantlings of the vessel for a fixed torsional moment value may be estimated, using the following relationship between torsioal moments for the two designs under consideration by Journée, Pinkster and Tan (1998):

$$\frac{\left(\dfrac{2t_{s2}\cdot t_{d2}\cdot(B-t_{s2})^2\cdot(D_2-t_{d2})^2}{B\cdot t_{s2}+D_2\cdot t_{d2}-t_{s2}^{\;2}-t_{d2}^{\;2}}\right)}{\left(\dfrac{2t_{s1}\cdot t_{d1}\cdot(B-t_{s1})^2\cdot(D_1-t_{d1})^2}{B\cdot t_{s1}+D_1\cdot t_{d1}-t_{s1}^{\;2}-t_{d1}^{\;2}}\right)}=\frac{T_2}{T_1}$$

Equation 5

The index 1 refers to the ESC-1 design and the index 2 to the alternative with the increased depth. The value t_s/t_d refers to the average thickness of the ship's side/deck (including plating and stiffeners etc.). B refers to the ship's breadth and D to the depth.
The basic formula used to derive Equation 5 is that giving the torsion angle, q:

$$\left(\frac{T\cdot L}{K\cdot G}\right)_1 = q = \left(\frac{T\cdot L}{K\cdot G}\right)_2$$

Equation 6

The index 1 refers to the ESC-1 design and the index 2 to the alternative with the increased depth. The value T refers to torsional moment, K is a factor depending on form and dimensions of the cross section involved, G refers to the modulus of rigidity of the material and L is equal to the length of the member. In a similar fashion as described in the previous paragraph, the cross sectional area ration A_2/A_1 can again be determined as a function of T_2/T_1, see Figure 9.

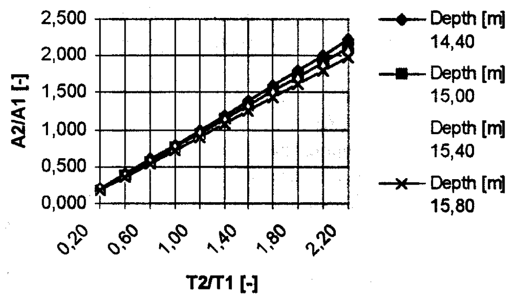

Figure 9 Effect of T_2/T_1 on Ratio Cross Sectional Area of ESC-1 Alternatives

Since $T_2/T_1 = 0.42$ as far as torsion is concerned in the case under investigation in this paper, a reduction of approximately 16% in steel weight may be achievable. This gives a decrease of approximately 1000 tons for D = 15.00, 15.40 and 15.80 meter. This could lead to a reduction in building costs, with a maximum of approximately 7%.

7 Wave Periods

A sensitivity analysis has been conducted into the relation between wave period and wave direction on torsional and vertical bending moments at a speed of 15 knots. The results are shown in Figure 10.

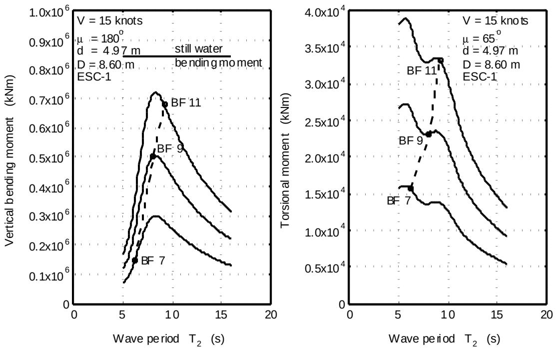

Figure 10 Effect of Wave Period for a Given Wave Direction on Torsional and Vertical Bending Moments at a Speed of 15 Knots

Figure 10 shows the effect of a change of wave period (zero up-crossing period T_2) on the significant amplitude of the bending and torsional moments for different wave directions and Beaufort numbers. The broken line in both graphs show the combinations of these parameters, utilised in the study presented here. Clearly, the chosen wave period has a large influence on the above mentioned moments.

8 Economic Evaluation

In order to make an economical evaluation, the building costs of the different design alternatives were estimated using the original building costs of the base ship, of which all costs components were known. These costs were corrected for changes in steel mass of the hull, extra painting costs (cleaning, preparation and painting) and extra machinery costs. Due to the fact that it was not clear at this stage whether the main scantlings were determined by vertical bending moments or torsional moments, the change in steel mass was taken as being the average of both possible reductions as estimated under at sections 5 and 6 respectively. The actual differences in building costs are indexed with regard to the ESC-1 in Table 4.

Index	ESC-1	ESC-1 0.60	ESC-1 1.00	ESC-1 1.40
Building costs	1.00	0.970	0.960	0.960
Power at 22 kn	1.00	0.998	0.997	0.995
Operational costs	1.00	0.980	0.980	0.980

Table 4 Results of Economical Calculations

9 Conclusions

The following conclusions are drawn with regard to further optimisation of the Enlarged Ship Concept applied to a freight carrying vessel by increasing the depth of the ESC-1 design alternative (see also Table 2).

- The vertical amidships bending moment in rough weather does not significantly change as the vessel depth increases. In Beaufort 11 the increase is still of the same order as the expected increase of the calm water bending moment which is proportional to the square of the ratio between vessel length and base ship length.
- The torsional moment in rough weather does significantly change as the vessel depth increases. In Beaufort 11 the increase is approximately 40%.
- Increasing the depth of ESC-1 may be able to cause an average maximum reduction in steel weight of approximately 8%. This is, more or less, constant for all investigated depth increases.
- Consequently, the building costs of the vessel may be reduced by about 4%.
- The operational costs of the vessel may be reduced by approximately 2% by increasing the depth.

- Due to the fact that the vessel steel weight is reduced due to the increased depth, the vessel draft may be somewhat reduced. This yields a further improvement in concept design with regard to a significant improvement in survival capability after having suffered the ingress of water into the hull. The condition that the lowest hold remains empty and optimally subdivided for this purpose must be respected.

10 Acknowledgement

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