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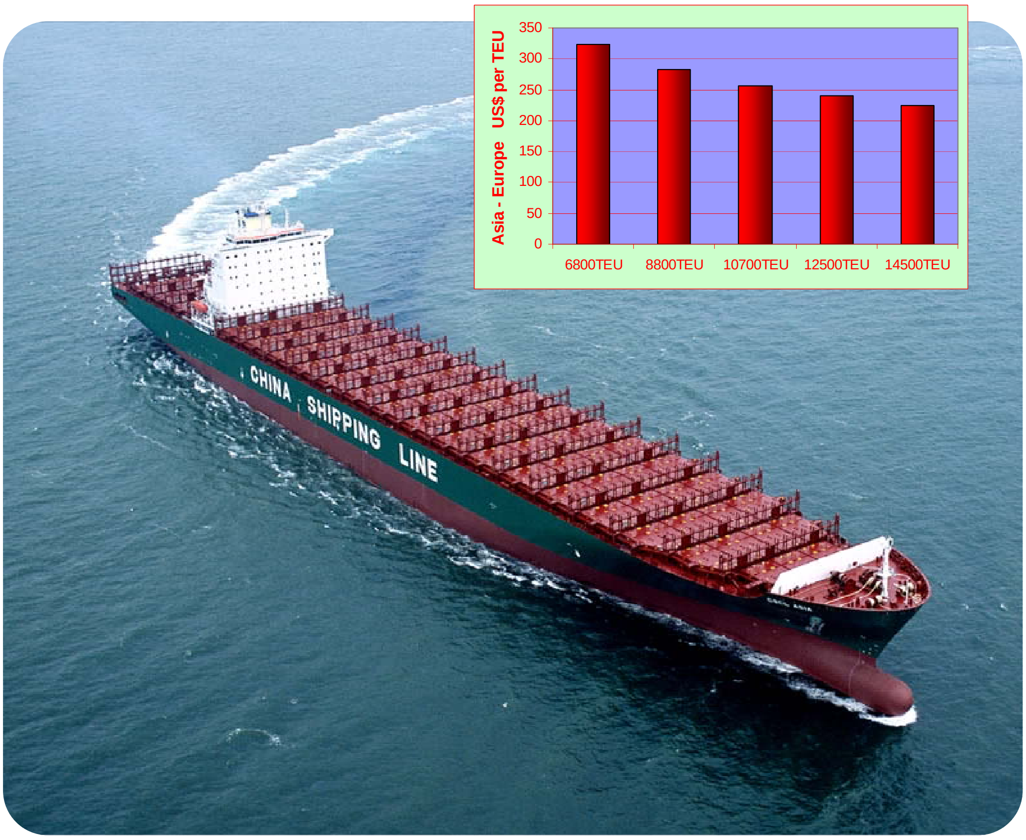
Design challenges of large container ships



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Synopsis

The paper considers the anticipated future demand growth for container shipping, noting in passing the severe shortage of feeder / intra-regional tonnage, and then examines some of the technical challenges associated with the design and operation of the largest vessels.

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1. Introduction

The concept of containerised cargo has advanced at a tremendous pace since its invention by Malcom McLean in 1937. An ever-increasing proportion of the world's manufactured goods is shipped in freight containers, with some 16 million containers reported to be on the move at any one time.

The size of the ships which carry these containers has increased accordingly. There are currently over 170 container ships in service with capacities of greater than 6,000 teu and about 250 more on order or under construction, comprising 2 million teu, or 46% of the orderbook. In tandem with the growth in size, a serious demand scenario has developed at the other end of the size spectrum, in the feeder market.

China Shipping Group now have container ships in service with capacities of 8,500 teu, and more on order at Samsung Heavy Industries with 9,600 teu capacity. A P Møller have on order a series of 9,100 teu ships at Samsung Heavy Industries. China Ocean Shipping Corporation (COSCO) has recently ordered a series of even larger container ships of 10,000 teu to be built by Hyundai Heavy Industries. We are pleased to say that all of these ships are Lloyd's Register class.

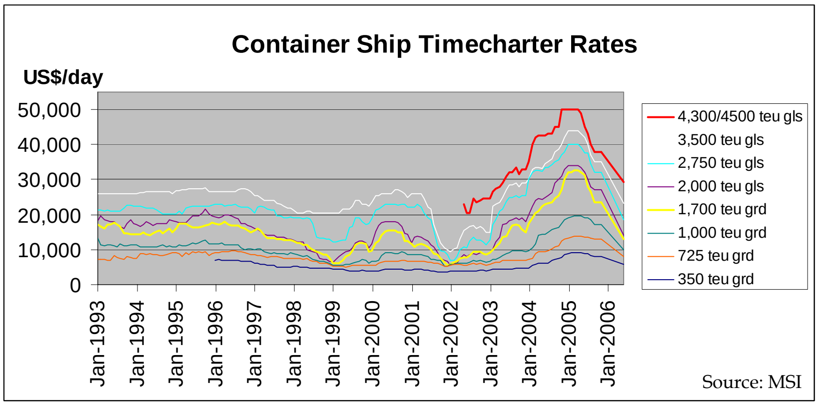
The container fleet has now reached the "magic" 10,000 teu. The questions are, how big are these ships going to get, and how many will the market need to meet the apparently insatiable demand for containerisation?

This paper looks briefly at the anticipated future demand growth, noting in passing the severe shortage of feeder / intra-regional tonnage, and then examines some of the technical challenges associated with these largest vessels.

2. Container market outlook

2.1 Demand growth in the container sector

Because containers are used principally for the carriage of manufactured goods, the container trades tend to be volatile. Charter rates surge up and down in a cyclical manner as the market responds to changes in the world economic climate and in the container shipping supply-demand balance. Last year the rates were good, but the market is now tightening as new tonnage comes on stream. But how far will the rates fall?



Source: MSI

Figure 1 - Container ship timecharter rates

One factor pointing to a soft landing for the container market is the expectation that the underlying demand for containerisation will continue to rise rapidly. During the period 1991-2003 the average growth rate was 11% per year, and over the next decade the growth is expected to continue at an average rate of nearly 10% per year. In fact, it is predicted that by 2010 the amount of cargo being transported by container will have reached nearly twice the 2003 figure.

Whilst this growth forecast is encouraging, it is worth keeping in mind the volume of the current orderbook and the impact that new deliveries into the market are likely to have on tempering the positive effects of increased demand. In 2004 the growth in the container trades was 13%, but the world fleet grew by just 9.5%. In 2005, however, the world fleet grew by about 13% (1 million teu), faster than the container trade demand. The picture in 2006 looks more unbalanced, with an expected increase in the world fleet of 15% and demand increasing by only 6%.

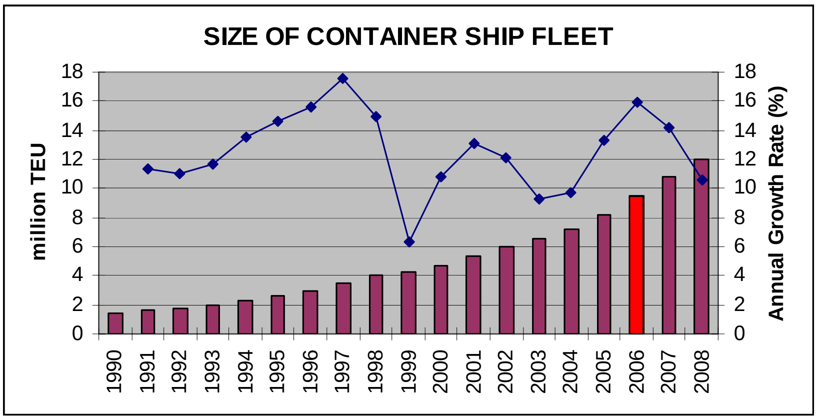


Figure 2 - Growth of container ship fleet

So, how will the balance pan out? Towards the end of 2004 there was fear that the 'China effect' would cease and that many container ships would struggle to find employment, but today the general view in the market place is more bullish. It is generally considered that the supply of new tonnage which will be delivered during the next couple of years will not over-run significantly the trade demand. If this view proves to be correct, it is likely that charter rates will, during the next few years, settle at sustainable levels which were typical in the mid-1990s.

2.2 Need for feeders becoming critical

The surge in the size of large container ships has been accompanied by a linked increase in demand for transhipment which has so far been met but may soon upset the economics of deepsea container transport. Transhipment has increased rapidly since the early 1990s, with the associated demand for container feeder shipping rising during the same period. These growth patterns are not only expected to continue going forward, but will intensify due to other factors impacting the feeder trades.

Analysis of predicted regional trading requirements for feeder and intra-regional operations indicates an 84% increase in trade volume during the period 2004- 2015. This is a substantial increase which cannot be met by the current fleet, even allowing for some larger ships cascading down into the feeder trades.

If factors such as ship size and speed were to remain equal, this would indicate that the fleet would have to nearly double in capacity simply to maintain the current market balance. However, the situation is much more complex than this. Up to 40% of the world's feeder fleet is comprised of vessels which are at least 15 years old, and much of this tonnage will be removed from the market by 2012, which means that in addition to the expected rise in trade volumes, there will also be a significant replacement demand to be met.

If the new tonnage were to be delivered at a constant rate from now until 2015, this would mean more than 200 new feeder vessels entering the market each year. Clearly this is not currently the case.

The lack of efficient modern feeder tonnage is a major threat to the container sector which could potentially compromise the industry's investment in new large post-panamax tonnage. There is a clear need for modern feeder designs which are flexible yet targeted, but so far there is little evidence that this opportunity has been realised and few orders have been placed.

Lloyd's Register, in association with Ocean Shipping Consultants Ltd, has identified a range of feeder designs, each optimised for a particular trading region.

The feeder trades could potentially become one of the most important sectors for the container industry, but to date there has been a failure to recognise the scale of the future demand. Without proper investment, the lack of capacity could constrain demand and adversely impact on deepsea vessel economics.

2.3 Classification of large container ships

Lloyd's Register is well placed to support the industry as the drive towards ever larger container ships continues. It is the number one classification society for container ships of +6,000 teu, having won 30% of all orders for this ship type over the past year.

Our market share reinforces our position as the class society with the greatest experience of the design, construction and operational support for these large ships. We have accumulated some 150 ship years' worth of service experience with container ships of +6,000 teu, a full 25% more than our nearest competitor. Likewise, our decade of experience with this ship type puts us well ahead.

It is because the container fleet is growing so strongly and because we class such a large proportion of the fleet, that Lloyd's Register is investing heavily in technological developments which focus particularly on container ships, ensuring that our global service experience of large container ships feeds back into the ship design and construction phases, and hence into in-service monitoring through classification surveys, to ensure that container ship owners and operators have the most reliable vessels possible.

3. Lloyd's Register updated ULCS study

Just a few years ago, container ships of 8,000 teu and above were considered an outlandish concept; today, the first 8,500 teu ships are already in service, with orders for ships even larger than these being commonly placed by the world's leading container ship operators.

Anticipating the trend towards even larger container ships, Lloyd's Register commenced its ultra-large container ship (ULCS) study in 1999 to determine just where this trend would take the industry. The first phase of the study, carried out in association with Ocean Shipping Consultants Ltd, examined the capabilities of the major container terminals to berth large container ships, as it was understood that this would be one of the main limiting factors for container ship size. It was determined that ship breadth would be limited by available gantry outreach to 22 boxes abreast on deck. The draught would be limited to 14.5 metres, similar to the design draught of today's largest container ships. Such a ship would have a capacity of about 12,500 teu.

The second phase examined the interaction between ship size and speed. A ULCS loaded to 14.5 metres draught cannot be driven at 25 knots without risking propeller cavitation problems. It was thus determined that the maximum practical ship size for 25 knots was 10,700 teu. Alternatively, a 12,500 teu ULCS could be propelled at 23 knots. An economic assessment then examined these options and determined that the larger, slower vessel provided the most cost-effective solution, in terms of $/teu shipped.

3.1 ULCS III

Lloyd's Register, in association with Ocean Shipping Consultants Ltd (OSC), has now undertaken the third phase of the ULCS study.

A review of infrastructure developments has confirmed that progress is very much in line with what was anticipated in the earlier studies. In fact, investment in ULCS quayside gantries has been rapid, Figure 3. By the end of last year, more than 200 of these gantries were in service. With a unit cost of about $8.5 million this is no minor investment by the container terminals.

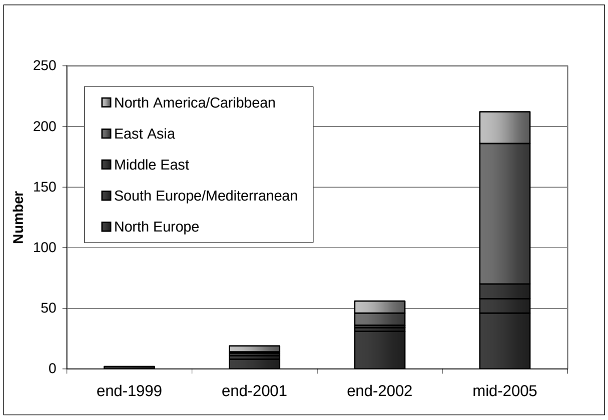


Figure 3 - Distribution of ULCS gantry cranes by region

Return on this investment looks safe. The container trades have been growing at a healthy rate of about 10% per year for many years, and it looks like this trend is set to continue for some years yet, albeit with a glitch in the next couple of years as the large number of post-panamax ships which are currently on order or under construction enter service and close the supply-demand gap.

In phase III of the study, the most significant modification of the ULCS concept has been the exclusion of the twin engine option. The previous studies considered both single- and twin-screw solutions, from which it was ascertained that a single-screw ship provides a more cost-effective solution than a twin-screw ship, principally because of the additional new construction cost (approximately $12 million extra) and increased manning costs when in service. This view was further reinforced by discussions with major owners. Furthermore, an analysis of regular weekly trades provided using 25½ knot and 23 knot vessels (the latter requiring the provision of an extra vessel) has established that the fleet of faster vessels provides a more cost effective solution, in terms of $/TEU delivered, than their slower counterparts, despite the increased bunker consumption.

Further consideration has therefore been given to the overall relation between length, beam and draught in favour of a finer and deeper design, with actual trading draughts being taken into account. This approach takes advantage of the variability of trading draught at the various ports of call, including careful analysis of actual container weights.

4. Design considerations for large container ships

As described in our earlier papers to the Royal Institution of Naval Architects[1] and Boxship conferences[2,3,4], amongst others, scale economies have been - and will continue to be - the driving force behind larger container vessels. However, the actual maximum vessel size will be determined by the interplay between what can be constructed and propelled at the required speed and what can be handled effectively by the container terminals.

Maximum vessel size will be determined by:

- the ability of container terminals to physically berth the vessels;
- the capacity of the terminals to load and discharge these vessels within an acceptable timeframe; and,
- the capabilities of the terminals to deliver and despatch large consignments of containers - that is, the effectiveness of hinterland linkages.

These issues are discussed in detail in a Lloyd's Register Technical Association report[5]. To summarise the findings, it was concluded that the optimum next generation large container ship – for which we introduced the term "Ultra-Large Container Ship (ULCS)" will be configured as follows:

- LOA around 400m (Lpp = 381m).
- Breadth about 57m (22 boxes abreast on deck).
- Design draught 14.5m.
- Design speed between 23-25 knots depending upon powering considerations.
- Overall capacity 12,500 TEU.

The study also examined in some detail the structural design and manufacturing challenges associated with such large vessels. It was ascertained that, whilst special consideration will be required to address certain design issues, no insurmountable problems are anticipated. Similarly, propulsion options were examined and, while it was determined that propeller design will provide an upper bound on ship size or speed (rather than the availability of main engines capable of providing the large amount of power necessary) it will be possible to propel such vessels without excessive extrapolation from current experience.

These conclusions have, so far, stood the test of time. Terminal infra-structure developments have been very much as anticipated and, indeed, the first step towards the introduction of these new vessels – the step to 9,000 teu – has already been taken, and passed.

There have recently been a number of developments within the operational sphere which will influence the design parameters of future new tonnage and these are discussed below.

4.1 High cube containers

There is currently a clear trend towards the use of high cube containers [note]. In the UK about 29% of all containers handled today are high cube. About 55% of all 40′ containers handled are high cube; this is expected to increase to about 80% by the end of this decade. These figures are considered to be representative of the global position.

Given that approximately half of a container ship's capacity, in general terms, is carried below decks, it is apparent that future ship designs must be able to accommodate many high cube containers in the holds. The ULCS in the configuration with the bridge at approximately midships, Figure 4, has 45%

[note] Standard containers today are 8′ 6″ high, whereas high cube containers are 9′ 6″ high. Even higher containers (10′ 6″) have recently been proposed.

of the container capacity located below decks. If 50% capacity is to be high cube, then it is becoming increasingly beneficial to be able to carry large numbers of high cube containers in the holds.

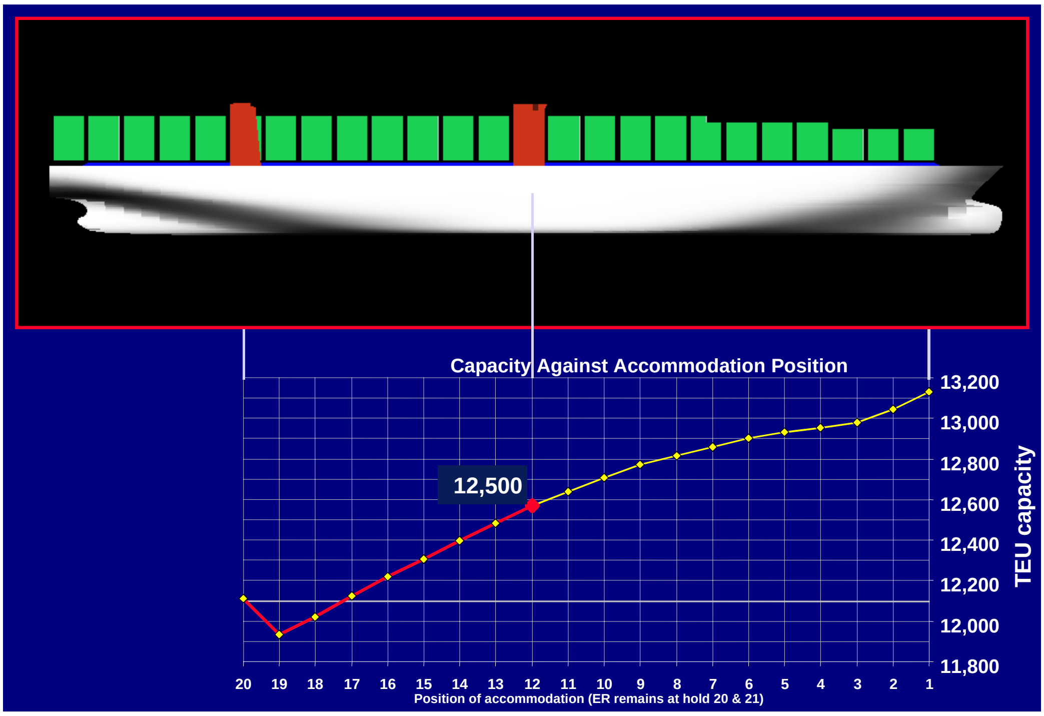


Figure 4 - Effect of Re-locating Superstructure

Our earlier material on ULCS container ships made an assumption throughout that future vessels would be designed to accommodate high cube containers in the holds as well as on deck [Ref.5, page 27]. The depth of the ship was calculated to accommodate the height of the double bottom (for the majority of container ships this is close to the minimum value specified in Lloyd's Register's Rules, i.e. 28B + 205√T) and nine tiers of high cube containers.

The high cube definition of capacity was not only used to determine the required depth of the hull. It also gives a better definition of the earning capability of the vessel. That is, high cubes (9′ 6″ high) may be 12% deeper than standard height (8′ 6″) containers, but does their earning capability increase in the same ratio? Not necessarily, so the high cube definition of capacity provides a conservative estimate of the profitability of these ships and therefore served the purpose of challenging the assessment of their viability. Further, consideration of the proportion of high cube containers carried also gives a more realistic estimation of the number of container lifts and hence the turn-around time in port.

In terms of the standard definition of "TEU", this means that the ULCS previously described as 12,500 teu could alternatively be defined as 12,500 x 9.5 ÷ 8.5 = 13,970 teu. This gives a consistent measure of the relative size of the vessels but, as described above, is not necessarily the best definition when calculating earning capability.

4.2 Forty-five foot containers

In the same way that there is a trend towards high cube containers, which if fully loaded can provide improved transport efficiency compared to standard height boxes, there is a similar (but less clear) trend towards the use of 45′ boxes.

Currently, with just a few exceptions, 45′ containers must be carried on deck. As the proportion of 45′ containers increases, it will be necessary to accommodate these in the cargo holds. This will be problematic for ship designers because it is difficult to envisage an in-hold securing arrangement which will readily accommodate 20′, 40′ and 45′ containers. The most likely approach is to dedicate certain container bays to 45′ containers only. This will represent a constraint on cargo planning.

An interim solution is to construct vessels with some bays designed for 45′ containers, but to fit buttresses for the carriage of 40′, and 20′, containers. These buttresses can be removed once the trend to 45′ containers has developed sufficiently to necessitate their carriage in the holds.

4.3 Trading draught

A significant change has occurred in recent years in the draughts at which large container ships are trading.

In 1999-2000, when the first phase of the ULCS study was underway, it was common for ships to sail close to their design draughts, typically 14.5m. For the Asia-Europe trades a typical scenario would be:

Head haul	Singapore – Rotterdam	85% design draught	Cargo weight	97,100	tonne
Back haul	Rotterdam – Singapore	94% design draught	Cargo weight	118,300	tonne

Thus, the back haul leg was sailed at a deeper draught than the head-haul. This apparent anomaly was caused by the imbalance in the east-west container trades. Whereas westbound the ships carry a full compliment of lightly loaded containers, on the return journey they must carry a large number of empties. Thus the carriage of low value cargoes such as scrap steel is cost-effective eastbound. These low value cargoes tend to be heavy, which results in the deeper draught on the eastbound leg.

However, the position has now changed. A detailed review of the cargo weights associated with the deployment of ULCS tonnage on the key trade between Asia and North Europe, utilising actual voyage data, has allowed a true picture to be defined of the current container cargo weights and the ratio of empty to loaded containers. The review has identified a significant change in trading draughts between Asia and Europe. Two effects have become apparent:

- There are insufficient containers in Asia, so in some circumstances it is more cost-effective to carry empty containers to Asia, rather than risk running out of available boxes for the westbound leg.
- There is insufficient low value cargo to fill the ever-increasing number of empty boxes being returned to Asia.

The latest position may be summarised as follows:

Head haul	Singapore – Rotterdam	86% design draught	Cargo weight	100,200	tonne
Back haul	Rotterdam – Singapore	83% design draught	Cargo weight	92,000	tonne

The position has therefore reversed; the head-haul is now at the deeper draught. Furthermore, whereas the vessels were spending a high proportion of their time at sea at a draught of 94% design draught, the deepest draught at which they spend a high proportion of their time at sea is now only 86% design draught. We thus have a situation where:

- there is a much greater difference between the design draught and the draught at which the ship spends most of its life sailing, and
- the difference in draught between the eastbound and westbound legs has reduced from 9% to 3%.

These developments beg the question is this trend likely to intensify further? It is difficult to say, but there is little to suggest globalisation will be slowed or reversed. On this basis, it is prudent to assume that these balances will be typical for the future, as there are simply insufficient low value, high weight products to be positioned from Europe to Asia. The structural imbalance will continue over the forecast period and continue to result in actual draughts being significantly lower than design draughts.

Phase I of the ULCS study determined that most of the major container terminals could accommodate vessels at a draught of 14.5m.

Phase II considered three conditions:

- A "powering" condition (deep draught condition typical for Europe-Asia leg). T = 13.8m
- A "light" condition (lighter draught condition typical for Asia-Europe leg, particular consideration of propeller cavitation). T = 12.65m
- A "deep" condition (maximum trading draught). T = 14.5m

Phase III has now taken cognisance of the recent developments in the container trades. It is apparent that the changes in trading draughts create an opportunity to re-consider the design conditions. If the main terminals can still accommodate 14.5m maximum, which is still generally the case, there is an opportunity to take this as the principal trading draught and increase the design draught to a somewhat greater value.

On the basis of the latest container weights, etc, the phase III conditions are therefore:

- "powering" condition T = 13.5m
- "light" condition T = 13.0m
- "deep" condition T = 15.0m

As the trading draught remains the same, so the block coefficient can reduce. Thus, hull resistance is reduced and propeller design is simplified. Detailed calculations of hull resistance and propeller design[6] indicate that, in this way, a single screw 12,500 teu capacity ULCS trading at 25 knots is now feasible.

The principal parameters for a 12,500 teu ULCS are as follows:

Length between perpendiculars L_{pp}	381.0	m
Length along the waterline L_{wl}	384.0	m
Moulded Breadth B(mld)	57.0	m
Design Draught T_{des}	15.0	m
Block coefficient at T_{des}	0.630	
Waterplane Area Coefficient at T_{des}	0.786	
Block coefficient at T=13.5m	0.613	
Waterplane Area Coefficient at T=13.5m	0.75	
Shaft Power at T=13.5m, 25 knots	67.3	MW
(15% sea margin)	90	rpm
Engine Power at T=13.5m, 25 knots	79	MW
(based on 85% mcr)	(14 cylinders)	

5. Technical challenges

Growth in ship size may bring with it economic benefits for the shipowner, but it also creates technical challenges for designers, builders and class.

Lloyd's Register has been working closely with major shipbuilders over the years to address the technical challenges posed by large container ships. These ships are driven by some of the most powerful marine diesel engines in service today, and the engines themselves are growing larger to maintain the service speed of 25 knots demanded by today's liner trades. The reliability of these installations is of utmost importance to the operator, whose clients expect delivery of their goods on time, every time.

5.1 Hull girder strength

Achieving the necessary hull girder strength has always been challenging for container ship designers. Being fine form ships, container ships always hog and, as they have very little upper deck area, they are flexible in torsion.

Torsional stiffness can be provided by two means:

- increasing the 'enclosed area' of the hull cross-section, thereby increasing the St Venant torsional stiffness;
- increasing the warping stiffness of the hull.

For a container ship, the latter is the most effective method, so both torsional and bending strength requirements lead to the same structural arrangement – heavy scantlings in the topside area.

The upper deck and side coamings of a modern large container ship may be fabricated from steel as thick as 100 mm; the yield strength will likely also be higher than most other types of ship, with some designs employing steels with a yield strength of 390 N/mm^2.

These scantlings are becoming a challenge for shipbuilders, and steel mills. Steel scantlings are close to the upper practical limit. The heavy scantlings are being driven by two key factors:

- Hull depth is fixed by the height of container stacks in the holds. This has reached an upper limit because, without intermediate supports for the container stacks, the collapse strength of the containers has been reached. Therefore, the depth of new, larger container ship designs remains constant irrespective of capacity, Figure 5.
- Increased hull depth increases tonnage, and this increases operating costs.

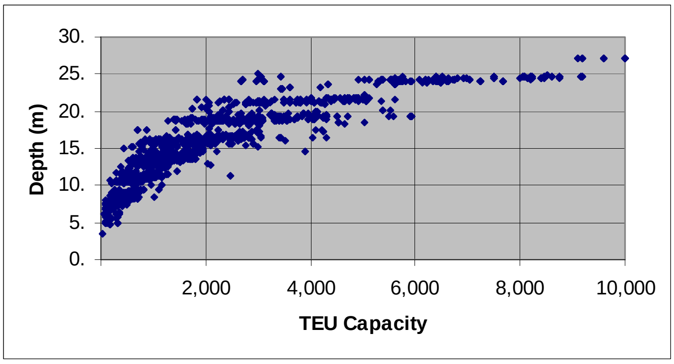


Figure 5 – Relationship between TEU capacity and hull depth

Fortunately, the increasing number of high cube containers which these vessels are required to carry will necessitate an increase in hull depth. The increased revenue should compensate for the costs associated with increased tonnage. It would seem, therefore, that the push for ever thicker and ever stronger topside structure may not apply to future designs. If so, this will certainly be welcomed by shipbuilders, who are challenged to source and fabricate the steels which are being used today.

The increasing number of 45′ containers will present a particular challenge for ship designers. As indicated above, it will probably be necessary for future container ship designs to be arranged with a number of holds which are 45′ long.

45′ containers may be accommodated in two ways, either by reducing the number of holds so as to keep the hull length the same, or by increasing ship length.

The first solution could be achieved by removing nine 40′ cargo bays and introducing eight 45′ bays. This, in approximate terms, will keep the ship length the same. As the surge loads on the transverse bulkheads are likely to be greater (assuming 45′ containers will be heavier than 40′ containers) the fore and aft width of the cross-deck strips will need to increase, but this will have a small effect on the overall length of the ship. The loss of one container bay will, or course, lead to a loss of revenue.

The preferred solution may be to lengthen some of the cargo holds and thus increase the length of the ship. However, if say, eight bays are lengthened, this will necessitate an increase of about 7% in the hull girder midship section modulus to accommodate the consequential increase in still water bending moment and wave bending moment. If hull depth is not increased, this will require topside scantlings to be heavier, by about 10mm. As scantlings are already approaching the upper limit of what can be constructed, this may be too much and an alternative solution should be sought. Fortunately increasing hull depth, which may become necessary to accommodate high cube containers, is a satisfactory method for achieving the required strength.

5.2 Hydrodynamic loads

The high speed and hence the fine hull form of these ships presents challenges which are quite different from other, slower ship types. For many vessel types, the passage of waves past the ship has an effect on the hull which is quite readily calculated. However, the passage of even a wave of modest size along a container ship can result in the stern counter going in and out of the water which, mathematically speaking, is far more complex.

Similarly, the pronounced bow flare required to maximise the deck stow forward results in a much greater change of buoyancy than a wall-sided section would exhibit. It is apparent, therefore, that comprehensive analysis of the interaction between the ship, its motions and the wave environment in which it is operating is required. The use of sophisticated, nonlinear analytical techniques is required to help ensure that these interactions are adequately represented.

A programme of full-scale measurements currently underway will help us to verify that the mathematical methods adequately represent the actual dynamic loads experienced by the hull.

5.3 Design and construction

Design and construction must be executed with great care to ensure reliable service. Lloyd’s Register uses advanced mathematical modelling techniques to represent the structural response of large container ship hulls, encompassed by the procedures within ShipRight SDA (structural design assessment) and FDA (fatigue design assessment). This detailed examination is followed by the application of our ShipRight CM (construction monitoring) procedure to ensure that the most critical details are fabricated in accordance with our detail design and construction standards.

5.4 Rudder design for large container ships

Analysis and testing of proposed rudder designs using advanced scale model and computational fluid dynamic techniques is required to ensure that rudder erosion or failure are prevented, especially for the new generation of larger container ships.

When high power and speed are defined for a ship propulsion solution, careful attention to the rudder design is essential if a continuing series of cavitation erosion problems is to be avoided. Cavitation erosion also facilitates several forms of corrosion attack which tend to compound the problem. This situation is particularly true for large container ships where attention to the rudder profile and detail of design are paramount.

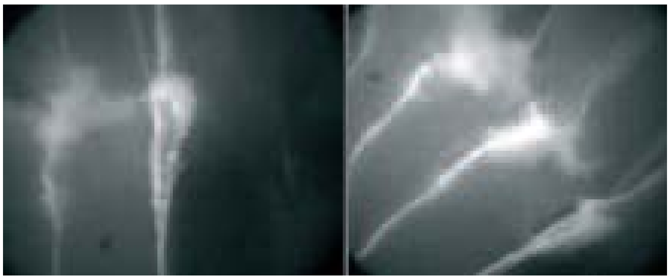


Figure 6 - Propeller cavitation (Courtesy EROCAV)

Because the rudder operates in a combination of the helicoidal flow field produced by the propeller and the ship's boundary layer, the incident flow presented to the rudder has a strong rotational component, as evidenced by the behaviour of the propeller blade tip vortices (see Figure 6). In general, the rudder tends to distort the flow field such that the slipstream generated by the propeller normally rises up the leading edge of the rudder by a small amount. Within this complex flow field, data collected from a large container ship investigated within the European Union's EROCAV (Erosion on Ship Propeller and Rudders - The Influence of Cavitation on Material Damages) project (see Figure 6), in which Lloyd's Register was a member as part of its continuing commitment to research, shows that the vortex interacts with the supercavitating sheet cavitation, causing it to be twisted violently and thrown outwards and forwards from the vortex core.

Partial ring vortices can also be produced in the direction of the twisting motion. In this process the off-blade sheet cavity volume reduces significantly, leaving a fine residue of vapour mist. The tip vortex can also reduce in volume but, in Lloyd's Register's experience based on a number of full-scale studies, the cavitating vortex generally remains in the flow field, although in a weaker form, as it is convected towards the rudder leading edge when it undergoes a number of significant changes due to the pressure field of the rudder.

While the presence of cavitation does not necessarily imply erosion, it is true that many rudders fitted to large container ships experience erosion. Frequently, attempts have been made to attenuate the erosive effects of cavitation by fitting stainless steel or stellite armour to the rudder and horn, particularly in the leading edge regions but also on other parts of the rudder. Such attempts, however, have often met with only partial success and have required continuous maintenance during the service life of the ship.

To achieve an acceptable solution for high-powered ships a careful design strategy comprising elements of computation and model testing should be implemented. Such a strategy might involve the measurement of the rudder incident flow field generated by the propeller and the ship's boundary layer, recognising that this latter flow field component will require some modification from model scale values due to the significant scale effects present on large container ships.

In the case of the gap interfaces between the horn and blade, very careful attention to these details both at the design and rudder fabrication stages are necessary. Care should especially be taken during fabrication to ensure that the design intent is achieved because design tolerances are small in these types of flow conditions. Such considerations will normally result in a unique specification for the design for each ship, which may include the incorporation of scissor and deflector plates to provide protection in or near gap regions, the advised use of profile curvature and, on occasions, the deployment of vortex generators. Within this context, large-scale model cavitation tests, centring particularly on the mid-region of the rudder so as to minimise scale effects, have been found to be a particularly valuable aid to design.

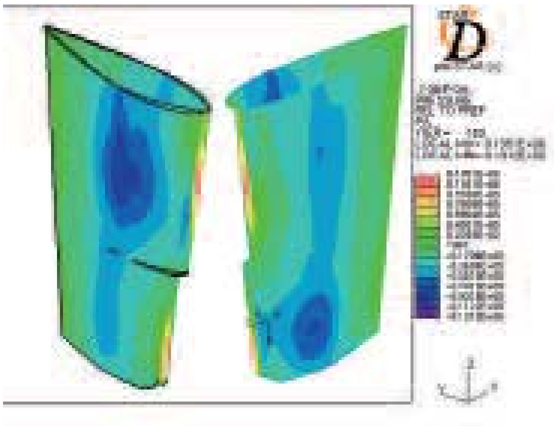


Figure 7 - CFD dynamic pressure analysis on container ship rudder

Clearly, one alternative to the conventional rudder horn-blade configuration is the use of the variable geometry spade rudder concept. This design option allows, in a mean flow sense, for the rotational characteristic of the incident flow from the propeller. Furthermore, computational fluid dynamic studies have shown good correlation between the predicted actuating torques and bearing bending moments and side forces with the results of model tests. Figure 7 illustrates a typical pressure distribution around a spade rudder at a given operating condition for a large container ship.

Notwithstanding this, and recognising that computational fluid dynamics can provide both a valuable design aid and insights into flow phenomena that can be used in combination with other techniques, such as model testing and direct calculation methods, care must be exercised in not taking the technique too far beyond the range of correlation, since significant errors may result in the predictions which are often attributable to turbulence modelling.

5.5 Achieving low-sulphur container operations

Regulations 14 and 18 of MARPOL Annex VI and the coming into force of so-called sulphur emission control areas (SECA) will have a profound impact on container ship operations.

The regulations came into effect on May 19, 2005, applying to all ships of 400 gt or above. They set limits on the sulphur content of marine fuel and require that certain procedures are followed during its delivery.

Regulation 14 addresses the mechanisms for controlling sulphur oxide (SOx) emissions from ships and sets a global cap of 4.5% m/m on the sulphur content of all marine fuels.

Regulation 18 covers issues relating to fuel quality, sampling and delivery.

The current average sulphur content of a residual marine fuel is approximately 2.7% m/m, and so compliance with Regulations 14 and 18 will cause few difficulties in many cases, provided that the statutory procedures are followed. However, the full impact of the Regulations will be felt on May 19, 2006, when the Baltic Sea becomes the first SECA.

In a SECA, the maximum fuel sulphur content permitted will be much lower than the global limit: under Regulation 14 it will not be allowed to exceed 1.5% m/m unless an exhaust gas cleaning or other abatement system is installed to reduce emissions to a maximum of 6g SOx/kWh. Further SECAs will be introduced in the future, and it is expected that the North Sea and English Channel will become SECAs around November 2007.

A number of options are now or will be available to vessels in order to ensure that they comply with the more restrictive requirements within SECAs. These are described in more detail in Lloyd's Register's *Container Ship Focus* magazine[7]. For container ships the most likely option is to carry both high- and low-sulphur fuel and allocate segregated tanks. Most container ships have sufficient storage tanks to reserve one, or possibly two, specifically for low-sulphur SECA operations. For those ships on global routes, the passage time through a SECA may be just a few days. The necessary fuel changeover procedures are unfamiliar to today's crews but easily taught once clear, ship-specific guidelines are documented.

For newbuildings, the number and layout of storage tanks need to be considered carefully to provide sufficient flexibility for trading through SECAs and other environmentally restricted areas. In years to come, more SECAs will be established and ships built with SECA flexibility will therefore have greater saleability. Ideally, there should be two service and settling tanks and two cylinder oil storage tanks, along with one or more storage tanks allocated for low-sulphur fuels. For even greater flexibility, consideration should be given to holding low- and higher-sulphur marine gas oils as these, too, will be subject to limits as a result of EU and US national restrictions on vessels in port areas.

The technical implications of using a low-sulphur fuel will depend on the particular machinery plant. As a rule, operators should approach their machinery manufacturers for advice in moving from high- to low-sulphur fuel operations, and Lloyd's Register's fuel oil and bunker analysis and advisory service (FOBAS) is able to provide independent engineering advice on fuel quality and Annex VI compliance issues.

6. Conclusions

During the past 40 years the size of container ships has increased substantially, in response to the demand for greater fleet capacity and improved economy.

In the last few years the size of the largest ships has increased dramatically. In 1996 A P Møller brought the world's first post-6,000 teu container ship into service. Today, just 10 years later, there are ships in service with capacities greater than 8,000 teu, others building with capacities of 10,000 teu and there are designs being developed with capacities of 12,000 teu and more. Lloyd's Register is pleased to have been, and to continue to be, at the forefront of the introduction of these new vessels.

Development work by Lloyd's Register, which includes the ULCS phase III study, confirms the viability, both technical and economic, of these new large container ships and concludes that the quayside facilities at the major container terminals will be able to handle these ships within manageable turn-around times. It remains our view that ULCS vessels will be in service by the end of this decade.

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7. References

[1] Tozer, D.R. and Penfold, A. "Container Ships: Design Aspects of Larger Vessels", Lloyd's Register and Ocean Shipping Consultants Ltd., RINA/IMarE Presentation, London, March 2000.

[2] Tozer, D.R. and Penfold, A. "Ultra-Large Container Ships: Designing to the Limit of Current and Projected Terminal Infrastructure Capabilities", Lloyd's Register and Ocean Shipping Consultants Ltd, Proceedings of "Boxship 2001 – Future evolution of the containership", London, May 2001.

[3] Tozer, D.R. and Penfold, A. "A Review of Prospects for Ultra-large Container Ships and Implications for the Support Fleet", Boxship 2003, London, October 2003.

[4] Tozer, D.R. "Design Challenges of Large Container Ships", Boxship 2005, Hamburg, September 2005.

[5] Tozer, D.R. and Penfold, A. "Ultra-Large Container Ships (ULCS): designing to the limit of current and projected terminal infrastructure capabilities", Lloyd's Register Technical Association Paper No.5, Session 2001-2002.

[6] Carlton, J. S. "The Propulsion of a 12500 teu Container Ship", Lloyd's Register, Proceedings of the Institute of Marine Engineering, Science and Technology, January 2006.

[7] "Container Ship Focus" magazine, Issue 1, Lloyd's Register, August 2005.

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9. Author Biography

David Tozer trained with the Royal Corps of Naval Constructors before moving to Newcastle to work for BSRA, where his work in the structural analysis group included studies of the *Kurdistan* and *Derbyshire*. When he joined Lloyd's Register in 1984, he was involved in development of torsional analysis procedures and software. He was also a member of the team which studied the "long thin/short fat" warship hull design inquiry. After 5 years he transferred to Class Computational Services and, until autumn 2001, worked in the Dry Cargo/Ship Structures group where his primary responsibility was the design appraisal of container ships. He is now Lloyd's Register Business Manager for Container Ships. David is married with two children.