The Inaugural Keppel Lecture held at the
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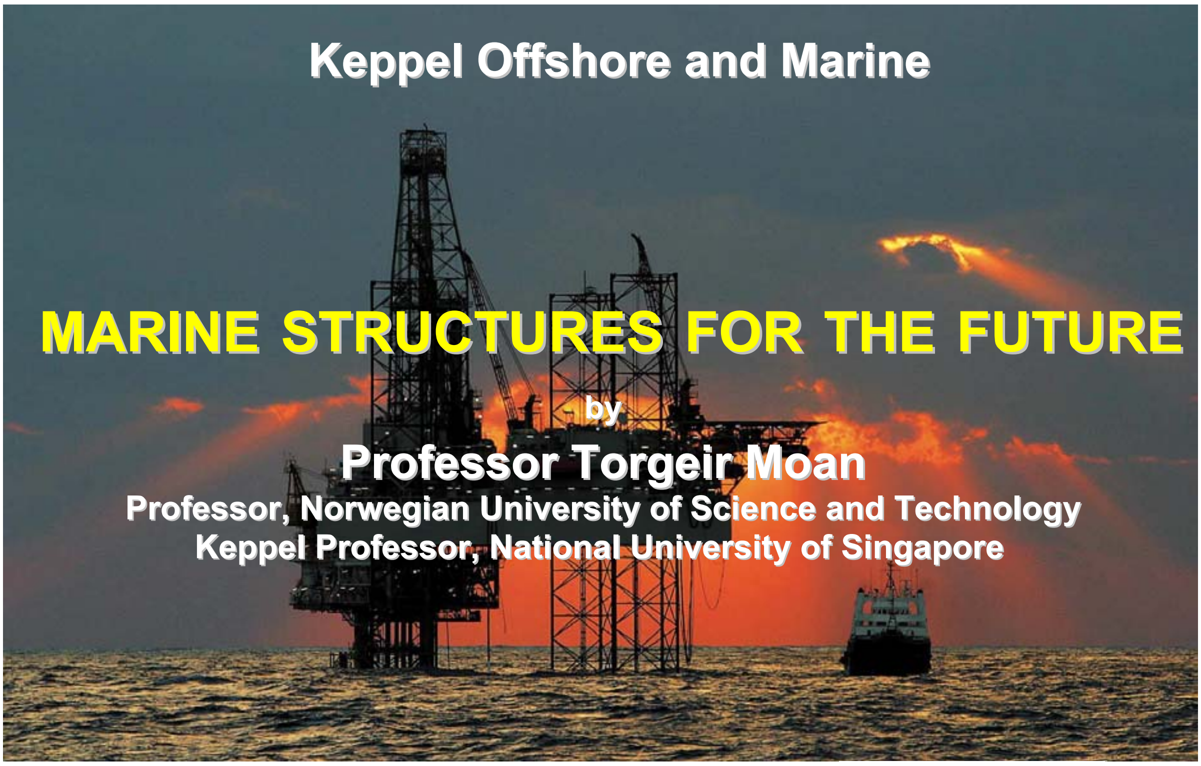

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Marine Structures for the Future – a Sea of Opportunities

Torgeir Moan, Centre for Ships and Ocean Structures
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
E-mail: tormo@marin.ntnu.no

Summary

This paper describes current trends and expected future changes regarding design, fabrication and operation of marine structures. Such structures would be needed for ocean transport, exploitation of subsea hydrocarbons and wave energy, sea food production as well as for marine infrastructure. The main purpose of this paper is to demonstrate the sea of opportunities that exists for developing new structures and operational procedures, for rational methods to handle new technology as well as the corresponding needs for research and development.

1 Introduction

We live in the blue planet (Fig. 1). About seventy percent of the earth's surface is covered by oceans, which have a vital function for the life on earth.

Fig. 1 Photo of the blue planet from Apollo. December 1972

Fig. 2 A sea of opportunities for developing marine structures

The oceans contribute to food, energy as well as mineral resources and provide means for transport and other infra- structure. Moreover, hydrocarbons are produced from sub-sea reservoirs. The ocean also plays a strategic role and they will play an increasing role for recreation. There is truly a sea of opportunities. For all these purposes indicated in Fig. 2 we need vehicles and facilities.

In this paper the opportunities for transport, energy, food and more – that the sea offer, are first described. Then some trends with regard to design are outlined. In particular design targets such as safety and serviceability during operation and producability are emphasized. An important issue in this connection is how we can stay competitive by employing enabling technologies as well as generally using competence-intensive technology.

Finally the different marine segments are described by identifying technology trends and focus areas in research and development.

The variety of industrial activities relating to the sea calls for marine structures with different functions, and hence different layouts. Fig. 3 shows a sketch of some structures for various functions. The variety of shapes and sizes clearly show the sea of opportunities for innovation.

Fig. 4 illustrates how food and energy as well as transport services and other benefits result from an integrated effort based upon technology, science and management. Commercial success fundamentally depends on economic, management and organizational excellence. However, in the present paper the focus will be on technology, and especially marine technology. The success of marine technology in the future requires exploration and implementation of relevant enabling technologies such as information & communication technology, automatic control, materials & fabrication as well as logistics. By utilizing enabling technologies the added value of the product is increased and it is made more competitive.

Fig. 3 A variety of marine structures

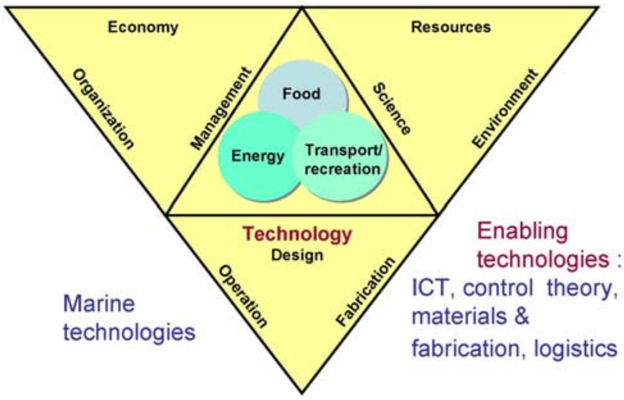


Fig. 4 Knowledge based maritime activities

2 Structural life cycles

2.1 Design targets

The life cycle of marine systems is similar to that of other systems. The main phases are design, fabrication and operation (Fig. 5). However, in view of the ecological issue, removal- or clean-up need to be considered. In this connection, reuse of the material becomes an important issue.

In the recent years emphasis is placed on the total life cycle – for instance in terms of energy use (ISO 14040, 1997) as well as the total costs. This includes the life cycle assessment (LCA) of environmental issues as well as life cycle cost analyses (LCC) of the total costs.

Moreover, the life cycle consideration also emphasizes design as the crucial life cycle phase in which important decisions can be made regarding :

- fabrication method

- serviceability during operation
- safety during operation

In the design phase the optimal choice of layout, materials and equipment are to be made, based on fulfillment of requirements with regard to serviceability and safety (Fig. 6).

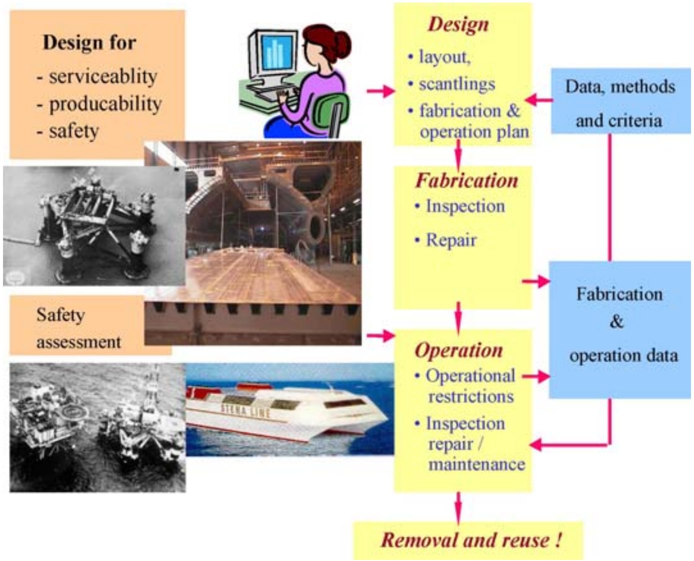


Fig. 5 Life cycle phases of marine structures

For ships used for transport, ease of loading/unloading in ports, low resistance in order to limit power requirement, are important requirements. Thus, the overall hull form is commonly determined by transport economics.

An oil production facility, such as the production ship shown in Fig. 6, is receiving oil and gas through pipes (risers) from the seafloor. These risers are truly the umbilical chords of the offshore production system. On the production ship the hydrocarbons are processed and exported through pipes. Efficient production of hydrocarbons requires among other properties, structures with proper payload capacity and deck area, limited motions and station-keeping to avoid damage to risers.

The most important safety requirements for ships and floating platforms refer to avoidance of capsizing of sinking and structural failure. Ultimately such failure modes can cause fatalities, pollution or loss of property. These issues may be illustrated by two accidents. On 6 March 1987 the Ferry Herald of Free Enterprise sank in the British Channel after flooding through an open loading door in the bow. The accident resulted in capsizing, as shown in Fig. 7.

The platform P-36 in Brazil experienced a burst collapse of the emergency drainage tank, followed by an accidental explosion in a column. The resulting damage caused flooding and finally capsizing and sinking 6 days later (Petrobras and Coppe 2001). A series of operational errors were identified as the main cause of the first event and also the sinking.

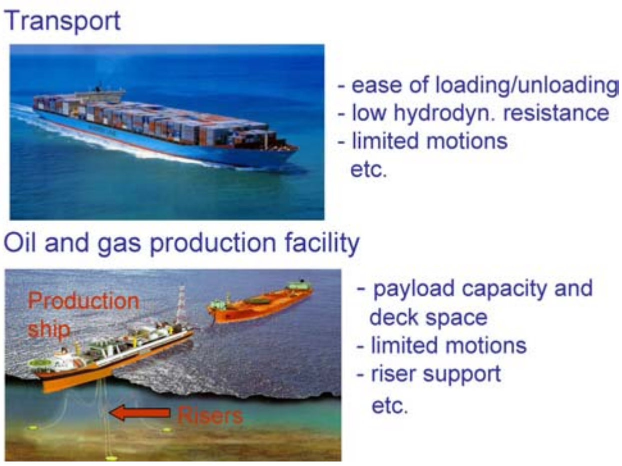


Fig. 6 Design for functionality or serviceability

Fig. 7 Design for safety

A common feature of these two accidents and actually 90% of accidents is the contribution of human errors to the accidents. Operational errors are the primary causes of accidental events such as explosions, fires, and ship impacts. Also contributing to accidents is the failure to comply with operational restrictions assumed during design. In addition, the occurrence of design and fabrication errors could cause a deficiency in strength. Hence, to achieve safety, it is crucial to avoid errors in design, fabrication and operation. Primarily it is important to avoid errors by those who do the work in the first place. Secondly efficient QA/QC procedures should be developed and implemented for all cycle phases. In addition, the structural system should be designed as a robust system, i.e. to ensure that a small damage caused by fabrication defect or accidental loads such as fires, explosions and ship impacts during operation, does not escalate to catastrophic events (Moan 1994). This implies design for robustness, as described later.

Risk assessment (Qualitative Risk assessment, Formal Safety Analysis etc.) is a tool to support decision regarding the safety of systems. The application of risk assessment has evolved over 20 years in the offshore industry and within the last 5 years in the marine industry, albeit in different directions. The offshore industry has focused on the application of risk assessment to evaluate the safety of individual offshore facilities. The maritime industry has primarily focused on the application of risk assessment to further enhance and bring greater clarity to the international rule making process (Moore *et al*. 2003).

To achieve competitive fabrication costs, design for producability is also crucial (Fig. 8). This especially implies designing the structure and outfitting with a simple geometry. Moreover, the structure should be built up by repeatable modules to facilitate parallel production and cost saving by achieving the benefit of serial production.

Another issue is the design for automated fabrication by exploiting of new joining technologies such as laser welding etc. Some yards in Europe have survived because they have been successful in this respect (Wilckens *et al*. 2003).

Fabrication of marine structures is often characterized by short-series productions, often one-of-its kind; some of the largest made-made structures on earth as well as severe environmental restrictions to comply with.

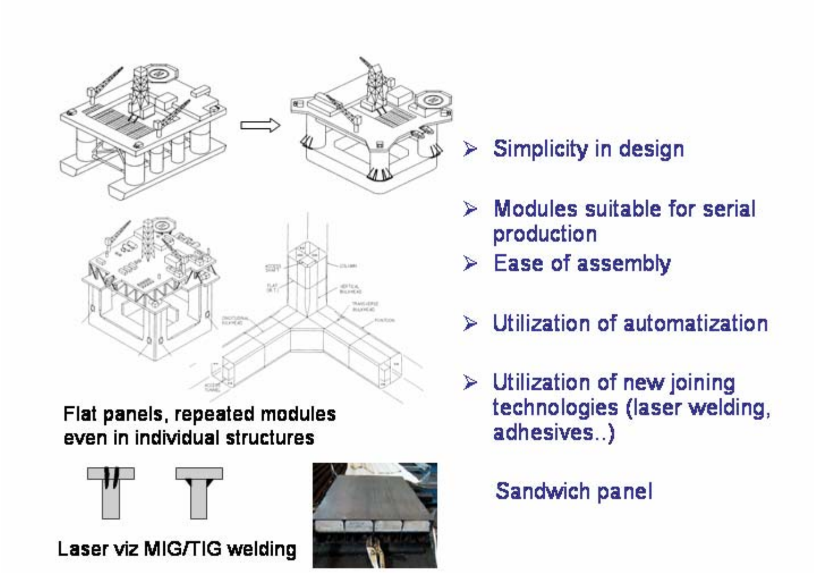


Fig. 8 Design for producability – as exemplified for platforms

Yet, the maritime industry needs to:

- Act in a very competitive market and subsequently reducing costs.
- Deliver within short times.
- Adopt a high level of quality instance.
- Use ultimate production techniques (JIT, automation, robotics).
- Design environment-friendly products (low emission of fuel cell engines, reduced sinking risks).
- Deal with scientific and technological innovation.
- Introduce ultimate technology on board (propulsion, navigation, passengers comfort).

This goal can only be achieved if powerful processes and tools are used for design, production and planning/logistics. These processes have to be integrated or linked together and must rely on computer tools to allow efficiency, speed and reliability.

The fact that the production series are short, excludes the possibility of making prototypes used e.g. in the automobile and aerospace industries. The prototypes integrate and illuminate a number of different aspects that enhances system reliability (e.g. identification of locations susceptible to cracks, production factors, operability). The advantage of prototyping is rarely encountered in marine design with the possible exception of specialized naval vessels such as the trimaran frigates and surface effect ships.

The shipyard is also becoming increasingly "digital" by utilizing methods for integrating product and production information. New embedded production logistic systems reduce costs and error potentials. The “Total” solution approach can result in production process and production plant improvements. Substantial further research seems to be necessary in order to harvest the possibilities available (Pradillon *et al.* 2003).

A generic technology that increasingly provides new opportunities for innovative marine structures is materials technology. The main structural materials currently used, are steels, especially HTS and aluminium (Fig. 9).

Titanium and fibre-reinforced plastics are applied for specialized application in the offshore and high speed/passenger ship field, respectively (Wilckens *et al*. 2003).

An important issue in connection with new materials is the joining technology. While metal structures are traditionally joined by TIG or MIG welding, the use of particular welding techniques like laser and friction stir welding might offer particular advantages. Also the use of adhesives is common for FRP, and is also explored for aluminium and even steel structures.

High strength steels offer interesting opportunities for marine structures, but their applicability will be limited by the fact that the fatigue strength of welded joints does not increase with the higher static (yield) strength. Laser welding has made it possible to fabricate steel sandwich panels that it has improved fabrication efficiency.

Aluminium and FRP are currently used for instance in high speed crafts. The objective is then to utilize the low density and yet high strength to achieve weight reduction and therefore smaller hydrodynamics resistance and energy use. Moreover, lightweight materials are used in the upper deck levels of passenger vessels and offshore platforms, to improve stability or payload capacity. Aluminium offers particular advantages with respect to fabrication, that to some extent compensate its higher material costs. For instance, the stiffened aluminium panel in Fig. 10 is built-up by extruded box-stiffeners which are joined by friction stir welding. The implication is less welding as well as less weld-induced deformations than by using conventional procedures. The only longitudinal welds in the stiffened panels in Fig. 10 are in the middle, between boxes, as indicated by the arrows.

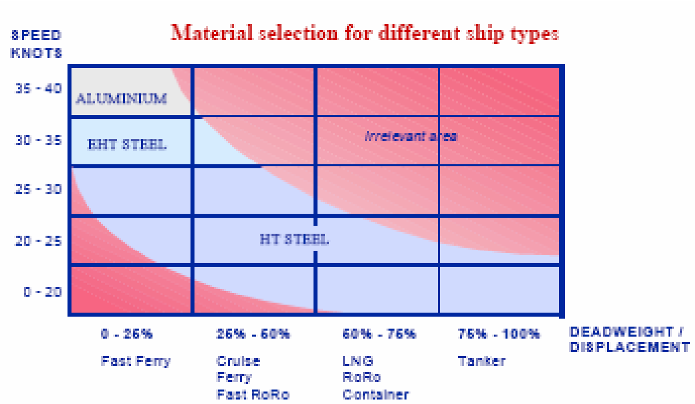


Fig. 9 Strategic use of materials to obtain weight and cost saving – as exemplified for ships

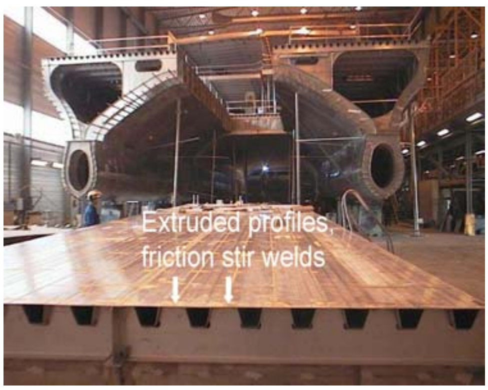


Fig. 10 Fabrication of high speed craft by using extended panels joined by friction stir welding

It is of interest to look at the trends in fabrication of marine structures at large. Fig. 11 shows the fabrication of ships as an example. This diagram shows the relative volume (tonnage) share of shipbuilding in different countries over the last 80 years. We notice that UK and Europe were dominant until 1950s, with an exception for the Second World War, when USA dominated. Then, Japan became an increasingly more important player, and managed well until the decline started in mid-1980s, and South Korea started its rapid development. We also notice the increasing importance of China.

To explain these trends we have to revert to labour costs, automatization efforts and development of specialized products. Japan managed to extend their role as a key yard industry by significant automatization efforts. By extrapolating the trend in the 1960s and 1970s for Europe, shipbuilding should have been dead by early 1990s, but it continues to be competitive by adding value to special ship products by using laser welded panels etc. Probably the picture is more flattering if the value, not the volume of the ship production, is considered.

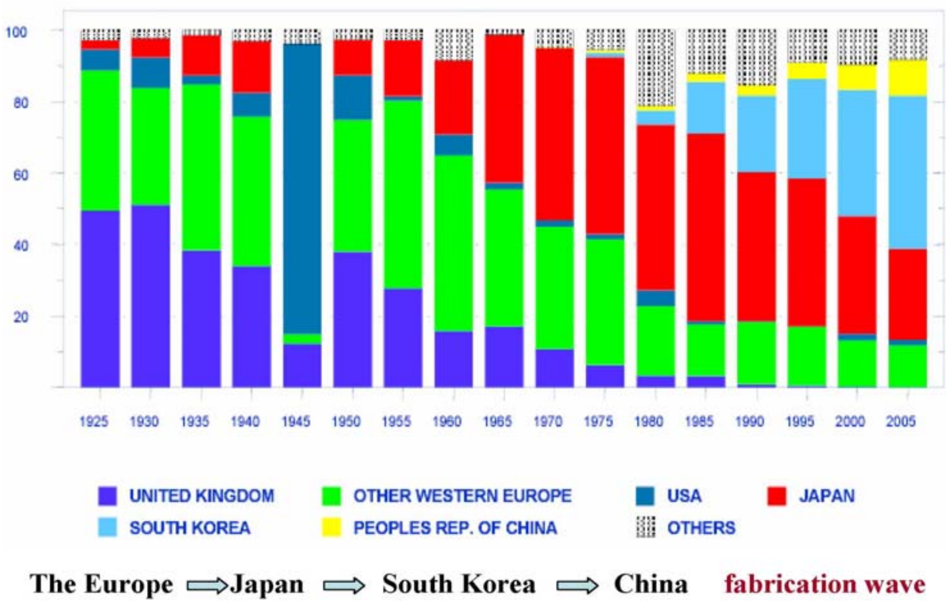


Fig. 11 Historical development of production volume of ships by country

2.2 Design criteria

Naval architecture is an old engineering field. Empiricism has been a characteristic feature of the field until a few decades ago. Such empiricism based on prescriptive "rule-book" approaches, can only be extended to new problems in small steps. It is difficult to extend such knowledge to innovative designs. Fortunately, offshore developments in particular in the recent decades have contributed to more rational approaches – by analysis for design of marine structures.

Design by first principles requires explicit criteria for serviceability and safety. Structural safety is ensured in terms of load effects and strength depending upon relevant failure modes, also denoted limit states. For marine structures, limit state criteria should include: ultimate (ULS); fatigue (FLS) as well as accidental collapse limit state (ALS) relates to ultimate failure of the overall structure, caused by some initial damage, typically by accidental loads or deficient strength (Fig. 12).

Current strength criteria are not based on truly (ULS) criteria, i.e. they are based on elastic buckling with some plastic correction factor.

Moreover, until recently explicit fatigue calculations were rare: adequate fatigue strength was achieved implicitly by the allowable stress checks based on static strength and extreme loads. To combine two basic design criteria does not allow optimal material usage and design.

A rational design approach should be based on:

- Goal-setting; not prescriptive
- Probabilistic; not deterministic
- First principles; not purely experimental
- Integrated total; not separately
- Balance of safety elements; not hardware

This is particularly the case for high speed crafts. For such vessels the requirement of serviceability is high speed and low energy consumption and implies a lightweight, minimal structure while operational hazards (collisions, grounding and severe wave loading) imply a robust structure (Moan 2003).

The overall aim of structural design should be to reach an agreed acceptable safety level by appropriate probabilistic definitions of loads, and resistance as well as safety factors. Such criteria should be verified by reliability and risk approaches.

While ULS and FLS criteria are well established, ALS criteria represent a novel safety approach for structural strength, even though this principle has existed for a long time with respect to damage stability criteria. In the same way as the vessel should be able to survive damage without sinking or capsizing, it should not suffer global loss of structural integrity. Hence, the ALS approach should also cover accidental conditions associated with structural integrity (Fig. 13).

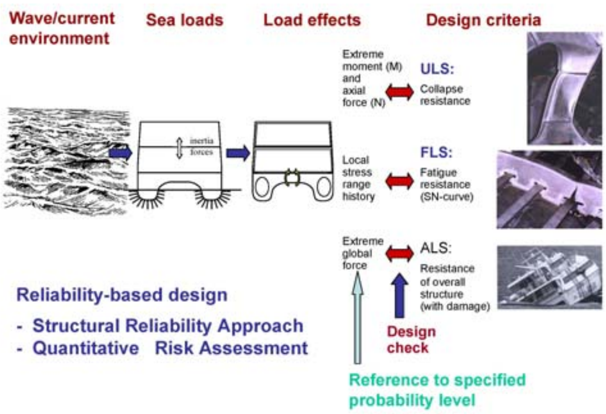


Fig. 12. Structural design based on direct analysis of load effects and strength

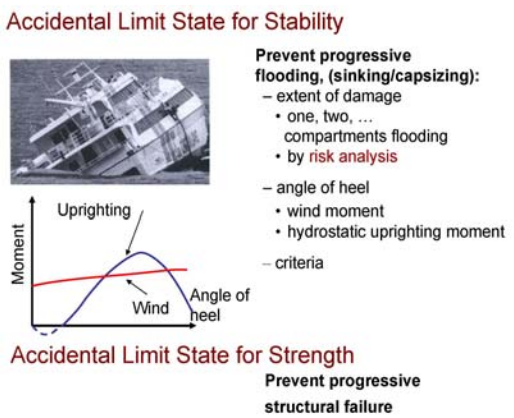


Fig. 13. Accidental limit state criteria for stability and strength

An important aspect of this development is the use of competence intensive technology based for instance on information and materials technology to its full extent.

An important issue in modern design practice is to predict how ships and other marine structures move and are stressed under the action of waves, as well as their stability and structural strength in chaotic waves and other conditions. Fig. 14 illustrates that in-service experiences, experiments and theoretical approaches need to be utilized to the full extent in this connection.

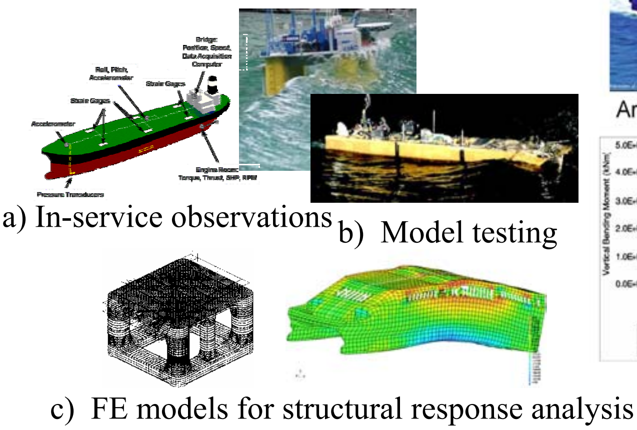


Fig. 14 Theoretical and experimental basis for design with respect to seaworthiness

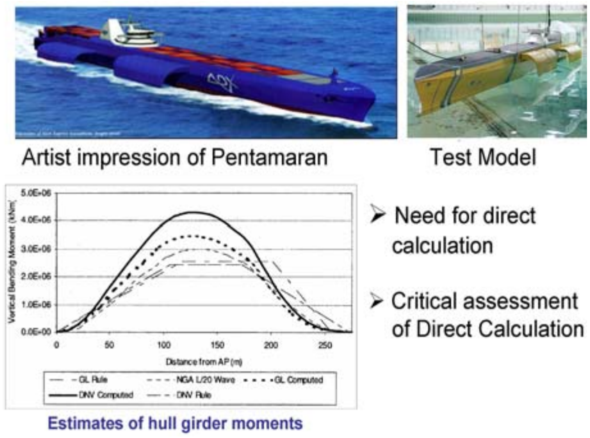


Fig. 15 Global wave loading on a pentamaran (Dudson *et al*. 2001)

As a more specific example, consider the wave loading on a novel type of ship, namely the pentamaran as shown in Fig. 15. It is seen that the conventional Rule-book formula underestimates the loading estimated by direct calculation and verified by model tests (Dudson *et al*. 2001).

Hence, direct calculations should obviously be made for new concepts , especially when the structural response involve springing or whipping. This is because such phenomena depend upon the structural dynamic properties of the vessel they are not yet included in simplified Rule-book formula. But the discrepancy between different approaches is also noted. This fact suggests a critical evaluation of methods for direct calculation of load effects.

2.3 Research and development

Research and development play an important role in establishing methods and tools for design, fabrications as well as operations planning for new activities in the marine environment. One area of knowledge which is unique to the marine technology field is how structures or facilities behave in ocean waves.

The overall aim of the R&D is then to develop mathematical methods of the real physical behaviour of such structures. The theoretical methods are normally verified by comparing with model test results. The model testing is necessary because it allows better control of the conditions than will be the case during in-service measurements. The validated model can then be applied to predict the behaviour during in-service conditions.

The main challenges regarding wave-induced loads and response are concerned with phenomena illustrated in Fig. 17. They involve water entry and exit problems (slamming), green water and sloshing in tanks.

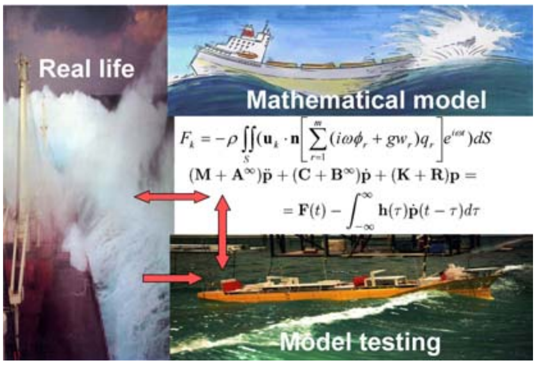


Fig. 16 Investigation of the behaviour of structures in ocean waves requires a combination of theoretical and experimental approach

Fig. 17 Challenging phenomena in the analysis of wave-induced load effects

A variety of methods are applied in calculating the global wave-induced response of ships, platforms and other marine structures. As indicated in Fig. 18 the methods can be distinguished depending upon how they deal with among other aspects:

- long term variability of sea states, wave heading etc.
- 2 (strip) viz 3 D (panel) modelling of the fluid
- which nonlinearities, eg relating to water entry/exit are accounted for
- for catamarans and other multi-hull vessels: to what extent interaction between the hulls is considered

It is desirable for the users in industry that rule formula and direct calculation methods exhibit consistency. This means that they should give the same results for cases which in principle could be covered by rule formulae.

Most importantly, efforts should be devoted to estimating the model uncertainty and the possible statistical error due to limiting sampling size in time domain analyses. To obtain an explicit safety measure for structures, the model uncertainty of the relevant calculation method should be determined.

Design based on direct calculation methods requires explicit data about ultimate and fatigue strength (Fig. 19). While such data have been developed for some decades for steel structures (Paik and Thayambslli 2002), more limited information is available for aluminium (Moan 2003) and concrete-steel sandwich structures (Iwata *et al*. 2000).

A particular feature of aluminium is the 15-30 mm soft zone adjacent to welds where the yield strength may be reduced as much as 50% of that of the base material. Other fabrication factors, such as initial deformations and residual stresses, may also be different for aluminium compared to steel structures. These particular properties of as-welded aluminium structures will influence the ultimate strength of panels and need to be accounted for. Data are required especially for the basic building block of aluminium ships: namely the stiffened panel, subjected to axial, transverse and lateral loads.

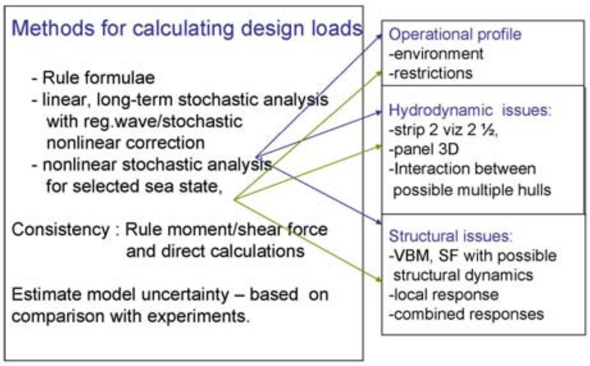


Fig. 18 Alternative methods envisaged for direct calculation of global design loads for marine structures

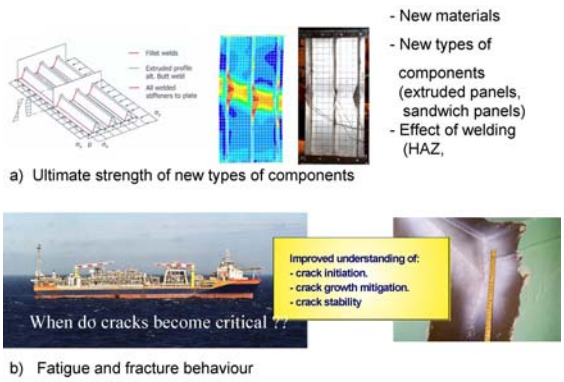


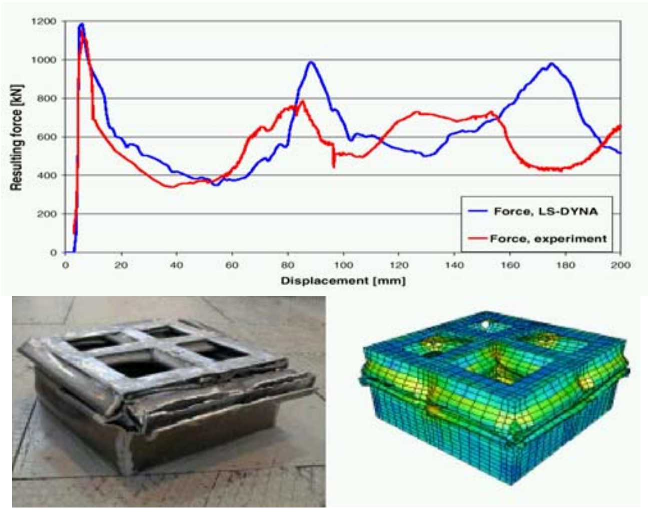
Fig. 19 Strength properties of new types of structures

By the increasing use of materials with high static strength and the desire for long service lives, fatigue and fracture properties are of increasing concern. A particular challenge is the growth of large cracks. Moreover, a better understanding of the development of cracks into fracture is of concern. This is an issue especially relevant in view of conversions, and extended service life of existing marine structures.

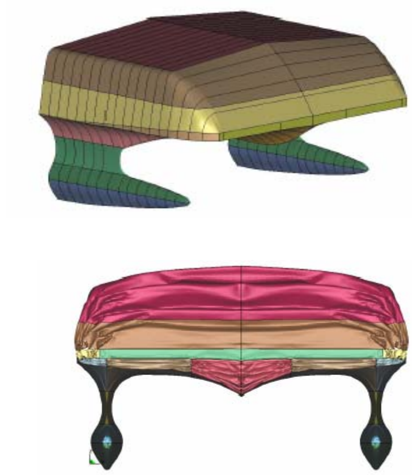
Significant progress has been made regarding predicting the behaviour of marine structures under the effect of accidental loads – which are important for assessing the safety of these structures. Fig. 20a shows an example where the crushing behaviour of an aluminium box structure predicted by LS-DYNA (2001) is compared with test results for the same specimen. Methods that are verified in this manner are then applied to predict the crushing behaviour of high speed vessels under in-service conditions. Fig. 20b shows the initial shape of the bow of a high speed catamaran (to the left) and how it is deformed after hitting a rock (to the right). The prediction of the deformed shape, associated forces and energy absorption took 10 days on a modern computer. Much efforts have therefore, been directed towards developing simplified and faster methods which are calibrated against such refined FE analyses (Urban 2003).

The effect of explosions hazards is also of significant concern especially for offshore structures, as shown in Fig. 21. The determination of explosion damage involves simulating the development of explosion pressure in the topside structure, as shown in the upper left corner of this slide. To the right, one can see the calculated damage to the deck structure.

Despite the significant development of risk and reliability methods over the last decades, further work is needed to establish methods and collect data for realistic prediction of failure probabilities and risk.



a) Comparison between analysis with LS-DYNA



b) Prediction of crushing behaviour of a catamaran bow

Fig. 20 Validation of crashworthiness analyses by finite element method and application to high speed catamaran

A special discipline- that has been called computational welding mechanics – has emerged over the last 15-20 years with the aim to predict the stresses and distortions caused by welding. Knowledge about such fabrication effects is crucial for an efficient planning of the fabrication, especially when automatization is to be utilized to the extent possible. Also, the expected level of welding distortions and stresses would also have an effect on the design values of structural strength. Because of the complexity of large welded structures a complete numerical analysis of the total structure is not yet feasible. It seems necessary to undertake further research on this subject in order to arrive at a better and rational assessment of this problem.

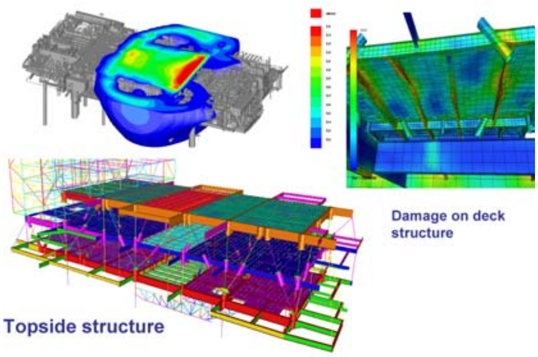


Fig. 21 Prediction of damage the deck structure of an offshore platform, caused by explosion (Czujko, 2003).

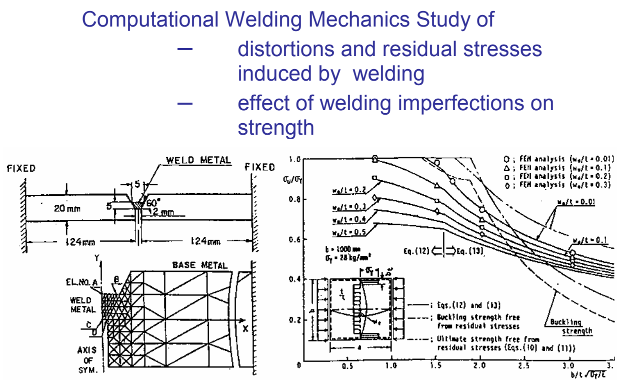


Fig. 22 Analysis of welding deformation and residual stresses

Another important issue is product modelling, to represent geometry and material properties and other features of the structure by computer models. Fig. 23 shows a photograph inside a ship to the left and the corresponding virtual reality model in the computer to the right. Especially by providing an efficient communication between analysis models used in design, fabrication and operation such product models contribute more efficient handling of structures and facilities over their life cycles.

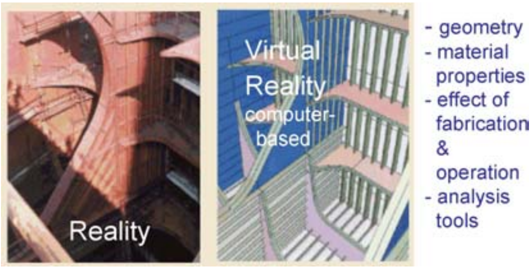


Fig. 23 Product modelling for improved the efficiency of communication between life cycle phases (Source: Det Norske Veritas)

Fig. 24 Ships and ports are the main elements in transport at sea

Improvements in real time computer graphics have now made virtual reality feasible for the design process and the training of the operators. It is possible to simulate and display accident scenarios including sea keeping damage stability and flooding coupled with passenger evacuation. Virtual reality design can incorporate the trinity of technical disciplines, human resources and organisational factors, which includes the economical aspects. The main challenge that remains is still concerned with the data exchange between the various simulation tools and graphical presentation tools.

Besides addressing virtual reality tools R&D in information technology applied to design of marine structures also needs to develop (MIF, 2002)

- Communication technologies – to support the establishment and management of virtual enterprises, integrating distributed design agents
- Standardisation of the EDI design tools – by continuing the development of the ISO/STEP Ship Product Model and of the methodologies and tools required to its implementation

3 Development of vessels for sea transport

The modern world economy is bound together by sea transport. Over 70% of world trade and 95% of the international transport takes place by ships, and no country is independent of the fuels, raw materials, food or manufactured goods moved across the world's oceans.

Ports are an important part of the transport system, by serving as the meeting point of land and sea transport. To deal with the enormous quantities of cargo moved through ports in an efficient manner, highly specialized bulk handling equipment and container technology are necessary. Ports themselves have become locational factors for industries, and most of the great cities are ports.

Modern ships are highly complex and specialized and many are of enormous size. The costs of vessels depend upon their complexity and whether production can take place in a series or by one-of-its kind. In Fig. 25 the cost ranking (according to European cost level) for different types of vessels is indicated. The most expensive vessels are naval vessels as well as floating hotels like cruise ships and passenger vessels used for recreation.

Another feature of recent development is the increase in size to improve transportation efficiency. The bulk carrying ships, the "work horses" of the sea, make up 40% of the trading fleet and carry 66% of the world trade. This reflects their greater ship size dictated by the economics of scale. Currently design of bulk carriers as large as 600 000 tons and 450m length is pursued.

Fig. 25 Specialization of ship functions and relative (European) cost of fabrication

Fig. 26 Container transport

For container ships over-Panamax type has appeared since 1990 and its size has been increased to about 7000-TEU type to date. It is said that the upsizing trend is considered to continue in the future. Remarkable concepts of a 15 000 TEU ship with a speed of 25-30 knots are being explored. The target LNG vessels so far have a capacity of 145 000 m^3 . Assessment of vessels with almost twice that capacity is currently made. In passenger ships also, the upsizing trends have continued. Since the 1987 built "Sovereign of the Seas" of 73,000 GT, the upsizing has been accelerated and has exceeded 100,000 GT in the 1996 built "Carnival Destiny". The number of large passenger ships delivered or expected for delivery in 2000 to 2006 is more that 60, of which 15 are larger than 100,000 GT class and the largest one is "Queen Mary II" of 150,000 GT. The era for very large cruising vessels is coming.

For tankers, the 300,000 DWT class is the maximum size of oil tankers these years, and this trend is considered to continue in the future. On the other hand, the tanker fleet will be influenced by regulations issued to prevent environmental pollution. The new regulations resulting from the Exxon Valdez accident in 1989, and Erika in 1999 explicitly require the single hull tankers to be phased out before 2015. As a consequence, more than 2000 oil tankers, with 175 million tons deadweight will be phased out between 2003 and 2015, and allow new building. The new safety standard is primarily met by double hull vessels. Also, innovative design based on steel-concrete sandwich concept (Iwata *et al*. 2000; Naval Architect, 2003) is noted.

Container ships provide an efficient cargo transport. Increasing speed of the vessel has been a recent issue. Currently a 40-knot, slender pentamaran vessel is under construction.

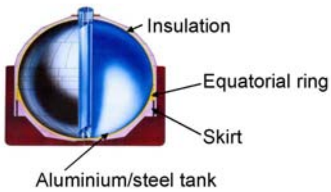
The integration between waterborne and land-based transport is crucial. Recent research has been devoted to sea – land interface – especially in so-called short-sea shipping in the European Community.

Gas is an important commodity, with a significant need for transport because of the large distance between the locations of production and use. During the past decade the Liquefied Natural Gas (LNG) market has doubled. It has been forecasted that the global LNG market will double in size over the next decade and the industry is therefore preparing to meet the demand. The forecasted increase in the LNG market is heavily driven by continued demand for a cleaner burning fuel and the need to bring “stranded” gas from deepwater and remote areas to the market.

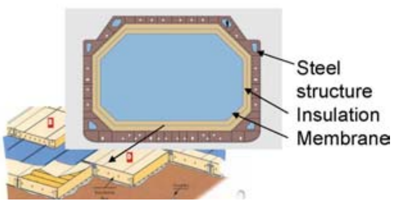
Although the fundamental technology behind LNG tankers has already been developed and proven to a high level, endeavours are continuing to further extend the technology with respect to enhanced reliability and efficiency and minimal environmental impact. Efficient transport requires reduced volume by low temperature, or high pressure or both, as indicated in Fig. 27.

Traditionally the gas has been liquefied by low temperature (-163°C). The challenge is to find a containment which carries the fluid loading and yet provides a proper thermal insulation. Two solutions of this problem have so far been implemented. In the Moss containment system metal spherical tanks are applied. Each tank is supported on a cylinder along an equatorial ring. In this concept the load carrying function and thermal insulation is well separated. In the GTT containment system tightness is provided by a metal membrane with a thickness of the order of 1mm. The membrane is supported by a continuously distributed insulation material, shown in yellow in Fig. 28b. Insulation is provided by foam or by wooden boxes filled with insulation material, which needs to carry pressure loads.

Fig. 27 LNG transport concepts



a) Moss containment system



b) GTT containment system

Fig. 28 Low temperature containment

These solutions are currently re-examined for use in connection with construction of vessels twice the size of the current maximum vessel size. One of the challenges in this connection is sizing of tanks in view of possible sloshing pressures.

For ship transport of LNG, terminals at the production site and user end of the transport chain are needed. The terminal at the user end need to be close but not too close to users due to the hazards involved. There are two main types of offshore LNG terminals: loading terminals and discharge terminals. Figure 29 provides a conceptual view of two mechanisms for offshore LNG offloading; one with a LNG carrier along side with an LNG Floating Production Storage/Offloading (FPSO) unit; and one with offloading at the stern of the FPSO. Figure 29 also indicates segregated pressure barrier containment system.

Fig. 29 Offshore LNG terminals (LNG-terminals, 2002)

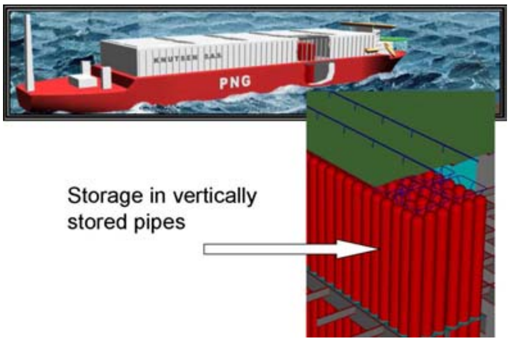


Fig. 30 Gas transport based on natural gas compressed at 250 bars at room temperature

An alternative way to transport the gas is by compressing it with a pressure of the order of 200-250 bars. Currently several companies are pursuing this challenge by various novel concepts. Figure 30 shows one of the options based on storage of gas in long vertical bottles with small diameter. Economic advantages are envisaged for the PNG as compared to LNG, especially for local distribution of gas, i.e. for transport distances less than 2000 nm and for gas productions around 100-200 MMscfd. The CNG solution may therefore be particularly relevant for transport of stranded and associated gas.

As indicated in Figure 31 people spend time on the sea for recreation or for transport. The recreation – cruise market was a rapidly increasing market, until the tragedy of September 11, 2001. To some extent this segment of marine activity is recovering.

While cruise in a way is to enjoy the sea and to move around slowly, another issue is fast transport of people – and increasingly – special cargo. So far we have seen catamarans and monohull vessels with a length of 125 – 150 m and speed of 35-40 knots. High-speed crafts (HSCs) require technology that resembles that of aeronautics. For instance, waterjets are used instead of propellers for propulsion at high speed.

Ride control, i.e. automatic control of motions, offers significant advantages. New, lightweight materials such as aluminium or fibre reinforced plastics would normally be advantageous for the hull structure.

Maintaining safety during operation in view of increased risk of collision or grounding due to the high speed, and complying with operational restrictions, are significant challenges for HSC operations (Moan 2003).

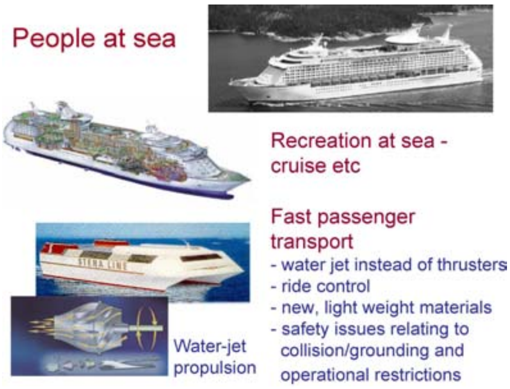


Fig. 31 People at sea

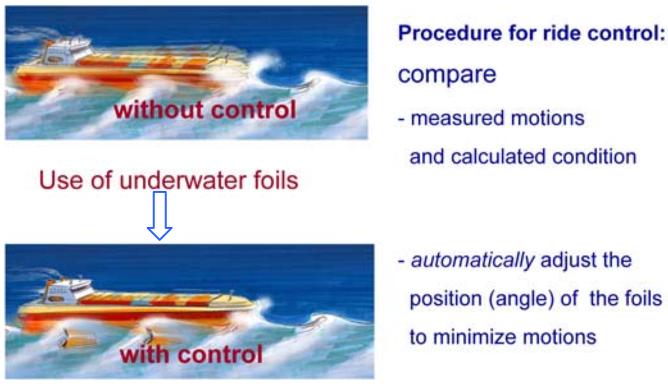
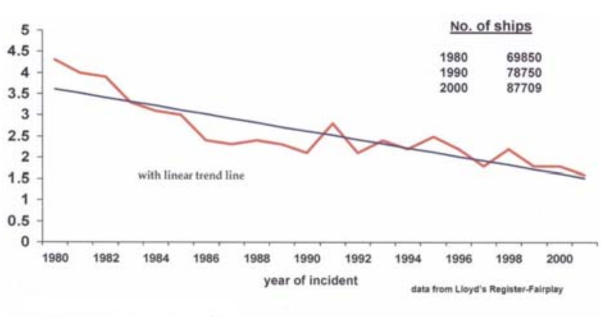


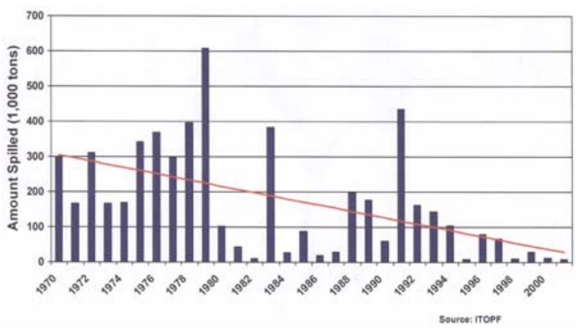
Fig. 32 Ride control

As indicated above, automatic control of motions can be applied to increase comfort and, hence, the serviceability of HSC. As indicated in Figure 32, foils can for instance be used to provide the necessary forces to achieve this feature. This ride control is based upon comparing the measured and calculated condition of the vessel, and automatically adjusting the position of the foils to introduce forces to limit the motions.

There is an increasing concern about safety for men and reduction of pollution. Even though the trend has been a decreasing risk level, as illustrated in Figure 33, it is observed that the increasing size and speed, increase the risk of heavy weather damage. Faulkner (2002) therefore recommends the introduction of a survival design, considering extreme waves. However, the majority of losses are caused by collision and grounding, fires and explosion and other accidental events. Degradation of ship and other structures due to corrosion and development of cracks also have led to catastrophic events and great public concern (Fig. 34). However, this degradation process is gradual, and there is ample time for preventing that such degradation does not cause catastrophic events, as experienced with, for instance, Erika. To maintain a positive public image of our field, it is important to avoid such events by properly managing the maintenance and repair during operation.



a) Percentage loss rate per 1000 ships



b) Amount of spilled oil

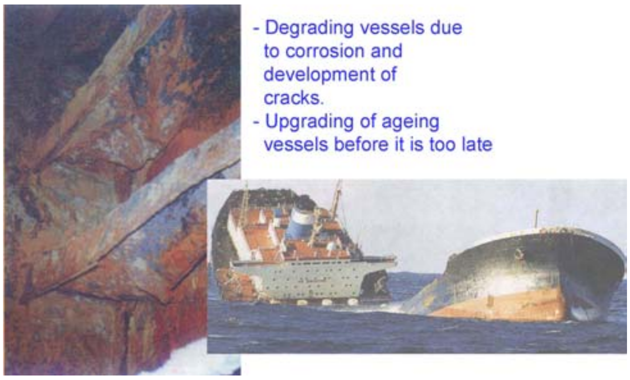
Fig. 33 Accident rate for ships (Liu 2003)

4 Development in the offshore oil and gas industry

Besides sea transport, offshore oil and gas is the most important marine industry. Hydrocarbons represent the dominant source of energy today. Twenty percent of the oil and gas production takes place in offshore areas. New reserves to be exploited would increasingly be sought in deeper waters and call for challenging new technologies (Fig. 35).

The map in Figure 36 shows where the sedimentary basins are located and hence where potential hydrocarbon provinces may be located.

Different types of platforms are envisaged for various functions in the oil and gas industry. Platforms are required for exploratory drilling to identify hydrocarbons. The main functional requirements to such platforms are payload capacity and area for drilling equipment limited motions and good mobility. Other types of platforms are needed for producing hydrocarbons. Production platforms carry chemical plants which consist of separators, pumps, etc. Mobility normally is not needed for production platforms when the production period corresponds to the platform service life. The layout and size of production platforms vary, depending upon water depth, production rate, etc. as illustrated in Figure 37. Floating platforms for instance include Tension Leg Platforms (TLP), Floating Production, Storage and Offloading (FPSO) types of structures and semi-submersibles.



a) Corroded side longitudinals b) Hull girder collapse

Fig. 34 Backside of the medal

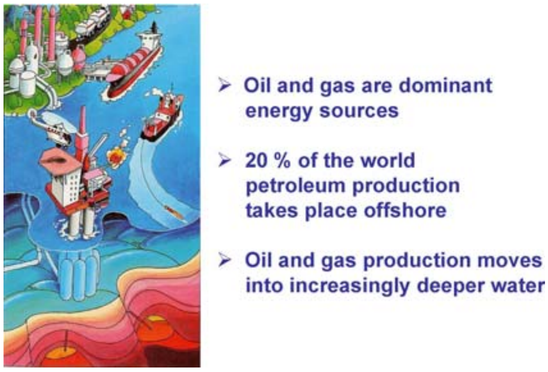


Fig. 35 Hydrocarbons from subsea reservoir to the user

The vast majority of offshore production structures are fixed-bottom platforms. These fixed platforms are primarily steel framed structures that are connected to the seabed by piles. As the water depth increases, the expense of the platform increases at a tremendous rate. In general, the economics dictate that the industry introduce floating instead of fixed platforms for the water depths between about 300 and 600 m. A number of large fields at depths of 1500 to 2000 m are currently under development in Gulf of Mexico, West Africa and Brazil. New technology for water depths down to 3 km now needs to be qualified.

Figure 38 shows the change of physical effects with increasing water depth. The effect of waves is limited to a depth approximately equal to half the wave length. Yet, possible floating structures will be affected by wave action. However, the use of spar platforms with a draft of 200 – 250 m to the wave heave motion will be limited. In this connection the variation of wave conditions at different offshore sites is noted. Figure 39 displays so-called contour curves for different locations. These contour curves describe extreme sea states corresponding to 100-year wave conditions, by means of significant wave height and wave period corresponding to the waves in the sea state with the largest energy.

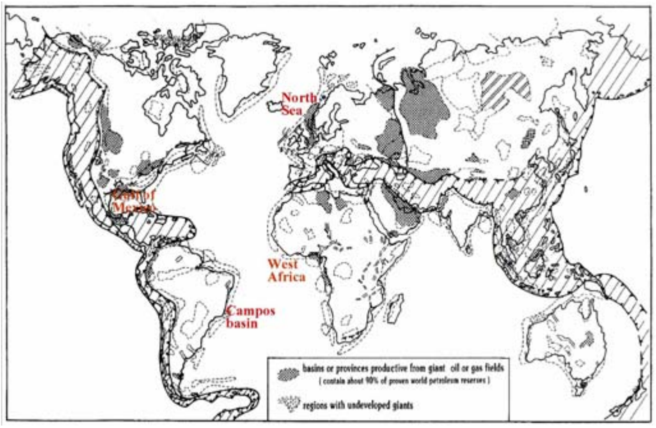


Fig. 36 Sedimentary basins with potential hydrocarbon

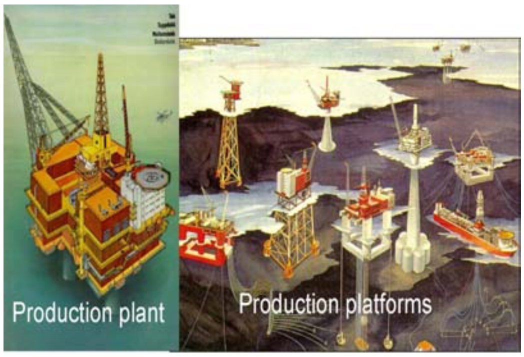


Fig. 37 A variety of offshore structures for different functions

Safety has been of great concern in the offshore industry, because of the serious consequences of offshore accidents to the society and the operators themselves. This is especially the case in harsh environments such as the North Sea, where three of the accidents displayed in Figure 40 happened.

The fact that 90% or more of accidents are due to human errors in design fabrication or operation makes quality assurance and control during all life cycle phases of the structure an important issue.

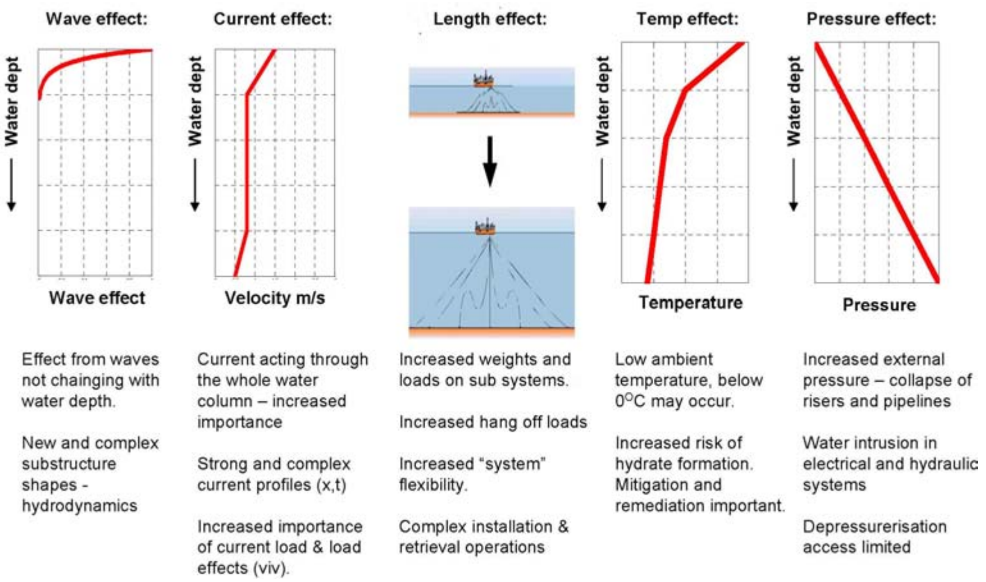


Fig. 38 Change of physical effects related to increasing water depth

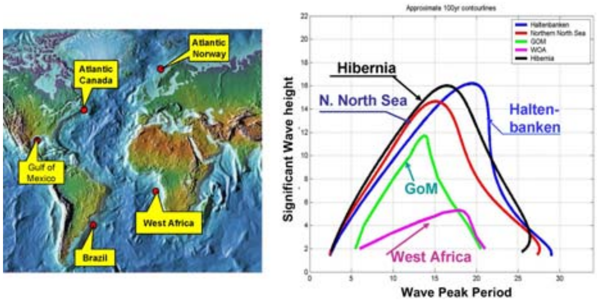


Fig. 39 Design contour curves at different offshore sites world wide

Fig. 40 Offshore accidents. Alexander L. Kielland (ALK): fatigue failure of brace, loss of buoyancy and capsizing. Ocean Ranger: accidental flooding and capsizing. Transocean: explosion. Piper Alpha: fire and explosion

Design of new production platforms is both a challenging and an exciting task. For instance, in connection with a recent field development in the North Sea, the oil company compared the various alternative production platforms shown in Figure 41 on the basis of costs, flexibility with respect to future extended use and risk.

Obviously, both the contenders as well as the oil company had a challenging task before a so-called TLP and semi-submersible were selected for further evaluation.

Figure 42 shows the number of floating production systems in use up to now and forecasts for the future.

In some offshore oil and gas fields, conversion of existing structures is a good alternative to new building. Most commonly tankers are converted into FPSOs. But also drilling rigs, like semi-submersibles, are modified to production units. Figure 43 shows how the buoyancy is increased for a semi-submersible by adding parts, indicated by red, to obtain sufficient payload capacity when it is converted to a production platform. At the same time the platform had to be strengthened to carry more payload and tolerate the larger wave loads.

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Platforms provide a dry environment for production facilities. But various kinds of underwater structures and equipment are required. The so-called risers are pipes that carry hydrocarbons from the subsea reservoirs to the platforms and can rightly be called the umbilical chords of the platforms.
In increasing water depths, it is considered to be an advantage to place production equipment on the seafloor. Since the subsea equipment needs to be remotely operated, various kinds of competence, for instance, from marine technology, mechanical engineering and cybernetic would have to be combined to deal with such systems. (Fig. 44).

Fig. 41 Production platform selection for a given field development

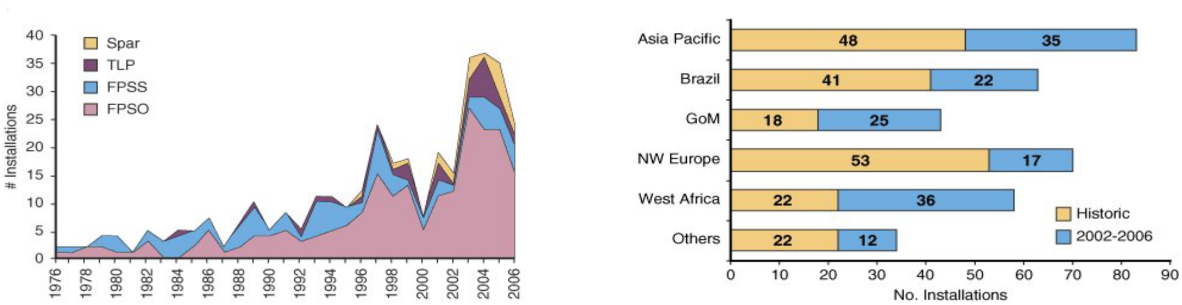


Fig. 42 Historical development and future prospects of floating production systems (Douglas-Westwood 2002)

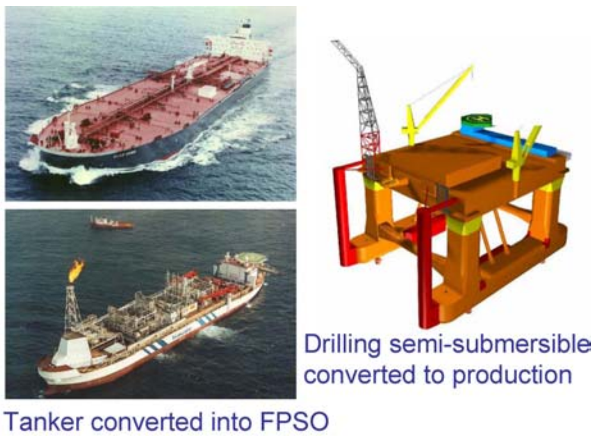
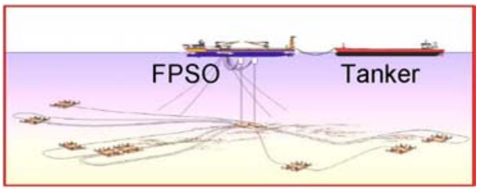


Fig. 43 Conversion of platforms from drilling to production units

Fig. 44 Sub-sea technology

Fig. 45 indicates two different production facilities systems both based on floating structures. However, the system (a) is based on more subsea completions of wells than the other one. The production facilities are different – an FPSO in the upper system and a TLP at the system shown in the bottom of Fig. 45. The transport of the oil from the offshore site to shore (in this case) is based on ships in both cases. However, in case (a) the oil is loaded directly into the tanker while for case (b), it goes via a pipeline to the tanker.

The actual choice of field development technology would depend upon production volume, distance to shore, environmental conditions, possibly shared services with other fields etc. Field developments in deeper water introduce new aspects in the choice between production plants on the platforms or on the seafloor.



a)

b)

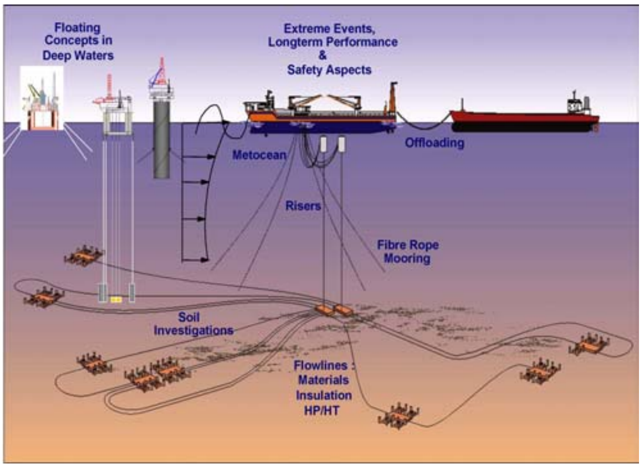


Fig. 45. Field development towards year 2010 (Source: Statoil)

Fig. 46.Research areas for offshore structures.

There is a need to develop structures for harsh environments and larger water depths. Also, the understanding of concept rating and selection by integrating floating and sub-sea production system should be further developed.

Research & Development is partly focused on developing new types of floating platforms or vessels, met-ocean data, especially relating to currents, as well as risers and station-keeping systems, which obviously become more challenging in deeper water. As indicated above, a critical issue of the behaviour of platforms is their performance in severe seas (Fig. 46).

Risers and positioning systems are key elements in deepwater production systems. The research problems in this area are related to the effect of so-called vortex-induced vibrations, especially of multiple risers (Fig. 47)

The use of lightweight polyester ropes for mooring and further development of dynamic positioning are key research issues for station-keeping systems.

5 Marine operations offshore

In connection with transport, installation and operation of offshore structures, various marine operations are required. Fig. 48 shows a 31,500-ton semi-submersible production platform transported on the vessel Mighty Servant 1 in the Pacific Ocean. The semi-submersible has length and width of 81.2 m and a height of 55m.

Other marine operations are carried out in connection with lifting or lowering of objects to the seafloor and during installations of platform substructures and decks. The picture in the middle of Fig. 49 shows the Crane with largest lifting capacity, 14000 tons. Passing through the wave zone is a particular challenge for wet lifts. Use of automatic control of the relative motion between the suspended load and water surface will reduce the wave (slamming) forces and increase the operability – weather window (Fig. 49).

Yet another category of marine operations is offshore loading of a shuttle tanker from an FPSO. So far, systems for offloading of oil have been developed. The system of Fig. 50a is made for harsh North Sea conditions. More simple systems are used in benign waters. This includes the FPSO for a field offshore Libya, shown to the right in Fig. 50a.

A main challenge is currently to develop systems for gas offloading – at cryogenic temperatures or high pressure. The system indicated in Fig. 50b is being assessed for use in benign environments.

The research on marine lifting operations, for instance, focuses on installation of subsea equipment, with and without automatic control. Development of "smart" or intelligent deployment and heavy lift operations are other research topics. Finally, assessment of risk associated with deployment operations is being addressed (Fig. 51).

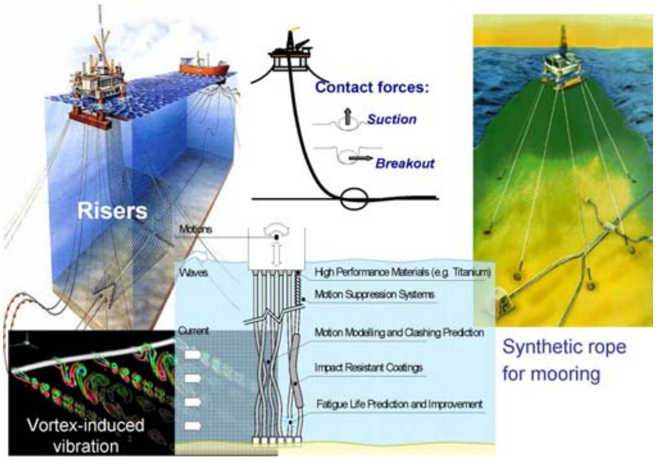


Fig. 47. Challenges for risers and mooring lines in deep water

Fig. 48 Pacific Ocean transport of a 31500 ton FPU Nakika on board Mighty Servant 1 (Dockwise, 2002)

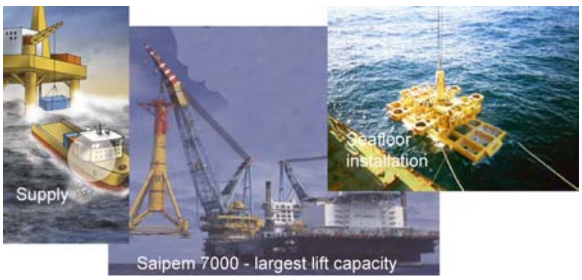


Fig. 49. Crane operations

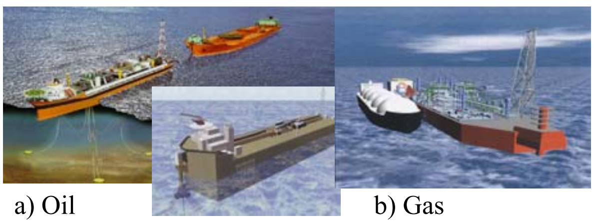


Fig. 50. Offloading operations

6 Dynamic positioning and manoeuvring

Two vessels can be kept in position by a combined dynamic positioning and mooring system (Fig. 52). The DP systems works in principle in the same way as for the foil system for HSC. The FPSO is moored by turret system that makes it possible to rotate the vessel around a geostationary cylinder that is connected to the sea floor. Thrusters are used to rotate the vessel to be head-on the weather. A DP system with thrusters and automatic control provide the positioning of the shuttle tanker. Ideally the tanker should be kept in line with the FPSO. However, human intervention could take place under certain conditions and could also cause critical situations. An important issue is to find the balance between automatic control and human control for this kind of operation.

As indicated earlier, DP can be applied for positioning of vessels, but it could also be used for manoeuvring of vessels and other marine operations which involve structures with forward speed. Fig. 53 shows various situations according to the velocity of the vessel(s) involved.

The research challenges in connection with automatic control of positioning and manoeuvring are two-fold:

- handling two or more vessels or other complex system – as well as
- performance of the DP under extreme conditions (when propellers thrusters ventilate to air etc.)

Fig. 51. Research on marine operations.

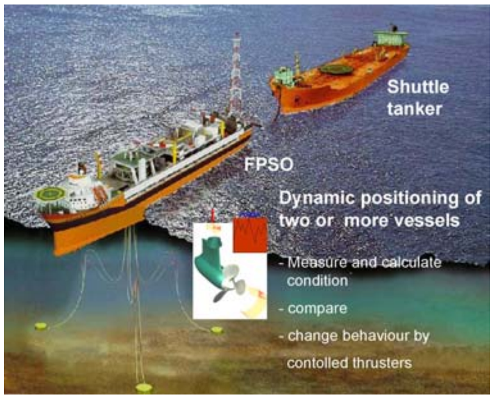


Fig. 52. Offloading by FPSO and shuttle tanker in a tandem

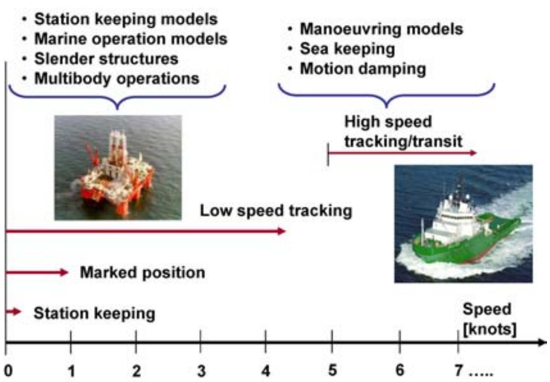
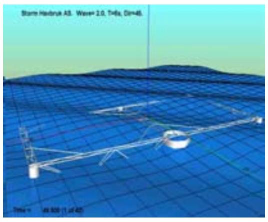


Fig. 53. Dynamic positioning, manoeuvring and marine operations.

7 Food from the sea

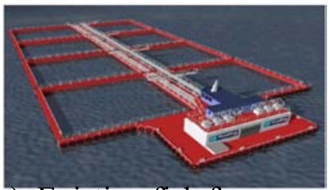
The third marine industry to be mentioned is food production. However, the catch of wild fish in the world has reached an apparent limit of yield of about 100 mill tons per year. Thus, the increase in seafood production can primarily be achieved only by fish farming in an industrial setting (Fig. 54).

a) Catching wild fish



b) Fish farm

Fig. 54. Food from the sea.



a) Existing fish farm

b) Future fish farm

c) Elevable, mobile fish farm for the future

Fig. 55. Challenges for future fish farming.

The potential increase in the yield from fish farming is large. But it requires supply of cheap feeding in large quantities. Moreover, the plants need to be industrialized, i.e. they need to be large in size, for use in the open sea, be mobile and elevable to avoid surface algae attack and pollution (Fig. 55).

The transfer of offshore technology becomes important in the future development of this industry.

8 Marine infrastructure

In addition to the three major marine industries described above, there are some other potential uses of the sea that need to explored.

For instance, the marine structures can serve as part of the infrastructure of the society. Fig. 56 for instance shows an existing offshore oil storage tank in Japan and potential submerged buoyant bridge and a floating airport that have been engineered to an extent that shows their feasibility.

The research on Very Large Floating Structures (VLFS) in the last decade was initiated by two major projects:

- The US Office of Naval Research focuses on a Mobile Offshore Base (MOB) for military purposes. A MOB is composed of several units of semi-submersible type, which are connectable/disconnectable (MOB 2001)

- The Japanese program on the Mega-Float, undertaken by the technical association of seventeen shipbuilders and steel manufacturers, known as Technological Research Association of Mega-Float (TRAM), established in 1995, to carry out joint research and development into the creation of a large scale floating structure. A Mega-Float is a large pontoon, generally moored at a fixed position and it is often supplemented with a breakwater to protect it against severe wave conditions.

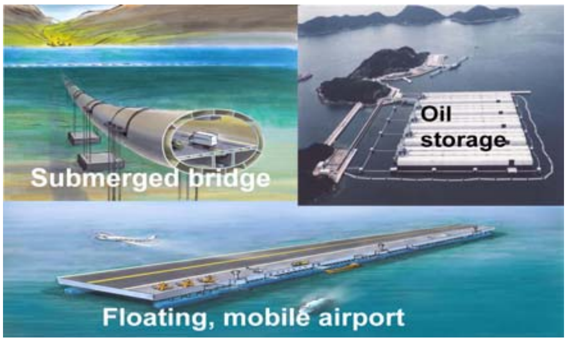


Fig. 56. Examples on marine infrastructure

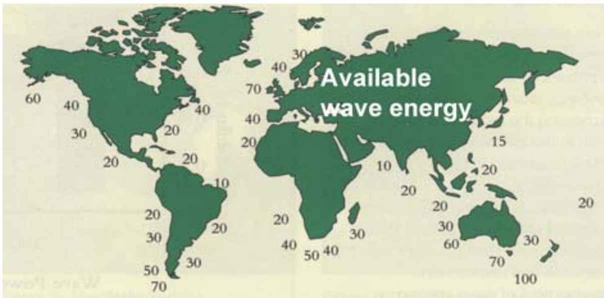


Fig. 57.Availability of wave power (Thorpe 2002) (kW/m wave crest)

The MOB concept is designed for *Operational* conditions that would correspond to a significant wave height of approximately 1.9 meters, and wave periods concentrated around 9 seconds. *Design* survival conditions would require that the MOB withstand loads from waves in the significant wave height range of 16 meters, and periods in the range of 20 seconds (Remmers *et al.* 1999).

For the Mobile Offshore base concept to be demonstrated as viable, research and design need to continue in multiple areas. These include:

- Validation of computational load and response prediction tools
- Inter-module connector design and analysis
- Alternative concepts
- Long-life resilient marine materials
- Construction technologies
- Long-term maintenance and repair
- Station keeping (mooring, anchoring, dynamic positioning)

In Phase 2, starting in 1998, TRAM initiated studies on unresolved questions by building a 1000-m long, 60 (120) m wide and 3 m deep model of a Mega-Float airport for experiments with takeoff and landing of small aeroplanes. Apart from this application, research was also conducted under TRAM in view of requirements for floating bases with many other functions, as port facilities, distribution bases, recreation facilities, etc. In general the application of Mega-float is intended for more benign condition than the MOB (TRAM, 2002).

9 Renewable energy from the sea

Besides the exploitation of hydrocarbons from subsea reservoirs, the sea can provide energy by wave energy, current or wind, as well as the thermal difference in seawater. While the early work on exploiting wave energy in the 1970'ies failed to deliver economic supplies of electricity from wave energy, it advanced the technology considerably. In recent years wave energy has started to make a comeback (Thorpe 2002, World Energy Council 2003). The map in Fig. 57 shows the average power obtainable (kW/m pr m wave crest) in various areas of the world. The global supply is estimated to be of the order of 1 million MW.

Various devices to transform this energy into electrical power have been proposed. One alternative is shown in Fig. 58. The Pelamis concept (Fig. 58) is a semi-submerged device composed of cylindrical sections linked by hinged joints. The device points into the incoming waves. The energy is extracted from the relative movements between sections. A 750 kW device is being developed for Scotland.

The most common design of shoreline device is the oscillating water column (OWC). These take the form of a partially submerged chamber that has a small exit at the top and a large opening below the sea level. As the sea water flows in and out of the device, the column of air above the water level in the chamber is pressed through a pneumatic turbine, which can generate electricity.

Fig. 58 The Pelamis wave energy plant (Ocean Power 2003)

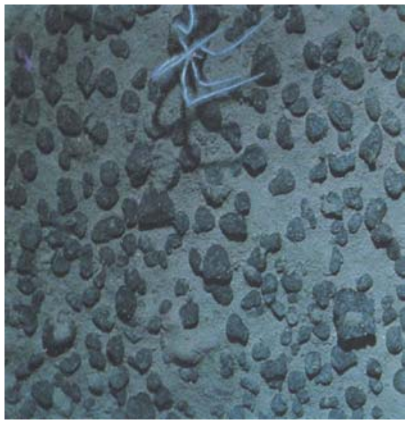


Fig. 59 Manganese nodules at the sea bottom of deep sea contain copper, iron, nickel and cobalt

10 Subsea minerals

An other potential resource in the sea not yet exploited, is the minerals such as gold, platinum, copper, titanium and not least manganese – which is abundantly available in nodules (Fig. 59). But unfortunately, these minerals are generally located on great depths. It is a significant challenge to develop the technology that makes these resources competitive. Moreover, the political and ecological issues associated with these resources must be resolved.

11 Strategic use of the sea

Another use of the sea is for strategic purposes. Naval forces utilize the depth, expanse and freedom to navigate in the international sea space. They monitor each other and protect territorial seas. For this purpose various vehicles and facilities are required. Fig. 60 shows an aircraft carrier, a mobile airport and the semi-submersible sea launch platform.

Fig. 60. Strategic use of the sea.

12 Concluding remarks

It is expected that the seas in foreseeable future will continue to be a source for transport, energy, food and other uses.

The industry that is involved in exploiting these resources in a sustainable manner, will change. The competitiveness will be determined by the levels of cost, competence and quality. In particular, those that continuously pursue competence- intensive products will be the winners. R & D plays an important role in this connection.

Moreover, to be able to provide the highest quality to be the best, it will be important to join efforts by cooperation along multiple axes. For instance along the axis of enabling and marine technologies as well as the axis of design-fabrication and operation. This is illustrated in Fig. 61 by the Marine/Maritime cluster.

Cooperation along multiple axes-based on strategic alliances:

– Marine and enabling technologies
– design, fabrication and operation
– different organizations
– different geographical regions

Fig. 61. The marine/maritime cluster

Acknowledgement

The Inaugural Keppel lecture was delivered by the author at the National University of Singapore (NUS) on July 18, 2003 in the presence of an audience of more than 400 persons, with Mr. Yeo Cheow Tong, the Minister of Transport of Singapore, as the guest of honour. This paper is the written version of the lecture. The support from NUS and Keppel Corporation is sincerely acknowledged.

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