Engineering 2015, 1(1): 131–138
DOI 10.15302/J-ENG-2015004

Research
Marine Structures—Perspective

Marine Structures: Future Trends and the Role of Universities

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ABSTRACT This paper emphasizes some of the challenges and trends associated with the future development of marine structures. Its main focus is on ways to improve the efficiency of energy-consuming ships, and on design challenges related to energy-producing offshore structures. This paper also discusses the analysis tools that are most needed to enable sustainable designs for future ships and offshore structures. The last section of the paper contains thoughts on the role of universities in education, research, and innovation regarding marine structures. It discusses curriculum requirements for maritime-technology education, basic research activities, and international cooperation.

KEYWORDS marine structures, ships, offshore structures, curriculum, research activities

1 Introduction

Seventy percent of the surface of planet Earth is water, with a mean depth of 3800 m. The oceans are of immense importance in maintaining a reasonable standard of living for an ever-increasing global population, for these reasons:

- The oceans are enormously important in the global exchange of goods; current global trade could not take place without the use of oceans as a transportation medium.
- The oceans and the ocean floors contain large reservoirs of raw materials such as hydrocarbons.
- The oceans have a large potential for exploration and for the future cultivation of living resources in the form of fish and plankton.
- The oceans receive 70% of our primary sustainable energy source: radiation from the sun. This energy can be harvested in the form of thermal gradients, wind, current or wave energy, salt gradients, and so on.

Marine structures are necessary in order to exploit these possibilities. Since marine structures such as ships and offshore structures are massive, capital-intensive, and complicated structures placed in a special unfriendly environment, their design and development require research and skilled engineers. For any country wishing to participate in industrial development within this area, therefore, education and university research are essential.

2 Ship structures

Without commercial shipping, the rapid development in the global standard of living over the past 50 years would not have occurred. Over the last 200 years, ships have been by far the largest and most complex mobile structures built by humankind. In the period between 1800 and 1900, ship structures underwent a revolution. The main driver for this development was a technology push: Building materials changed from wood to iron, and then to steel; power sources changed from sail to steam, and thereafter to diesel engines; and propulsion means changed from paddlewheels to propellers. As a result, in 1912 the first ocean-going diesel motor ship, *MS Selandia*, was put into service between Asia and Europe. This ship possessed most of the main characteristics of a modern ship (Figure 1).

Since *MS Selandia*, ship development has evolved from empirical building rules to design by first principles. Continued optimization occurs, as the size and main dimensions of a ship are determined by

Figure 1. ***MS Selandia*.** The first ocean-going diesel motor ship, carrying 6800 DWT, built by B&W in 1912 and assigned to the EAC. (http://selandia100.dk/diesel-2, 12 February 2015)

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Received 12 February 2015; received in revised form 13 March 2015; accepted 17 March 2015

its mission. In addition to the basic functional considerations that are influenced by cargoes and routes, requirements include low resistance, high propulsive efficiency, stability, and navigational limitations on draft and beam, all of which influence the choice of dimensions and layout. This continued optimization has led to the development of highly optimized structures. For example, the mass of the hull plus machinery of a modern tanker or bulk carrier is now less than 15% of the mass of the carried deadweight.

Today, about 90% of the world trade in raw materials and finished goods are transported by ship. The resulting CO_2 emissions are approximately 4% of the global total. As a result, the main driver for current development in ship structures is a society pull. Public focus is primarily on the reduction of emissions per transported unit, and on shipping accidents. This focus has resulted in more severe international [1] and regional requirements, and has caused non-environmentally friendly ships and operations to be punished by port and coastal states. In addition, the public has increased expectations for green supply chains.

The response from the shipping industry has been to improve efficiency. Although large two-stroke diesel engines have a very high thermal efficiency (around 50%), it is still possible to gain further fuel efficiency. One possibility is to install a waste-heat recovery system that utilizes exhaust heat to generate power for a shaft generator.

Research on propellers has led to new optimized propeller shapes, devices for recovering rotational losses from the propeller stream, and improvements in the water flow to the propeller. Researchers are also using computational fluid dynamics (CFD) to explore alternatives to propeller propulsion, such as fin propulsion.

By using CFD in combination with model-tank testing, researchers have made progress in hull-shape optimization, resulting in reduced calm-water propulsion resistance.

However, what really matters is size and speed. As shown in Figure 2, energy efficiency, and thereby emission reduction ($g\ CO_2 \cdot (t \cdot mile)^{-1}$), strongly improves with speed reduction as well as with vessel size. The capital cost and the manning cost per deadweight ton are also strongly reduced with larger vessel sizes.

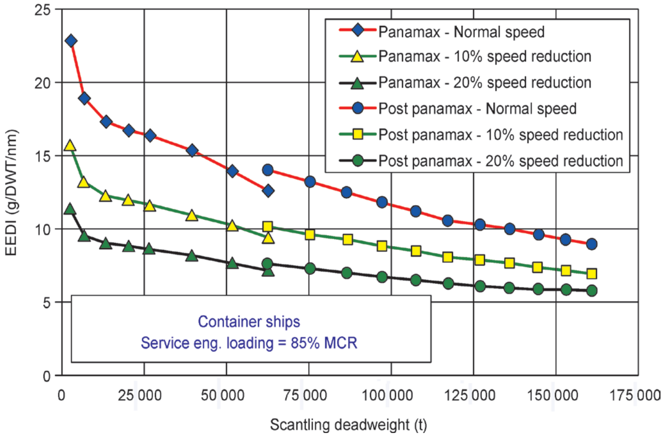

Figure 2. EEDI (energy-efficiency design index) in $g\ CO_2 \cdot (t \cdot mile)^{-1}$ as a function of size for different speeds [2].

These benefits have been major drivers in a development towards larger and larger ships. Container ships are a good example of this development. The first specially designed container ship was put into use in 1960, and could carry 610 TEU (twenty-foot equivalent units). In 1988, as the size of containerships increased to about 4500 TEU, it became necessary to design vessels that exceeded the existing maximum breadth (Panamax) of the Panama Canal.

Figure 3. The *Triple E*. An example of the new generation of large containerships; it is 400 m long and 59 m wide, has a speed of 19 kn and carries 165 000 DWT. (http://www.maersk.com/en/search?q=Tripple%20e&t=images, 12 February 2015)

This development has continued exponentially, so that the new generation of large containerships, which have scantling deadweights of about 195 000 DWT and relatively low speed, can carry around 20 000 twenty-foot containers (Figure 3). Use of these ships has resulted in a 50% reduction in CO_2 per transported unit, compared to the industry average for Asia-Europe trade.

2.1 Research needed for ship structures

The drive towards larger ships has not stopped. However, the structural design of such large vessels poses a number of technical challenges. The increase in size has been so rapid that there has been no feedback from service experience. That is, these ultra-large steel structures have to be designed by direct calculations. They have large bow flare and therefore highly non-linear wave-induced loading. When ships increase in size, and if materials with higher strength are used, hull flexibility plays an important role in the response of the vessel. For ultra-large container ships, the lowest hull-girder natural frequencies are as low as 0.40 Hz (or 2.5 s in natural period). The hull-girder vibration natural frequencies become so small for these ships that in order to calculate the wave-induced loads, it is not sufficient to consider the ship hull as a rigid body (Figure 4). Slamming-induced *whipping vibrations* of the hull girder determine the maximum hull-girder loads, and therefore the ultimate limit state. Full-scale measurements show that the higher frequency whipping stresses can be as large as the direct wave-frequency part of the stresses in high sea-states, as shown in Figure 5.

Another serious wave-induced effect on the fatigue strength of flexible ship hulls is *springing*, that is, a continuous excitation of the lowest hull-girder natural frequencies, due to the high-frequency components in the wave spectrum

Figure 4. An example of a ship hull that was broken due to wave-induced stresses in the hull girder. (http://www.rina.org.uk/mol_comfort_accident.html, 12 February 2015)

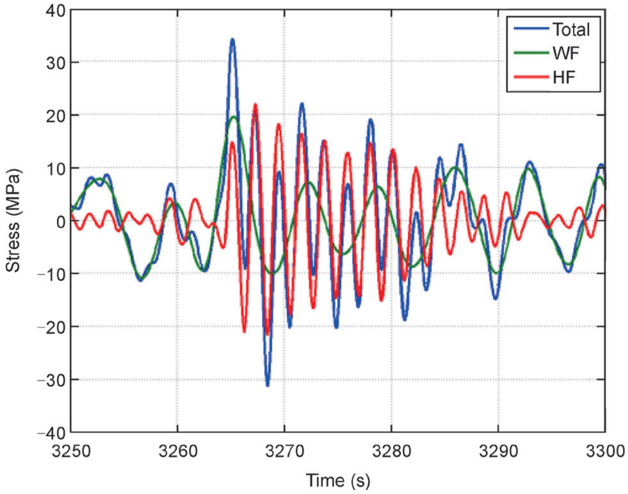

Figure 5. Stress measurements amidships on a large container vessel in a high sea-state. Direct wave-induced stresses on the rigid hull (WF), slamming-induced whipping stresses (HF) and the total combined stress [3].

Figure 6. The cruise vessel *Costa Concordia* hit a rock on Giglio Island in Italy in January 2012. (Taken by Pedersen)

and to non-linear excitation effects. Since container vessels have very open deck areas in order to facilitate the easy loading and unloading of containers below deck, the hull girders of these vessels also have very low torsional rigidity. Thus, when these ships sail in oblique waves, the hydrodynamic torsional loads may cause considerable torsional deformation. The result is deformations of the hatch openings, large stresses where the deck beams are attached to the side shell, and especially large stresses in front of the accommodation and engine modules. On existing ships, fatigue cracks are often found in these areas.

Scientific development is also needed in relation to accidental loads. The risks of accidental loads include fatalities, environmental pollution, and loss of property. It is notable that collision and grounding constitute by far the main risk for ships. Accident statistics from the European Maritime Safety Agency [4] show that these events cause about 70% of serious vessel accidents. Therefore, in order to improve shipping safety, more focus is required on accidental loads and on the hull girder strength after collision and grounding incidents. Accidents such as the *Costa Concordia* grounding (Figure 6) are of course very often caused by human error. However, despite the role of human error in road traffic accidents, research efforts have been able to reduce the number of fatalities from such accidents every year. A similar effort should be made for ships.

As a consequence of global warming and the resulting shrinking ice cover, the world will see increased shipping activity in the arctic. Arctic routes shave close to two weeks off a typical voyage from China to Europe—a trip that usually requires sailing through the Suez Canal. The main research challenge related to arctic shipping involves estimating ice loads and the motion of icebergs and ice sheets. Thus, arctic shipping will bring new types of environmental and accidental loading.

2.2 Enabling analysis tools for ship structures

At present, there are a number of unsolved challenges associated with designing based on the first principles of large ships. The most-needed enabling analysis tools are described below.

2.2.1 Improved CFD calculation procedures

Numerical hydrodynamic calculation tools are required that include free surfaces for the prediction of, for example: the flow field around the hull in calm water as well as in waves; calm-water resistance and scale effects; viscous and scale effects on wave making; propeller inflow; propeller torque; thrust and cavitation phenomena; seakeeping; wave-induced pressure distributions in non-linear confused sea; slamming pressures; and maneuvering [5].

2.2.2 Development of consistent fluid-structure interaction theory

Consistent procedures are required for: the calculation of coupling between impulsive sea loads and structure; the influence of hull flexibility on wave-induced loads; the structural effect of sloshing in tanks; and wave-induced springing excitation of ship hulls [6].

2.2.3 Non-linear probabilistic design procedures

Like the sea itself, the loads imposed by the sea are random in nature and can only be expressed in probabilistic terms [7]. Therefore, it is generally not possible to determine a single value for the maximum loading that a ship will be exposed to during, say, a 25-year operation in the North Atlantic. Rather, it is necessary to use a probabilistic representation of the loads. In addition, as a consequence of the complexity of the structure itself and the limitations of our analysis capabilities, it is not possible to achieve absolute accuracy in predicting the structural response of the structure, even if the loading is known exactly. The design process must be built on reliability-based methods [8], and the degradation of the structures with time due to corrosion, fatigue cracks, and so on must be taken into account.

2.2.4 New lightweight materials

To reduce weight and energy consumption, advanced lightweight composite materials should be developed for application in ship design. Not only do these materials have excellent strength/weight properties, but they are also resistant to corrosion.

2.2.5 Accidental load procedures

A need exists for the development of probabilistic tools to enable rational estimation of the risk associated with accidental loads, such as the probability and consequences of ship-ship collisions and grounding, in order to introduce rational risk-control options for future ship designs [9].

3 Deep-sea exploration and excavation structures

Special structural challenges are associated with the development of equipment for the exploration and excavation of minerals from the seabed. Previously, remotely operated vehicles (ROVs) were used to collect mineral samples from prospective mine sites on the seabed. Recently, however, technological research in China has led to the development of a manned submarine, the *Jiaolong* (Figure 7), which can be used to collect samples from water depths up to 7000 m. This manned vehicle will be able to explore more than 99% of the ocean floor [12].

One of the structural challenges of such a submarine is to design the manned pressure hull so that it is lightweight, while simultaneously providing a safe space for pilots and scientists when subjected to the high water-pressure load.

While ROVs and submarines are important in mapping resources, there are other unsolved challenges relating to excavating for minerals and transporting them up to the sea surface.

4 Offshore structures

Marine structures are being constructed for a large number of offshore activities, such as extraction of hydrocarbons below the seabed and minerals on the seabed, and offshore sustainable-energy production. Oil and gas will remain the primary energy resources for our society for many years to come. However, the extraction of newly discovered oil and gas resources situated under the seabed at great water depths or in arctic waters constitutes an enormous technological challenge.

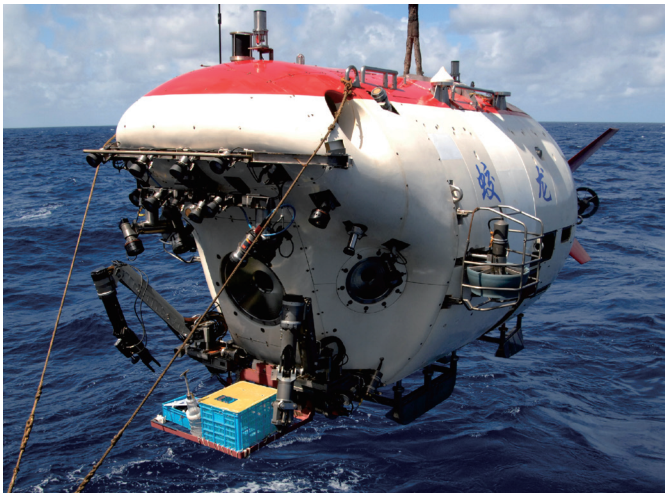

Figure 7. China's deep-sea manned submersible *Jiaolong*. (Reproduced from China.org.com, Xinhua, 28 July 2011)

Deep-water oil exploitation from the ocean surface can currently be done at a water depth of up to about 3000 m, using either floating production, storage, and offloading vessels (FPSO); tension-leg platforms; or spar platforms. All types of platform are huge floating units, and they require design development in the areas of hydro-elasticity, fluid-structure interaction, and probabilistic-design procedures. Very deep water implies the use of subsea systems.

The overall design goal for these platforms is to prevent direct resonance with dominant ocean wave frequencies. As shown in Figure 8, the wave energy in the North Atlantic is concentrated at wave periods between 7 s and 25 s, independent of the prevailing characteristic wave height.

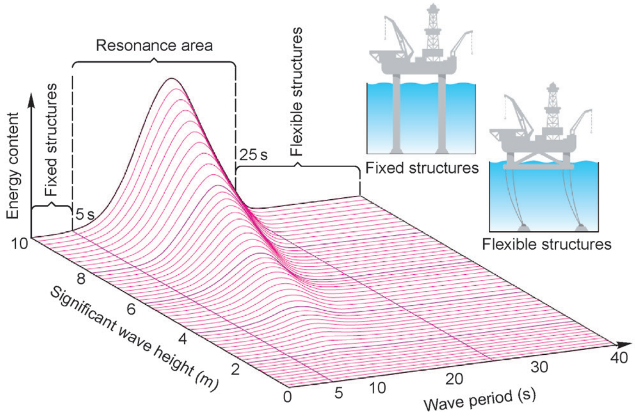

Figure 8. Wave spectra for the North Atlantic [2].

For this reason, fixed structures should have global resonance periods less than 6–9 s. For example, tension-leg platforms have natural vibration periods below 5 s in the vertical direction, and above 25 s in the horizontal plane.

4.1 Research needed for offshore structures

A proper estimation of wave loads and wave-load effects on these structures requires not only the inclusion of non-linear effects, but also (as for ships) consideration of the randomness of the loads imposed by the sea. However, in contrast to ships, which are designed for worldwide trade, these offshore structures are designed for a specific location. Due to the high cost of such a structure, detailed information on the wave environment at the intended location is typically collected by wave buoys, allowing a more accurate statistical description of the sea states. The non-linearities in the wave loads can often only be treated by time-domain simulations in short-term sea states. These simulations must then be integrated with long-term extreme-value predictions and fatigue-damage estimates.

A direct time-domain analysis procedure can be too time-consuming, even considering the huge cost of such structures. Therefore, several approximate, albeit still quite accurate, procedures have been developed and validated. For short-term analyses, the first-order reliability method (FORM), developed within structural mechanics, has proved to be very useful for stochastic wave and wind-load predictions. One of the outcomes of the FORM analysis is the most probable wave scenario leading to a certain response [10]. For example, Figure 9 illustrates the extreme overturning moment on a jack-up rig. This type of rig is used for oil exploitation in water depths up to 120 m. Dynamic effects are important for this type of rig, as the fundamental period of a jack-up drilling rig at maximum water depth is about 9 s.

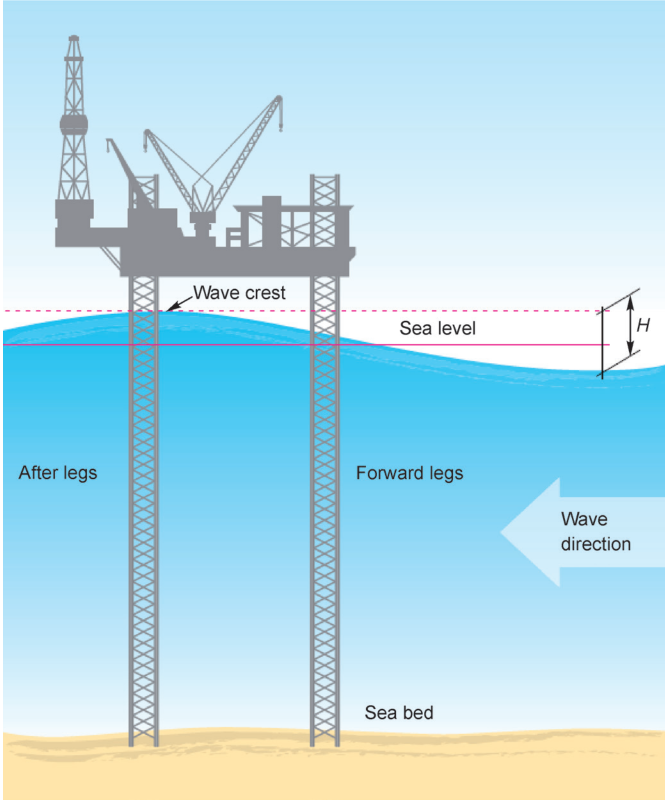

Figure 9. Overturning wave loading on a jack-up rig.

In part due to these dynamic constraints, the extraction of newly discovered oil and gas resources situated below the seabed at great water depths or in arctic waters calls for advanced analysis and design techniques, which include fluid-structure interaction and probabilistic-design procedures for ultimate-limit states as well as for fatigue-limit states. As for ship structures, it is necessary to consider accidental loads to offshore installations. Experience shows that fire and explosion risks are relatively high, and statistics [11] show that the average worldwide ship collision frequency per installation year is about 1 in 1000 platform years. These statistics are strongly dependent on location. In the North Sea, for example, statistics show even higher incident rates. At present, the risk of accidents is to a large extent limiting attempts to explore hydrocarbon resources in arctic waters.

The most promising concepts for energy harvest offshore are structures for wind-power and wave-energy extraction. Offshore wind turbines have seen a rapid increase in recent years. In shallow water areas, standard mono-pile or jacket concepts from the offshore oil-production industry are usually applied. Scour and resonance frequencies are the main design problems, but these issues do not differ much from those for oil-production platforms.

For deeper waters, a spar-type floating wind turbine and a wind turbine placed on a semi-submersible have both been put into service. Additional offshore wind-turbine concepts are under evaluation, based on tension-leg platforms and on floating islands that host several wind turbines, although no commercial full-scale construction is in operation yet.

Wind turbines that float offshore present a new challenge compared to the platforms used in the oil industry: the restrictions imposed on the acceleration of the nacelle and on the yaw and pitch motions of the platform.

The concept of harvesting sustainable energy from ocean waves is still in its infancy. Researchers have presented and evaluated many different designs on a model scale (Figure 10), but a real breakthrough has not yet occurred. One problem is the much larger variation in wave forces compared to wind forces. Thus, it becomes a challenge to design wave-energy devices that can cope with extreme wave loads, while remaining economically feasible for the exploitation of energy at low characteristic wave heights [13].

Figure 10. A 1∶2 scale jack-up structure that draws energy from the waves by means of floating point absorbers. (Permission by Wave Star A/S)

4.2 Enabling analysis tools needed

The essential scientific-analysis and design tools for different types of offshore structures and secondary structures such as risers are quite similar to those needed for the first-principle design of large ships. Development is needed in the following

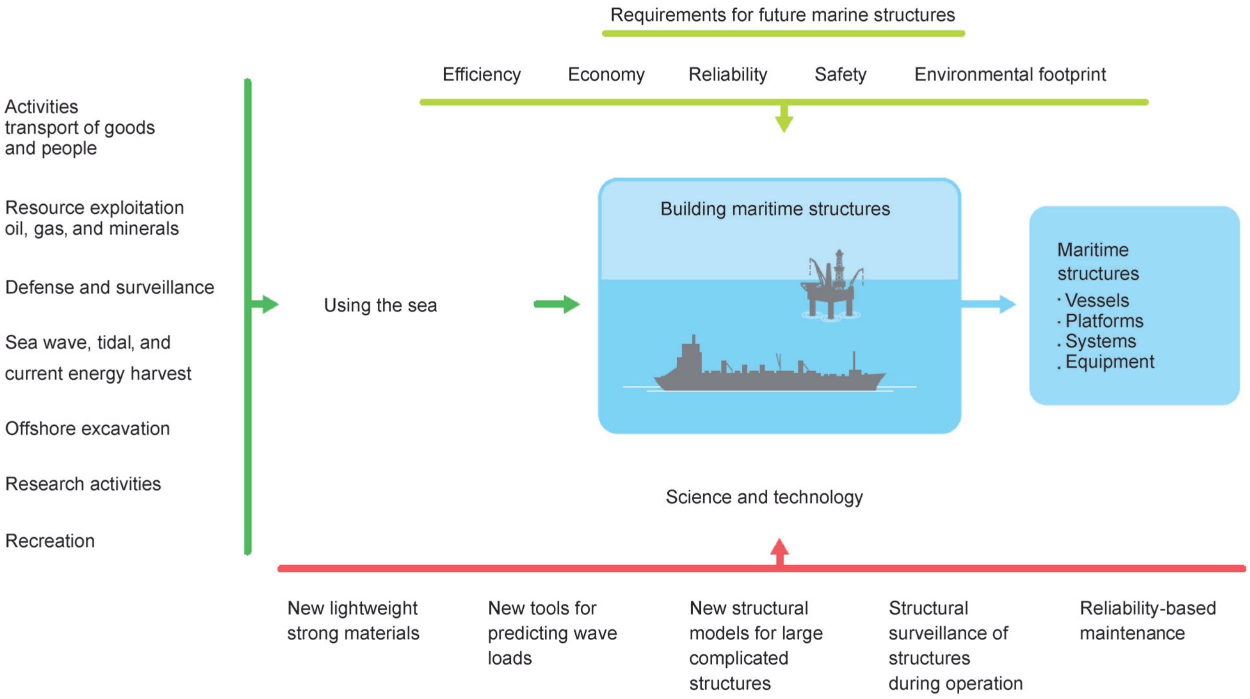

Figure 11. Activities, requirements, and scientific and technological disciplines that constitute the complex framework for industrial exploitation of marine structures [2].

areas:

- Hydrodynamic calculation procedures, including flow around slender bodies, slamming pressures, and marine operations;
- Ultimate-strength calculations, including uncertainty analysis, structural reliability, and stochastic dynamic analysis of extreme-load effects;
- Fatigue-damage prediction procedures for stochastic loads and corrosive environments;
- Accidental-load procedures, including probabilities, consequences, and risk-control options;
- New lightweight materials, such as composite materials for improved weight/strength relations and improved lifetime cost; and
- Monitoring of structures, including decision-support systems and operations.

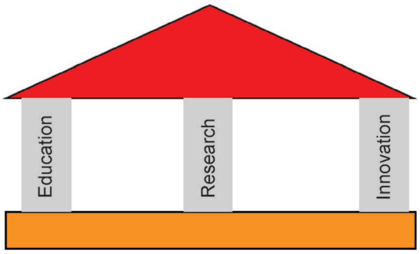

Figure 12. Three primary goals, or "pillars" in the structure of a university: education, research, and innovation.

5 The role of universities

Engineering education is vital for the activities, requirements, and scientific disciplines that constitute the framework for the industrial exploitation of marine structures (see Figure 11).

Most universities today have three primary goals, as shown in Figure 12. Historically, education was the first goal of universities: The original European universities were based purely on education (in theology). Today, governments still provide funding to universities with the primary goal of education. The second goal, basic and applied research, became important over the past couple of centuries. In recent years, universities have also been expected to contribute to innovation: for example, to facilitate the design or construction of structures, systems, products, processes, and services.

In relation to the field of marine structures, these three goals translate into the following roles:

- Training qualified candidates: Shipbuilding was previously an art (naval architecture), but today it is substantially an applied science, in which maritime engineers must master a wide range of scientific disciplines.
- Creating a window for scientific development: New discoveries and analysis tools usually come from universities. Examples include finite element method, CFD, fracture mechanics, and probabilistic methods.
- Cooperating with authorities and industry: Universities are often strong on developing analytical tools but weak on design. Universities need good external contacts in order to select promising research areas.

5.1 Curriculum in maritime technology

Curriculum should ensure interaction between the technical sciences and the natural sciences, and should offer a program that disseminates the most relevant knowledge and expertise to students. It is important to provide research-based education, so that cutting-edge knowledge and expertise are integrated into courses and projects. The aim should be to provide long-term sustainable knowledge, that is, to focus on fundamentals, and teach students to adopt a constructive and critical approach to research findings.

Since the field of marine technology is an international one, a university curriculum should allow students to gain international experience by actively participating in international study environments.

5.2 Research by engineering faculty

Research must produce new knowledge and understanding of marine technical problems. In addition, research activities should supply research-based emergency preparedness, in order to provide analysis and consulting services to the industry and to public authorities in predicting long-range problems, including impacts and possible solutions.

Since marine technology is a multidisciplinary subject, and a large amount of the relevant research takes place in other areas, the transfer of knowledge and experience from other fields to this one is an important task. Research results should be published in the open literature in order to promote international research cooperation. It is also important to disseminate research results through graduate students.

All good research should fulfill three criteria.

- Quality: Research without quality is worthless and a waste of time.
- Ambition: Research goals should be ambitious, and researchers should continuously identify research areas that may play an important role in the future.
- Relevance: Value is created by research application in the maritime industrial, educational, and public sectors.

5.3 International cooperation

International cooperation is essential between leading research centers, and especially between leading universities. A significant proportion of graduates should carry out part of their studies at recognized universities beyond their own, and the exchange of scientific personnel (i.e., guest professors) should be encouraged. Universities should promote publication in leading academic journals and participation in international conferences.

6 Conclusions

Climate change poses both risks to and opportunities in all parts of the maritime sector. It is an issue requiring urgent and extensive action from all parts of society, if the risk of serious damage to global prosperity and security is to be avoided. Thus, it is natural that maritime research is strongly focused on the reduction of emissions and on new renewable energy sources.

Shipping is in general the most energy-efficient mode of transport, so a shift from land-based transport of goods to ship-based transport could provide a significant advantage in reducing energy use. However, if increasing volumes of goods are transported by ship, greenhouse-gas emissions from maritime activities are projected to constitute a significant percentage of total human-produced emissions in the future, unless technological improvements occur.

In the foreseeable future, we will still need oil and gas. An increasing proportion of new hydrocarbon discoveries will be from offshore drilling in much harsher environments than we are accustomed to today. In addition, since the ocean acts as an energy concentrator for much of the sustainable energy Earth receives from the sun, it is not difficult to predict that in future, researchers will devote more emphasis to harvesting offshore wind energy and wind-driven wave energy. These technological developments will require maritime structures.

Factors common to maritime structures in general include:

- They are in a special environment—the sea—that poses unique requirements regarding loads, response and materials;
- Prototype testing is normally not possible, so analysis and design must be based on first principles;
- Loads and response can only be expressed in probabilistic terms;
- They participate in global activity, so they are governed by international laws and regulations; and
- They require high investments.

For these reasons, and in order to ensure growth in this field, there will be a strong future need for talent in marine-structure research and development.

Universities should contribute to the field of maritime structures by:

- Focusing on building fundamental scientific competence and providing long-term scientific research as a basis for innovation;
- Safeguarding academic freedom and scientific independence;
- Training professional skilled engineers in cooperation with the maritime industries;
- Possessing state-of-the-art knowledge and insight within the technical and natural sciences;
- Being an attractive partner for knowledge-building, in order to gather and exchange results and expertise; and
- Acknowledging that graduates are an important source of dissemination and utilization of research results.

References

1. International Maritime Organization. Prevention of air pollution from ships, MEPC 59/INF 10, April 2009
2. P. T. Pedersen, J. J. Jensen. Marine structures: Consuming and producing energy. In: C. B. Hansen, ed. *Engineering Challenges: Energy, Climate Change & Health*. Copenhagen: Technical University of Denmark, 2009: 6–17
3. I. M. V. Andersen. Full scale measurements of the hydro-elastic response of large container ships for decision support (Dissertation for the Doctoral Degree). Copenhagen: Technical University of Denmark, 2014
4. European Maritime Safety Agency. Annual overview of marine casualties and incidents. 2014
5. O. M. Faltinsen. *Hydrodynamics of High-speed Marine Vehicles*. Cambridge: Cambridge University Press, 2005
6. Y. S. Wu, C. Tian. A non-linear hydroelasticity theory of ships and its application. In: Edwin Kreuzer, ed. *IUTAM Symposium on Fluid-Structure Interaction in Ocean Engineering*. Berlin, Heidelberg: Springer, 2007: 307–320
7. J. J. Jensen. *Load and Global Strength*. Amsterdam: Elsevier Science Publ., 2001

8. A. Mansour, D. Liu. *Strength of Ships and Ocean Structur*es. Jersey City, USA: The Society of Naval Architects and Marine Engineers, 2008
9. P. T. Pedersen. Review and application of ship collision and grounding analysis procedures. *Mar. Struct*., 2010, 23(3): 241–262
10. F. Liu, W. Cui, X. Y. Li. China's first deep manned submersible, JIAOLONG. *Sci. China Earth Sci*., 2010, 53(10): 1407–1410
11. J. J. Jensen. Extreme value predictions using Monte Carlo simulations with artificially increased load spectrum. *Probabilist Eng. Mech*., 2011, 26(2): 399–404
12. International Association of Oil & Gas Producers. Worldwide statistics for ship collisions against offshore oil installations during 1980–2002. Risk Assessment Data Directory Report No. 434/16, 2010
13. A. F. de O. Falcão. Wave energy utilization: A review of technologies. *Renew. Sust. Energ. Rev*., 2010, 14(3): 899–918