Special Issue Article

Institution of MECHANICAL ENGINEERS

Journal of ENGINEERING FOR THE MARITIME ENVIRONMENT

Proc IMechE Part M:
J Engineering for the Maritime Environment
1–10

DOI: 10.1177/1475090220951027
journals.sagepub.com/home/pim
SAGE

On some fundamental issues about the safety of marine structures

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Abstract

Safety analysis and prediction of a marine structure is a very important field which has received attention from many scientists. Prof. R. Ajit Shenoi has made significant contributions in investigating various issues in this field. In this invited paper of recollection nature, a philosophical attitude is taken to re-examine some fundamental issues about the safety of marine structures with a purpose to identify the key issues to be solved in the future. It is intended to help young generations of scientists how to focus on more important problems related to the safety of marine structures.

Keywords

Safety, marine structures, systems approach, loading, resistance, strength deterioration

Date received: 30 March 2020; accepted: 26 July 2020

Introduction

It was a great pleasure to be invited by Prof. Yonghwan Kim, present Editor-in-Chief of Journal of Engineering for the Maritime Environment (JEME), to write a paper for this special issue dedicated to Prof. R. Ajit Shenoi, the founder of this journal.

I knew Ajit in May 1992 when my former supervisor, Prof. Yousheng Wu, visited University of Southampton. At that time, I was a post-doctorate research fellow in the Department of Aerospace Engineering, University of Bristol. I was working on the delamination of composite materials with tapered thickness with Prof. Michael R. Wisnom. Prof. Wu asked me to have a meet with him at Southampton and introduced me to Prof. W. Geraint Price, Prof. Pandeli Temarel and Prof. Ajit Shenoi. Since Ajit also worked in the areas of mechanics of composite materials and design of lightweight structures, he invited me to visit his laboratory and meet his team members. I was very impressed by the work done in his lab. After that, we established very good cooperation relationship and in the period from 1993 to 1995, I also worked in the investigation of dynamical response of composite hull of a minesweeper under underwater explosion which was close to his research field. In 1996, I sent my PhD student, Mr. Weibo Wang to Ajit's lab and worked with him for the PhD. In the summer of 2002, I took a sabbatical study with Ajit in the University of Southampton and we were collaborating on the use of fatigue crack propagation (FCP) theory to predict the fatigue life of marine structures instead of the S-N curve approach adopted in many design rules.[1,2]

Of course, Ajit's research scope is much wider than mentioned above and his research fields covered (1) mechanics of composite materials; (2) design of lightweight structures; (3) concurrent engineering and (4) structural health monitoring. All these are related to the safety of marine structures.

I started my research in naval architecture and ocean engineering since I returned to China Ship Scientific Research Center in 1993 and first worked on the prediction of ultimate strength of ship structures and then the fatigue life and finally the safety of marine structures. After more than 25 years investigation, I became far less confident than I just started to work on the issue whether our scientists or designers can really guarantee the safety of a marine structure. Prof. Ajit Shenoi and many other big names such as Torgeir Moan, Carlos Guedes Soares, Jeom Kee Paik also devoted nearly whole their academic lives to the safety of marine structures. Now it seems the time that we are going to leave this issue to young generations. In this paper of recollection nature, I would like to take a philosophical attitude to discuss some fundamental

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problems and to apply a systematic approach to identify the key issues to be solved in order to ensure the safety of a marine structure. This might be of some help to young scientists to focus their energy on more important problems related to the safety of marine structures.

The problem nature for the safety of a marine structure

It is well-known nowadays that the general problem for the safety of a marine structure or even any engineering structure can be expressed by the following mathematical model

$$G(t) = C(t) - D(t) > 0 \tag{1}$$

where C(t) is the capacity of the structure to resist the external loading and D(t) is the external loading acted on the structure and G(t) is called the limit state. In general, both C and D varies with time and they are random processes, possibly non-stationary. I leave this problem to be discussed in section 6 and temporarily we treat it using a deterministic approach. Whether we can calculate accurately the loading and resistance at a particular time for a given structure is fundamentally a selection problem based on scientist's personal philosophical belief. Different selection will have different attitude on the scientific research to this issue of ensuring the safety of marine structures.

Before the occurrence of quantum mechanics, all scientists believed that the world operates with deterministic rules and our human beings are able to disclose these rules. Therefore, people at that time believed that the nature of the world operation is deterministic and due to the lack of information, probabilistic theory was used to handle the uncertainty existed in the concrete issue. A typical example is the throw of a coin. Due to the difficulty in describing the initial condition, it is hard to predict the final result of head or tail. In dealing with such a type of gambling problems, the probability theory was born.[3] However, in order to explain the phenomena observed in the subatomic world, Bohr, Heisenberg and many other scientists had made another choice and they claimed that the fundamental nature of the microworld operation is random which is completely different from the macroworld operation. Of course, this worldview made many scientists unhappy including Einstein. Einstein and Bohr have debated this worldview for the rest of their lives and after that, physicists have been divided into two schools.[4] Up to now, the Copenhagen Interpretation is the main orthodox theory of quantum mechanics but another school of deterministic theory of quantum mechanics, known as Bohmian mechanics, co-exists[5,6] and recently new evidences have been found to support the quantum trajectory theory.[7]

Based on the above progress, the present author has made some study to these philosophical issues and come to the conclusion that they can be unified. His main argument was that the Einstein-Bohr debate was created by Bohr's over-claim. Bohr did not provide any proof to show that the nature of the microworld operation was random. Furthermore, Bohr's agnosticism to the question itself was in paradox with his scientific research behavior. The correct way of thinking should be as follows. Philosophically, we should believe that (1) no matter it is a macro world or a micro world, if it is finite, it is always worked deterministically, and the rules can be disclosed through scientific research of generations; (2) practically, due to the complexity of the problem and the limited ability of a human being to know the world, no matter it is a macro world or a micro world, uncertainty always exists and the rules we discovered can only be regarded as an approximation to the ultimate truth. The detailed arguments for this unification of Einstein-Bohr controversy was presented in Ref.[8]

Thus, back to the question whether the safety of a marine structure is deterministic or indeterministic (probabilistic or random), I recommend to select the deterministic worldview. This is the justification of our scientific research to any problems.

In terms of how to address the issue of the safety of a marine structure, we can take a system model. A general system usually consists of five elements, the system itself, boundary conditions of time and space, constraint conditions, input and output. If the system, constraint conditions, boundary conditions are given, the output is a function of the input. This function is defined as the transfer function. The task of the safety analysis for a marine structure is to determine the transfer function as accurate as possible.

However, due to the complexity of the practical engineering system and the limited time given to the investigator, it is impossible to consider all the influencing factors. Thus, how to identify quickly the most influencing factors becomes very important.[9]

Since it is very hard to quantify all the influencing factors and especially those related to human factors such as the manufacturing quality and measurement quality, C and D are best described as random variables. Traditionally, the characteristic values of C and D under a certain probability level such as 95% for resistance and 99% for loading are used to define the safety factor, that is,

$$F = C_c/D_c \tag{2}$$

If both C and D are treated as random variables, then only the probability of failure (P_f) can be calculated and $1\text{-}P_f$ is regarded as the reliability of the marine structure.[10] So in the reliability analysis of a marine structure, the essence is the calculation of the resistance C(t) and the loading D(t) as accurate as possible. It is our belief that scientific methods have the capability to perform these two tasks.

To identify the key factors through a system thinking

Brief Introduction to general system theory

Now let us discuss the issues how to calculate more accurately C(t) and D(t). When C(t) and D(t) are known, the calculation of P_f is standard and commercial programs are available.[10] Here I recommend the use of a system thinking to identify the possible factors affecting these calculations.

Von Bertalanffy was commonly regarded as the founder of general system theory (GST) with his milestone book.[11] According to him, every problem we encountered from concrete objects to abstract events or processes can be regarded as a system. He called this method a system thinking which is a new scientific paradigm. Using system thinking, we can know that the limit state function G is generally a function of other variables such as environmental factors, material factors, structural factors, loading factors[9] and each factor may be highly influenced by human beings. From statistics we knew that most of structural accidents are caused by human factors[10] but we do not have good theoretical tools to consider this influence.

Recently, it is demonstrated by Papageorgiou and Kamperi[12] that quantum probability theory developed by Yukalov and Sornette[13] may be able to overcome this problem since this theory can consider the influences of biases, emotions and feelings of participants. Basically, the probability for a composite prospect (π_j) can be written as

$$p(\pi_j) = f(\pi_j) + q(\pi_j) \tag{3}$$

where the first term is called utility factor which corresponds to the classical probability and the second term is called attraction factor which can represent the prospect's quantum interference. So instead of the classical probability theory frequently used in the reliability analysis of a marine structure, it is recommended to use quantum probability theory to do safety analysis for marine structures.

In using the system thinking, the decomposition and synthesis are the two general methods to be used and in carrying out these two processes, three principles need to be followed: the wholeness principle, the hierarchy principle and the decomposition-coordination principle.[14]

The principle of systemic wholeness refers to that the system is an organic whole composed of several elements with certain new functions.[14] The functions of the whole are greater than the simple addition of the functions of all elements. This principle of wholeness is different from the traditional theory of holism. The traditional holism does not encourage scientific research on elements, so it can be called the synthesis without analysis. The principle of wholeness is always connected with analysis and synthesis. Analysis is to decompose the whole into smaller parts for understanding and the cognition of parts is the main task of analysis. However, it emphasizes that during this process, some functions of the system may be lost and they should be brought back during the synthesis.

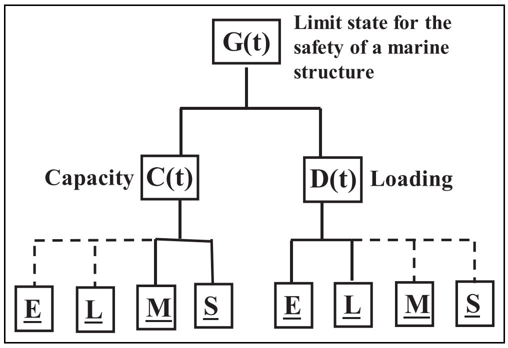

Figure 1. A hierarchy for the safety of a marine structure.

The hierarchy principle refers to that due to the differences in the elements that make up the system, including the differences in the way of combination, the quantitative differences of elements are arranged in the same level while the qualitative differences are arranged in the different level. This is defined as a hierarchy which is an arrangement of items in which the items are represented as being "above", "below", or "at the same level as" one another. The hierarchy for the safety of a marine structure is shown in Figure 1.[14]

The decomposition-coordination principle refers to the decomposability and coordination of the system.[14] That is, in order for a better understanding of the system, the system is first decomposed into a number of mutually connected and related parts. By studying and coordinating the relations of these parts, the function of the system can be optimized. Therefore, this principle is to emphasize the purpose of decomposition-coordination to optimize the overall function of the system by adjusting the relationship between subsystems and large systems. In this way, there is an iterative coordination process, in which the (local) optimization of each subsystem is limited by the parameters given by the superior coordination controller (or control mechanism) and related subsystems. The most difficult coordination problem is the coordination between local optimization and global optimization. Coordination can only be achieved through multiple feedback adjustments.

Scientific research is inseparable from analysis. Without analysis, it is impossible to go deep into the inside of things and analyze the details of things. Scientific research also should not be separated from synthesis. Without synthesis, it is impossible to understand the whole system of study or the lost functions among various elements. Thus, we can say that synthesis is the depth of analysis, but also the destination of analysis. It is a revolution and progress of scientific thought that the contemporary scientific research paradigm changes from analysis to synthesis and from classification to systematic synthesis. This system thinking is a very power tool for the study of the safety of a marine structure.

Key factors in the calculation of the resistance of a marine structure

Let us look at a typical scenario of marine structures working at sea shown in Figure 2, they can be categorized either as movable structures such as ships and fixed structures such as platforms or surface structures subjected to actions from winds and waves and underwater structures subjected to only deep sea pressure. But in terms of their capability to resist the external loading, the strength can be expressed by the following equation[9]:

$$C = f(\underline{M}, \underline{S}, \underline{L}, \underline{E}) \tag{4}$$

where $\underline{\mathbf{M}}$ are material factors, $\underline{\mathbf{S}}$ are structural factors, $\underline{\mathbf{L}}$ are loading factors and $\underline{\mathbf{E}}$ are environmental factors. Using such a systematic identification method, we will not miss any important factors to affect the system.

For a given state of the structure, many methods are available to calculate its ultimate strength such as analytical methods, semi-analytical methods and numerical methods[15] and most of the methods have been experimentally validated to be quite accurate, say within 10% of error. Therefore, the accuracy improvement to these methods are not so urgent. Since strength is greatly degraded by corrosion and fatigue crack and they are very sensitive to human factors such as the manufacturing quality and the maintenance, how to calculate accurately the degradation state of the corrosion level and the crack growth level are the key factors.

In general, we often thought that capacity C is independent of loading ($\underline{L}$), but only functions of material factors $\underline{M}$, structural factors $\underline{S}$, and environmental factors $\underline{E}$. However, in the fatigue crack growth process, the load amplitude and load sequence will also influence the crack growth result and the strain rate and temperature will also influence the material properties.[16] Therefore, strictly speaking, the capacity of a structure itself will also depend on the external loading. This interaction has often been ignored in the safety analysis.

Traditionally, we take material properties such as Young's modulus E, Poisson's ratio ν and yield strength σ_y as the fundamental parameters for calculating the ultimate strength. As micromechanics progresses, we know that they are functions of other micro parameters such as lattice structure and voids and now people can design and improve the material properties

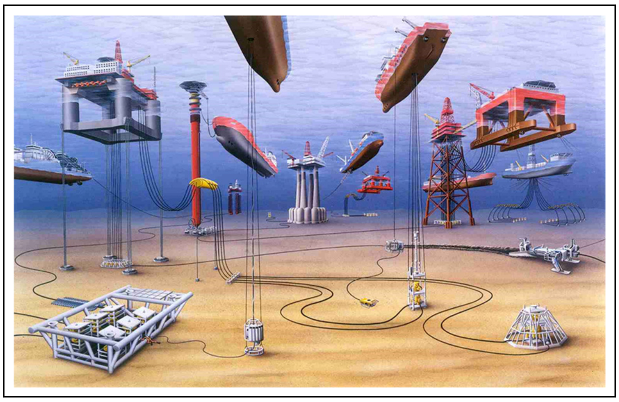

Figure 2. A schematic representation of various marine structures.

in the subatomic level. In this level, the human factors such as how and who to measure the property will influence the result. How to combine the micro scale models with macro scale models is a challenging problem. Since material properties are the functions of the same micro scale parameters, the dependence among different variables such as yield strength, ultimate strength, the Young's modulus and toughness needs to be considered.

In terms of fatigue, even up to now, all the rules in the classification societies are S-N curve based and this is basically the integration of the crack growth rate relation given by the following equation:

$$N_f = \int_{a_0}^{a_f} 1/\frac{da}{dN} da \tag{5}$$

The main implication of this relation is that the crack growth rate curve and the S-N curve are not independent if the failure definition is the same. Generally speaking, the crack growth rate curve is more fundamental while S-N curves are one level higher. Both initial crack size and final crack size will have influence on the S-N curves and thus without a clear specification of these two parameters, it is not so meaningful to use the S-N curves to represent the material properties.[17] That can explain the wide scatter observed in standard specimens.[16] Furthermore, using S-N curve approach to predict the fatigue life, the degradation effect of crack size on ultimate strength can not be considered.

So now more and more people are appealing to use the facture mechanics approach to calculate the crack growth under the fatigue loading process. However, in selecting the crack growth rate format, most people still select the Paris equation due to its simplicity. Certainly, this expression cannot explain the load ratio ($R = K_{min}/K_{max}$) and load sequence effects. So the accuracy of the fracture mechanics approach depends on the capability of the crack growth rate expression one used. This involves two problems to be determined, the crack driving force and the function format.

The early concept of the stress intensity factor K was proposed for linear elastic material. In order to take account of the nonlinear material behavior, people either use the J-integral or generalize the K concept by including a plastic zone length. Up to now, the following two problems have not been fully resolved:

1. Which quantity or quantities is (or are) the best parameter(s) as fatigue crack driving force? Strictly speaking, stress (σ), strain (ε), strain energy density (e), stress intensity factor (K), the J-integral (J) and the crack tip opening displacement (CTOD) can all be used and if they are properly defined as a single-valued function of load (P) or displacement (δ), they are equivalent. For describing the cyclic loading, two independent parameters such as (min, max) or (range, ratio) are necessary and they are functions of the crack length (a). Therefore, three independent parameters (two for cyclic loading and one for crack length) have to be used to describe the fatigue crack driving force. Any reduction such as from two-parameter of cyclic loading to one as done in Paris equation will induce some approximation and only be valid in a certain range.
2. Whether can the crack growth rate equation cover the whole fatigue crack process from microstructural level to macrostructural level, from crack initiation to unstable fracture? A single crack growth rate relation is certainly simple to handle but some people, for example, Miller,[18] have proposed to divide the whole process into three regions of microstructurally small crack, physically small crack and long crack and to use three crack growth rate curves to describe the whole crack growth process. In such a situation, determination of the two boundaries involves some difficulty. So strictly speaking, fatigue crack growth is a multi-scale problem and up to now, few researches have been seen in marine community to consider this issue.

Even just consider a single crack growth rate equation for macro cracks, tests showed that the general crack growth rate curve is of a sigmoidal shape as shown in Figure 3. When the applied cyclic load is lower than a threshold value, the crack will not propagate and the component will have infinite fatigue life. If the load level is slightly higher than the threshold, the crack will propagate but with a very low crack growth rate, so this is a high cycle fatigue (HCF) problem. When the maximum load in a cycle reaches the ultimate strength of a component, the component will fail in that cycle. This is a static collapse condition if the frequency effect is insignificant. If the maximum load in a cycle is slightly less than the ultimate strength, the static collapse will not occur in that cycle but crack will propagate in a high rate. This is a low cycle fatigue (LCF) problem. For LCF the maximum stress generally exceeds the yield stress of the material, so the nonlinear material behavior needs to be considered.

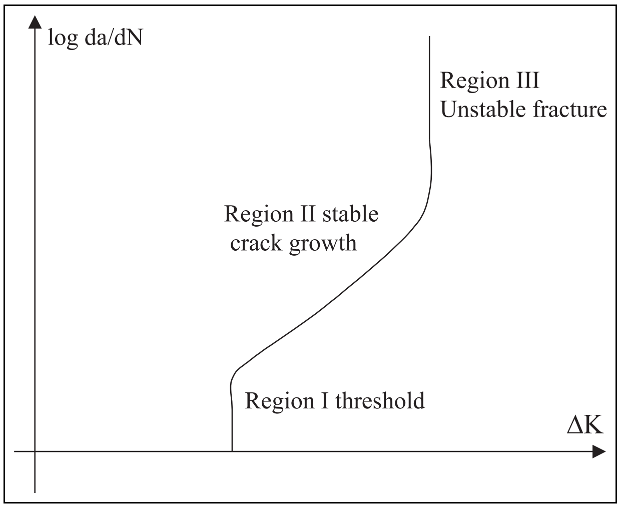

Figure 3. A representation of a complete crack growth rate curve.

Therefore, the general crack growth rate curve includes three regions. Region I is called threshold region and for stress intensities below ΔK_{th}, there is no crack growth. Region II is a stable propagation region while region III is an unstable region. In describing this general crack growth rate curve, at least four material parameters C, m, ΔK_{th} and K_c needs to be determined. How to determine more accurately these four material parameters should be the current focus of fatigue research for marine structures.[9]

Fatigue and fracture are our definitions of two failure modes for two ideal loading situations, constant amplitude loading to failure and monotonic increase loading to failure. Traditionally, these two problems are separately treated, that is, strength theory for fracture and S-N based theory for fatigue. However, the actual failure of a marine structure is a continuous process and in the fracture mechanics based approach, these two methods can be combined into one. For any variable amplitude loading a marine structure is subjected to, it is a crack propagation process from initial defect to unstable fracture. Thus, the structural strength attained in the unstable fracture condition can be taken as the ultimate strength of that structure. "$K_{max} = K_c$" is the condition for unstable fracture and K_c is the fracture toughness used to denote that condition. Whether K_c is a material parameter or a structural parameter needs to be further studied.

Corrosion will also affect the resistance and there are two types of corrosion, uniform corrosion and pitting corrosion and given the damage level of corrosion, the calculation of the strength degradation has no difficulty, but the prediction of corrosion damage with time is quite challenging. Our present understanding of the corrosion mechanism is still inadequate.[19]

Key factors in the calculation of the loading of a marine structure

The loading to a marine structure can be expressed by the following equation:

$$D = f(\underline{M}, \underline{S}, \underline{E}) \quad (6)$$

In this equation, material factors may only be relevant for some special structures such as hydroelasticity plays a significant role. In general, we are calculating the structural loading under winds and waves. Nowadays, for a given wind or wave condition, the loading can be calculated quite accurately using analytical, semi-analytical or numerical methods.[15] The key difficulty is the determination of the design load for the next 20 to 40 years for the marine structure. It is well-known that due to the technology progress, the influence of the collective human behavior on climate change becomes larger and larger. The quick increase of the carbon dioxide content in the air, the rise of the sea level and more frequent extreme environmental disasters in recent years provide some evidences for this statement. Therefore, extrapolation from the past statistics to derive the future design load involves a large uncertainty. In order to reduce this uncertainty, some sort of feedback model which can take account of the influence of the collective human behavior on earth is needed.

As mentioned, marine structures have two types, fixed platforms and movable ships. Due to the progress of weather forecasting, people can know the extreme wind and wave state at some early time say one to three days earlier before its occurrence and this gives the chance for the movable structure to avoid the encounter of extreme sea state through changing the course of cruise. Therefore, for such a type of structures, we can guarantee the maximum loading not to be exceeded through management.

For the fixed structure such as a platform, traditionally the structure is designed directly against the extreme sea state. This may not be the most cost-effective way to handle the extreme sea state. Other methods such as to design the structure with a diving capability may be worth exploring. Before the typhoon arrives, the top part of the platform may dive to 50m or 100m below the surface in order to avoid the encounter of the extreme wind and waves. This might be more cost-effective especially when no people are required to stay on-site for operation.

In terms of the conventional wind and wave loading, accidental loads such as explosion, collision and grounding may be more severe and for this type of loading, the prevention procedure may be more effective than increasing the resistance.

A practical example for illustration

Let us take a platform as an example to demonstrate how to apply a system thinking approach to analyze the safety of this platform.

A design company (A) is contracted from a government (B) to design, manufacture and install a platform at sea location (C) and this platform will be operated by company (D) owned by government (B). In the design contract, it is specified that the platform should work safely for the next 25 years after installation. And our question now is that whether this platform is really safe in the next 25 years or how the operator (D) makes efforts to realize this target.

The life cycle of a platform is generally divided into five stages, design, manufacture, installation, operation and decommission. Each stage will involve quite a lot of persons to participate and the quality of the finished work by these professionals have significant impact on the safety of this platform.

In the design of the platform, the first task of the design team is the determination of the design load. The current practice is to collect the historical weather data at this site (C) and apply a statistical analysis method specified in the design rule to derive the design load. After that, the structural designer will design the platform with a predefined probability of failure. In order to reduce the human errors in the design and calculation, a classification society is involved to approve the design. In this stage, the methods to calculate the loading and resistance play a significant role.

Then, the design company will sub-contracted to a manufacturer (E) to manufacture and install the platform to the site (C) and after the test operation, the platform is handed to company (D) for commercial operation. Certainly, the material properties and manufacturing quality of the structure are very important. The on-site installation of a platform in the severe sea state is also a challenging task and will after the quality of the installation. In order to guarantee the qualities in these two stages, the classification society is also involved and most of the problems at these two stages can be detected and removed in the test operation. Both A and E have finished their duties now and from onwards, the safety of this platform is supposed to be in the hand of D. Let us help D to identify the potential risks to the safety of this platform.

The first risk is certainly the extreme weather such as hurricanes and tornadoes. Theoretically speaking, if the platform encounters a state of extreme weather more severe than the design state, the platform will fail. The occurrence of this situation is certainly not in the hand of D and even any stakeholders. However, if the platform is designed to have the capability to lower the platform below the sea surface, the risk can be avoided. Therefore, D can play some role if he sets the requirement in the design contract.

The second risk is by accidents. For example, the platform is collided by a sailing ship due to the fog. In order to avoid this risk, some sort of automatic detection and warning measures and protection measures may be effective. The collision analysis is helpful to reduce this risk.

The third risk is the poor inspection and maintenance. Theoretically if the weather condition does not exceed the design state, the platform should be safe. However, after installation, the platform is subjected to external fatigue loading and corrosive environment. Cracks may occur at some high stress locations and all the steel structures are corroded. The actual structural resistance is degrading all the time. If this problem is not detected immediately and no repair measures are taken, the platform can collapse at a load level lower than the design load. So the calculation of the actual resistance considering the influences of fatigue cracking and corrosion is useful at this stage but the most effective measure is certainly the good inspection and maintenance. In order to make sure the maintenance is adequate, the classification society is also requested to be involved.

The fourth risk is the attack from human beings. Suppose the site (C) is located in a disputed area between two countries of government (B) and government (F), and if government (F) decides to attack the platform, then, operator (D) is hard to manage this situation and the safety is in the hands of politicians. A recent airplane accident of Boeing 737-8KV of Ukrainian flight PS752 is a typical example of this risk and in the future, this type of risks may become more and more dominant.

Some potential problems from a system perspective

As is well-known, the whole universe is a connected web and everything including a life or a lifeless object is connected with the rest of objects through various forces and at the moment we only know four types of forces existed between two objects, the gravitational force, the electromagnetic force, the weak nuclear force, and the strong nuclear force. We are not sure whether these four types of forces are complete or not. It is still possible that new type of forces may be found and this will certainly affect the system behavior. Secondly, how many substances exist in the universe? The early materialist philosophy thought that matter made of inseparable atoms is the only fundamental substance in the universe, but later, we have found that atom can be further decomposed into other small particles such as leptons, quarks, and gluons. Now we are even less sure whether these smaller particles than atoms are inseparable or not. From special relativity theory, Einstein pointed out that any particle with mass is equivalent to energy, $m = E/c^2$, where c is the speed of light, thus, energy may be more fundamental than particles. In the development of cybernetics, the concept of information was used and Norbert Wiener defined information as neither matter nor energy,[20] so what is it? Afterwards, in explaining the expansion of the universe, dark matter and dark energy have been introduced,[21] so now there are five physical substances (matter, energy, dark matter, dark energy, information) existed in the system we are going to study including the system of the safety of a marine structure, what are their relations among the five substances? How many fundamental substances? Any system is a part of the universe and it is an open system. An isolated system or a closed system is a simplified assumption and it may be valid for some particular problems. At the moment, we have some measures to prevent the exchange of matter and some types of energy and information, but no measures to prevent the exchange of other types of energy and information, and no measures to prevent the exchange of dark matter and dark energy at all. Whether these exchanges will affect the system behavior is also the issue we need to concern. We may continue to neglect the influences of dark matter and dark energy but the influence of information on the stakeholders must be considered since each person has a mobile phone and can receive information instantaneously. It is well-known that stakeholders have great influence on the safety of marine structures. From these questions, we can realize that the issue of the safety of a marine structure is also related to the frontier subjects such as information science and technology, cosmology, general relativity and quantum mechanics. We should closely monitor the progresses in these fields in order to provide more accurate prediction for the safety of marine structures.

Challenges for advanced safety studies of marine structures

The problems potentially encountered in the analysis of the safety of a marine structure have been identified in previous sections by applying a system thinking approach and in this section, some challenges for advanced safety studies of marine structures are summarized again for an easy reading.

The first challenge is the unification of deterministic thinking and the probabilistic treatment for the safety analysis of marine structures. Currently there are two different beliefs on the system behavior, one is the deterministic belief that the operation of any system is governed by deterministic laws and our human beings are able to reveal these laws and the second belief is that fundamentally speaking the operation of any system is random but we can find some statistical laws for the collective behavior of elements. From the present author's point of view, the second belief is preventing the deepening researches. With the first belief, the scientific research can be carried out in two directions. One is to solve the engineering problem with current knowledge of influencing factors. It is obvious that for a complex problem such as the safety analysis of marine structures, many influencing factors have not been identified and in this case, the probabilistic method is more advanced than the deterministic method in dealing with the uncertainty. In particular, the structural safety is often associated with accidents which are the result of volatile, uncertain, complex and ambiguous (VUCA) environmental and operational conditions. The utilization of risk-based methods along with the probabilistic characterization of all aspects is currently the best way to effectively manage VUCA environments and ultimately resolve such challenges.[22,23] However, we should not stop here and further researches to identify more influencing factors should be carried out. For example, for the prediction of fatigue life, present design rules are mostly based on the S-N curve approach and in this approach, the initial defect size, the final crack size, the load ratio and the load sequence are all ignored but many experiments have demonstrated that these factors are very important to fatigue life. In order to consider these factors, a fracture mechanics based approach is developed. These two lines of research should compliment with each other rather than the conflict of two philosophical beliefs. In equation (1), both C(t) and D(t) are treated as random variables but strictly speaking, they are random processes. To estimate the statistical properties of the random process is much more complex since they are non-stationary. The effect of this simplification from random processes to random variables is certainly worth further investigating.

The second challenge is the environmental prediction considering the feedback influence of human behavior. The safety design of a marine structure mainly involves three aspects of calculations, to predict the future environmental data based on past measurement, to calculate the design load based on the predicted future environmental data, to calculate the structural response and damage based on the design load. In the past, most of the researches focused on the second and third problems and the linear extrapolation method is used for the first problem. However, due to the technology development, the influence of human behavior on the environment becomes more and more important, and the linear extrapolation is found to be far away from the real situation. This feedback influence should be considered. Furthermore, ocean movement is a global phenomenon and it may be influenced by other stars in the solar system. Similar as in the hydrodynamics calculation, we need to analyze the fluid field much larger than the ship, if we want to predict the ocean movement better, we may need to analyze the whole solar system.

The third challenge is the integration of new developments in other fields of sciences into the safety analysis of marine structures. From a system point of view, the whole universe is the largest system and any other system we study is a subsystem of this general system. All the subsystems we can study are open systems which can have exchange with the environment of potential five substances (matter, energy, dark matter, dark energy, information), how to determine the exchange of these five substances at the boundary is a big challenge. Furthermore, most of the laws are derived under the condition of a closed system or an isolated system which does not exist in reality. Thus, what are the application range of these laws should be scrutinized. Of course, these fundamental problems are very challenging and may take a long time to be progressed in other subject fields. However, some of the cutting-edge research tools and technologies, such as ship big data, artificial intelligence, ship digitalization, new materials (composite, very high tensile steel), can be immediately applied to the safety analysis and prediction of marine structures.

Summary and conclusions

Safety of marine structures is very important and the problem has been investigated for many decades and many scientists such as Caldwell, Ueda, Mansour, Faulkner, Hughes, Pedersen, Moan, Guedes Soares, Melchers, Paik and Shenoi have devoted their whole academic lives to develop more accurate methods to calculate the resistance, the loading or the probability of failure for a given marine structure. In this special issue to acknowledge the great contributions made by Prof. Ajit Shenoi, I took a systemic approach to reexamine the nature of the problem based on my own research experience with an intention to identify some key areas for future research. My main points can be summarized as follows:

1. The safety of a marine structure is a very complex system issue and the designer cannot guarantee the safety of the structure. Other stakeholders and even the general public could also play a big influence on the result. In the platform example, the politicians are identified as a significant player in the safety of this platform which are outside of the designers and operators.
2. In recognition to this complexity, a scientific researcher could select a deterministic worldview or an indeterministic (probabilistic) worldview. This selection may not have much difference for the short-term practical application but for the long-term understanding, a deterministic worldview is more logically consistent for the justification of scientific research and beneficial.
3. In order to guarantee the safety of a marine structure, the extreme loading avoidance procedure may be much more cost-effective than increasing the resistance of the structure. Therefore, human factors must be considered in all the processes relevant to the safety of the marine structure. Mathematical models which can explicitly consider these human factors are in urgent need. Quantum probability theory can act as a starter.

4. In the determination of the design load for a marine structure working for the next 20 to 40 years, traditional extrapolation method based on past history data is at risk and one needs to use a feedback model to consider the influence of collective human behavior on the earth on wind and waves.
5. In comparing the resistance and load calculations, the uncertainty in loading is much higher than that in resistance, so further reduction of the uncertainty in resistance calculation is not very effective to the improvement of the safety of marine structures. As we know the accuracy of predicting the safety of a marine structure based on equation (1) is approximately equal to $\sqrt{\varepsilon_c^2 + \varepsilon_D^2}$, where ε_C and ε_D are the accuracies of loading prediction and resistance prediction, respectively. Presently the accuracy for the resistance prediction may be less than 10% while the accuracy for the loading prediction may be higher than 20%. Thus, the reduction of ε_C is much more effective than the further reduction of ε_D.
6. In order to improve the accuracy of resistance calculation, accurately predicting the time degradation factors such as the corrosion progress or the crack growth should be the key focus. These results can be combined with the existing calculation methods for the ultimate strength calculation. A simulation software to model the whole degradation process of the structural resistance would be helpful.
7. Any system is a part of the universe and it is connected with the rest of the universe through the exchange of matter, energy, information, dark matter and dark energy. Whether these exchanges will affect the system behavior is also an issue we need to concern. In particular, we know that information can affect the human behavior significantly and since almost every stakeholder has a mobile phone and stakeholders play some quite important roles in ensuring the safety of a marine structure, this influence should be considered. Therefore, the issue of the safety of a marine structure is also related to the frontier subjects such as information science and technology, cosmology, general relativity and quantum mechanics. We should closely monitor the progresses in these fields in order to provide more accurate prediction for the safety of marine structures.

Acknowledgement

The author appreciates very much to two anonymous reviewers for the comments and suggestions to this paper.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the General Program of National Natural Science of China Grant No. 51879157 and the "Construction of a Leading Innovation Team" project by the Hangzhou Municipal government.

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References

1. Cui WC and Shenoi RA. On the use of FCP theory to predict the fatigue life of ship structures. In: *Proceedings of international symposium on naval architecture and ocean engineering*, Shanghai, China, 23–26 September 2003, pp.8-1–8-9. Shanghai: Shanghai Jiao Tong University Press.
2. Cui WC. A feasible study of fatigue life prediction for marine structures based on crack propagation analysis. *Proc IME M J Eng Marit Environ* 2003; 217(1): 11–23.
3. Debnath L and Basu K. A short history of probability theory and its applications. *Int J Math Educ* 2015; 46(1): 1–23.
4. Whitaker A. *Einstein, Bohr and the Quantum Dilemma - From Quantum Theory to Quantum Information*. 2nd ed. Cambridge: Cambridge University Press, 2006.
5. Bohm D. A suggested interpretation of quantum theory in terms of hidden variables. *Phys Rev* 1952; 85: 166–189.
6. Szabo LE. Quantum mechanics in an entirely deterministic universe. *Int J Theor Phys* 1995; 34(8): 1751–1766.
7. Minev ZK, Mundhada SO, Shankar S, et al. To catch and reverse a quantum jump mid-flight. *Nature*. Epub ahead of print 3 June 2019. DOI: 10.1038/s41586-019-1287-z.
8. Cui WC. A simple idea on the unification of Einstein-Bohr controversy. *Ann Soc Sci Manage Stud* 2019; 2(5): 120–121.
9. Cui WC. On a systematic identification of key factors on safety of marine structures and their potential treatment methods. OMAE2017-62294. In: *Proceedings of the ASME 2017 37th international conference on Ocean, Offshore and Arctic Engineering (OMAE2017)*, 25–30 June 2017, Trondheim, Norway.
10. Melchers RE and Beck AT. *Structural reliability analysis and prediction*. 3rd ed. Hoboken: Wiley, 2017.
11. Bertalanffy LV. *General system theory: foundations, development, applications*. New York: George Braziller, 1968.
12. Papageorgiou E and Kamperi EE. Quantum-based decision making under uncertainty in the presence of entanglement for the development of optimal strategies in engineering design. *Stud Eng Technol* 2017; 4(1): 35–52.
13. Yukalov VI and Sornette D. Quantum probability and quantum decision-making. *Phil Trans R Soc* 2015; 374: 1–15. https://doi.org/10.1098/rsta.2015.0100
14. Wei HS and Zeng GP. *Systematicism-A philosophy of system science*. Beijing: Tsinghua University Press, 1995.
15. Hughes O and Paik JK. *Ship structural analysis and design*. Jersey City, NJ: The Society of Naval Architects & Marine Engineers, 2010.

16. Xu TD, Wang MQ and He HM. Mechanical property-tensile strain rate curve of metals. *Phys Exam Test* 2019; 37(2): 54–59 (in Chinese).
17. Cui WC, Huang XP and Wang F. *Towards a unified fatigue life prediction method for marine structures*. Hangzhou: Zhejiang University Press and Springer, 2013.
18. Miller KJ. A historical perspective of the important parameters of metal fatigue and problems for the next century. In: Wu XR and Wang ZG (eds) *Proceedings of the seventh international fatigue congress (Fatigue'99)* Beijing, China, 8–12 June 1999, pp.15–39. Beijing: Higher Education Press.
19. Melchers RE. Progress in developing realistic corrosion models. *Struct Infrastruct Eng* 2018; 14(12): 1–11.
20. Wiener N. Cybernetics: or control and communication in the animal and the machine. Cambridge, MA: MIT Press, 1948.
21. Arun K, Gudennavar SB and Sivaram C. Dark matter, dark energy, and alternate models: a review. *Adv Space Res* 2017; 60: 166–186.
22. Paik JK. *Ultimate limit state analysis and design of plated structures*. 2nd ed. Hoboken: John Wiley & Sons, 2018.
23. Paik JK. *Advanced structural safety studies with extreme conditions and accidents*. Germany: Springer, 2019.