TOWARD A MORE RATIONAL FIRST-PRINCIPLE-BASED STRENGTH ASSESSMENT SYSTEM FOR SHIP STRUCTURES

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Abstract

This paper outlines a more rational first-principle-based strength assessment system (FPB-SAS) for ship structures, which allows integration of all relevant aspects of technology and considers interactions among various factors affecting the ship structural strength. The basic considerations of the FPB-SAS system are: (1) the damage is of accumulative nature; and (2) the accumulated damage will gradually decrease the strength. So for a given loading history with known sequence, the strength is a function of time (or number of load cycles) and the system can provide the complete picture of this variation. For a given random loading with only statistical characteristics, the system can provide the statistical characteristics of strength at any instant of time. In comparing with the current strength assessment procedure adopted by ship classification societies, this system (1) fully integrates the fatigue strength assessment with ultimate strength assessment; (2) is open and can include any relevant aspects thus it can be easily updated to the latest level of technology development; (3) could be more strictly first-principle-based and does not rely on the past experience as largely as before. Some key problems to be resolved for the development of such a system are also pointed out.

Key Words: Strength Assessment; Ship Structures; First-Principle-Based; Accumulative Damage.

1. INTRODUCTION

Traditional strength assessment procedure implemented in ship structural design rules is highly experience-based due to the complexity of the structure and its operational environment. With the fast development of computer technology, software and hardware, the possibility to accurately assess the ship structural strength based on the strict principles of mechanics increases. In response considerable research has been done into first-principle-based design criteria, e.g. [1,2]. Substantial changes made in ship classification rules in the last two decades are the results of these efforts.

However, it is widely recognized that even the latest ship classification rules are still far away from the "real" first-principle-based. An important evidence of this statement is that the strength is assessed in different global (hull girder) and local (stiffened panel and welded joints) levels and in different failure modes (yielding, buckling and fatigue), e.g. [3]. The relationship among them is not considered and the relative success of this strength assessment procedure is largely based on past experiences. Furthermore, in most of the fatigue strength assessment methods that are S-N curve based, the effects of initial defects and load sequence have been ignored and the damage state has not been specified. These together with some other factors that are also not properly accounted for lead to large scatter of the predicted fatigue life, e.g. [4]. Significant improvements with regard to the fatigue strength assessment methodology for ship structures are required [5].

The effect of fatigue damage on ultimate strength is also not considered. Thus, for existing ship structures operated for some time period, the strength analyzed may not represent the actual strength a ship structure possessed. Risk analysis based on current strength analysis procedure is then rather uncertain. Inspection and maintenance decision based on the assessment may not reflect the actual "optimum".

The purpose of this paper is to propose a more rational first-principle-based strength assessment system (FPB-SAS) for ship structures. Similar efforts have also been seen by some classification societies, e.g. NK [6]. The general requirements and the system structure are described. The advantages and the potential utility of the system are also discussed. Finally, some key problems to be resolved for the development of such a system are pointed out.

2. BASIC REQUIREMENTS AND TERMINOLOGIES

For the more rational first-principle-based strength assessment system, it should at least satisfy the following two requirements:

(1) At least in principle it should be fully mechanics based and it should reflect the actual failure process according to the actual failure mechanism. The interactions among different factors, which cause damage and failure, should be taken into account.

(2) The system must be open and allow the integration of latest developments in every aspect relevant to the strength assessment.

The following three concepts are fundamental to the FPB-SAS system and they are redefined as follows:

Damage: Any crack type defects which affect the structural strength are called damage. These include initial cracks embedded in welding joints, fatigue cracks, accidental damages induced by collision, grounding and explosion etc.

Strength/Ultimate Strength: Strength can be defined in many different levels, e.g. local strength, global strength, serviceability strength and ultimate strength. In FPB-SAS system, the strength is often referred to as ultimate strength which is the maximum structural capacity a structure possesses.

Loading History/Random Loading: The loading history in the FPB-SAS system specifically denotes the loading history with known sequence. For unknown sequence, it is called random loading.

3. DESCRIPTION OF THE FPB-SAS SYSTEM

The overall structure of the FPB-SAS system can be shown in Fig.1. The system consists of five modules with mutual relationships: Data, Load, Damage, Strength and Recommendation. The purpose, functions and general contents of each module are briefly described as follows.

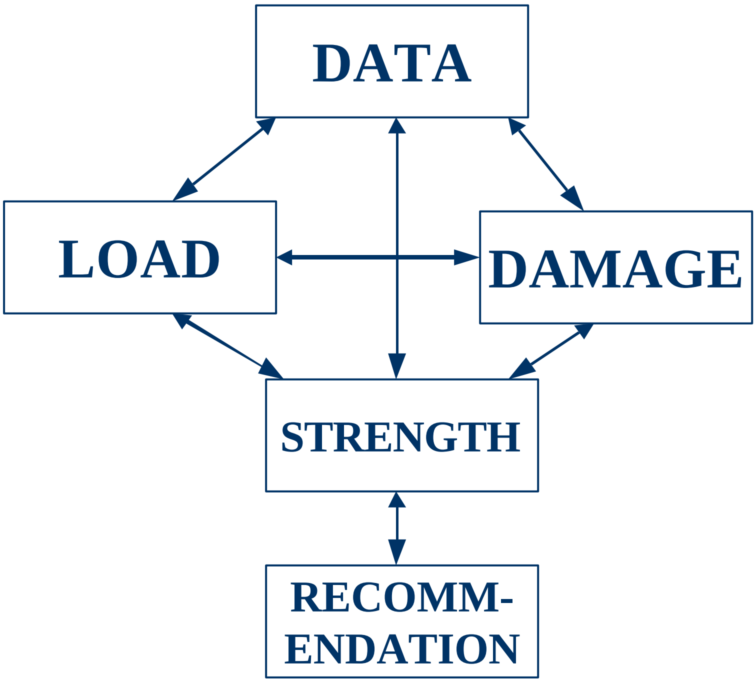

Fig.1 Overall Structure of the FPB-SAS System

Data module inputs all the necessary information for the strength assessment. The data must be organized in a scientific way and any repeat must be avoided. User-friendly interface must be provided for a modern software system. For a ship structure, the data may be organized into the following three groups:

- Structural geometry and material specification;
- Operational environment including cargo loading and sea condition;
- Damage state including accumulated corrosion and fatigue damage and accidental damage.

Load module calculates all the loads acting on the ship structure with given damage at any instant over the lifetime. Most types of damage may not affect the load calculation but some types of damage such as breaking holes caused by collision and grounding will affect the load distribution in ship structures and this effect should be considered.

Damage module calculates the accumulated damage for a given load history. Damage includes many types such as fatigue, corrosion and accidental damage if any. Fatigue damage should be calculated on a cycle-by-cycle basis simulating the actual failure process according to the actual failure mechanism. Crack propagation theory should be employed for this calculation instead of the S-N curve approach [7]. This allows a clear definition of the fatigue damage state to be obtained by integration over the loading history. The effects of initial defects and load sequence have to be accounted for [8].

Appropriate corrosion model should be employed to model the corrosion damage including uniform thickness decrease and pitting corrosion [9]. The possible interaction between corrosion and fatigue could be accounted for in the crack growth rate relation. If the ship has suffered from some accidents such as collision, grounding and explosion, the accidental damage should also be calculated.

Strength module calculates the residual ultimate strength of ship structures with damage. Different approaches can be used. These include:

- Analytical formulations derived based on the assumed stress distribution at failure. This is basically the extension of Caldwell method. A typical reference is Paik and Mansour [10] and their formulations have been extended by Qi and Cui [11] to asymmetric transverse sections.
- Idealized Structural Unit Method (ISUM)/Plastic Node Method (PNM) or Smith method for progressive failure analysis [2]. Using this type of methods, the ultimate strength calculations of beam-columns, unstiffened plates and stiffened panels are the key elements. Cui and his colleague [12-13] have showed that the ultimate strengths of unstiffened plates and stiffened panels can be predicted using a simplified analytical method under combined loading.
- Full finite element analysis [14]. The main difficulty in this method is to introduce the appropriate failure criteria into the analysis and to handle the post-buckling behavior. Some success has been seen but due to its very time consuming, it is not suitable for routine assessment.

Many references can be found to use analytical or ISUM approaches to calculate the ultimate strength for intact ship structures, some references can also be found to calculate the residual ultimate strength considering large damage induced by collision and grounding [2], but few references could be found to calculate the residual ultimate strength considering the distribution of small fatigue cracks [15]. This requires further study.

Recommendation module is to make some recommendation or conclusion based on the calculated residual ultimate strength. For example, whether the newly-designed (or built) ship structure has the adequate safety margin over the lifetime? Whether some repair actions are needed for some part of the structure and over a certain period of operation time? What is the optimal inspection planning? Risk analysis by considering future operation and environmental conditions should be based on this strength assessment results which have considered the influence of damage due to past operation history.

4. ADVANTAGES AND POTENTIAL UNILITY OF THE FPB-SAS SYSTEM

In comparing with the existing strength assessment procedure implemented in ship classification rules, the FPB-SAS system is a more rational first-principle-based. It has the following distinguished advantages:

(1) It allows easy tailoring of the complexities in each module. In principle, it could be more strictly first-principle-based, but in practice certain level of simplifications still need to be accompanied with.

(2) It is an open system which allows easy integration of the latest development in relevant researches.

(3) The effect of the accumulated damage on ultimate strength and the interactions among various factors affecting the strength can be accounted for.

(4) The effects of initial defects and load sequence on fatigue damage and thus on ultimate strength could be taken into account.

(5) The statistical characteristics of the ultimate strength under random loading may be estimated using computer random number generation (RNG) system.

The FPB-SAS system can be viewed as a “numerical testing machine” for structural strength. It can be used in following three situations:

- Strength prediction for new ships;
- Strength assessment for existing ships;
- Structural monitoring system for operating ships.

5. KEY PROBLEMS TO BE RESOLVED FOR THE DEVELOPMENT OF THE FPB-SAS SYSTEM

With the fast development of computer technology, it is the time now to develop a more rational first-principle-based strength assessment system for ship structures. However, current technologies have not been developed to such a level that the FPB-SAS system can be implemented with sufficient accuracy. For this purpose, more researches are needed for the following key problems:

(1) Accurate load calculation for intact and damaged ships;
(2) To establish an accurate crack growth rate relation covering at least from physically small crack to long crack regime;
(3) To establish an accurate corrosion model considering the corrosion protection system;
(4) Rational calculation methods and standard code for ultimate strength of typical ship structures to reduce the scatter of the present estimations.
(5) Residual ultimate strength analysis for damaged structures with particular emphasis on fatigue damage.

6. SUMMARY

In this paper, a more rational first-principle-based strength assessment system (FPB-SAS) for ship structures has been proposed. Its requirements, advantages and potential utility have been discussed. Key problems to be resolved for the development of such a system are pointed out. It is the authors' hope that in near future such a system can be developed and employed by ship classification societies.

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