COMPUTATIONAL MECHANICS
WCCM VI in conjunction with APCOM’04, *Sept. 5-10, 2004, Beijing, China*

Computer Simulation of Ultimate Strength Degradation of Ship Structures by Corrosion and Fatigue

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Abstract Current ship structure strength assessment procedures used by ship classification societies are mostly experience-based. The degradation effects of damages including fatigue, corrosion, collision and grounding on ultimate strength are seldom taken into account. Cui and Wu [1] proposed a more rational ship structure strength assessment method, First-Principle-Based Strength Assessment System (FBP-SAS), which take all damages into account. The calculation results depend on the input data and the input data depend on the aim of assessment. For newly designed ships, statistical damage data and loading data can be used and the calculating results are reliability results. For inspecting the ship in service, the actual damage data based on measuring can be inputted and the calculating results are the ship structure’s actual residual ultimate strength. The purpose of this paper is to address how such a computer simulation system is developed and what problems need to be solved in order to realize practical application. Corrosion and fatigue are two main factors for strength degradation. Based on the recent research work carried out in authors group, the ultimate strength degradation of ship structures by corrosion and fatigue is studied in this paper and this result acts as a demonstration to the FPB-SAS method.

Key words: Strength assessment; Computer simulation; Fatigue crack; Corrosion; Damage

INTRODUCTION

Assessing ship structure’s strength exactly can reduce the ship’s manufacture and maintenance costs, and increase ship’s life and safety. For these purposes, each ship classification society has provided relatively integrated ship structure strength assessment methods. Also those assessment methods have achieved great successes in practical application, although they are still far from perfection.

Current ship structure assessment procedures implemented in ship structure design rules are highly experience-based due to the complexity of ship’s structures and working conditions. 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). The relationship among them is not considered and the relative success of these strength assessment procedures is largely based on past experiences. Furthermore, in most of the fatigue strength assessment methods, which 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, which are also not properly accounted for, lead to large scatter of the predicted fatigue lives. Significant improvements with regard to the fatigue strength assessment methodology for ship structures are required. Similar situation also holds for corrosion.

The degradation effects of damages including fatigue, corrosion, collision and grounding on ultimate strength are 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 procedures is then rather uncertain. Inspection and maintenance decision based on the risk assessment may not reflect the actual “optimum”.

The unsatisfactory situation of the strength assessment for ship structures is mainly due to the complexity of the structure and its operational environment. A strict assessment process involves much of the computation effort. 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 to this possibility, Cui and Wu [1] proposed 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.

By FPB-SAS method, calculating ship structure’s ultimate strength with the effect of damage is one of the most important tasks. Ship structure’s strength should be assessed based on mechanical calculations on damage instead of experience. But at present, it is still difficult to calculate some damages by analytical methods. Probabilistic and statistics tools are still useful in FPB-SAS method.

The purpose of this paper is to address how such a computer simulation system is developed and what problems need to be solved in order to realize practical application. Corrosion and fatigue are two main factors for strength degradation. Based on the recent research work carried out in authors group, the ultimate strength degradation of ship structures by corrosion and fatigue is studied in this paper and this result acts as a demonstration to the FPB-SAS method. The FPB-SAS method requires that the inspection and repair processes should be adequately taken into account. The effect of inspection and repair are also taken into account.

DESCRIPTIONS OF FPB－SAS

1. Basic concepts Before describing the FPB-SAS method, it may be useful to redefine the following concepts, which are particularly important in FPB-SAS method.

1)Damage: Any defects, which affect the structural strength, such as initial damages (e.g. initial cracks embedded in welding joints, weld residual stress, initial defection etc.), accumulative damages (e.g. fatigue cracks, corrosion, etc.), accidental damages (e.g. collision, grounding, explosion etc), are called damage.

2)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 method, the strength is often referred to as ultimate strength, which is the maximum structural capacity a structure possesses.

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

2. Assessment procedure of FPB_SAS The overall analysis flow of the FPB-SAS method is shown in Fig.1. The assessment procedure consists of five modules, Basic Data Input, Load, Damage, Strength Assessment and Recommendation. The purpose, functions and general contents of each module are briefly described as follows.

1)Basic Data Input: module inputs all the basic 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 parameters: Unstiffened plate, stiffened panel and beam-column are the basic elements to constitute the ship’s hull. We should number all the elements and input each element’s basic data before assessing structures’ strength. Those basic data include geometry, material parameters, corrosion type, crack type and element coordinates.
- Initial damage data: All the corrosion types and fatigue crack types are numbered at first. We should input basic parameters of each type of corrosion and fatigue crack in this module. These parameters can be transferred according to the type number. Other damage parameters such as grounding and collision should also be inputted in this module if existed.
- Statistical data: FPB-SAS method can unify deterministic and probabilistic analyses. If we input the statistical data, the system will output statistical results.

2)Load module: calculates all the loads acting on the ship structure with given damage at any instant over the lifetime. Most types of damages 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.

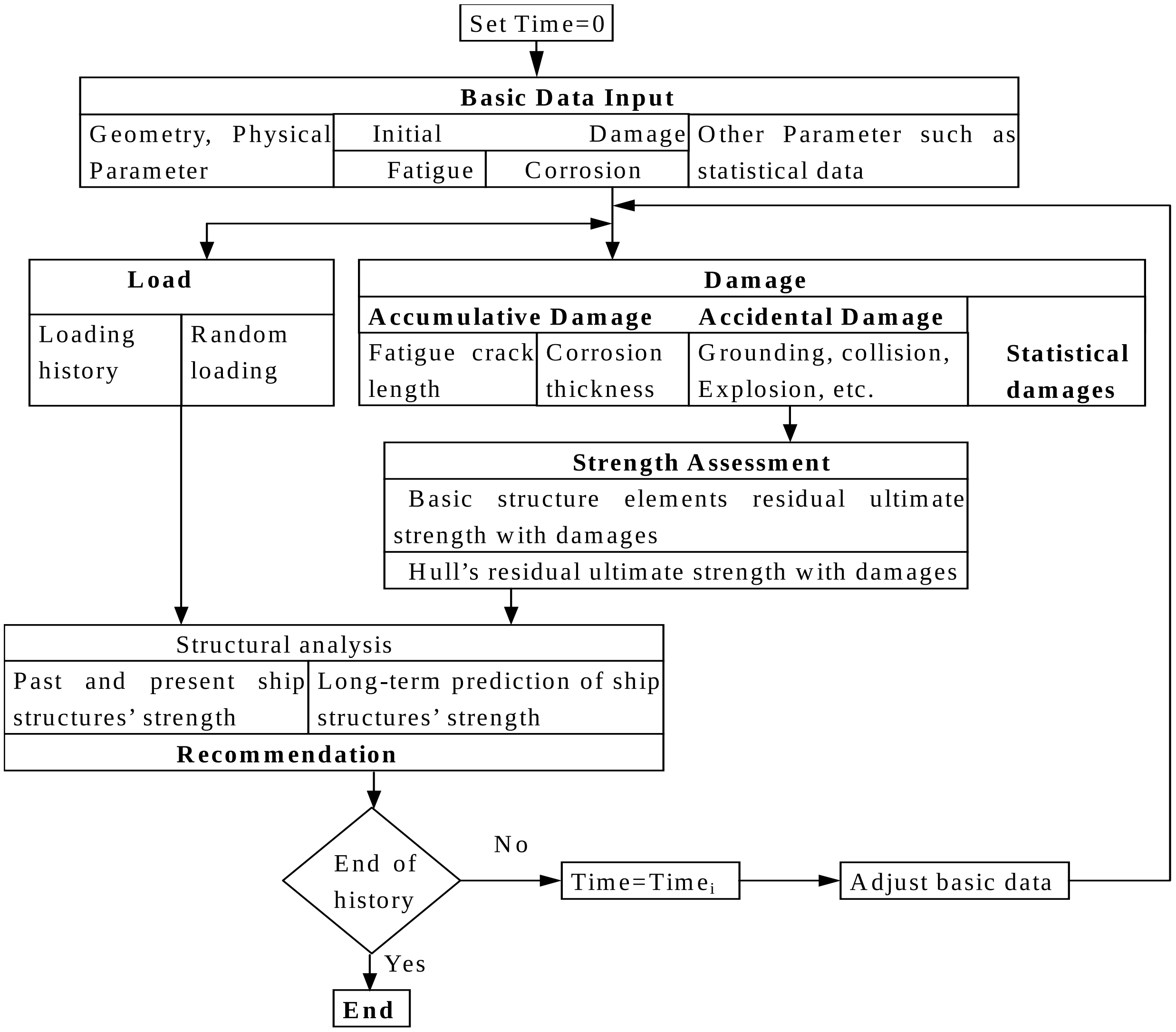

Fig.1 Overall Analysis Flow of the FPB-SAS System

3)Damage module*:* calculates the accumulated damage for a given load history. Damage includes many types such as fatigue, corrosion damage and accidental damage. Fatigue damage is calculated on a cycle-by-cycle basis simulating the actual failure process according to the actual failure mechanism. Crack propagation theory is employed for this calculation instead of the S-N curve approach. This allows a clear definition of the fatigue damage state to be obtained by integration over the loading history. The effect of load sequence has also been accounted for. The actual damage degree should be obtained through measuring.

For a given damage degree, the FPB-SAS method tries to obtain the actual residual ultimate strengths of damaged ship structures, which are most important for repair decision. But we could not measure the damages at any moment. So it is necessary to predict the accumulative damage of ship structures in the future. The damage of the future of the ship structures, such as the degree of corrosion and the place where initial crack will occur, is a random phenomenon. So statistical data and probability tools can be used to predict ship structure damages in the future.

Appropriate corrosion model is employed to model the corrosion damage including uniform thickness decrease and pitting corrosion. Thickness reduction will induce an increase of nominal stresses, which in turn produces a faster speed of crack propagation. 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.

4)Strength Assessment module: calculates the residual ultimate strength of ship structures with damage. In order to calculate the whole ship hull's ultimate strength, basic elements' ultimate strength should be calculated at first. Some elements are intact structures and others are damaged structures. For intact structures, Cui and his colleagues [2-5] have showed that the ultimate strengths of unstiffened plates and stiffened panels can be predicted using a simplified analytical method under combined loading. If the elements include crack damage, it is not easy to predict the elements' residual ultimate strength using analytical method at present. Finite element method can be employed. But the efficiency is very low. In reference [6], a series of empirical formulae are developed to calculate stiffened panels and unstiffened plates' residual ultimate strength with crack damages under combined loading based on FEM results and experimental results. To assess ship hull's residual ultimate strength, different approaches can be used. These include,

- Analytical formulations to be derived based on the assumed stress distribution at failure. This is basically the extension of Caldwell method. A typical reference is Paik and Mansour [7] and their formulations have been extended by Qi and Cui [8] to unsymmetric transverse sections.
- Idealized Structural Unit Method (ISUM) / Plastic Node Method (PNM) or Smith method for progressive failure analysis. Using this type of methods, the ultimate strength calculations of beam-columns, unstiffened plates and stiffened panels are the key elements. 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, but few references could be found to calculate the residual ultimate strength considering the distribution of small fatigue cracks. This requires further study.
- Full finite element analysis. 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 it is not suitable for routine assessment due to its very time consuming.

5)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 over a certain period of operation time? What is the optimal inspection planning?

DAMAGE CALCULATION METHODS

To assess the effects of damages on the ship structures residual ultimate strength is one of the most important tasks in FPB_SAS method. Before analysis the effects of damages on the ship structures residual ultimate strength, the damage extent should be predicted exactly. All the damages will be accumulated with the time. The following are the methods to calculate the damages. In fact, FPB_SAS method is an open system. We can replace the following methods with the latest developing methods.

1. Corrosion damage model Qin and Cui [9] proposed a four-parameter model, which can describe the three phases satisfactorily. In this model, a Weibull function is used to describe the corrosion rate. The corrosion thickness is represented by

$$d(t)=\begin{cases}0 & 0\le t\le T_{st}\\ d_\infty\left\{1-\exp\left[-\left(\frac{t-T_{st}}{\eta}\right)^{\beta}\right]\right\} & T_{st}\le t\le T_L\end{cases} \tag{1}$$

Where $d(t)$ is corrosion thickness, d_∞ is the long-term thickness of the corrosion wastage, T_{st} is the coating life, β and η are Weibull parameters.

2. Propagation of fatigue crack damage In order to consider the influence of fatigue crack on structural ultimate strength, the cumulative fatigue crack length should be predicted at first. But many factors, such as material properties, geometry, loading, will affect crack propagation. Many parameters are necessary to describe crack propagation. A nine-parameter crack propagation model is proposed in Ref. [10]. The fatigue crack growth rate can be described as:

$$\frac{da}{dN}=\frac{AM^2}{1-\left(\frac{K_{\max}}{K_c}\right)^n} \qquad (2)$$

Where a is the crack length, N is the cycles, A is material constant, $K_{\max}$ is maximum stress intensity factor, K_C is the fracture toughness of the material. One can get the expressions of parameters A and M in reference [10].

3. The residual ultimate strength of unstiffened plate and stiffened panel with crack damage

In Ref. [6], the unstiffened plate and stiffened panel's residual ultimate strength with crack damage under combined loading was investigated by FE method. A series of empirical formulae were obtained based on FE results and experimental results. When the unstiffened plate is subjectd to tensile stress,

$\phi_{ux}=\sigma_u/\sigma_Y$ ＝1.27947-3.4973(C/B)+8.97394(C/B)2-11.9747(C/B)3+5.23022(C/B)4

for center crack (3)

$\phi_{ux}=\sigma_u/\sigma_Y$ ＝1.28099-4.04518(C/B)+6.61614(C/B)2-5.19403(C/B)3+1.35456(C/B)4

for edge crack (4)

Where σ_Y is the material yield stress, C is the crack length, B is the plate width, ϕ_{ux} is the cracked plate's ultimate strength under tensile load.

When the unstiffened plate is subjected to compressive stress,

$$\phi_{u-x}=0.104287+\phi_\beta.\phi_{C/B} \qquad (5)$$

where

$$\phi_\beta=1.31071-0.35075\beta+0.03006\beta^2-0.0000277779\beta^3$$

$$\phi_{C/B}=0.830528-0.23082(C/B)-0.67362(C/B)^2-0.0829(C/B)^3$$

$$\phi_{u-x}=\sigma_{u-x}/\sigma_Y\ ,\quad \beta=\frac{B}{T}\sqrt{\frac{\sigma_Y}{E}}$$

where ϕ_{u-x} is the cracked plate's ultimate strength under compressive load, T is the plate's thickness.

When the stiffened panel is subjected to tensile stress,

$$\sigma_{usp}=(\phi_{us}\cdot\sigma_{os}\cdot t_w\cdot h_w+\phi_{up}\cdot\sigma_{os}\cdot t\cdot b) \qquad (6)$$

where σ_{usp} is the stiffened panel's ultimate strength under tensile loading, σ_{os} is the stiffener's yield stress, σ_{op} is the plat's yield stress, ϕ_{up} can be obtained through Eq.(3), ϕ_{us} can be obtained through Eq.(4)。

SHIP HULL'S ULTIMATE STRENGTH

In FPB_SAS method, numerical methods are not suitable to predict ship hull's ultimate strength because the ship hull's ultimate strength should be calculated at each time. Numerical methods will consume a great deal of computer time to predict the degradation of ship hull's residual ultimate strength in its lifetime. So, simple formulations are more suitable in FPB_SAS method. Paik and Mansour [7] developed Caldwell's method further. The ultimate limit state of ship hull girder is defined that the deck and part of upside reach its ultimate compressive strength and the out bottom reach its ultimate tensile strength under sagging condition or the out bottom and part of lower side reach its ultimate compressive strength and the deck reach its ultimate tensile strength under hogging condition. This method is used in the following demonstration example.

A NUMERICAL EXAMPLE

Table 1. Dimensions and material properties of each element

Element Number	Plating					Stiffener								
	b_p (mm)	t_p(mm)		σ_Y (MPa)		h_w (mm)	t_w(mm)		b_f(mm)	t_f(mm)		σ_Y (MPa)	
		Mean	COV	Mean	COV		Mean	COV		Mean	COV	Mean	COV
16-17	800	14	0.05	235.0	0.1	200	9	0.05	90	12	0.05	353.0	0.1
12-15	800	14	0.05	235.0	0.1	300	10.5	0.05	100	15	0.05	353.0	0.1
2-5 7-10	800	12.5	0.05	235.0	0.1	350	9	0.05	90	13	0.05	353.0	0.1
18-43	750	12.5	0.05	235.0	0.1	300	10.5	0.05	120	16	0.05	235.0	0.1
44-56	750	13.5	0.05	235.0	0.1	350	10.5	0.05	120	18	0.05	235.0	0.1
61-73	750	14	0.05	235.0	0.1	350	10.5	0.05	120	16	0.05	235.0	0.1
57-60	750	12.5	0.05	235.0	0.1	350	10.5	0.05	120	16	0.05	235.0	0.1
74-81	1100	14	0.05	235.0	0.1	350	10.5	0.05	120	18	0.05	235.0	0.1
1 6 11	800	15	0.05	235.0	0.1	1050	10.5	0.05	300	15	0.05	235.0	0.1

A double bottom tanker with a length of 168.5 m and a breath of 28 m was used to demonstrate the assessment procedure, Fig.2. The whole section of the ship is divided into 159 stiffened panel elements. The dimensions of each element are showed in Table 1. The distance between transversal frames is 3925 mm.

The mean value of Yong's modulus E is 210000.0Mpa and the COV of E is 0.003. It is assumed that t_p, σ_Y, t_w, t_f and E obey normal distribution.

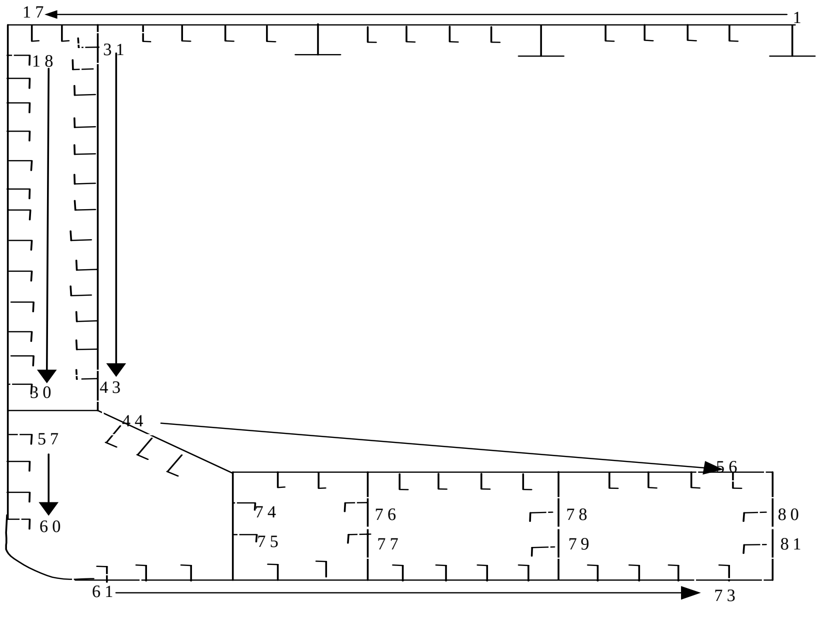

Fig.2 Half Cross Section of a Tanker

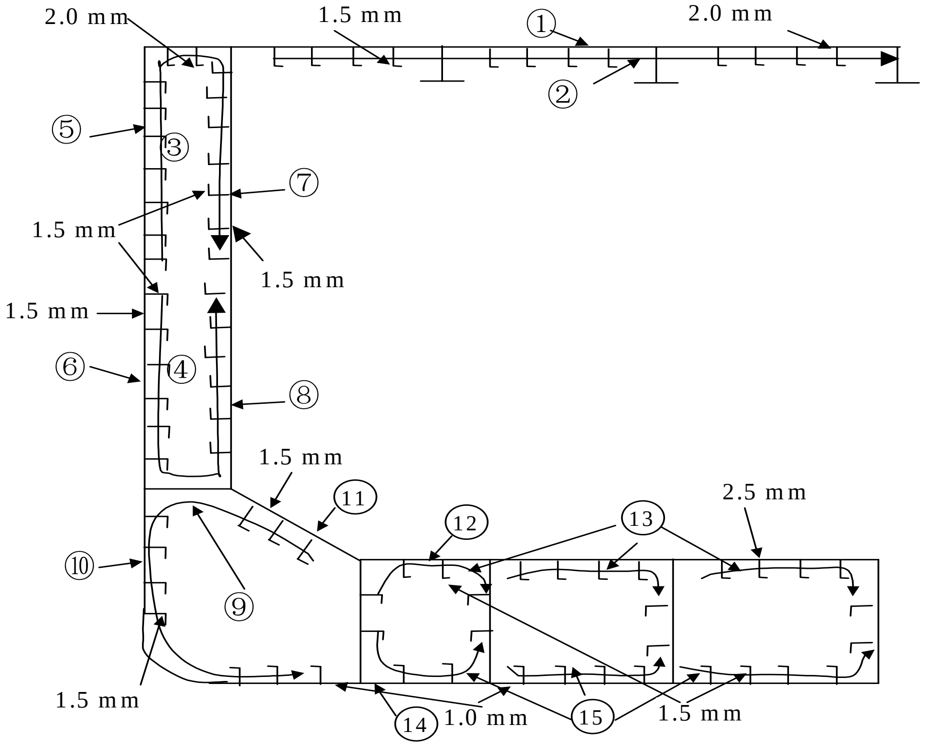

Fig.3 Corrosion number and the maximums allowable corrosion thickness

In some cases, such as inner bottom plating and side shells, each side of the elements is exposed to different environments. Corrosion rate would be different for each side. The corrosion rates should be considered respectively. But in this paper, only the total wastage of the elements is considered. In this paper, two types of corrosion models, i.e. constant corrosion model and non-linear corrosion model are used to simulate the corrosion rates. For the inner bottom plating and low sloping plating, constant corrosion model (Model I) were used, and for other places, non-linear corrosion model (Model II) were used. The corrosion rates are different for different elements. For one element, the corrosion rates of plating, web and flange are still different. But for one stiffener, the web and flange are usually exposed to similar environments, and the corrosion rates are very close. So in this paper, the corrosion rates of web and flange are the same, which are different from the corrosion rate of the plating. Fig.3 shows the corrosion element group number of each element and the maximum allowable wastage. Table 2 shows corrosion model parameters of each corrosion element group.

Table 2. Corrosion model parameters of each corrosion element group

Corrosion number	Corrosion model	T_{st}		d_∞		β		η	
		Mean	COV	Mean	COV	Mean	COV	Mean	COV
1	II	12	0.2	3.5	0.5	15	0.3	2	0.4
2	II	12	0.2	3	0.5	15	0.3	2	0.4
3	II	10	0.2	2.5	0.5	18	0.3	2	0.4
4	II	10	0.2	2.75	0.5	18	0.3	2	0.4
5	II	12	0.2	2	0.5	20	0.3	2	0.4
6	II	10	0.2	2.25	0.5	20	0.3	2	0.4
7	II	10	0.2	3	0.5	18	0.3	2	0.4
8	II	9	0.2	3	0.5	18	0.3	2	0.4
9	II	10	0.2	2	0.5	20	0.3	2	0.4
10	II	8	0.2	2.5	0.5	18	0.3	2	0.4
13	II	8	0.2	3	0.5	15	0.3	2	0.4
14	II	10	0.2	2.5	0.5	18	0.3	2	0.4
15	II	10	0.2	2.25	0.5	18	0.3	2	0.4
11	I	0.13 mm/yr				COV 0.5			
12	I	0.14 mm/yr				COV 0.5			

It is assumed that all elements will be inspected every 5 years and the method of inspection is such that plates with thickness can be lower than minimum basic thickness $t_{\min}$ at the next inspection time are detected. New ones with a thickness equal to their original values will replace the detected plates.
Fig.4 shows the mean value of the midship section area as a function of time. Fig.5 shows the standard deviation of the midship section modulus as a function of time.

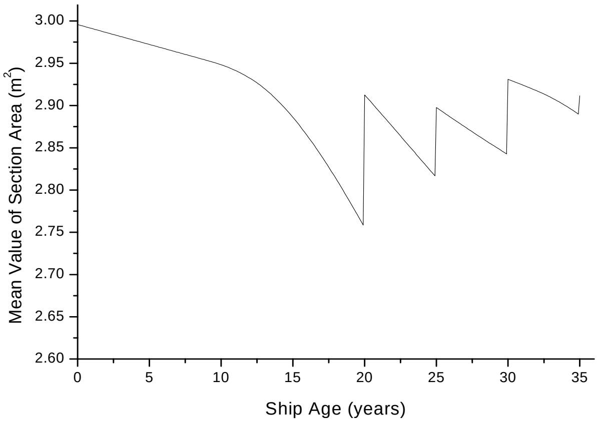

Fig.4 Mean value of the midship section area as a function of time

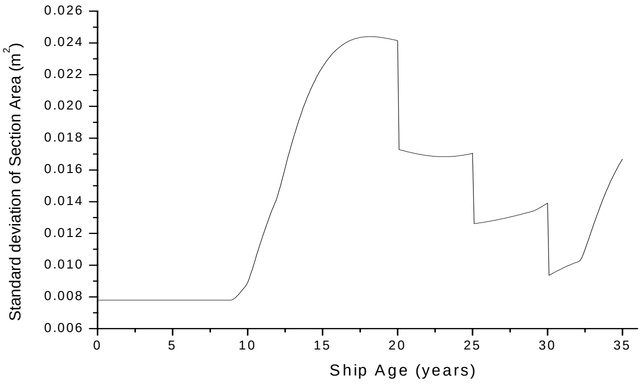

Fig.5 Standard deviation of the midship section modulus as a function of time

Table.3 shows the calculation results of different hull girder strengths for time equal to zero.

Table.3 Bending moment for T=0

Initial yield bending moment M_{Y0}	Fully plastic bending moment M_{p0}	Ultimate bending moment	
		Sagging M_{US0}	Hogging M_{UH0}
3.82×10^9 nm	5.31×10^9 nm	4.03×109 nm	4.69×10^9 nm

Fig.6, Fig.7, Fig.8 and Fig.9 show the variation of nominal initial yield bending moment, fully plastic bending moment and ultimate bending moment under the condition of repair and no repair respectively. Fig.10 shows the reliability index based on sagging condition.

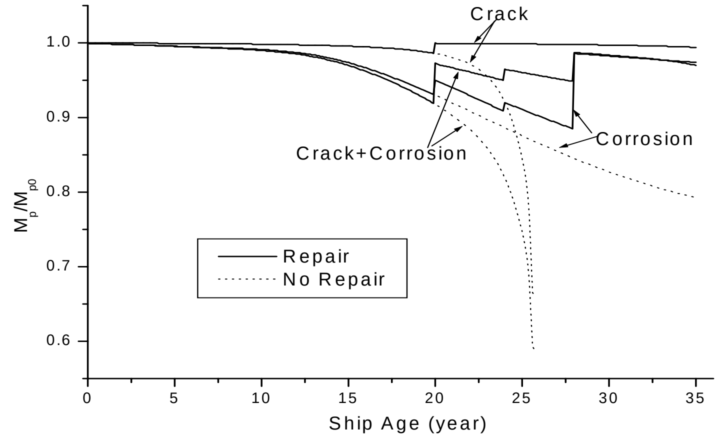

Fig.6 Mean value variation of fully plastic bending moment with time

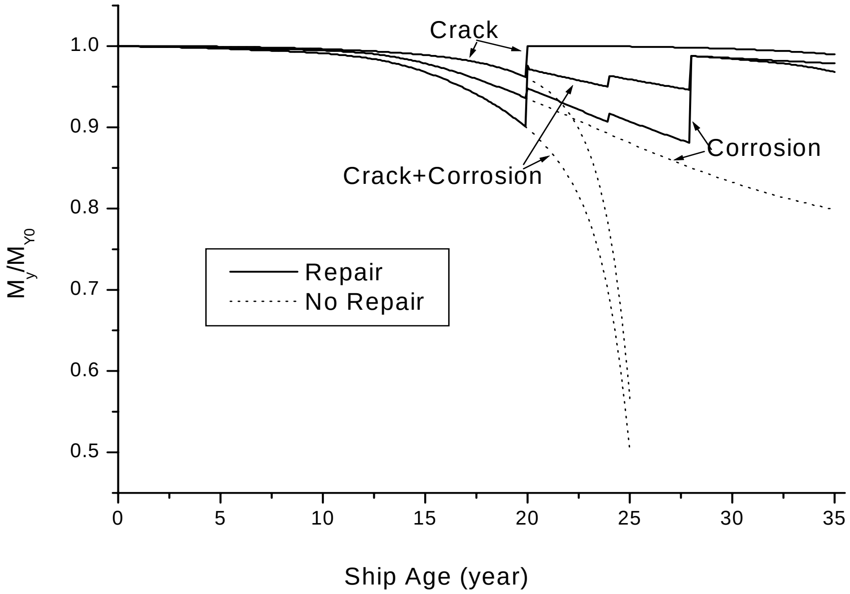

Fig.7 Mean value variation of initial yielding bending moment with time

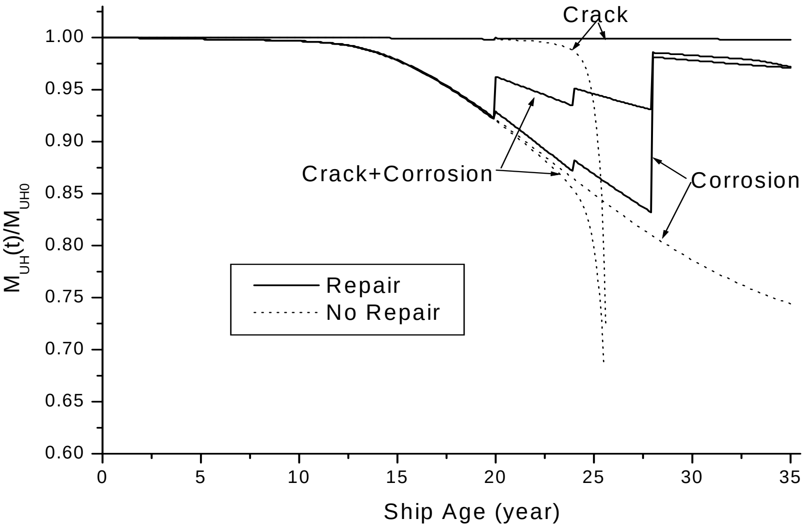

Fig.8 Mean value variation of ultimate bending moment with time under hogging condition

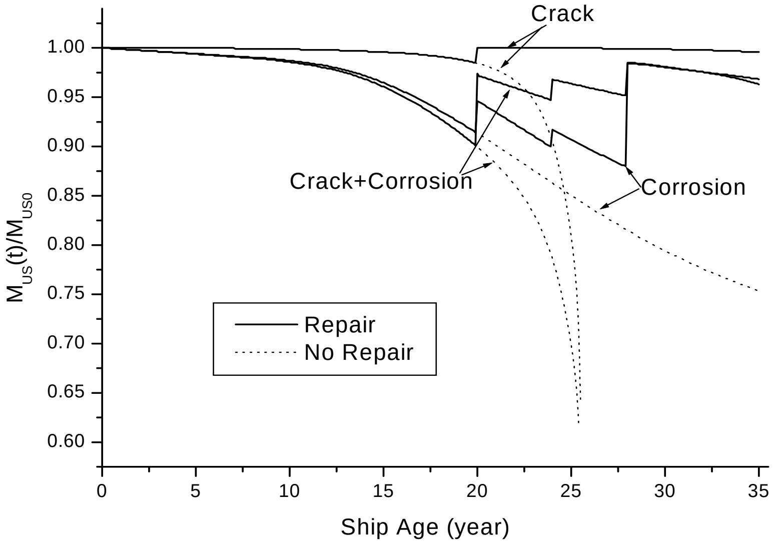

Fig.9 Mean value variation of ultimate bending moment with time under sagging condition

Fig.10 reliability index based on sagging ultimate bending moment

To this tanker, sagging condition is the most dangerous condition. Fig.11 shows the variation of deviation of ultimate bending moment in sagging condition.

Fig.11 Standard deviation of ultimate bending moment

If one assumes that the ultimate bending moment of hull girder obey normal distribution in sagging condition, Fig.12 shows the probability density at each repair year.

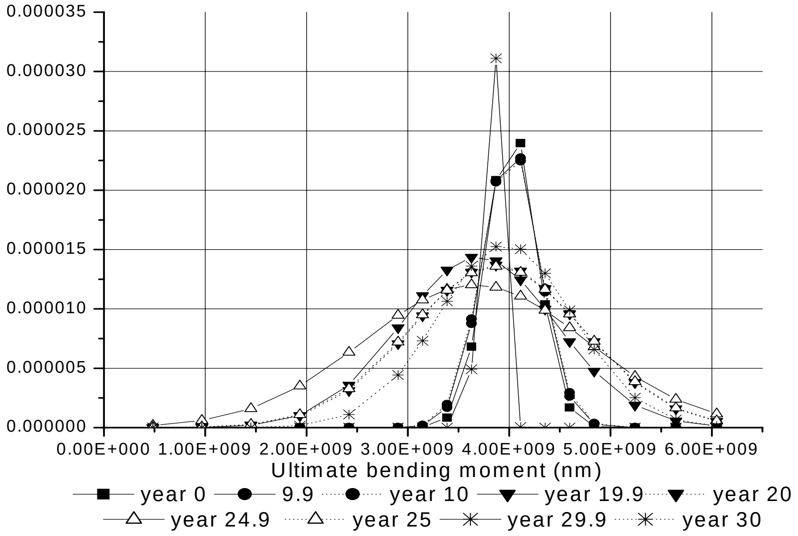

Fig.12 The probability density at each repair year

CONCLUDING REMARKS

In this paper, a new computer simulation system of ultimate strength of aging ship structures is demonstrated. The theory frame of this system is described. The procedures developed in the present study should be useful for assessing ultimate strength reliability of aging hulls taking into account the degradation effects of corrosion and fatigue crack. The described methodology is applied to assess a double bottom tanker. The calculation results indicate influences of the fatigue crack, corrosion and repair on the ultimate strength reliability of the ship hull girder.

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