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A Study on Hull Structures for Ageing Ships

- A basic study on life assessment of ships and offshore structures

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ABSTRACT

In order to extend a life of ageing ships, it is necessary to be made a study on feasibility for extending planned life. The feasibility study consists of a life assessment with a condition survey/assessment, a life prediction technique and an availability assessment. We (Nippon Kaiji Kyokai : NK, a classification society) have made a basic study for developing a life assessment system of ships and offshore structures. The logic of procedures for the life assessment is shown diagrammatically in the paper. Hull integrities for life extension having conventional structures will be examined by an empirical method if the structures are well protected from corrosions. However, hull structures with the greater use of high tensile steels have no experience used for a long life exceeding 15 to 20 years as they are of a new generation. Therefore, at a life extension for such a ship, special care shall be paid for its fatigue strength as well as protecting corrosions. In the paper, studies on fatigue strength for hull structure with mild and high tensile steels and maintenance procedures for well protecting corrosion are briefly reviewed. And a discussion is made to a procedure of an assessment for life extension of ageing ships.

1. INTRODUCTION

In order to extend a life of ageing ships, it is necessary to be made a safety assessment for extending planned life. The safety assessment is of course carried out in accordance with the minimum requirements by classification society's rules. NK (Nippon Kaiji Kyokai : a classification society) has also specified such requirements by the rules and has developed in 1989 a special standard of condition surveys on hull structures for ageing ships.[1)]

A feasibility study of the life extension is generally carried out as the shipping companies concerned likes. However, a precise and rational feasibility study may be required by the parties widely concerned for a specially high grade ship, such as LNG carriers. The rational feasibility study shall consist of a life assessment with a condition survey/assessment, a life prediction technique and an availability assessment. The assessments may be carried out by a joint study cooperated the shipowners or operators and technical bodies e.g. shipyards/designers, classification societies, authorities of the assessments etc. We have made a basic study for developing a rational life assessment system of ships and off-shore structures. The logic of the procedures for the assessment is shown diagrammatically in Fig.1. A high grade ship operated with a good maintenance policy is a main objective of this study, but the result of this study can be also applicable to any ships and off-shore structures.

The paper summaries the results of the basic study and describes a strategy and method for assessing a planned life with a high reliability similar to the past one of the subjected ship(s).

2. LIFE ASSESSMENT METHOD AND BACK UP SYSTEM

2.1. Procedures of the Life Assessment

The procedures shown in Fig.1 include both of economical/social and technical problems to be considered at the assessment. The formers are mainly considered by shipping companies concerned etc., while the laters are considered by the shipping companies with an assistance of technical parties such as shipyards/designers, classification societies. Nos. with a parenthesis ( ) in Fig.1 show the technical problems involved the parties, and their details are as follows ;

(1) Identification of potential failure causes

Potential failure causes which may result in significant unplanned ship outages differ depending upon the ship's kinds, construction and equipment, machinery and many other items. At the first stage, potential failure causes to be considered for the assessment are clarified and identified in each case as per the subjected ships and the life extending plans which are given at requests. A concept for identifying the potential failure causes is proposed in 2.2.1. It is necessary to provide data bases such as shown in Fig.1 for revealing the potential failure causes.

(2) Preliminary survey

The preliminary survey prior to the condition survey/assessment is of literature surveys on documents and hearings from the concerns. The following documents are gathered and surveyed ;

(a) Terms of design and construction of the ships ; specification, drawings, calculation sheets, test results and so on of the main hull structures, cargo containment systems, propulsive and other's essential machinery and equipment

(b) Plans of operation and maintenance ; instructions, manuals etc.

(c) Service records ; operational records, survey reports, maintenance & repair records, failure/incidents records etc.

(3) Planning of condition survey procedures

According to the preliminary survey, procedures of the condition survey are planned and fixed with the parties concerned. In this planning, essential informations for the potential failure causes are also given from the data bases and back up systems. The plan clearly shows ;

(a) Criteria to be assessed ; i.e. Identification of potential failure causes to be assessed, as prescribed in (1)

(b) Ship(s) to be survey and duration(s) of the survey(s).

(c) Structures, machinery and equipment to be surveyed, their conditions at the surveys including inspection methods and persons in charge.

(d) Report form of the condition survey

(4) Condition survey

A format of the condition survey is proposed in 2.4.

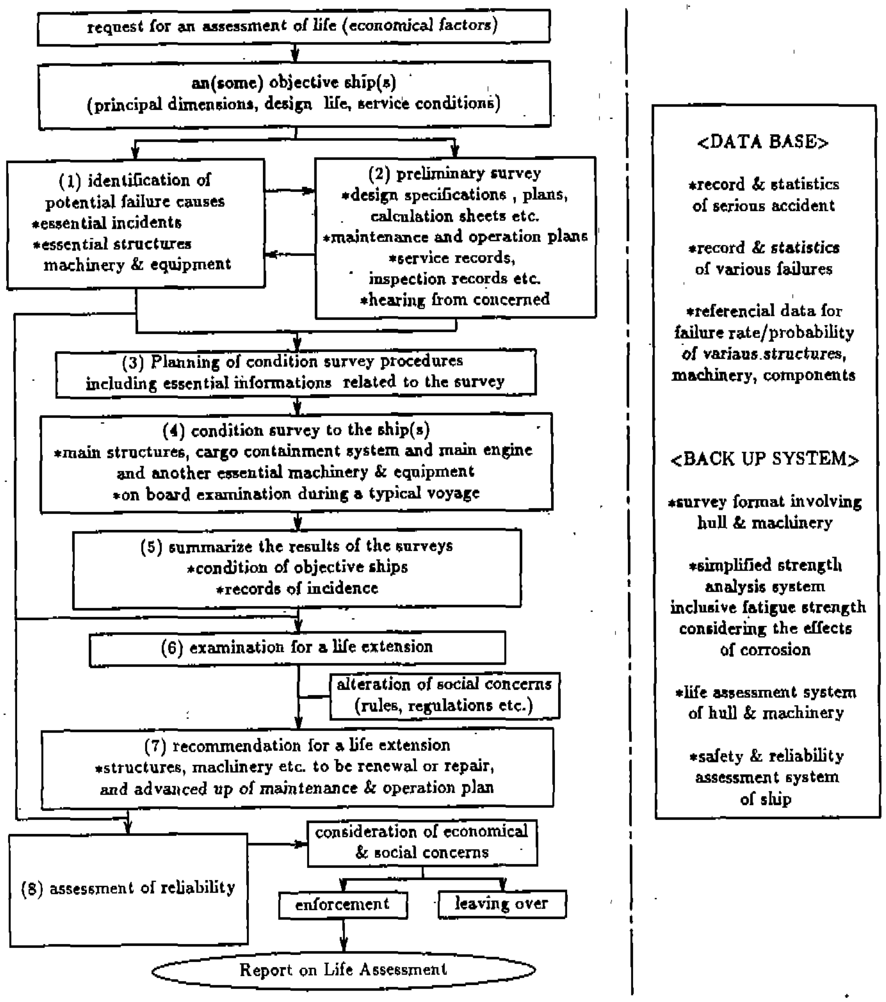


Fig.1 NK's performance on life extension study
Items (1) to (8) in each or total are possible to be conducted by the Society

Table 1 Category of Incident Effect

Index	Effect to Availability	Incident Effect
A	practically negligible	Incidents which do not affect availability in practical. Outage time due ti the incidents is 24 hours or less.
B	a few	Outage period due to the incidents is abt. 2 or 3 days or less.
C	Some effect	Ditto, abt. 1 week or less
D	Large	Ditto, abt. 1 month (4 weeks) or less
E	Very Large	Ditto, abt. 1 month (4 weeks) or above

Table 2 Category of Incident Probability

Index	Incident Probability	
0	Negligible	$< 10^{-5}$ / ship-year
1	a very few	10^{-5} - 10^{-4} / ship-year
2	a few	10^{-4} - 10^{-3} / ship-year
3	Low	10^{-3} - 10^{-2} / ship-year
4	Somewhat frequent	10^{-2} - 10^{-1} / ship-year
5	Frequent	$> 10^{-1}$ / ship-year

Table 3 Important Index of Incident

Important Index	Rank Index	Rank of Reliability
A-1,A-2,A-3 B-1,B-2,C-1	I	Sufficiently acceptable level (High Reliability)
A-4,B-3,C-2 D-1,E-0	II	Generally acceptable level (Good Reliability)
A-5,B-4,C-3 D-2,E-1	III	It is preferable to be level up of the rank as far as possible
A-5 *,B-5,C-4 D-3,E-2	IV	It is necessary to be level up of the rank

N.B. ; - A to E and 0 to 5 are defined by Table 1 and 2
- A-5 * is one of which the effect is 12 hours or above and the probability is very frequent (> 1/ship-year)

(5) Result of the condition survey (Survey report)

The report summarizes the results of the survey, such as (a) condition of the ship(s) (defects, corrosions, wears and tears, deformation etc. of the structures, machinery and equipment) and (b) records of essential incidents (kinds, extents and effects, causes, statistics), and (c) essential comments to the result of the condition survey.

(6) Examination for life extension

The results of the condition survey are to be examined, and if necessary the stress analyses, fatigue strength analyses considering effects of corrosion, ageing property tests of non-metallic materials etc. shall be carried out.

(7) Recommendation for a planned life extension

According to the condition survey/assessment, recommendations for a planned life extension shall be made to the applicants. For examples, structures, machinery and equipment to be renewal or repair, advanced up of maintenance and operation plans. Special attention is to be paid for preventing corrosion of the hull structures.

(8) Assessment of safety and reliability

The ship's reliability i.e. availability for the planned life extension will be assessed in accordance with a systematic procedures. A proposal of such a procedure is described in 2.2.3.

2.2. A Proposal of Life Assessment System

2.2.1. Identification of Incident to be considered

There are many incidents which cause to outages in ships, and many kinds of failures on structures, machinery and equipment have risks resulted in such incidents. It is so complicated but unremunerative for the result of the assessment to examine all the risks. It is then rational that the survey/assessment is carried out for essential structures etc. which may generate a critical failures much affected the ship's safety and availability. Such structures etc. are revealed by a guidance with the incidents categorized as shown in Table 1,2 and 3. The incidents categorized by these Tables are considered to ones caused by structural defects only, and incidents caused by outside factors e.g. collisions, groundings are not taken into account because it seems that such incidents are occurred at random regardless of the ship's ages.

In general, it seems practical to the purposes that the incidents to be surveyed/assessed are identified by the Category E-2. If it is preferable to be surveyed/assessed in more details, the rank IV or III and IV shall be taken into account. This identification is determined in discussions with the parties concerned.

2.2.2. Identification of Structures, Machinery and Equipment to be surveyed/assessed

The structures, machinery and equipment to be surveyed/assessed are identified in accordance with the concept as described in 2.2.1. When we empirically choose the essential structures, machinery and equipment for the survey/assessment, examples are as follows ;

(a) Main hull structures

(b) Cargo containment and handling systems

(c) Propulsive machinery and others essential machinery & equipment.

Generally the items (a) and (b) can be easily identified, but it is some of difficulties to identify the machinery and equipment of the item (c) because there are many kinds of machinery & equipment and their components on the ship. Therefore concept of the identification as described in 2.2.1 and a life expected (permanent, indeterminate or limited life) of the machinery etc. may be introduced for the assessment.

If E-2 criteria is adopted, examples are as follows ;

(i) Shaftings of the propulsion are considered as a permanent life and Category D-2 or E-2 even if an extent use, and they shall be carried out the condition survey/assessment and subsequently be examined for the life assessment

(ii) Rudder is considered to be a permanent life and Category E-0 or E-1 even if an extent use as it has been well maintained in due course, and its condition survey/assessment only shall be carried out for the confirmation of its integrity. Availability assessment of the rudder is not necessary because unavailability due to an incident of this Category is so small.

(iii) Anchors and chain cables are of equipment having a limited life and their condition survey/assessment shall be carried out only for the confirmation of their maintenance and inspection procedures.

(iv) Main electric cables are considered as category D-2 or E-2 and they are of equipment with an indeterminate life. The condition survey/assessment and examination for an extent use including a test to demonstrate their integrities for the extent use shall be carried out for the cables.

At the identification, consideration is to be paid for an essential failure even if it seems a minor one. e.g. a small crack of an inner hull structure consisted of a supporting structure of cargo containment systems with some types of liquefied gas carries, or a small leak from fuel transfer pipes in engine rooms. The former may cause a serious incident as like the insulations are widely attacked by ballast waters. The later may cause a big fire in the engine rooms.

Accordingly, a systematic risk analysis such as E.T.A, F.T.A etc. are carried out at the identifications of the essential incidents and structures etc. At this stage, the analysis may be of a briefly quantitative one so that the incidents can be so categorized as the Table 1, 2, and 3 and it is possible to be analyzed in comparatively less difficulty by an experimental knowledge with sufficient and useful data bases.

2.2.3. Availability Assessment

Purpose of the availability assessment in the life assessment is to provide evidence to demonstrate that the subjected ship(s) will have an acceptable availability over an extending planned life, and this acceptable availability is determined with reference to that achieved in the past operation records. Availability (Av) is given as follows ;

$$Av = 1 - U \quad (\text{unavailability of a ship}) \tag{1}$$

$$U = U_{SF} + U_{PL} + U_{OT} \tag{2}$$

hence, U_{SF} is unavailability due to incidents caused by structural defects. U_{PL} is a planned unavailability e.g. regular docking, margins etc., U_{OT} is unavailability due to incidents caused by others factors i.e. outside factors and pure human errors during operations, e.g. collisions, it seems that U_{PL} is intentional but indeterminable at the initial stage of the assessment and U_{OT} is unchangeable to the ship's ages. Then, U_{SF} only is considered in the assessments.

$$U_{SF} = \sum U_{SF_i} = \sum \frac{MTTR_i}{MTTR_i + MTBF_i} \tag{3}$$

$MTTR_i$ is mean time repair or restore to the regular operation, $MTBF_i$ is mean time between failure or incident $= 1/\lambda_i$. Suffix "i" indicates a failure or incident "i" resulted in an outage of the ship. λ_i is failure or incident rate per ship - year or day.

Acceptable or expective U_{SF} is given by the planning of the of the life extension and as discussed in the above the past experiences of the subjected ship and the sister ships are also taken into account for its decision. Generally, Av, U, U_{SF} etc. are remarkably variable values because they depend on many complicated factors.

Examples of unavailabilities caused by structural defects (U_{SF}) are shown in Table 4. Unavailability caused by a design and construction defect i.e. early failures is not considered for the assessment of aged ships because such problems ought to have been solved in the past. Acceptable or expective U_{SF} may be determined with reference to the past records and in consideration of the above discussion.

Table 4 Unavailability due to Structural defects (U_{SF}).

Ships	U_{SF} per ship		Remarks
	Year/Year	Days/Year	
Two LNG carriers (1964 ~ 1972) 16.3 ship-year	0.035	12.8	include causing design and construction
	0.014	5.1	exclude causing seemingly design & construction
11 LNG carriers 14.8 ship-year	0.017	6.3	ditto
Two LNG carriers (1969 ~ 1972) 7 ship-year	0.024	8.8	ditto
Shell plating's opening	0.03	12.0	MTTR=3 days (assumed)
fracture & crack 6000 cargo ships in 1989	0.01	3.6	ditto except corrosion

N.B. ; The above is derived from the references [2),3),4)]. For the first two ships their regular docking durations are assumed as 25 days/ship-year.

Conclusively, the procedures of the assessment are summarized as follows ;

(a) to determine criteria of the assessment by Table 1, 2 and 3 and acceptable or expective U_{SF}.

(b) to identify the essential incidents / failures of the structures etc. to be surveyed/assessed taking into account potential failure causes, i.e. to put the "i" concretely.

(c) to make the condition survey/assessment in accordance with the procedures which are fixed in advanced and if necessary, to make recommendations to the life extension.

(d) to predict $MTBF_i$ ($= 1/\lambda_i$) in accordance with the result of the condition survey/assessment and the subsequent examinations involved for ageing effects to the structures, machinery and equipment. The data base and back up system assist to this prediction.

(e) to predict MTTRi with reference to kinds and extents of the failures/incidents, the operation plans and the maintenance/repairing programs of the ships

(f) to predict U_{SF} for the planned life extension.

(g) if U_{SF} is acceptable with simultaneously taking into account U_{PL} the assessment will be completed. If not, countermeasures for decreasing U_{SF} will be examined and recommended.

2.3. Data Base and Back up System

NK has a sufficient knowledge and experience to carry out a full or a part of the rational life assessment in accordance with the procedures shown in Fig.1. Such a full assessment has however a big problem, i.e. the assessment accompanies with extensive works and it takes a long time to complete. To solve such a problem as far as possible, it is preferable to prepare data bases and back up system involved for assisting the assessment. According to the basic study, it is concluded that the following data bases and back up systems shall be developed for the rational life assessments. Some of those are under developing.

(1) Data bases

(a) Records and statistics of accidents ; accidents of ships, off-shore structures and others.

(b) Failure data ; data of failures of the essential structures, machinery, equipment and their components are to be gathered and so put in order as probability of the failures can be predicted for the life assessment inclusive of ageing effects.

(c) Basic data for predicting incidents/failures effects ; data and knowledges for predicting a time to repair or restore to the regular operations at a failure/incident.

(2) Back up system

(a) Format of condition survey including preliminary survey.

(b) Simplified analysis system to evaluate the hull strength (ultimate and fatigue) taking into account effects of corrosions and wears.

(c) Consulting system to examine and evaluate a condition of the essential structures, machinery, equipment and their components.

(d) Consulting system to the ship's management system of the maintenance for extending life with a satisfactory condition.

(e) Special inspection techniques of the condition survey/assessment for the life assessment.

(f) Safety and reliability assessment system of ships and offshore structures.

2.4. Condition Survey Format

Condition survey is generally carried out for the purpose of the ship condition assessment in all respects of hull structures, machinery, electrical installations and equipment in order to extend the life of a ship. In this survey, maintenance plans including spare stocks of the materials, machinery/equipment and their components are also important objectives to be examined.

Survey records of the past class surveys can provide the concerned with necessary information/data for the preliminary survey, e.g.;

(a) results of external/internal examination of hull structures

(b) results of thickness measurements for main hull structures which are required at every Special Survey in Rules of this Society

(c) results of hydrostatic tests of tanks

(d) results of external/overhaul examination of the essential machinery, electrical installations and equipment

(e) results of hydraulic/pressure tests of pressure vessels in machinery and equipment such as boilers

If preferable, information/data of sister ships should be taken into consideration in the preliminary survey.

Results of the preliminary survey defined in 2.1(2) being taken into consideration, extent and procedures of condition survey are fixed in details. Among many items of the condition survey the respect of assessment of corrosion in hull structures is described hereinafter, which is the most essential in this survey.

This Society can provide the applicants with the prediction of progress of corrosion with assistance of data base for this purpose and advise them how to maintain the hull integrity for a long time. Accordingly, results of the condition survey of the existing hull structures are to be reported as a rating of the following five levels.

"**cA**" is excellent condition, where no rusting and blistering on painted construction are observed, or even if observed in a very few areas, no corrosions of hull structure members are observed with paint coating in good condition.

"cB" is very good condition, where rusting on a little of edge part and/or welding joint and on the localized flat part of hull structure members are observed, but little corrosions are observed.

"cC" is good condition, where rusting on some edge parts, welding joints and flat parts of hull structure members are observed. Blistering and pealing off parts of paint coating are observed. Small numbers of pitting corrosion of hull structure members are observed.

"cD" is good condition as far as the hull scantling, i.e. no decrease of the scantling is observed and small number of local and pitting corrosion of hull structural members only are observed. Paint coating is partly pealed off in extensive areas.

"cE" is a condition being in an advanced corrosion than "cD" level. This is acceptable condition in a conventional periodical class survey including such conditions as to be required repair works to the heavily corroded hull structures. Paint coating may be damaged in large areas including highly stressed parts.

Definitions of the hull conditions also include an intermediate level of the above, e.g. "cA/cB, "cC/cD" etc.

It is delicate to write in a plain style about the hull conditions of the rating levels. The society have then provide standardized colour pictures of the above levels in each location of the hull structures. An expert involved such as the society's surveyors can discriminate the rating of the hull condition by the above information.

The above distinctions have a trend to be somewhat precise to the good conditions, whereas rough to the opposite condition levels. They are however rational to make an appropriate planning of the protecting corrosions as watching a progress of deterioration of the protecting effects.

In order to planning refurbishment of the hull structures themselves, it is necessary to divide "cE" level into more detail such as "cE-a" (corroded but acceptable), "cE-ℓ" (reach to acceptable limit), "cE-u" (unacceptable) etc, or to add a concrete description of the corroded conditions of "cE". The corroded conditions are significantly variable in case by case, and it seems that the later format is preferable in the condition survey.

In case where condition survey is applied to the ships in "cE" level ;

(i) thickness measurements for all hull construction is required in order to assess the distribution of hull corrosion.

(ii) sizes and distributions of heavy local corrosions are to be measured and recorded.

(iii)hydrostatic tests for tanks in which heavy corrosions are observed are required to demonstrate their integrity.

Results of condition survey in the respect of corrosion reveal not only the prediction of progress of corrosion of hull members themselves but also the prediction of deterioration of paint coating etc. The applicants can be adviced from the Society on the countermeasures for protecting corrosion. An example is shown in Table 5.

3. A STUDY ON CORROSION OF HULL STRUCTURES

3.1. Investigation of Hull Conditions

Extensive investigation of hull conditions has been carried out for 48 ships of 5000 gross tonnage or above at their Special Survey or others in dockings in line of the categories of hull conditions introduced in 2.4. Surveyors of this Society have classified condition of shell plating, upper decks, cargo spaces, ballast tanks, etc., and have recorded major maintenance operated in the past if appropriate. Standard color pictures which show typical corroded hull structure have been provided as guidance to make the evaluation consistent. No problem has been reported so far at the execution of rating. Summaries of the rating are shown in Fig.2 through Fig.4. Care is to be paid for that the investigations were performed to many of the ships with goods conditions because of the objective of this study to find a means for well protecting corrosions. It seems that these Figs show somewhat good examples compared with our experiences.

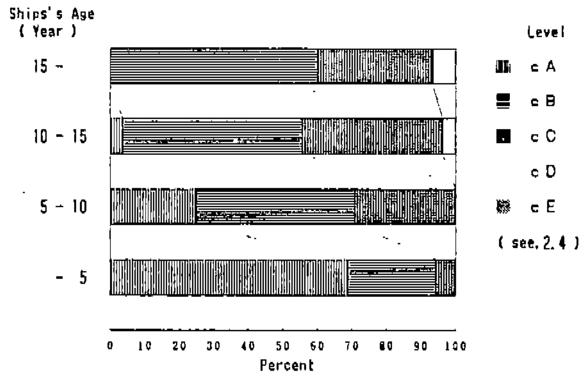


Fig.2 Shell Plating

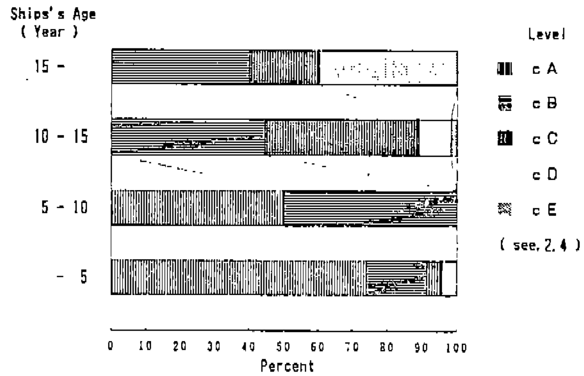


Fig.3 Upper Deck

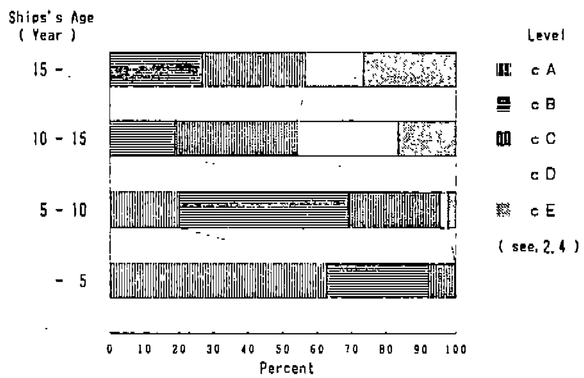


Fig.4 Ballast Tank

The results of the investigations indicate that ;

(a) Shell plating, especially below the water line are very well maintained normally, and they are corrosion level in "cB" on average, in "cC" at the worst even after 15 years operation. There are nothing of the condition "cD" and "cE" in the investigated hull structures, but such conditions have sometimes found on shell plating especially near or above the water line due to insufficient maintenances.

(b) Upper decks are in more rusty condition than shell plating, because normally upper decks have not been re-painted for a long period. Average corrosion level is "cC" for the ships of age more than 15 years-old. Pitting corrosions were found on upper decks of the some ships. Such cases have been often found on ships less than 10 years-old especially ore carriers,

Table 5 Example of Report and Recommendation of Condition Survey on Hull
(Ship age : 10 years, Top Side WBT)

Historical record

1) initially tar epoxy paint by normal practice
2) Anodes were provided in all the tanks at 5 years ago, and apropriately supplemented thereafter.
3) No.3 TS WBT(P) steel works for repairing shell plates abt. $8m^2$ and their internal members due to a contact incident. They have been re-painted by the same as the initial one.

Hull condition ; rating at present and recommendation / prediction

Tk Nos & location	at cond. survey	recommend	after 5 years	(after 7 or 8 years)	after 10 years
N0.1 TSWBT(p,s)	cD	cA (re-paint)	cC*	(repaint) (not re-paint)	cC* cE
No.2 ~ 4 TSWBT(p,s) (expect here in below)	cB	–	cB/cC		cC/cD
Ditto, upper part (Tk top below 3m)	cC/cD	cA* (re-paint)	cC*	(re-paint) (not re-paint)	cC* cE
No.4 aft. wall of TSWBT(p,s)	cD/cE	cA* (re-paint)	cC*	(re-paint) (not re-paint)	cC* cE

Surveyers Note

It seems initial paint works were good, and anodes were effective to places flooded in water at ballast cond. Hull cond. were generally good proportionate to the age.

No.4 aft. walls were adjacent to FOT, and their paints and anodes were somewhat ineffective, and the corroded conditions were as shown in attached plan.

No.1 TSWBT (p,s) have been used as almost empty or sometimes half ballasting, and anodes were ineffective.

Recommendation

(1) Anodes to be refitted in due course and repaints to be after touch up works.
(2) No.1 TSWBT and aft. wall of No.4 TSWBT to be carefully monitored and, after 7 or 8 years to be re-painted.
(3) No.4 TSWBT aft. walls have sufficient margin to the strength and some of heavy corrosions are then acceptable, however, careful monitoring to be duly carried out.

NB : * shows to have some traces of local corrosions.

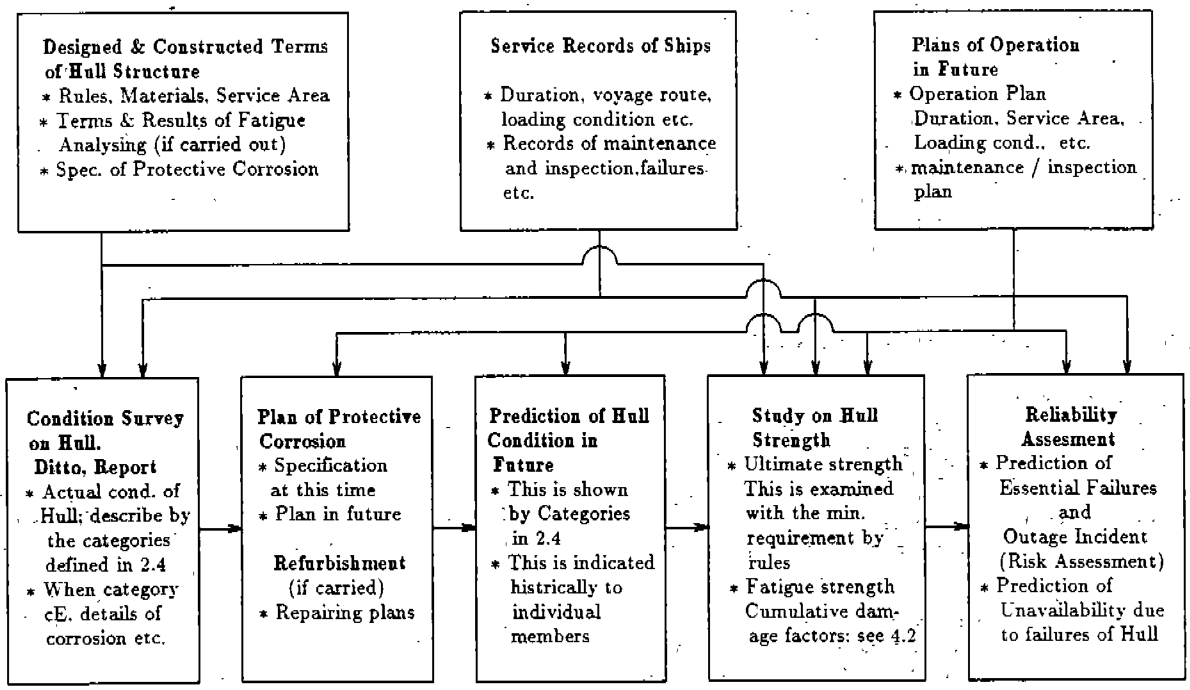


Fig.5 Procedures of Hull Strength Assessment

crude oil carriers etc.

(c) The condition of cargo spaces whose results of the rating are not shown herein, depends strongly on the types of cargoes and the maintenance. For instance, cargo holds of car carriers show frequently superior condition and in contrast, cargo holds of coal carriers without appropriate coating show often poorer condition than ballast tanks.

(d) Ballast tanks are the most corrosive environments. Average corrosion level is in between "cC" and "cD" for the ships of age more than 10 years-old. The conditions of the older ships more than 15 years vary considerably where about one fourth of ballast tanks deteriorate under the level "cE", while comparable number of ballast tanks maintain their condition in excellent state "cB".

(e) In the investigations there were examined two ships in a very good condition in spite of their ages near 20 years, but their results are excluded from the summaries in Fig.2, 3 and 4. Their main hull structures were almost rated as "cB" or above, and they have been operated with an excellent maintenance plan. This shows that hull structures can be maintained so as good as new for a long time under an excellent maintenance strategy.

Analysis of the results of rating in line of the rating system introduced may provide valuable and consistent information on hull conditions to the concerned in the assessments.

3.2. Protection of Hull Structures against Corrosion

Failure statistics [4] of our Society show that dominant cause of failure for the ships of age older than 10 years are corrosions and the number of corrosion/wastage damages grows as ships age, characteristic of which can be also seen in the result of rating mentioned above. Therefore, protection of hull structure against corrosion is a crucial feature for the prolonged life of ships. As for the fatigue damage, our statistics show no tendency of the number of fatigue failures to grow in aging ships. But, for the ships of new generation such as the ships with the greater use of high tensile steel whose fatigue life suspects to be shorter than conventional ships with mild steel, it seems that fatigue problems may pose another serious obstacles without appropriate maintenance to keep hull condition well beyond, say, corrosion level "cC".

Research committee organized by this Society in 1986 with the experts of coating manufacturers, ship owners and shipbuilders, investigated the specifications of coating in building stage and the maintenance procedures to protect hull structures and equipments from corrosion and report was published as a guidance note in 1986.[5]

This Society can advise the applicants in making the specification of protecting corrosions and also at the planning of the maintenance procedure based on the experience gained from the analysis of damage statistics , data on thickness measurements, and comprehensive investigation on aging ships carried out by ourselves.

An example of a recommendation to the maintenance procedures including predictions of hull conditions is shown in Table 5.

Trend of corrosion varies considerably depending upon the types of coating, initial painting procedure especially its workmanship (most of degraded paint works are caused by bad workmanship), environments of the structures and so on. Accordingly, periodical monitoring on hull condition should be carried out, where rating criteria introduced in 2.4 may be useful information to grasp the hull condition consistently, resulting in the appropriate maintenance plan based on the analysis of the data.

4. A STUDY ON RATIONAL LIFE ASSESSMENT

As discussed in Chapter 2, there are many problems in developing the rational life assessment system. The authors have carried out the basic study, and some of those are summarized in this chapter.

4.1. Hull Strength Assessment for Ageing Ships

Procedures of the hull strength assessment in the life extension plan is diagrammatically shown in Fig.5 with supplementary notes given below ;

(a) For an example, causes of failures on hull structures due to structural defects are assumed as shown in Table 6 from a statistics. [4] It then seems that the failure causes of aged ships except fatigues have been almost eliminated provided that the ship is operated in the same conditions as the past and the hull structures are well protected from corrosion or so refurbished as good as nearly original scantlings.

(b) Ultimate strength of the hull structures may be evaluated by success in the condition survey with good refurbishments, because the probability of the failures except those caused by corrosions and fatigues is expected as the same order to the past one.

(c) In general, fatigue strength of the conventional hull structures has not been examined at the initial design and any class survey, because experience shows that they have a sufficient margin to the fatigue strength. Cumulative damage factors and failure probabilities are inevitably increased for a long life over 15 or 20 years. Accordingly, it seems that an examination is to be carried out in order to demonstrate the integrity to the fatigue strength at the life extension study. Procedures of the fatigue strength assessment is shown in Fig.6 and a discussion of this problem is described in 4.2.

(d) It seems that a new generation of the hull structures has however a small margin to the fatigue strength. The fatigue strength of such hull structures are then to be exactly examined at the life assessment. Procedures of the fatigue analysis is shown in Fig.6 and a discussion is described in 4.2.

4.2. Discussion on Fatigue Strength Assessment

4.2.1. General

Recently, some members of hull structures with the greater use of high tensile steels (i.e. a new generation ship) were found cracked in early years after the ships entered into service. It is supposed that the direct cause of the failures lies in the shortage of fatigue strength of the local spots of the structure. In order to protect such failures, some classification societies developed a design guidance of the fatigue strength, and this Society also developed such a guidance. [6]

Conventional hull structures have also suffered fatigue failures, but they were sufficiently less than the aforesaid. A comparison study has been carried out and its result shows that a fatigue life of the end connections with lug of ordinary type on side longitudinals in the new generation VLCCs is about a half or less that of the conventional VLCCs. This comparison not take into account effects of corrosions, and the fatigue life of the new generation's shall be less than the above if effects of corrosion are taken into account. Therefore, protecting corrosion of the hull structures of the new generation's is more important problems to the fatigue strength.

As discussed in the above, the fatigue strength assessment is one of the most important items to demonstrate the structural integrity of the hull structures. Analytical techniques and data to be developed for the assessment are as follows ;

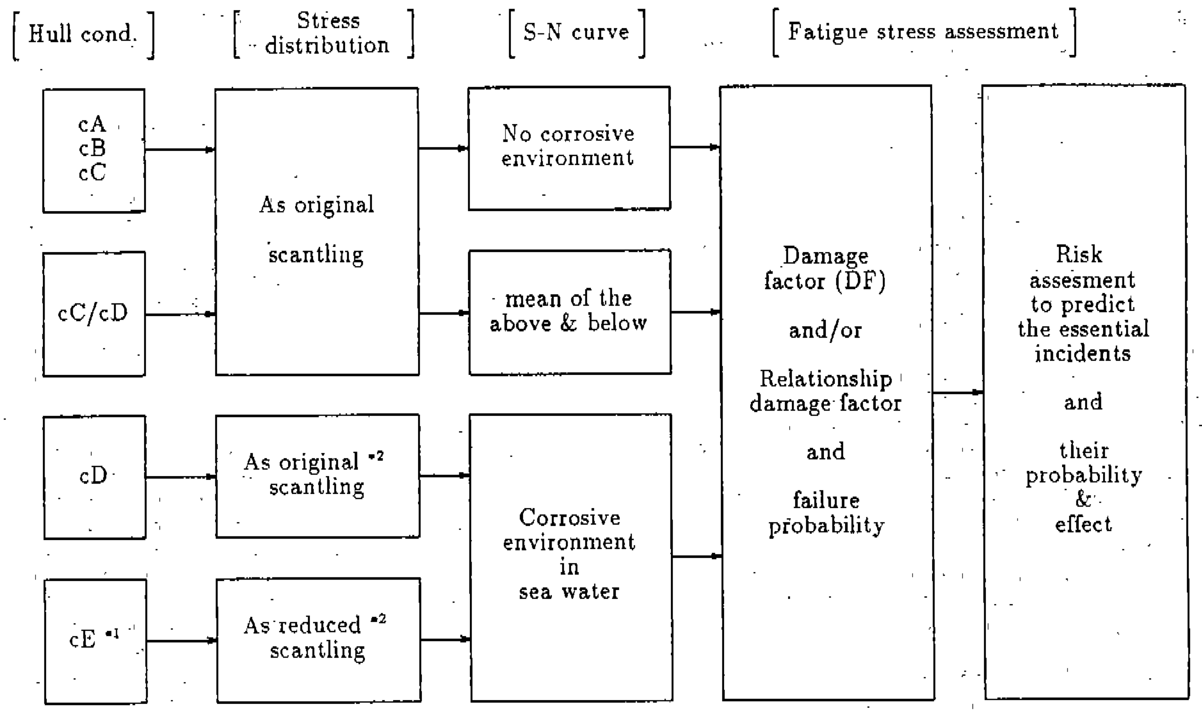
(a) a standard of the fatigue strength analysis

(b) S-N curves including corrosive environmental effects, local corrosion effects

(c) a method to estimate the stress distribution in the past and the future. i.e. strength analyses method and fatigue load estimation method according to the ship's operation area.

(d) a method to estimate relationship between cumulative damage and failure probability.

(e) a risk assessment method of the fatigue failures. i.e. an estimation method of the incident effects and probabilities due to the fatigue failures.



N.B. *1 To be reported with thickness measurement and distribution of a heavy local corrosion.
*2 Effect due to local corrosion is considered as stress consentration or other means.

Fig.6 Fatigue Strength Assessment of Hull Structure

Table 6 Causes of failures on hull structures due to the structural defects

Cause	All ships	Aged ships
corrosion *1	77 ~ 79 %	86 ~ 92 %
vibration	6 ~ 4 %	abt. 0
defect of design *2 & workmanship	4 ~ 11 %	abt. 0
excessive wave load and others	6 ~ 3 %	6 ~ 4 %
fatigue	7 ~ 3 %	8 ~ 4 %

N.B. ; *1 including corrosion fatigue
*2 early failures including a low cycle fatigue

(f) a method to demonstrate an effect of periods and accuracy of inspections.

(g) a crack propagation analysis to assist the analyses of the items (e) & (f).

(h) a simplified method to demonstrate the fatigue strength.

4.2.2. Discussion based on a Fatigue Strength Study

In order to demonstrate the fatigue strength of hull structures, it is necessary to consider following items ;

(a) estimation of wave induced loads ; the effects of size of ship, loading condition, service route etc.

(b) estimation of initiated stress due to wave induced loads ; for example, hot spot or peak stress range and its long-term distribution

(c) evaluation of fatigue crack initiation life ; the effects of welding condition, workmanship, tolerance during construction, environment etc.

And further, following items should be considered to maintain the safety of ship based on the consideration of fatigue strength ;

(d) analysis of fatigue crack propagation

(e) inspection procedure ; time to inspect, inspect or not, accuracy of inspection etc.

(f) plans for maintenance ; repair plan in the case of crack detection, plan for protecting-corrosion etc.

In this article 4.2.1, discussions are made on the fatigue strength assessment of hull structure based on the numerical examples considering all items except (d) as the mentioned above.

(1) Fatigue strength under corrosive environment.

Although the great majority of ship structural members are located in the corrosive environment, fatigue behavior under the corrosive environment has not been clear yet. J.de Back has reported [6),7)] that fatigue life in sea water is 1/2 times that in air. O.Vosikovsky et al. has reported [9)] that fatigue life in sea water is 1/2.5 times that in the region of lower stress level and 1/1.5 times in the region of higher stress level in air. K.Iida has also reported [10)] that the decreasing tendency of fatigue strength ratio of freely corroded fatigue strength to fatigue strength in air is common to all materials, but the ratio itself is different depending on a material.

To demonstrate these effects quantitatively, numerical calculations have been made for focusing on behavior of the bracket toe at hold frame end and intersection between hopper plate and inner bottom plate as shown in Fig.7. Assumptions in conducting calculations are as bellow ; (see Table 7)

(a) when the members are effectively protected from corrosions, fatigue strength of these members in corrosive environment are same as in air and fatigue limit could be considered by Haibach's law

(b) where the protection of corrosions become not effective, a fatigue life of these members is 1/2 times that in air and no fatigue limit is considered

(c) these members are inspected by each 2 years interval and when a fatigue crack is found, it is replaced by the new one but the condition for protecting corrosion is be not changed

(d) mean detectability of a small fatigue crack at the each inspection is assumed to be 0.9 and 0.1 for a conscientious inspection and a desultory inspection respectively

(e) following three types of the hull condition are accounted in ;

(i) protecting corrosion is effective(at least "cC" level defined in 2.4) for 20 years with a good maintenance.

(ii) protecting corrosion is effective ("cC") for the first 8 years and not effective("cD" level defined in 2.4) for the next 4 years but a complete protecting corrosion is to be conducted at that time. Assumption is made so as to be no decrease of the hull scantings in the period.

(iii) protecting corrosion is effective for the first 8 years and thereafter not effective without decrease of the scantling. This is only a case of a comparisons because the hull structures shall be heavy corroded for such a long period.

Cumulative fatigue damage based on Miner's law may be one of the most effective index for fatigue criterion. But it may not be useful where the effect of fatigue crack detection and its repair at the inspection are considered, and an expected failure probability formulated as shown in eq. (4) is then introduced here.

$$p_f(k) = \sum_{i=0}^{k-1} p_f(i)\, D_i \sum_{j=1}^{k-1} [F_T(t_{i+j}-t_i) - F_T(t_{i+j-1}-t_i)] \prod_{l=i+j}^{k-1} (1-D_l) \qquad (4)$$

where

$p_f(i)$; expected failure probability at i-th inspection

$F_T()$; cumulative density function of fatigue life

D_i ; probability of detecting a crack at i-th inspection

Results of calculations are shown in Figs. 8 to 13. Broken lines(---) in these Figures are of the cases of desultory inspections and solid lines(—) are the case of conscientious inspections. It is shown evidently that probabilities of failure are increased suddenly when the effectiveness of the protecting corrosions is not sufficient. But when the conscientious inspections within a interval of 2 years are conducted, it is expected to keep an enough reliability level even though the case (iii).

When the conscientious inspections are not expected, it is difficult for both of the cases(ii) and (iii) to keep an enough reliability level as that of case (i). And there is only a little difference between the cases(ii) and (iii).

From these results, it seems very important to keep a good hull condition continuously when considering the life extension of ship. And when many cracked members are detected suddenly, it is necessary to check the hull conditions and to take a conscientious inspection schedule.

(2) Effect of service route.

Where a fatigue analysis is carried out in the design stage, North-Atlantic route is generally adopted for the wave induced loads . And the ship's life is taken as 20 years which is equal to 10^8 cycles of the acting wave induced loads. But for some specific ships, they are taken into account the actual service route in evaluating the fatigue damage. A study has been carried out to examine a difference of the fatigue damage due to the service routes among (a)North-Atlantic route, (b)Persian Gulf-Japan route, (c)North-Pacific route and (d)Japan-Australia route. As an example, long-term distribution of hydrodynamic pressures acting on the ship's body is shown in Fig.14, and total numbers of wave cycles and cumulative fatigue damages in 20 years are summarized in Table 8. In this table, each value is normalized by the value of North-Atlantic route.

Fig.14 and Table 8 show the effects of difference of service routs evidently.

(3) Feed back system of inspection records.

In evaluating the possibility of life extension, the fatigue strength is one of the important items to be considered and it must be evaluated based on the present condition to add to the evaluation at design stage. But it may be impossible to evaluate the fatigue strength accurately because of the existence of many uncertainties that are involved in each stage described in the preamble (a) to (f) of this article 4.2.2.

H.Itagaki et al. proposed [10] the conceptual idea of the consideration of these uncertainties by feeding back in-service inspection records to the analysis method to evaluate the fatigue strength which involves uncertainty.

This concept may be applicable to reconsider some initial assumptions used for the fatigue analysis at design stage and to predict the fatigue activity based on the present condition. The authors will study how to apply this concept to the life assessment.

Table 7 Values of parameter used for numerical calculation

	bracket toe at frame end	intersection between hopper plate & inner bottom plate
S-N curve $[N_f S^m = C]$		
in air ; $N \leq 2\times10^6$		
m	2.390	6.293
C	2.75×10^8	2.43×10^{13}
in air ; $N>2\times10^6$		
m	3.780	11.586
C	4.82×10^9	2.21×10^{19}
sea water		
m	2.390	6.293
C	1.38×10^8	1.22×10^{13}
std. dev. ln(N)	0.5	0.5
local stress at hot point	22.2	42.02

Table 8 Comparison of each route (example of bracket toe at frame end)

	North Atlantic	P-G to Japan	North Pacific	Japan to Australia	P-G to Europe
long term Weibull distribution shape param.	0.91	0.88	0.92	0.88	0.92
stress level at 10^4 cycles	1.0	0.71	0.99	0.76	0.82
total number of wave cycles	1.0	1.26	0.96	1.20	1.06
cumulative damage at 20 years	1.0	0.34	0.96	0.41	0.55
cumulative damage at 40 years	2.0	0.68	1.9	0.82	1.10

N.B ; The above figures show by a ratio to the North Atlantic's, except the first line.

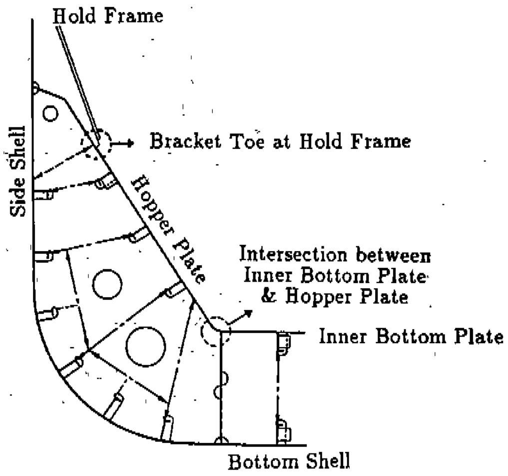


Fig.7 Example of hard spots of hull structural members

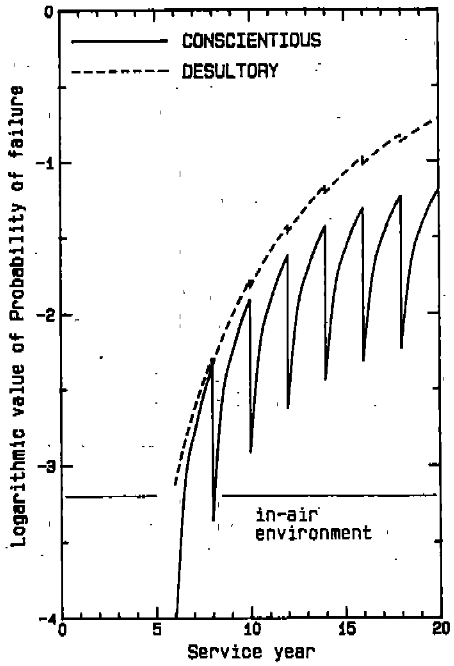


Fig.8 Expected probability of failure of bracket toe at frame end [case(i)]

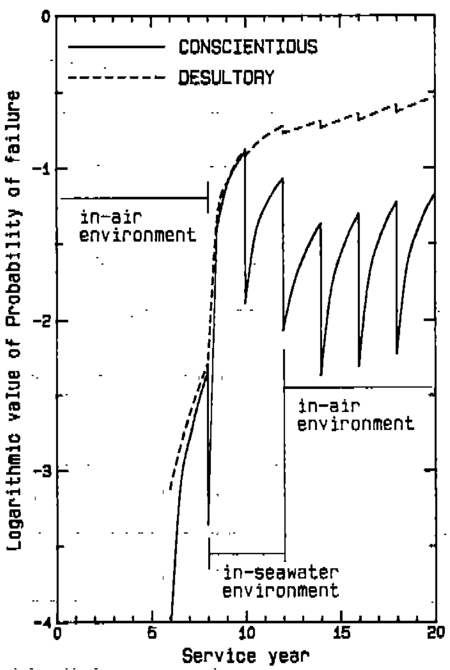


Fig.9 Expected probability of failure of bracket toe at frame end [case(ii)]

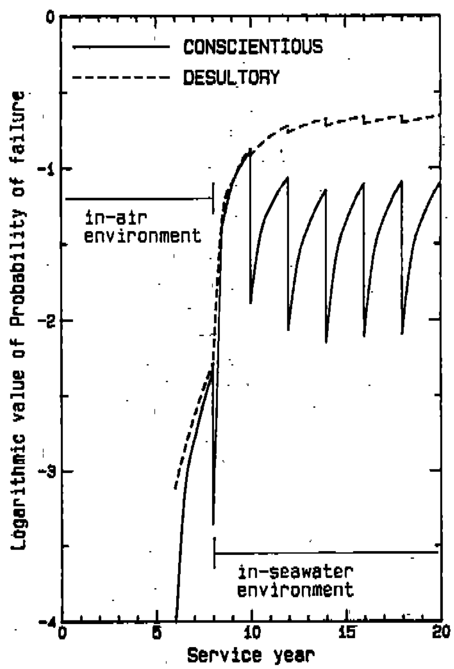


Fig.10 Expected probability of failure of bracket toe at frame end [case(iii)]

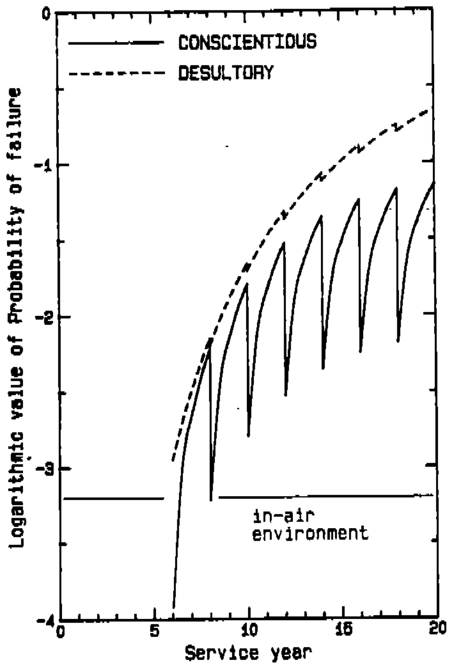


Fig.11 Expected probability of failure of intersection between hopper plate & inner bottom plate [case(i)]

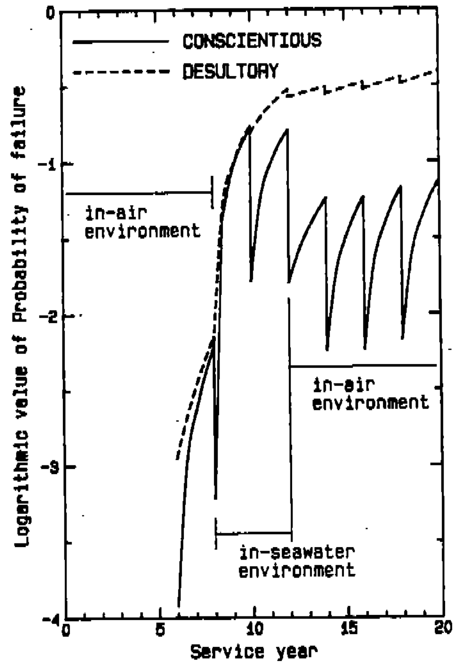


Fig.12 Expected probability of failure of intersection between hopper plate & inner bottom plate [case(ii)]

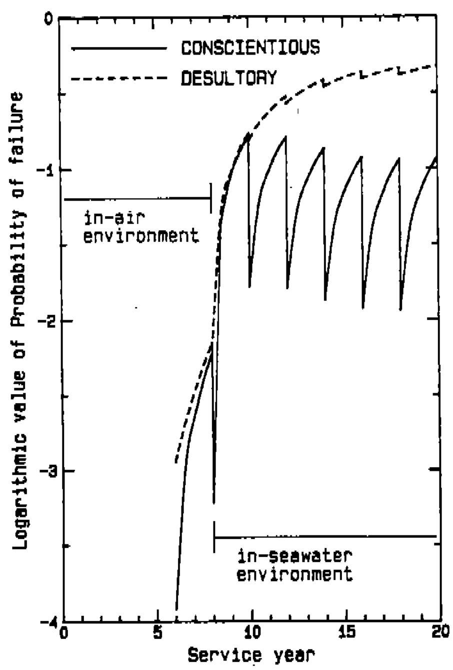


Fig.13 Expected probability of failure of intersection between hopper plate & inner bottom plate [case(iii)]

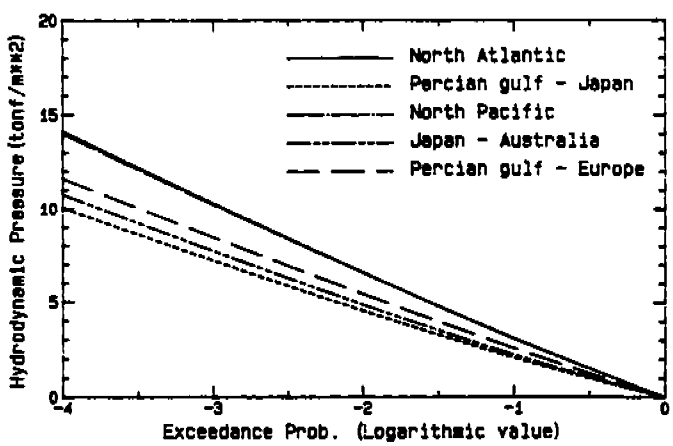


Fig.14 Long-term distribution of hydrodynamic pressure acting on the ship's body

Table 9 Frequencies of Failures of Essential Machinery every 5 years of ship age

No.	Item of machinery	Frequency (per ship-year)									
		All failures (x 10^2)					Failures causing ship breakdown/slowdown (x 10^4)				
		ship age					ship age				
		≤ 5	≤ 10	≤ 15	≤ 20	20 <	≤ 5	≤ 10	≤ 15	≤ 20	20 <
1	Propeller	1.7	2.3	2.4	1.3	0.9	3.6	1.0	—	6.2	—
2	Propeller Shaft	1.7	3.0	4.6	2.8	2.1	1.2	2.4	4.8	4.9	—
3	Stern Tube Bearing	1.5	3.6	7.0	5.4	3.8	—	1.2	0.8	3.7	—
4	Intermediate Shaft	0.31	0.48	0.79	0.84	0.45	2.6	3.6	8.1	11.1	—
5	Thrust Shaft (Including Block)	0.07	0.12	0.19	0.21	0.17	—	1.2	1.6	7.4	4.8
6	Piston of M/D	2.2	3.9	3.6	1.6	1.1	16	21	20	13	3.0
7	Crank Shaft of M/D	0.83	0.89	0.94	0.93	0.32	9.2	17.3	17.0	27.4	19.4
8	Cylinder Cover of M/D	0.75	1.76	1.75	0.72	0.57	0.8	4.5	2.4	1.7	—
9	Cylinder Liner of M/D	1.43	2.14	2.02	1.02	0.72	9.0	12.8	10.9	6.4	1.0

N.B.: The above data are of raw materials derived from NK's statristics, and some of them are less population for estimating probability of failure rates.

4.3. Discussion on Machinery and Equipment

As mentioned before in other words, following two viewpoints must be considered to assess the life of machinery and equipment for life extension.

(a) life on safety problems ; This is the life which must be taken into account when the machinery can't be used in the normal condition for some malfunction or damage. That is equivalent to "technical problems" in 2.1.

(b) life on non-safety problems ; This is the life caused by any reason other than (a) above, for an instance, deterioration of efficiency, lowering of availability without significant defects, oldness of design or increase of maintenance cost, etc. That is almost equivalent to "economical/social problems" in 2.1.

Machinery has the following characteristics compared with the hull structure.

(1) A unit of the machinery is generally assembled by many kinds of components, e.g. their materials, lives, etc.

(2) The load under operation can be estimated at the design stage.

(3) The plastic deformation must not be allowed usually because machinery has the movable part.

(4) Fatigue strength assessment is adopted in the design process.

(5) In usual operation, it is assumed for the component worn down to be changed.

(6) The planned function and life can be achieved under appropriate operation.

From these characteristics it can be said that "life on safety problems" of machinery does not expire, if the adequate work of maintenance is executed under the appropriate condition survey taking into account of the planned life at the design stage. That is, the machinery can be used forever by changing the worn component, apart from lowering of availability and increase of cost with changing work.

Then it must be needed for the actual life assessment of machinery to consider not only "life on safety problems" but also "life on non-safety problems" with the analysis of the factor necessary for the assessment. However it is not easy to make the procedure of such life assessment because the both "life" assessments are in the complex relation each other.

Table 9 shows the rates of all failures and of failures causing ship breakdown/slowdown every 5 year of ship age about the essential machinery. It can be said from these data in this Table that the reliability of machinery is not influenced greatly by the ship age. These data are the average values achieved under the maintenance works at operation and the repair at shipyards and it is not known how much such works influence these data. So the reliability calculated from these data can not be used as index to assess "life on safety problems" of the individual case. The reason is that there is seldom the data to quantify the difference between the life with adequate maintenance/repair works and the life without those works. Moreover the life of each machinery unit depends on the assessment of other units, so it is uncertain to assess the life.

One of the goal of the study is to make the procedure of the rational life assessment and two approaches will be thought of. The first one is to recognize the state of affairs by the statistical method on the macroscopic stand. The second one is to use the assessment model on the microscopic stand. Yet the statistical method is useful to analyze, it is necessary for the life assessment to evaluate by using the model.

For example, consider the availability mentioned in 2.2.3. The failure data such as in Table 9 is used to find the availability. If the life extension strategy including economic aspect is required, it is necessary to consider what maintenance/repair system does lead to the failure data such as in Table 9. As known from Fig.1, these two approaches are not exclusive but complementary, that is, the assessment model is constructed based on failure data derived from the statistics and the data are refined by the result from the estimation by the assessment model.

In considering the framework of the life estimation of machinery by the assessment model, because of the characteristics of machinery mentioned before, it is natural to select each machinery and equipment as the unit of the model. The procedure of constructing the assessment model may be divided into the following three steps.

(i) Identification of the machinery and equipment to be modeled ; All machinery equipments should be generally included in the life assessment system. But this strategy is not easy nor yet possible because of the work needed for modeling and the cost at the assessment. As mentioned in 2.2.1, it is necessary to select the equipment according to the categories proposed in Table 1, 2 and 3.

(ii) making the unit model and hierarchy of model structure ; The unit model used for the quantitative life assessment of the corresponding machinery and equipment is made and the hierarchy structure consisted of these models is built up. In this step, the unit model will be divided into three categories (permanent, indeterminate or limited life) mentioned in 2.2.2 for the convenience in modeling.

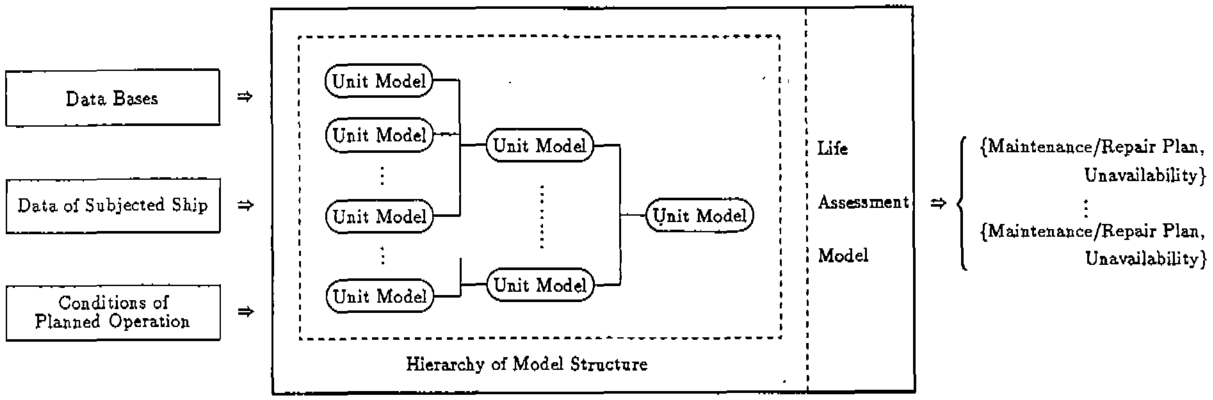


Fig.15 Concept of Model Structure for life Assessment

(iii)construction of the life assessment model ; The life assessment model for gathering the data used in the life assessment by the unit model hierarchy of (ii) is constructed.

Fig.15 shows the hierarchy of the unit model structure. It may be as almost same as E.T.A. and F.T.A., and is investigated in detail now.

4.4. Miscellaneous

In the ship, there is many structures, machinery and equipment other than those aforesaid of which failures may essentially affect to the availability. Comments to the miscellaneous are as follows ;

(1) Cargo containment system for liquefied gas carriers.

The cargo tanks of refrigerated liquefied gas carriers are generally not corroded and some of them have been carried out a fatigue strength analysis at the initial design. The assessment to such a case is carried out with less difficulty than that of the hull structures, because reference can be made to the design data and the corrosion effects are not taken into account. Procedures of the fatigue strength assessment are similar to that of the hull structures in principle. Relationship between cumulative damage and failure probability is to be studied for the unavailability assessment.

Insulation systems are considered as an indeterminate life and data of ageing effects of the materials are to be examined taking into account the past operation data and, if necessary, a test to demonstrate the ageing effects shall be carried out.

Others, e.g. secondary barriers, tank supporting material etc. are also examined on their properties of the ageing effects.

(2) Cargo handling system

Cargo handling system are one of the essential equipment of which failures may affect to the unavailability. The systems and their components then are objective of the assessment. The components have a different nature in each, e.g. the cargo pumps are of a limited life, the pipings are of a permanent life, some of the components have been designed with a fatigue analysis etc. The assessment are then to be carried out in an applicable manner respectively.

(3) Safety equipment

Safety equipment are related to not only the ship's safety but also the availability. e.g. a failure of the fire extinguishment system may result in a big fire accident from a minor one. Safety equipment are to be seriously examined by the governing bodies and ship's crews in view of the ship's safety rather than availability. They are however not always perfect, and an examination of the safety equipment is then necessary in the condition survey/assessment. Where some of deficiencies are found, they are of course to be refitted in order.

5. CONCLUDING REMARKS

Concluding remarks of the study are as follows ;

(a) A simplified system for the life assessment has been proposed. Main objective of the proposal is an aged ship in a good condition which is expected to continuously operate with a high reliability similar to that of the past. However the proposal is also applicable to any kinds of ships.

(b) In order to efficiently carry out the assessment as far as possible, it is necessary to provide back up systems supported by data bases. Necessary sorts of the systems have been examined and clarified, and subsequently some of such systems are going to develop. If the systems are completed, works of the assessments will be remarkably decreased. From our experience, it can be said that a full assessment required abt five or above person-year's works at present will be performed by abt five or above person-a half year.

(c) Extensive investigations were carried out for conditions of the hull structures. According to the result, we stress that means for protecting corrosions which are used to a general practice to many ships is insufficient to maintain a good condition of the hull structures for a long life. It is then preferable to be developed a high standard of protecting corrosions, and a guidance involved has been proposed to this end.

(d) Discussions have been made to the hull strength assessment including the fatigue strength. Comments to the fatigue strength of the hull structures in the life assessment have been described as a result of the study. For example, it has been demonstrated that notwithstanding an increase of the fatigue cumulative damage for a long life, risks of the outages due to the failures can be controlled within an acceptable level by a pertinent inspection strategy/method and a good maintenance plan.

(e) Deficiencies of the essential machinery and equipment much affect to the ship's unavailability as well as the hull structure's. The assessment of those can not be disregarded, and a discussion has been made to develop the assessment system involved.

(f) The most complicated problem of the life assessment is to predict the failure rates taking into account ageing effects of the essential structures, machinery, equipments and their components, besides many problems are to be examined for the refinement of the assessment system. The extensive studies involved shall be continued in order to make a success of the rational assessment system.

ACKNOWLEDGEMENT

The authors wish to acknowledge to persons who rendered their assistance and gave valuable comments to this study. Particular thanks are also to the shipping company which gave us a chance to participate an actual life extension study.

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DISCUSSION

Bahadir Inozu

First of all, I certainly agree with your conclusion that you didn't mention in your presentation that the machinery maintenance has to be considered in addition to the structural reliability in order to ensure ship availability. We've seen a lot of papers about structural reliability. It's very exciting the SMP project that Professor Bob Bea has initiated finally started but we should also consider the ship machinery availability.

In your paper you talk about two approaches for the machinery maintenance. You first talk about the microscopic stand, which is based on the statistical approach that you just mentioned. First of all, we know that the statistical methods require lifetime data. However, the existing field data is heavily censored leading to great uncertainties. What do you mean with "microscopic" stand? Are you planning to integrate fault diagnosis techniques with statistical techniques or do you have any other approaches?

The second comment that I have is about your Table 9 that I think is misleading. In this table you compare the machinery failures with the ship's age. Based on this table, you state that the reliability of machinery is not influenced greatly by the ship age. The results do not agree with the bath-tub curve that would indicate that the number of failures really increase with age after the infant mortality period. The number of failures should be compared with the age of the machinery itself, not the age of the ship.

A. Kumano

We thank you for your deep interest in our paper and for your questions with the point.

The answer to the first question is as follows. As mentioned in our paper, we think it is necessary for the rational life assessment to consider the procedure on both macroscopic and microscopic standpoints. One of the main reasons for using two standpoints is just the uncertainties of the statistical data as indicated in your question. So it will not be able to make assessment procedure from only the statistical model. To cope with this problem, we are now studying the assessment model shown in Fig. 15, which simulates the assessment procedure. This model has the hierarchical structure made from many unit models corresponding to the adequate grain for the assessment. The unit model at the lowest level of this hierarchy will have the data of the residual life, the maintenance and the operation environment as its internal components used at the life assessment. The assessment procedure is, in a sense, the semantics of this hierarchy model. Of course, it is impossible for this closed-world model to deal with the real open world. So we think that the statistical data will be useful as the interface between this model and the real world. In other words, we should determine the structure and the components in the assessment model as they must be compatible with the statistical model between the assessment model and the real world. At this time, we can't say the detail of the model structure, for example, whether it may be as almost the same as the tree structure used in various fault diagnosis techniques.

The answer to the second question is as follows. We agree with your opinion. As mentioned in our paper, it is natural to consider that the data in Table 9 should not be used in the assessment process without the adequate modification, because they are the average values achieved under the maintenance works at operation and the repair at the shipyard. By showing these data indicating the present condition, we want only to suggest that the practical maintenance methods is useful. We think it will contribute to make the rational life assessment system to generalize these practical methods in the assessment process.