A study of a Fatigue Management System for LNG Carriers using a New Fatigue Damage Sensor*

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Abstract:

A pro-active safety management system for ship structures which quantifies the effects of aging, such as deterioration of the ship's structural integrity due to fatigue and corrosion, is proposed as a new approach to the structural surveys of ships that have conventionally been made under a more passive management system. Some of the authors have developed a compact fatigue damage sensor that when attached can detect accumulated fatigue damage in welded structures. The authors have applied this sensor to the hull structures of an LNG carrier for experimental purposes, ascertained its long-term durability under the severe environments to which the ship was exposed, and obtained quantitative data on the accumulated fatigue damage. In this paper, the authors introduce a fatigue management system using this sensor called the Hull Aging Management System (HAMS) and propose it as a pro-active safety management system for LNG carrier hull structure aging and introduce a method to improve the accuracy of accumulated fatigue damage detection by using this sensor.

1. INTRODUCTION

LNG carriers are mostly operated as specified by long-term time charters (e.g., 25-year charter) for specific projects and have a high added value. Considering the depreciation period of LNG carriers, from the viewpoint of effective use of capital, it can be assumed that they should be kept in service for a longer period in compared to other vessel types. Furthermore, societal demands on LNG carriers as a means of transporting large quantities of LNG are increasing every year. These demands include safe transportation as a part of the corporate social responsibility (CSR) of LNG carrier operators and cargo consignees, and the stable supply of LNG as a major source of primary energy based on national energy policies.

It is therefore the most basic requirement for LNG carriers that they are capable of transporting cargo safely over a long time period. Deterioration over time, however, is the greatest problem awaiting solution for safe, long term use of LNG carriers. The following main factors are responsible for the deterioration of LNG carriers over time.

・Deterioration by corrosion (wear and tear damage)
・Deterioration by fatigue (fatigue damage)

This study focused on deterioration by fatigue

In addition to early detection of fatigue damage, preventing fatigue damage from occurring on LNG carriers is very important. In addition to early detection of fatigue damage, preventing fatigue damage from occurring on LNG carriers is very important. The following two types of measures are usually taken as measures against fatigue damage.

・Measures at design and building stages
・Measures during maintenance

These items are complementary and when these measures are satisfactory, they are sufficiently effective measures against fatigue damage.

In the past, measures focusing on qualitative methods, such as adoption of detailed design structures based on experience to avoid stress concentration were undertaken at the design and building stages. In recent years, it has been common to evaluate fatigue strength of the detailed

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structure of each LNG carrier in accordance with fatigue strength criteria at the design stage. By way of example, ClassNK (2001, 2005) developed a practical method of fatigue strength evaluation called the PS-FA (PrimeShip - Fatigue Assessment) based on the results of the latest research (Yamamoto and Matsuoka 2002) and development. This method has been widely used for fatigue strength design.

Maintenance measures for LNG carriers in service may either be mandatory survey items or operators' voluntary inspection and maintenance work items. Maintenance and management can be roughly classified into two types: passive management and pro-active management. Passive management involves taking corrective measures after the occurrence of problems, including damage. On the other hand, pro-active management is a method of preventing damage and other problems before they occur.

Practically, however, fatigue damage cannot be identified visually until it reaches a particular extent. In the past, whenever fatigue damage was identified, passive management measures such as replacement and/or reinforcement of the damaged parts (including other parts of similar structure) were undertaken.

Considering the fatigue life of each vessel in these two approaches, measures taken at the design and building stages cannot always give an exact value of the actual accumulated fatigue damage for any specific structural part of the vessel. The reason is that there are many vessels in operation on navigation routes under loading conditions that are different from the standard routes and loading conditions originally assumed for the vessels. Therefore, measures taken only at the design and building stages cannot always be sufficient or effective for appropriate maintenance and management of the respective vessels. Accordingly, the development of a pro-active approach, developed technically as maintenance measures for each vessel in service, is necessary for effective maintenance and management of the vessel, as well as the use of the vessel safely over a long period of time.

It is suggested that such a pro-active management approach could be realized with a new scheme that utilises a tool that directly or indirectly obtains information on the history of stress or accumulated fatigue damage to actual specific structural members. Referring to the monitoring concept of hull life proposed by Ship Research Panel 245 organized in the Shipbuilding Research Association of Japan (2002), the authors propose a hull fatigue management system as a new scheme and as the key element of the HAMS. The Hull Fatigue Management System (HFMS), as a core tool of the HAMS, is characterized by adoption of an accumulated fatigue damage evaluation by using a Fatigue Damage Sensor (FDS) developed by some of the authors.

In addition to introducing the HFMS, this study presents the results of an accuracy improvement test of the HFMS method using FDSs and evaluates the accumulated fatigue damage to the actual construction of vessels in service, along with the results of an application test of the FDS on vessels in operation. This study also examines the feasibility of the practical use of the FDS.

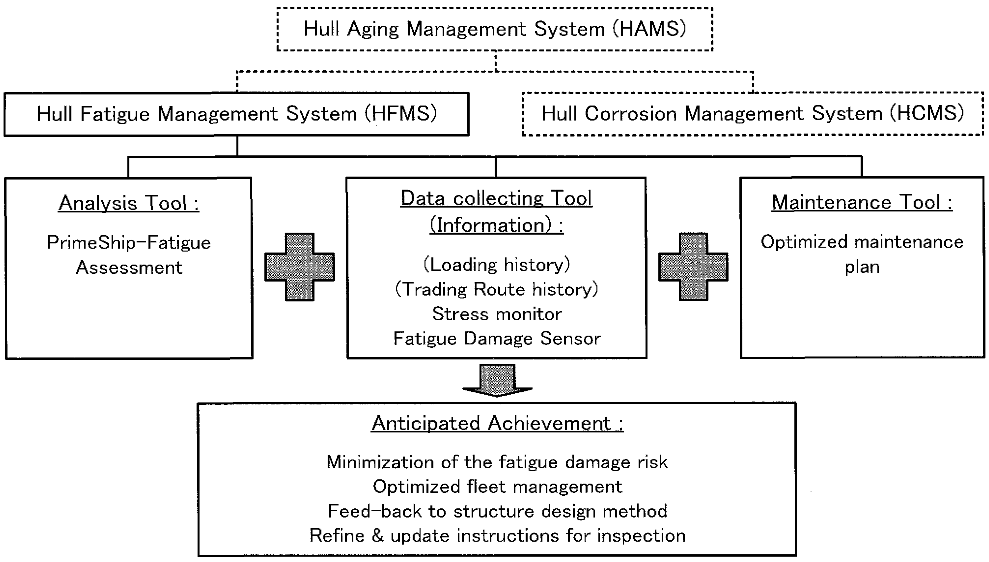

Figure 1 Schematic Diagram of Hull Fatigue Management System (HFMS)

2. Hull Fatigue Management System (HFMS)

Figure 1 shows the schematic diagram of the HFMS.

The HFMS consists of three tools:

Tool 1: Tool for fatigue strength design (Analysis Tool)

Tool 2: Tool for collecting data relevant to accumulated fatigue damage (Data collecting Tool)

Tool 3: Tool for maintenance and management (Maintenance Tool)

Tool 1 is the fatigue design method of PrimeShip-FA. In this method, at the request of the owner, a vessel's fatigue strength at the design stage is confirmed to be free from problems. Moreover, the relative fatigue sensitivity of each structural member can be clearly understood. This method can be used for selecting the measurement areas where Tool 2 is to be used. Several different data collection methods are suitable for use as Tool 2. Table 1 shows three typical methods.

In method A (navigation record method), recorded navigation routes and cargo loading data are fed back into the fatigue design tool for re-analysis at defined intervals, such as a maintenance schedule, and the stress values are obtained by re-analysis. The accumulated fatigue damage to the structure at that moment is then calculated. In this method, the extent of fatigue damage or the history of stress actually accumulated can not be directly determined. Furthermore, the extent of the fatigue damage is obtained from analysis only. Therefore, there are a number of complications, such as the clarification of service routes and the frequency of loading as analysis conditions. Additionally, marine meteorological conditions are assumed and preset and use statistically processed data for measured values, which will differ from actual conditions.

Table 1 Comparison of Fatigue Damage Data Collection Tools

	A : Navigation Record Method	B : Stress Monitoring Method	C : Fatigue Sacrificial Specimen Method
Procedure	By recording for navigation routes and ship's condition	By stress monitoring for the subject members	By fatigue sacrificial specimens attached on the monitoring members
Equipment	-----	Strain gauges, cables, computers for data accumulation, etc.	Fatigue sacrificial specimen
Fatigue Damage Assessment	Re-analysis by a fatigue design standard	Re-analysis by using accumulated stress history	By conversion from propagated crack length on the specimens
Labor	Large	Large	Small
Maintenance	-----	Large	Small

In method B (stress monitoring method), a recorded history of stress is analysed in the fatigue strength design method to calculate the accumulated fatigue damage to the structure. The advantage here is that the processing of marine meteorological conditions and loading condition data is unnecessary, because the actual stress acting on the structure is used. On the other hand, the cost of installation work including the wiring of measuring equipment and the installation of a computer system to record the stress history can be very high.

Method C (fatigue “sacrificial specimen” method), which the authors recommend, uses a measured crack length, multiplied by the crack propagation length on the sensor, obtained in advance, along with a coefficient relating to the accumulated fatigue damage to the actual structure. The accumulated fatigue damage to the structure can then be obtained directly. This method offers the advantages of method B, while at the same time, keeping the cost of installation work low.

The operator's maintenance plan is an example of Tool 3 (a maintenance and management tool). By using more precise, updated data of the accumulated fatigue damage to specific parts of each vessel obtained from Tool 1 and Tool 2, better and more timely maintenance becomes possible. As a result, it will become possible to develop a maintenance plan optimised from a long-term point of view.

By making practical use of the HFMS as a new maintenance scheme as already explained, a number of advantages will be obtained, such as prevention of accumulated fatigue damage, more effective inspections and checks, employment of optimised fleets, and better operation planning. Consequently, the HFMS can contribute to the initial objectives, such as realization of safe LNG carrier service over a long period and effective use of the vessel as a valuable resource.

The authors have developed an evaluation method for accumulated fatigue damage that uses the FDS (method C in Table 1), which is a type of sacrificial test piece, as a tool that actually monitors accumulated fatigue damage in a simple, practical way. Figure 2 shows the operational flow of the HFMS using the FDS and this evaluation method.

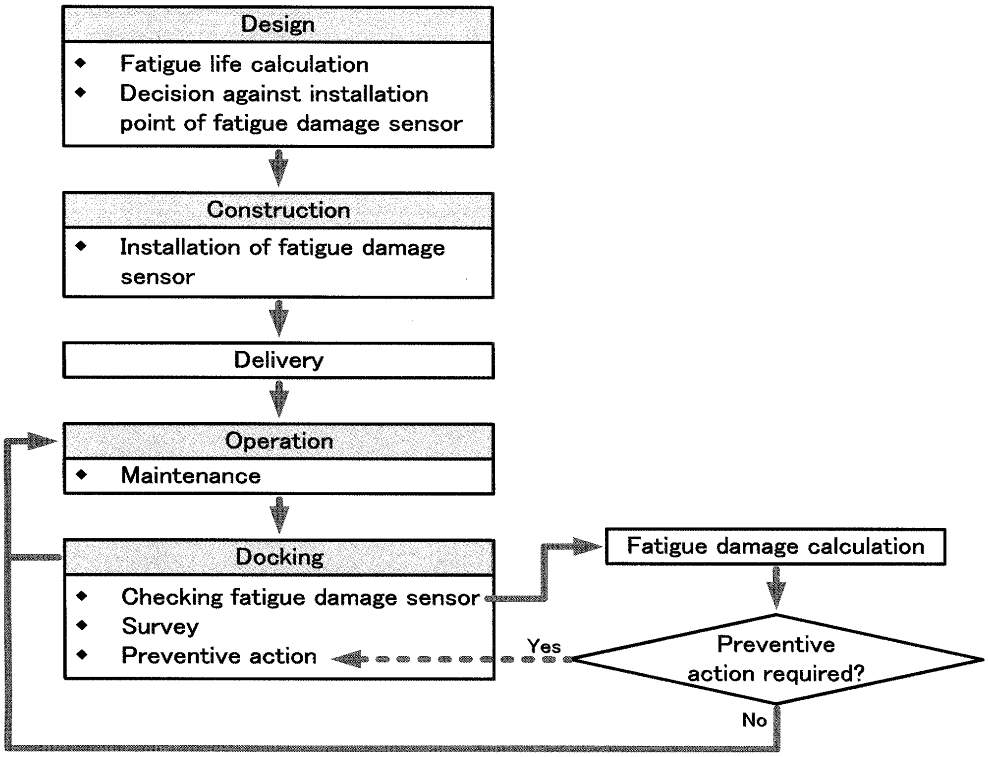

Figure 2 Flow Chart for Implementation of HFMS

3. Fatigue Damage Sensor (FDS)

3.1 Concept and principle of fatigue damage sensor (FDS)

(a) Concept of Fatigue Damage Sensor (FDS)

Muragishi et al. (2004) have developed the FDS as shown in Figure 3. When this sensor is attached firmly to a component of the hull structure for a certain period of time, the accumulated fatigue damage will be read into the FDS, so that the fatigue life of the component can be obtained.

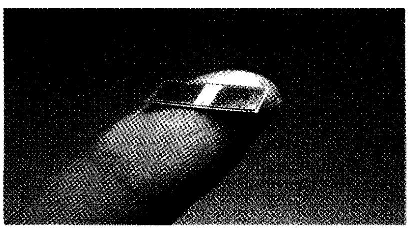

Figure 3 Fatigue Damage Sensor (FDS)

As shown in Figure 4, compared with the conventional strain gauge method (method B in Table 1), the above method has the following advantages.

- No other measuring equipment or wiring is required.
- Obtains information on the operating conditions of the actual system more precisely through long time use.
- Compact and direct use at a position of suspected stress concentration is possible.
- Adhesive type similar to strain gauges.

(b) Principle of the Fatigue Damage Sensor (FDS)

As shown in Figure 5, the FDS consists of a sensing foil and a base foil. A groove is formed in the central part of the sensing foil to amplify strain, and an initial notch is formed on one end of the groove at the middle.

When the FDS is attached near the welded line of a structural member, a fatigue crack will initiate and then propagate from the front end of the slit tip of the sensing foil in proportion to the level of stress amplitude. The degree of crack propagation (length) on the FDS depends on the stress range and the number of cycles. The characteristics of crack propagation are independent of the sensor crack length. In other words, the crack propagation (length) on the FDS is proportional to the accumulated fatigue damage to the structure during the period of installation.

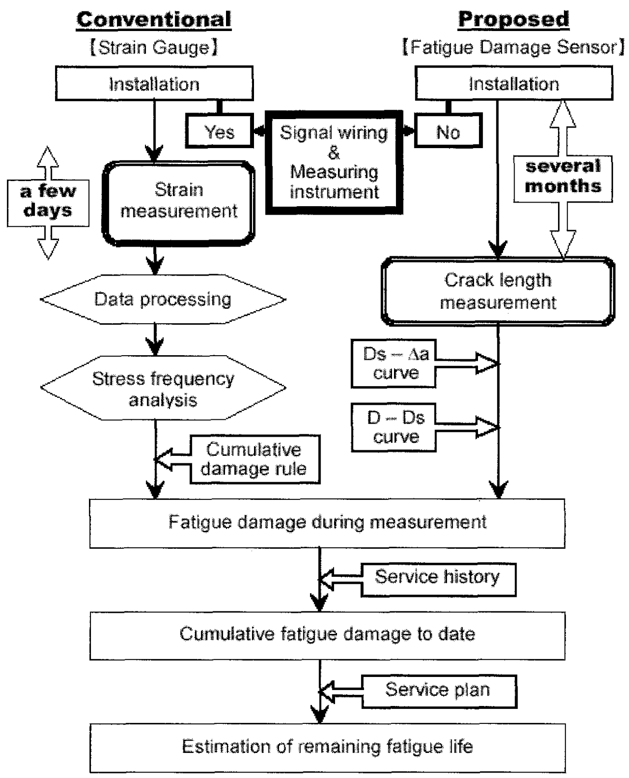

Figure 4 Comparison of fatigue remaining life estimation methods using strain gauge and FDS

Thus, according to the procedure shown in Figure 6, when the crack length on the FDS (Δa) is measured over a certain period of time, the accumulated fatigue damage to the FDS (Ds) can be obtained by the relation between Δa and Ds, and finally the accumulated fatigue damage to the actual structure (D), i.e., the fatigue life, can be obtained from the relation between Ds and D.

3.2 Characteristic acquisition test of Fatigue Damage Sensor (FDS) under actual stress on vessels

Kawaguchi et al. (2003) and Kobayashi et al. (2003) have verified that the FDS can find accumulated fatigue damage to actual steel bridges, rolling stock, and bogie frames under actual loads.

On the other hand, it is well known that there are stress conditions that are peculiar to seagoing vessels. For example, the stress fluctuation range of vessels caused by ocean waves greatly varies between calm weather and rough weather, and the mean stress on each vessel varies with the vessel's loading conditions. However, the effects of such a stress state on the crack propagation characteristics had not been fully explored previously. For this reason, the crack propagation characteristics of the FDS were checked in an experiment on an actual vessel under stress at sea. This paper introduces the effects of stress fluctuation under certain loading conditions due primarily to ocean waves.

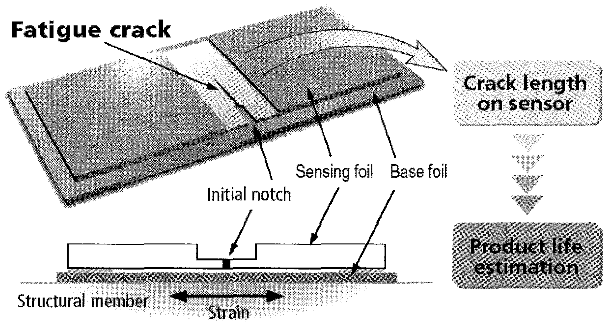

Figure 5 Construction of FDS

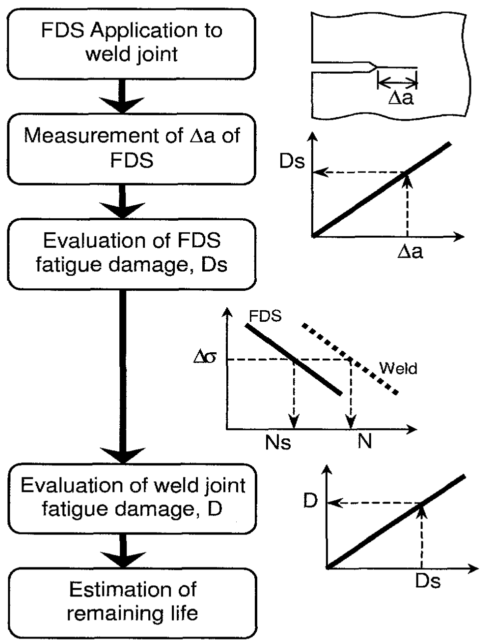

Figure 6 Flow of Fatigue Life Evaluation Using FDS

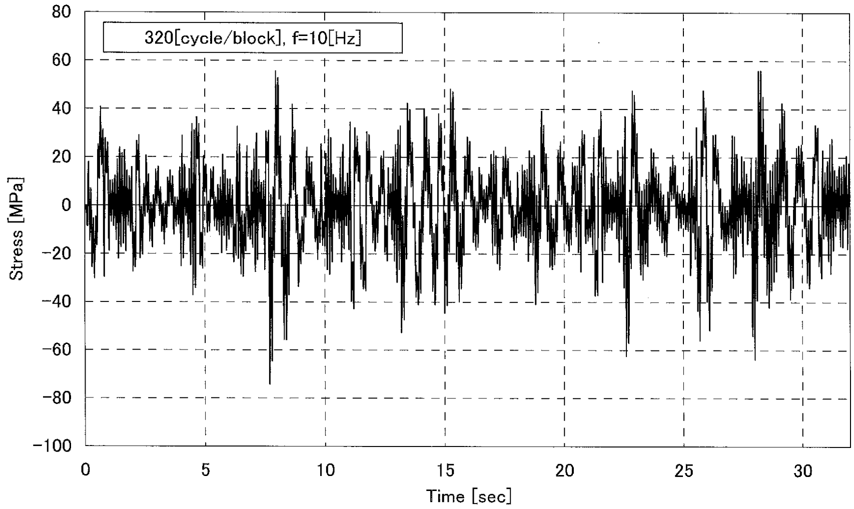

Figure 7 Input Stress Wave of Variable Stress range Test (Case-1)

(a) Fatigue Damage Sensor (FDS)

Several FDSs were microspot welded onto an 8-mm-thick and 40-mm-wide JIS-SS400 steel plate for each test. The long time durability of this welding method has been verified by a test on an actual ship as explained later in this paper. An electric- hydraulic servo control type fatigue testing machine was used to apply a load repeatedly on a component with FDSs welded onto it. The tests were conducted in normal atmosphere at normal temperature.

(b) Loading conditions

Yamamoto et al. (2006) measured the waveforms of the longitudinal bending stress on the hull of an actual vessel for about two years, and 20-minute measurement data on the waveforms under the roughest marine meteorological conditions were used as master data. The waveforms were processed as follows.

- The waveforms were rectified so that the mean stress would be almost zero.
- The test waveforms were multiplied in proportion to the measured waveforms. (The measured stress values were uniformly multiplied by an arbitrary coefficient α.)
- A sufficiently low stress range less than 10 MPa, which does not affect the crack propagation on the FDS, was excluded.

The waveforms after the above process were input into a fatigue testing machine. As an example, Figure 7 shows the input waveform with α set to 1.0. (The stress waveform in this example was set as in Case 1.) This stress waveform for a single block was repeatedly applied on a component with the FDS attached to it.

The measured stress was equivalent to the nominal stress (σ_n) in the component. Given that the nominal stress range ($\Delta\sigma_{ni}$) varies with ocean waves at the frequency (ni), the equivalent nominal stress range (($\Delta\sigma_{n,eq}$) and its equivalent repetitive number of cycles (neq) are calculated from the following formula according to the fatigue accumulation damage rule.

$$\Delta\sigma_{n,eq} = \left\{ \sum_i \left(\Delta\sigma_{n,i}{}^m \cdot n_i \right) \Big/ \sum_i n_i \right\}^{1/m} \quad (1)$$

$$n_{eq} = \sum_i n_i \quad (2)$$

where m is an index showing inclination (reciprocal of the gradient of the S-N curve). The FDS and the welded joint can be substituted with an m value of 3.

The loading conditions in Case 1, as loading conditions for the variable stress range test, are shown as an example in Table 2.

Table 2 Test Conditions for Variable Stress Range (Case 1)

α	1
Frequency	10[Hz]
$\Delta\sigma_{n,max}$	131[MPa]
$\Delta\sigma_{n,min}$	10[MPa]
$\Delta\sigma_{n,eq}$	44[MPa]
σ_{mean}	0[MPa]
n_{eq}	320[cycle/block]

Table 3 Test Conditions for Constant Stress Range

Frequency	10[Hz]
$\Delta\sigma_n$	44[MPa]
σ_{mean}	0[MPa]

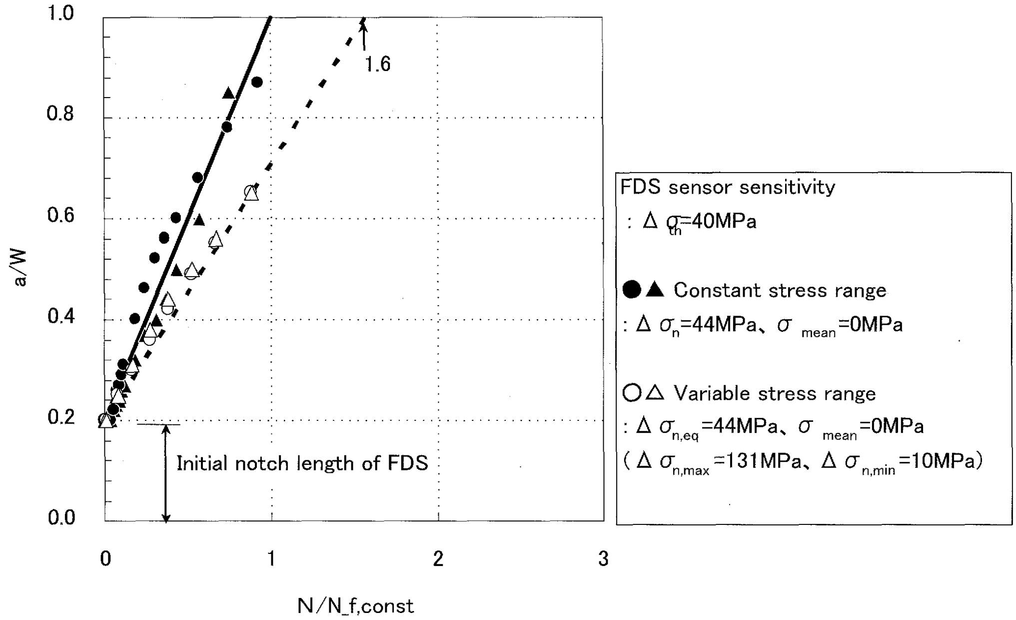

Figure 8 Crack propagation characteristics of FDS (Case 1)

A constant stress range test was conducted for comparison with the variable stress range test. A constant nominal value stress range ($\Delta\sigma_n$) was assumed in agreement with the equivalent nominal stress range ($\Delta\sigma_{n,eq}$) for the variable stress range test. The mean stress was regarded as zero, and the stress ratio R was revised to −1 in both tests. Table 3 shows the test conditions in Case 1 as an example.

(c) Test results

Stress was repeatedly applied on a component with the FDS welded onto it under the conditions specified in the previous section, and the relation between the crack length on the FDS and the number of loading cycles was obtained. Figure 8 shows the test results under the conditions in Case 1 as an example. Figure 8 shows the crack propagation characteristic of two FDSs under the variable stress range test and the constant stress range test. The vertical axis in Figure 8 is a dimensionless expression of the crack length of the FDS (a) divided by its width (W). The horizontal axis in Figure 8 is also a dimensionless expression of the number of load cycles, $N/N_{f,\ const}$ divided by the fracture life of the fatigue damage sensor under the constant stress range test ($N_{f,\ const}$).

In both tests, the FDS showed stable crack propagation characteristics regardless of the crack length. For the FDS used in this study, the crack propagation rate as a result of the variable stress range test showed a tendency to be delayed at a certain ratio (retardation effect) compared with the crack propagation rate as a result of the constant stress range test.

Based on the premise that the fatigue strength of the welded joint subject to evaluation was not affected by a stress fluctuation history within the variable range under actual voyage conditions and that it was subject to the accumulated fatigue damage under the assumption of the linear accumulated damage rule (Palmgrens-Miner rule), the evaluation of the accumulated fatigue damage to the welded joint was confirmed to be possible by just considering the effect of variable stress on the FDS.

3.3 Application to an LNG carrier

FDSs were used on an experimental basis on the hull structure of a MOSS-type LNG carrier (to be called "the carrier") with a cargo capacity of 145,000 m^3 built by Kawasaki Shipbuilding Corporation, and the accumulated fatigue damage to the structure under actual loads was obtained from the values measured with the sensors. Then the damage was compared with the results of a fatigue strength check using the NK PrimeShip-FA method for verification of the remaining life assessment of the hull structure with the FDS employed.

At the time of the final docking of the carrier in the shipyard, 20 FDSs in total were attached to six stress concentration areas of the hull structure under the conditions that the accumulated fatigue damage to the areas was considered to be relatively heavy based on the calculation results by the PrimeShip-FA method and also that the areas did not require permanent scaffolds. The areas selected for the sensor attachment were easy-to-inspect areas exposed to relatively heavy stress, such as the welded part on the exposed side of the cargo tank cover and the upper deck near the midship, the welded part of the foundation deck and the tank skirt bottom in the cargo hold area, and the weld intersection part of the longitudinal bulkhead and the foundation deck. Additionally, a number of FDSs were attached to the heel weld part of a vertical stiffener of a bottom longitudinal in a water ballast tank. The FDSs attached to each area were different from one another in stress sensitivity ($\Delta\sigma_{th}$), i.e., the sensitivity levels applied were 40 MPa, 60 MPa, and 80 MPa. Figure 9 shows an example of the FDSs as attached. In order to ensure that the FDSs would work without any problems during dock-to-dock diagnostic periods of the carrier, they were spot-welded for best durability except for some that were glued to the structure to check the durability of the adhesive agent on the actual vessel. The FDSs attached were well protected and each position was marked.

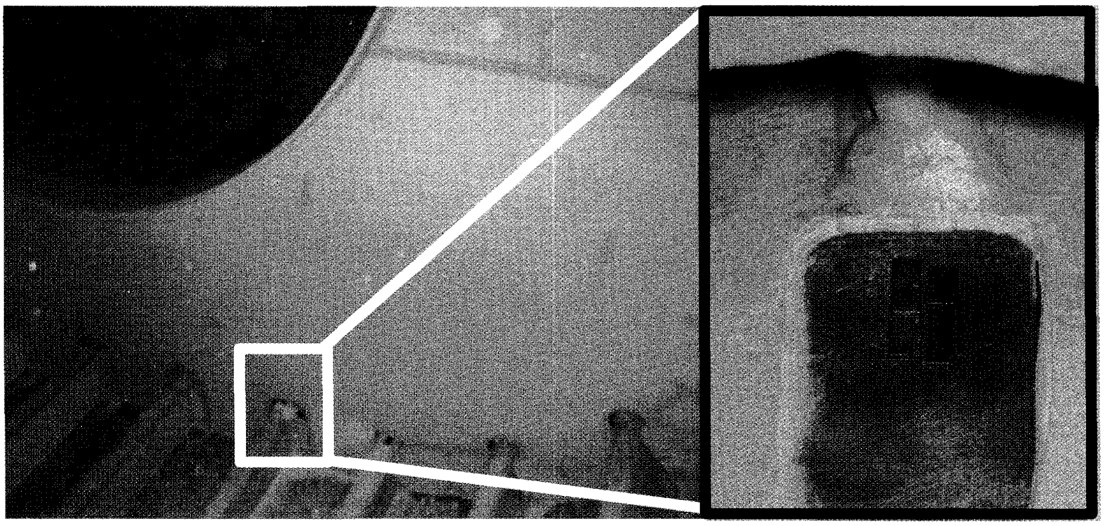

Figure 9 An Example of Application of FDS (Before touch-up painting)
(4 Sensors were attached to a Heel of a Bottom Longitudinal in a water ballast tank)

The period of remaining life assessment on an experimental basis for the carrier was approximately two years and two months up to the first docking survey.

It is possible to compare and verify survey data on accumulated fatigue damage with those obtained by using the FDSs, provided that a variety of survey data is collected while the carrier is at sea. The more the number of data items increases, the more the analysis of the data takes time. Considering the practical use of hull management systems, it is better to reduce the number of associated data items as much as possible and to complement the survey data on accumulated fatigue damage using the FDS. In this study, the authors decided to use only route data on the carrier (i.e., data on the loading ports, discharging ports, navigation routes and the number of navigation days) in the sensor monitoring period.

One result of the inspection of the fatigue damage sensor during the carrier's first docking survey was that the bonding of the 20 FDSs used did not have any problems. Therefore, it was demonstrated that the sensor is suitable for use for a dock-to-dock period of 2 to 2.5 years.

The following facts were discovered by comparing the accumulated fatigue damage at the FDS monitoring points as calculated by the PrimeShip-FA method and the monitoring values obtained from the FDSs. Compared to the calculated value of the accumulated fatigue damage at each part, there was no clear crack propagation on the

FDSs on the bottom longitudinal monitoring points despite the fact that more accumulated fatigue was damage anticipated. On the contrary, crack propagation was found on the FDSs at a part with less accumulated fatigue damage than was anticipated (i.e., the welded part on the exposed side of the tank cover and the upper deck). According to the calculation results for fatigue strength, the mean stress under fully loaded or ballast condition was on the compression side at the measuring point of the bottom longitudinal area which would result in heavy accumulated damage. Each variable stress range showed a similarity to the variable stress condition with a stress ratio of -∞ (pulsating compression)

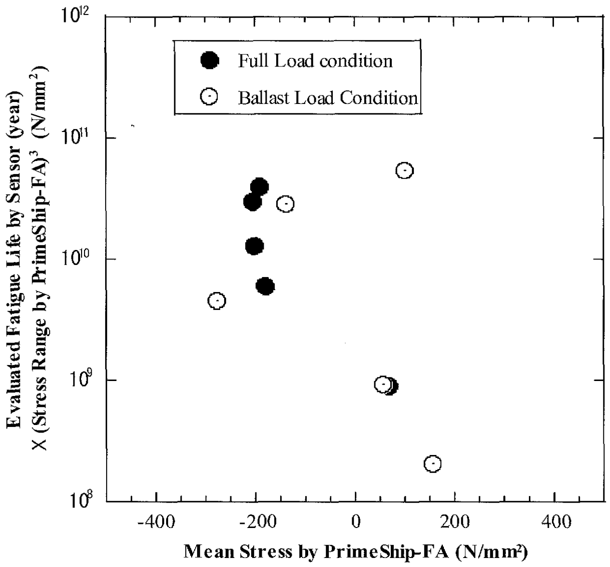

Figure 10 Sensor's Sensitivity to Mean Stress

On the other hand, in the areas where the crack propagation on the FDSs were noted (i.e., the welded part on the exposed side of the tank cover and the upper deck), the mean stress under fully loaded or ballast condition was on the tensile side. Each variable stress range showed a similarity to the variable stress condition of a stress ratio of 0 (pulsating tension). The accumulated fatigue damage calculated by the PrimeShip-FA method varies with the difference in residual stress or mean stress value. The S-N diagram used, however, showed that it was approximately related in logarithmic proportion to the third power of the variable stress range at an occurrence rate Q of 10^{-8} under the condition that the vessel was in fully loaded or ballast conditions.

Figure 10 shows the relation between the mean stress and the product of the third power of the maximum variable stress range, and the evaluated fatigue life with the sensors under each condition. With regard to the sensors where no crack propagation was observed, the fatigue life of the monitoring point was estimated based on the assumption that the highest sensitive sensor at the point had a micro-crack.

There were some sensors where no crack was observed. Then, the fatigue life expectancy of the monitoring point was obtained on the assumption that the sensor with the highest sensitivity at the point had a minute fatigue crack. It is possible to consider the fatigue life is in inverse proportion to approximately the third to the forth powers of the stress amplitude. If the crack propagation on the sensor is not affected by the mean stress, the inclination of Figure 10 is considered to be horizontal. As far as Figure 10 is concerned, however, the fatigue life judged from the sensor tends to be long when the mean stress value is on the compression side.

4. DISCUSSION

4.1 Correction factor for ship's navigating area

As a result of actual application of the FDS to the LNG carrier, it is possible to postulate that crack propagation on the sensor occurs in inverse proportion to the compression-side extent of the mean stress value and that there is a noteworthy difference from the calculation results from the PrimeShip-FA method. There is a need to discuss further how to consider the crack propagation on actual structures in compressive stress regions. It is also possible to consider that the crack propagation on the sensor is similar to the crack propagation of actual steel structures. This must be checked by a fatigue strength test on test specimens with the sensors attached in the compressive stress region. From the accumulated navigation routes on and after the carrier's maiden voyage, a correction factor for the ship's navigating area (η_s = 0.25) was obtained directly from the measured value by using the FDSs. As shown in Figure 8, the differences in sensitivity of each of the FDSs requires a coefficient of delay in crack propagation under a variable load. This value (a coefficient of delay of 1.6 from Figure 8) is multiplied by η_s, which is equivalent to accumulated damage, and a correction under the variable load is made to obtain a η_{smod} value of 0.4.

In the analysis using the PrimeShip-FA method, the correction factor for the ship's navigating area (η) is defined as 0.5 on the worldwide sailing route basis and 1.0 on the North Atlantic sailing route basis. The correction factor for the ship's navigating area (η_{smod} =

0.4) shows a difference from the correction factors for the ship's navigating area defined on the navigation route basis. According to the navigation route data on the carrier, the correction factor for the ship's navigating area obtained from the measured values for the FDSs coincides with the fact that the carrier was navigating under marine meteorological conditions that were milder than those on the worldwide sailing route defined by PrimeShip-FA.

If the structural members to be monitored are selected from an LNG carrier in full consideration of the characteristics of the FDS and by referring to the fatigue strength design results from the PrimeShip-FA method, the accumulated fatigue damage to the area, i.e., the life expectancy, can be obtained precisely. Further, relative comparison makes it possible to estimate the values of other stress concentrations, and the practical use of the concept of the HFMS will become possible. It is hoped that the development of the HFMS with higher precision for LNG carriers will become possible in the future by accumulating more measurement data from actual LNG carriers.

The life expectancy diagnosis of vessels under working loads has yet to be fully performed. Although it appears that there might be allowable errors in the actual measurements on the LNG carrier from the calculated values, it is significant that the pro-active development of hull repair schedules and procedures has now become feasible with a relatively small number of FDSs in selected areas.

4.2 Advantages of applying HFMS

The advantages of applying the HFMS are determined best determined by extensive, actual use. However, two major advantages can be expected: higher reliability that makes it possible to decrease the risk of potential cracks, and cost-effectiveness that can be realized through reasonable maintenance. It is expected that not only the makers of the FDS but also all the related industries including charterers, owners, shipyards, and classification societies will be able to gain favourable evaluations through incorporating the HFMS into their business in diverse ways, thus fully enjoying such advantages. Furthermore, the HFMS is expected to enable an effective use of resources and also enhance the corporate image of all related industries from the standpoint of CRS (corporate social responsibility).

The following section lists the respective advantages that can be expected.

- Charterers
  - ➢ Fatigue lives of ships can be recognized and anticipated. In other words, the risk of causing potential cracks can be identified, so that charterers can selectively charter ships that have a high degree of reliability.
  - ➢ Fatigue damage to chartered ships can be prevented, thus enabling charterers to provide a long-term stable supply of LNG. As a result, charterers will enjoy high evaluations from stockholders and the public.
- Owners
  - ➢ Reasonable maintenance and optimum cruising services can be performed to reduce cost, leading to a high evaluation from stockholders.
  - ➢ By controlling the fatigue life of hull structure, ships having a high degree of reliability can be provided for charterers, leading to a high evaluation from charterers,
  - ➢ Fatigue damage is prevented, thus enabling stable transportation of LNG over a long period of time, again leading to a high evaluation from charterers.

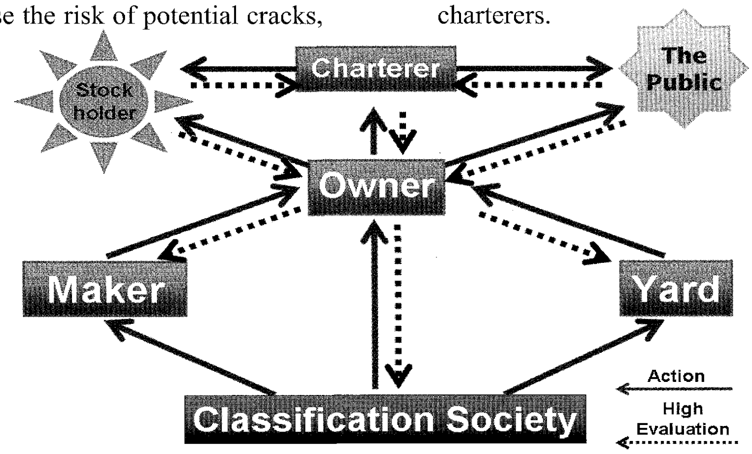

Figure 11 Correlation diagram of advantages of applying the HFMS

・Shipyards

➢ Shipyards can make proposals for ships that are designed with the FDS mounted and are capable of evaluating the fatigue life of hull structure. Thus, shipyards will receive a high evaluation from owners (leading to additional orders from them).

➢ Data based on findings from the FDS are fed back to the fatigue strength design of ships. Again, shipyards will receive a high evaluation from owners.

・Equipment makers

➢ Equipment that can effectively detect fatigue damage, such as the FDS, can be supplied. Makers will receive high evaluations from owners.

・Classification societies

➢ Classification societies can help contribute to safety of ships in service. Naturally, the classification societies will receive a high evaluation from owners.

➢ Data based on finding from the FDS are fed back to ship inspections and structural design reviews, which means that classification societies will receive a high evaluation from owners and shipyards.

➢ The HFMS will allow for ships to be built according to new design concepts as a sort of insurance. Consequently, classification societies will receive a high evaluation from owners and shipyards.

As already mentioned, it is quite obvious and significant that the use of the HFMS brings benefits to all the industries concerned. Figure 11 shows the correlation diagram of the advantages expected. In the future, differences in such benefit, which are caused depending on whether or not the HFMS is used, should become clear in quantitative terms.

5. CONCLUSION

The authors proposed the Hull Fatigue Management System (HFMS) as a new management scheme and as the key element of the Hull Aging Management System (HAMS).

As the core tool of the HFMS, a fatigue damage evaluation method employing the fatigue damage sensor (FDS) was developed for the simple and practical acquisition of data on accumulated fatigue damage.

The results of the application test on an LNG carrier were quite satisfactory. The authors will continue their study, among other topics, on the effects of mean stress evaluation where FDSs can be applied and the effect of hull conditions when attaching the FDS.

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