Structural Strength Rules Applied to Container Ships

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1. INTRODUCTION

ClassNK (hereinafter, the Society) completed a comprehensive revision of Part C of the Rules for the Survey and Construction of Steel Ships (hereinafter, Part C) [1)] in 2022 [2)]. Based on the knowledge of ship hull structures accumulated in ship classification work over a period of more than 100 years, in this comprehensive revision, the Society conducted research and development on the element technologies of load, corrosion, yielding, buckling, fatigue, etc. necessary in strength evaluations of the hull structure of ships in a rule development project that began in 2017, and adopted the results of the project in the revised rules. The former Rules, while based on load and strength formulae with a theoretical basis, frequently applied empirical engineering techniques, in which appropriate safety factors were derived by investigating the hull scantling necessary to avoid damage in each ship type or structure using records of damage up to the time. In contrast, following the comprehensive revision, the Rules are now based on techniques that accurately estimate and evaluate strength criteria, etc. which are directly tied to the rough sea states which ships encounter, the hull response under those rough sea states, and the condition of corrosion and occurrence of damage of ships in service, making it possible to use the design method called “design by analysis.” Therefore, although Part C of the Rules is applied to various ship types, including container ships, LNG carriers, general cargo ships, etc., the basic strength requirements are unified independent of the ship type. On the other hand, structural requirements specific to a certain ship type, or requirements for problems related to structural strength which are specific to a particular ship type are also necessary in some cases. Container ships have a comparatively large number of requirements of this type.

In response to both the recent sharp increases in fuel costs and the environmental regulations, slow steaming has been adopted. However, this has reduced container shipping efficiency, and progressively larger-scale container ships are being constructed in ways that compensate for this issue. In the 1990s, 9,000 TEU container ships were the largest scale vessels, but 23,000 TEU vessels with a length of more than 400 meters have now appeared.

Because extremely high strength, extremely thick steel plates of YP47 steel with a thickness of 100 mm are used in the upper deck plates and hatch side coamings of large container ships, it has become possible to reduce the amount of steel used in spite of the huge size of the hull structure. For this reason, there tends to be a relative decrease in the stiffness of the hull structure, and it has been pointed out that the effects of elastic vibration of the hull structure, i.e., whipping and springing, become greater. Moreover, since extremely thick steel plates are used under very high tensile stress conditions, the possibility of brittle fracture, which is a dangerous damage mode, has also been noted.

The Society developed the criteria for ensuring safety for these structural strength problems which are specific to large container ships through joint research, etc. with related industries and research institutes. The developed criteria are incorporated in Part C of the revised Rules, which are original structural rules of the Society, or adopted as Unified Requirements (URs) of the International Association of Classification Societies (IACS), through the efforts made by the Society.

This paper presents an overview of Part C of the Rules for the Survey and Construction of Steel Ships, focusing on container ships, and explains the content, history and technical background of the Society’s original strength requirements which are applied exclusively to container ships.

2. DESIGN LOADS OF CONTAINER SHIPS

The wave loads that act on a ship’s hull structure depend largely on the sea conditions which the ship encounters. Structural rules generally consider the sea states in the North Atlantic Ocean, which is thought to have the most severe sea conditions

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among the sea areas that ships navigate. It is possible to estimate waves loads that capture the distinctive characteristics of individual ships by combined use of wave load analysis tools such as the strip method, 3-dimensional panel method, etc.

However, due to practical consideration such as manhours, it would be difficult to use wave load analyses in the design of each individual ship. Therefore, simplified formulae using the principal particulars, etc. of ships are necessary, and several formulae have been established in the structural rules. On the other hand, simplified formulae inherently involve a trade-off between simplicity and accuracy. Thus, the Society has been studying for many years to develop techniques for ensuring a good balance of simplicity, accuracy and transparency of the technical background, and formulated and published the results of our research as the “Guidelines for Container Carrier Structures” in the early 2000s. In addition to the equivalent design wave concept later adopted in the Common Structural Rules (CSR) of the IACS, these Guidelines also provide design torsional loads that occurs in ships with large hatches.

Following the release of the Guidelines, the Society responded to the increasing scale of container ships and twin-island container ships, and also continuously performed tank tests, series calculations by numerical analysis, etc. to address the problem of whipping, which is an elastic vibration phenomenon caused by impact loads due to slamming (see Fig. 1 and Fig. 2). A major revision of the rules for container carriers was carried out from 2015 to 2016, and the related design loads were also refined.

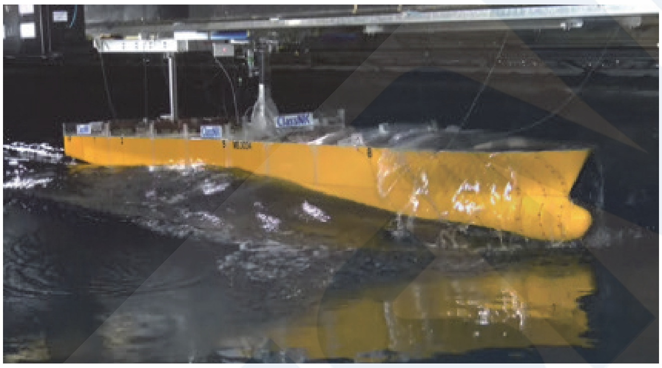


Fig. 1　Tank test of whipping

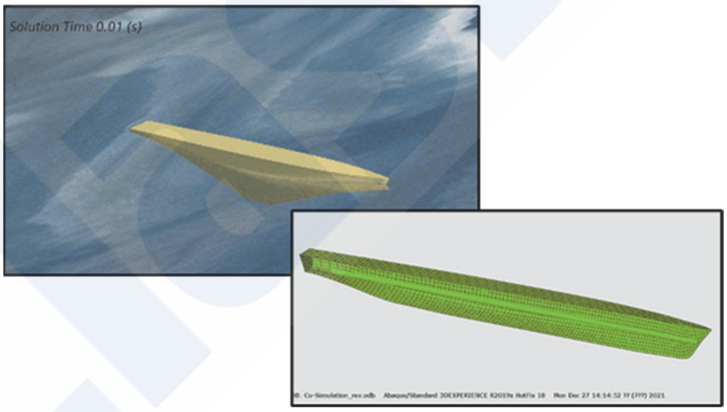


Fig. 2　Reproduction of whipping by analysis (coupled analysis using CFD and LS-dyna)

In the comprehensive revision projects of Part C carried out from 2017 to 2022, the simplified formulae were reviewed to make the design loads closer to the real phenomena, and concepts including the equivalent design wave were adopted throughout (see Fig. 3). Since the design loads for the equivalent design wave, etc. had already been introduced in the revision of Guidelines for Container Carriers in 2015-2016, no large changes are made in the concepts for container ships, but significant changes are made in the forms of the load formulae themselves.

In the above-mentioned comprehensive revision, a physical consideration based on theoretical formulae was carried out for the loads of acceleration and hydrodynamic pressure obtained by direct load analysis, the controlling factors were extracted for each component and their effects were investigated, and finally a careful verification was conducted with a large number of ships, not limited to container ships, based on the procedure of performing simplification. Through this process, design loads with high accuracy and greater generality have been successfully developed. In this project, ship operational effect (in addition, effect of a route that is applied in a fatigue strength assessment), which had been handled conventionally by an empirical engineering approach, is also clarified by a big data analysis, and those effects are specified in the rules in an explicit form. (For the details of this work, which was carried out in the said project, please refer to papers No. 3 and No. 5in this issue of ClassNK Technical Journal [3) 4) 5)].)

The comprehensive revision improved the transparency of the relationship between sea states and design loads, etc., and in the future, use is expected in various situations, not limited to structural rules.

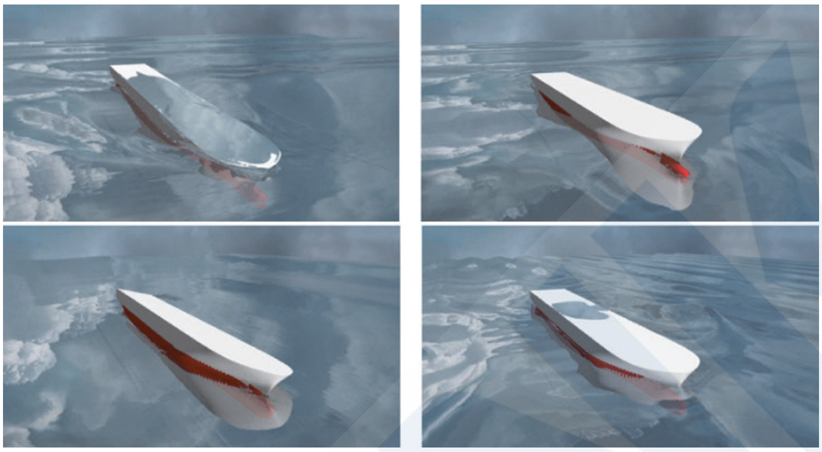


Fig. 3 Four equivalent design waves (top left: HM, top right: FM, bottom left: BR, bottom right: BP)

3. HULL GIRDER ULTIMATE STRENGTH CONSIDERING WHIPPING AND LATERAL LOAD EFFECTS

Based on hull failure accidents involving large container ships which have occurred in recent years, the Committee on Large Container Ship Safety [6)] of Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT), consisting of experts dispatched from shipbuilding companies and shipping companies, researchers and persons of learning and experience, and the Society's Investigative Panel on Large Container Ship Safety [7)] conducted various investigations and examinations, and presented recommendations on safety measures for container ships and action plans to be implemented in the future. The Society' Rules make it possible to guarantee structural safety more reliably for large container ships by developing original own strength requirements in line with the recommendations and action plan.

Hull girder ultimate strength refers to the maximum bending moment that a ship's hull treated as a single beam, can withstand without structural failures. Generally, when considering hull girder ultimate strength, it is assumed that only vertical bending moment acts on the ship's hull, and to the influence of the other loads acting on the hull is taken into account with a certain constant safety factors. However, particularly in large container ships, it is known that hull girder ultimate strength decreases significantly as a result of superposing the vertical bending stress and the stresses caused by the double bottom bending due to out-of-plane loads of sea pressure acting on the outer plates (shell plating) of the ship's bottom (Fig. 4). It is also known that the decrease ratio due to the superimposition also changes significantly depending on the design of the individual ship.

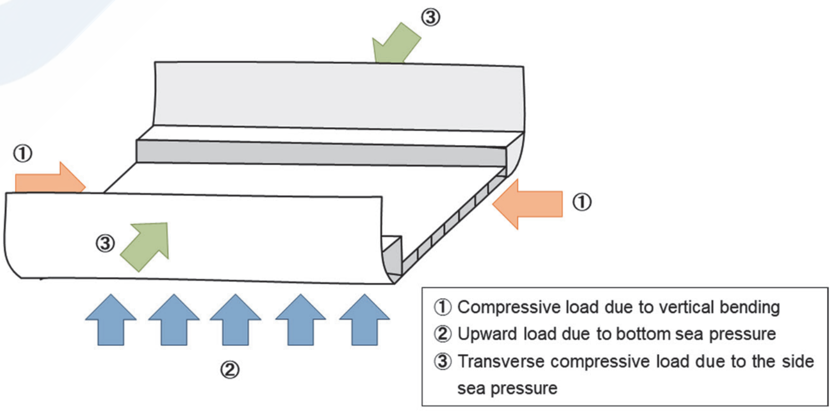


Fig. 4 Types of loads acting on bottom structure of container ships

Therefore, in the Society's Rules, the effects of these lateral loads are not expressed by safety factors with fixed values, but assessments can be carried out corresponding to the design of the individual ship. Concretely, the Rules adopt the simplified calculation method expressed by the following formula, which is derived by a comparative verification with a nonlinear finite element (FE) analysis that can directly consider the effects of lateral loads.

$$M_{U\_DB} = \alpha_U \sigma_{US\_avg} Z_B \times 10^3 \qquad (1)$$

M_{U_DB}: Hull girder ultimate strength considering the effects of lateral loads (*kNm*)
α_U: Correction factor derived by comparison with a nonlinear FE analysis (1.25)
Z_B: Section modulus at the ship's bottom (m^3)
σ_{US_avg}: Average ultimate strength for ship longitudinal loads of stiffened panels in the bottom shell plating (N/mm^2). The compressive stresses in the ship longitudinal direction and ship transverse direction acting on the bottom shell plates are derived from a cargo hold analysis, and the ultimate strength of the stiffened panels is obtained by considering the effects of the superposition of these stresses.

Vertical bending moment caused by elastic vibration of hull girders due to whipping is superimposed by the vertical bending moment induced by waves (see Fig. 5).

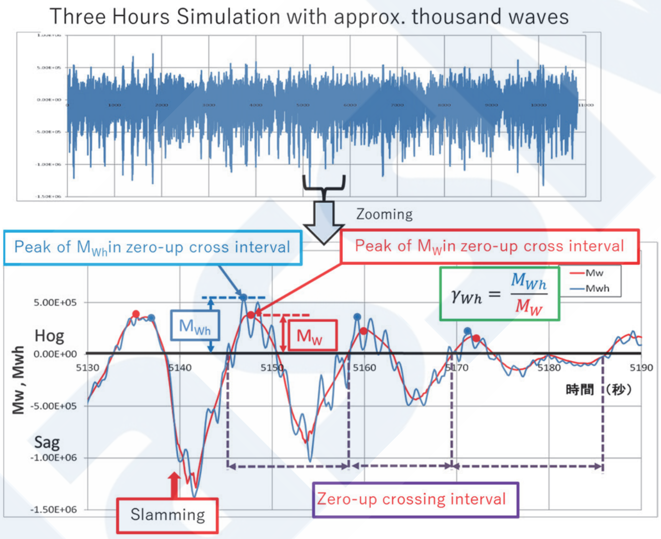


Fig. 5 Superposition of whipping moment

To determine the extent of the superimposed effect of the vertical bending moment, numerical simulations and tank tests using multiple sample ships were conducted as described above in Chapter 2. Based on these findings, a safety factor for the wave-induced vertical bending moment is set so as to enable a conservative assessment of the whipping effect for any container ship. Finally, the hull girder ultimate strength considering the effects of whipping and lateral loads is assessed as follows:

$$M_{Smax} + \gamma_{Wh} M_{W-Hog} \leq M_{U\_DB} \qquad (2)$$

M_{Smax}: Vertical bending moment in still water (*kNm*)
M_{W-Hog}: Vertical bending moment in waves (*kNm*)
γ_{Wh}: Safety factor considering whipping (1.5)

4. EFFECT OF ELASTIC VIBRATION IN FATIGUE STRENGTH ASSESSMENTS

Because elastic vibration of the hull girders is superimposed on the cyclic stresses generated by the vertical bending moment in waves, the stress range and number of cycles increase, and this also affects fatigue strength [8) 9)].

It is difficult to distinguish whether the vibrational phenomena that appear in a ship's hull are caused by springing or whipping. However, it is thought that the vibrational phenomena in sea states with a small significant wave height are caused by springing and those in sea states with a large significant wave height are caused by whipping.

In the design process, a fatigue assessment is typically carried out based on the stress range and the number of cycles caused by wave loads and it is difficult to directly consider the cyclic stresses due to superposition of elastic vibration and the resulting increase in the number of cycles. Moreover, it is also difficult to say that conducting a nonlinear elastic vibration response simulation is realistic. It is considered a convenient and rational approach to take into account the influence of elastic vibrations by multiplying a coefficient that considers the effect of elastic vibrations on the cumulative fatigue damage caused by ordinary wave loads. [10)].

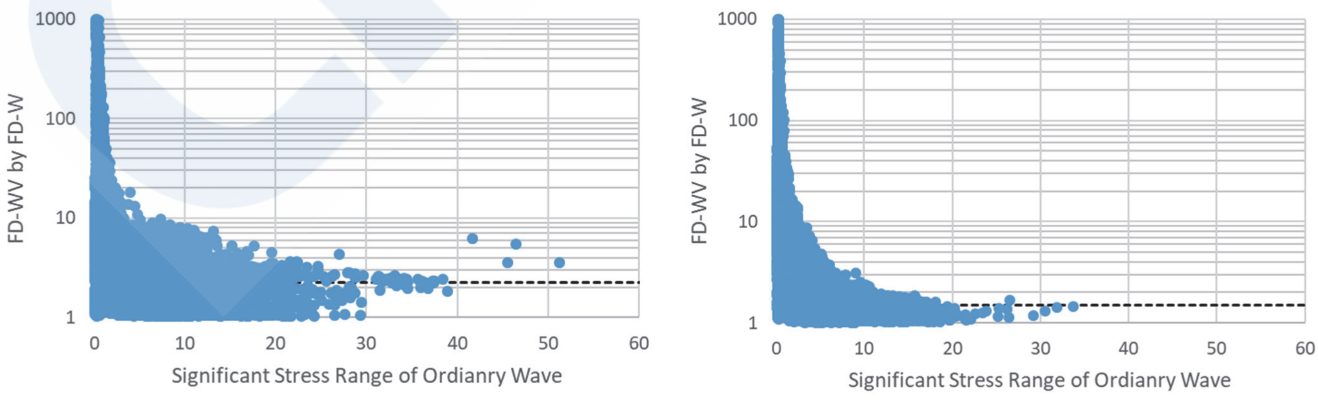
Therefore, in order to understand the nature of the elastic vibration that occurs in actual ships, the ship on-board measurement data for the vertical bending stress of two container ships (8600 TEU, 14000 TEU) were evaluated. The fatigue damage for the measured data for each 1-hour period were evaluated for the measured waveform *WV*, in which elastic vibration is superimposed, and the waveform *W* caused by ordinary wave loads with vibration component removed. The service routes of the 8600 TEU container ship were Asia-Europe and Asia-Europe-North America,via Cape of Good Hope, and back to Asia, while 14000 TEU vessel operated between Asia and Europe. The 8600 TEU container ship navigated severer sea areas.

Because the inverse of the slope of the S-N curve used in the assessment is 3, the fatigue damage is assumed to be proportional to the 3rd power of the stress range. The ratio of the sum of the 3rd powers for the stress ranges in *WV* and *W* for 1-hour period is equivalent to the ratio of the increase in the fatigue damage due to superposition of elastic vibration in welded joints.

$$C_{vib\_k} = \frac{\sum_{i=1}^{N_{WV\_k}} \Delta\sigma_{WV\_k,i}^{3}}{\sum_{j=1}^{N_{W\_k}} \Delta\sigma_{W\_k,j}^{3}} \tag{3}$$

Fig. 6 shows the relationship of the significant values of the stress range due to an ordinary wave for a 1-hour period, and the ratio of the increase in the fatigue damage due to superposition of elastic vibration. The dotted lines in the figures indicate the increase ratio of fatigue damage for the entire measurement period. This ratio was 2.25 for the 8600 TEU container ship and 1.51 for the 14000 TEU container ship.

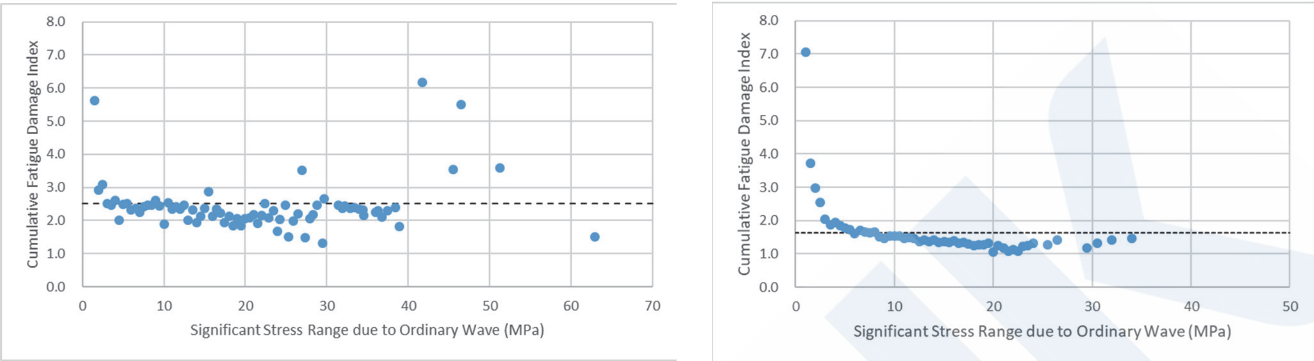
Larger variations in the increase ratio of the fatigue damage were observed as the stress range due to ordinary wave loads become smaller because the main factor is elastic vibration caused by springing, and in this case, relatively large vibration is superimposed in comparison with the stress range of ordinary wave loads. On the other hand, in the region of large stress ranges due to ordinary wave loads, where the main factor is elastic vibration caused by whipping, the variations are also small and appear to roughly converge near the average value.



(a) 8600 TEU container ship (b) 14000 TEU container ship

Fig. 6 Increase ratio of fatigue damage by superposition of elastic vibration for 1-hour period

Fig. 7 shows the result when the significant values of the stress range due to ordinary wave loads are divided into 0.5 MPa increments, and the expected value of increase ratio of the cumulative fatigue damage for each increment is taken. The dotted lines in these figures show the average values for the two container ships, which are 2.51 and 1.63, respectively. These results show that the values are almost constant irrespective of the significant values of the stress ranges and the type of vibration phenomenon, that is, springing or whipping. Based on this, by using the expected value of the increase ratio in cumulative fatigue damage as an influence coefficient, it is considered possible to take the effects of elastic vibration into account, without distinguishing springing and whipping..



(a) 8600 TEU container ship (b) 14000 TEU container ship

Fig. 7 Expected values of increase ratio of fatigue damage by superposition of elastic vibration in increments of 0.5 MPa of significant value of stress range

From the results described above, it is found that the influence coefficient of elastic vibration can be evaluated by performing elastic vibration simulations under sea states with a certain significant wave height. Therefore, in addition to the ship on-board measured data for the two container ships discussed above, elastic vibration simulations were carried out 10 times for the three container ships shown in Table 1, and the influence coefficients of elastic vibration were obtained as average values.

Based on the simulation results, the obtained influence coefficient for elastic vibrations is believed to be consistent with the results from on-board measurement, indicating generally good agreement. As for the ratio of increase in fatigue damage in cases where elastic vibrations occur, it can be considered to be approximately twice the fatigue damage caused by ordinary wave loads.

Table 1 Ships used in elastic vibration simulations and increase ratio of fatigue damage by elastic vibration

	CC-1	CC-2	CC-3
L (m)	350	300	200
Vs (kt)	21.85	27.25	22.50
C_{vib}	2.09	2.15	2.08

Based on a study of the effects of elastic vibration on fatigue strength, the following items are considered:

(1) Elastic vibration occurs under $\pm 30°$ head sea conditions.

(2) Elastic vibration is superimposed onto the cyclic stress caused by the vertical bending moment.

(3) In cases where elastic vibration is superimposed, the fatigue damage increases by approximately twice, regardless of whether it is springing or whipping and irrespective of the significant wave height.

(4) Stress assessment of the design loads in fatigue design is conducted for the long-term expected values of response for all wave directions.

(5) In finite element analysis by the direct method, the combined loads of the each load component are applied as the design load.

(6) Long-term cumulative fatigue damage is calculated based on the long-term distribution of the stress range for linear response.

Based on these items, how the influence of elastic vibration should be considered in the cumulative fatigue damage evaluated in the design stage was studied. In this study, the fatigue damage at the intersection between girders and longitudinal stiffeners of the target ships was examined as an example. In this evaluation, the vertical bending moment, horizontal bending moment, dynamic wave pressure and response amplitude operator of acceleration in the three directions X, Y and Z were used. The vertical bending moment, horizontal bending moment, stress range by wave and internal pressure at the evaluation position were calculated by using beam theory, and the combined stress considering the phases of the respective load components were obtained. When considering the effects of elastic vibration, a simplified evaluation was carried out by considering a multiplication factor for stress ranges that doubles the fatigue damage when elastic vibration occurred. Specifically, the response amplitude operator of the vertical bending moment in $\pm 30°$ head seas was multiplied by a factor of $\sqrt[3]{2}$. ISSC-1964 was used for the wave spectrum, and the distribution in the $\cos^2$ direction was considered. For the long-term predictions, the response values for all headings and the wave scatter diagram in IACS Rec.34 were used.

Long-term predictions were made for the stress range considering only ordinary wave loads (i.e., excluding stress due to elastic vibration) and for the case which also considers superposition of the stress due to elastic vibration on the vertical bending moment for $\pm 30°$ head seas, and the distributions of the stress range were obtained. Fig. 8 shows the long-term distribution of the stress range of a deck longitudinal, in which vertical bending stress is dominant, and Fig. 9 shows the long-term distribution of the stress range for a side longitudinal near the ship bottom, where both vertical bending stress and local bending stress are large.

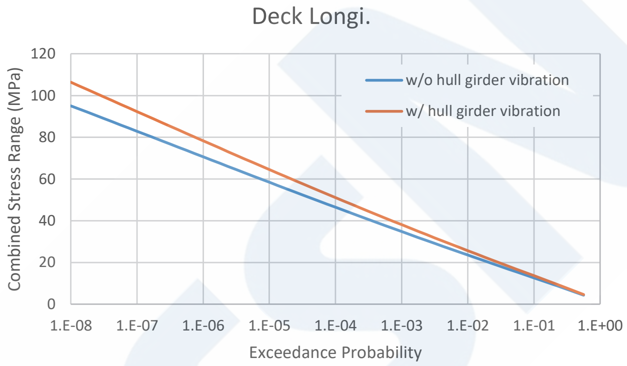


Fig. 8　Long-term distribution of stress range of deck longitudinal

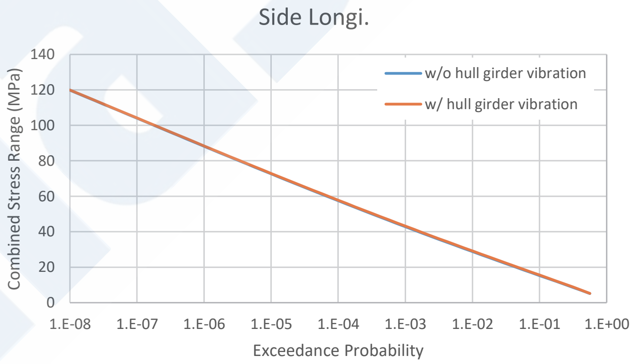
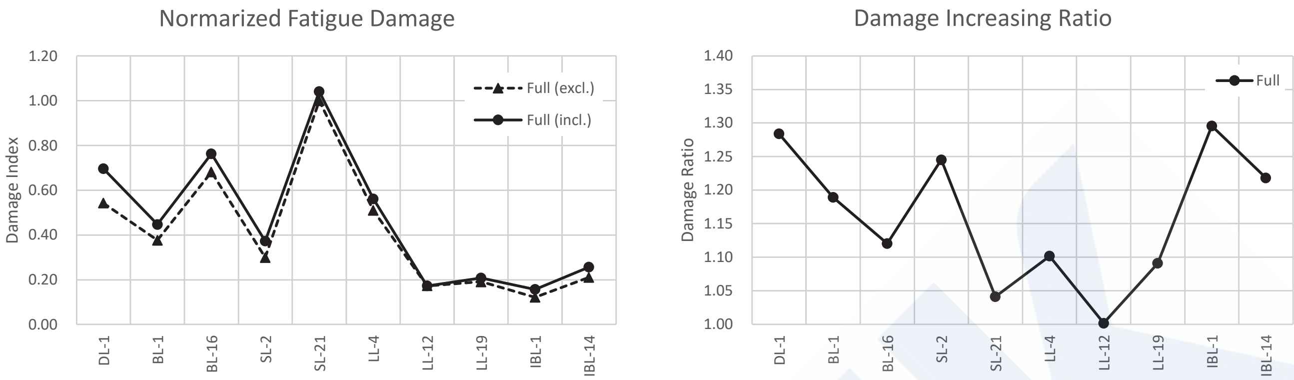


Fig. 9　Long-term distribution of stress range of side longitudinal near the ship bottom

Fig. 10 (a) shows the cumulative fatigue damage normalized by the longitudinal in which the largest cumulative fatigue damage occurred, and Fig. 10 (b) shows the increase ratio of the cumulative fatigue damage considering the effect of elastic vibration. The increase ratio of the cumulative fatigue damage differs depending on the longitudinals.

Fig. 11 shows the results of a comparison of the vertical bending stress and full stress for all load components (including elastic vibration) using the average values of the long-term distribution of the stress range when elastic vibration is superimposed. In the cases where the stress values of the members are substantially determined by the vertical bending stress (DL-1, BL-1, SL-2, IBL-1, IBL-14), the increase ratio of the fatigue damage is approximately 1.2 to 1.3, but when other load components are included, there is almost no increase in the fatigue damage. In other words, even in cases where elastic vibration is superimposed on vertical bending stress, it is considered to have a little influence on fatigue strength in members where the stress state is determined in combination with other load components, and in members where fatigue strength is determined only by vertical bending stress, the effects of elastic vibration can be considered by increasing the cumulative fatigue damage of 1.3.



(a) Cumulative fatigue damage (normalized by SL-21)

(b) Increase ratio of fatigue damage

Fig. 10 Comparison of cumulative fatigue damage including/excluding effects of elastic vibration (DL: deck longitudinal (upper deck girder), BL: bottom longitudinal, SL: side longitudinal, LL: longitudinal on longitudinal bulkhead, IBL: inner bottom longitudinal)

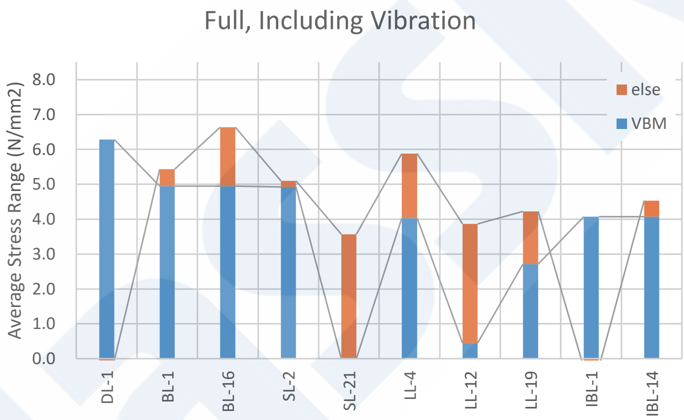


Fig. 11 Comparison of vertical bending stress component (vertical bending moment: VBM) and stress for all load components, including elastic vibration

The above-mentioned study can be summarized as follows.

- The expected value of the increase ratio of the cumulative fatigue damage in the short-term response in which elastic vibration occurs is approximately twice in the case of container ships, and is independent of the significant wave height and irrespective of springing or whipping.
- When elastic vibration is considered to occur in head sea states with directions of ±30°, the increase ratio of the long-term cumulative fatigue damage is approximately 1.3.
- When other load components are combined, the effect of elastic vibration is negligible.

Accordingly, it was decided that the effect of elastic vibration in fatigue strength assessments should be considered by multiplying the cumulative fatigue damage for ordinary wave loads by 1.3.

5. EXTERMELY-THICK STEEL PLATES AND CRACK ARREST BEHAVIOR

Accompanying the increasingly large scale of container ships from the 2000s, extremely thick steel plates with thicknesses of 50 mm to 100 mm and high yield point YP47 steel are adopted in hatch side coamings, strength decks (upper deck) and certain other members. However, at the same time, research results indicating the possibility that brittle cracks initiating from welded joints of extremely thick steel plates could lead to large scale damage were reported, and it became clear that there were also several issues with these materials. In view of the seriousness of this problem, the Society carried out various surveys and research studies with the generous cooperation from the industry, and issued “Guidelines on the Application of YP47 Steel for Hull Structures of Large Container Carrier” in October 2008 and “Guidelines on Brittle Crack Arrest Design” in September 2009 in advance of others worldwide. (Fig. 12 shows a schematic diagram of brittle crack arrest design, and Fig. 13 shows a photograph of a related experiment.)

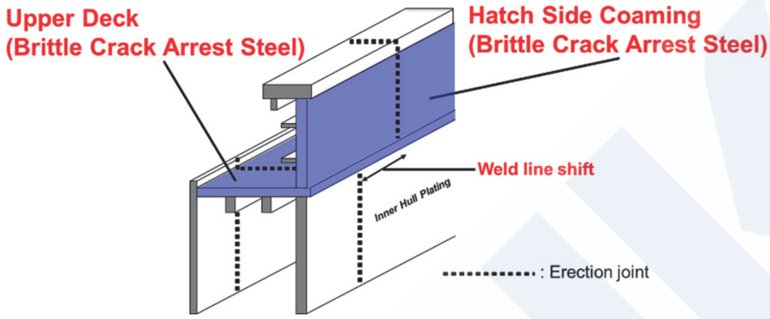


Fig. 12　Schematic diagram of brittle crack arrest design

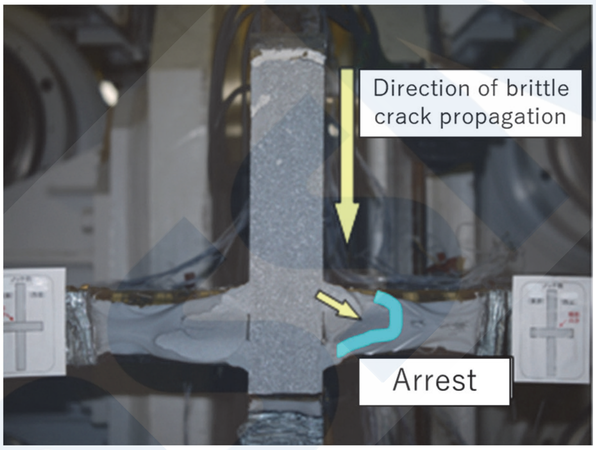


Fig. 13　Brittle crack propagation and arrest test simulating actual structure

In the IACS as well, discussions on brittle crack arrest design as a brittle fracture prevention measure for container ships using extremely thick steel plates were held under the leadership of the Society. The requirements for the use of extremely thick steel plates were studied based on the above-mentioned design guidelines developed by the Society, and these were adopted as the IACS Unified Requirement (*UR) S33 Requirements* for Use of Extremely Thick Steel Plates in Container Ships. At the same time, requirements based on the Society’s Guidelines for YP47 steel were also adopted as IACS UR W31 for YP47 Steels and Brittle Crack Arrest Steels.

The Society also actively conducted ongoing research following the establishment of these URs in 2013. As brittle crack prevention measures, the IACS’s URs do not provide concrete requirements for the brittle crack arrest properties when steel plates with thicknesses exceeding 80 mm are to be used as brittle crack arrest steel, and these requirements had been handled separately by each classification society. The Society conducted continuing joint research with industry, carried out large-scale experiments, numerical calculations, etc., and derived the arrest properties necessary in brittle crack arrest steel with plate thicknesses exceeding 80 mm. The Society then approached the IACS, leading to the adoption in 2019 of UR S33 (Rev. 2) and UR W31 (Rev. 2) [11], which reflected the results of the research by the Society.

Furthermore, active efforts were being made to research not only the properties of steel plates and related design methods but also the matter related to inspections. UR S33 (Rev. 3) [12], which was adopted in 2020, contains requirements that allow the use of advanced non-destructive testing techniques in place of the conventional ultrasonic testing for the all weld lines of butt joints between hull blocks of longitudinal hull girder members. For example, phased array ultrasonic testing (phased array UT) has been recognized as a method for this purpose. The Society conducted research on phased array UT in cooperation with industry and issued its own "Guidelines for Non-destructive Inspection by Phased Array Ultrasonic Testing" [13] in March 2020. These Guidelines summarize the requirements for nondestructive inspections by phased array UT, concrete flaw detection requirements, etc.

Thus, the Society's work is not limited to strength requirements, which occupy a large part of structural rules, but also includes efforts that make it possible to reflect state-of-the-art technologies at all times, even in different frameworks such as brittle crack arrest design, etc.

6. CONCLUSION

During the last quarter century, demand for container ships has expanded in line with the growth of the global economy and increased volume of international trade, and container ships have come to dominate a significant share in the classification of ship types. Although container movement has decreased since 2022 due to the effects of the invasion of Ukraine and rising commodity prices, the volume of container ship construction will continue to increase in the future.

While closely monitoring the trends in connection with the structural design and damage of container ships in the future, the Society will continuously conduct technology development related to structural strength evaluation, and will do its best to make it possible to create proactive rules, rather than rules established after accidents occur (i.e., rules as feedback), and carry out rule development that enables safe and rational design in the future.

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