Double Hull Tanker Structures – Some Practical Considerations about CSR Application

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Abstract

It is absolutely important for the design of tankers to reasonably keep structural safety and environmental friendliness at the same time. As one of keys to obtain this goal, Common Structural Rules (CSR) have been developed by IACS and design conditions have been clarified together with the clear correlation between corrosion additions and renewal thickness. We can say that universality and transparency of rules has been increased and safety level has also been upgraded by the increase of hull scantlings. However, we should be careful whether we could achieve the increase of safety level by reasonable hull steel increase or not.

By showing several advanced tanker designs and examples of details which are not necessarily required by CSR, this paper insists on the necessity of further considerations and understandings of hull structure. In addition, this paper shows the necessity of more goal-based approach rather than present prescriptive one to design more reasonable and robust tankers using examples of stress response function analysis for the prevention of unexpected damages.

1 Introduction

It is absolutely important for the design of tankers to reasonably keep structural safety and environmental friendliness at the same time. As one of keys to obtain this goal, Common Structural Rules (CSR) have been developed by IACS and design conditions have been clarified together with the clear correlation between corrosion additions and renewal thickness. Evaluation of wider range of failure modes such as ultimate strength and fatigue strength has been introduced. We can say that universality and transparency of rules has been increased and safety level has also been upgraded by the increase of hull scantlings. However, we should be careful whether we could achieve the increase of safety level by reasonable hull steel increase or not.

2 Abrupt Change of Depth of Longitudinally Successive Girder / Stiffener

Fig. 1 shows an example of a crack around bilge well structure, cited from Tanker Structure Co-operative Forum's publication [1]. This type of cracks is sometimes observed in way of structural discontinuity such as bilge well structure. Reference [1] says that the factors contributing to this damage are:

1. Stress concentration due to unsuitable bracket shape.
2. Asymmetrical sectional shape of inner bottom longitudinal.

However, actually most essential root cause for this damage is the difference of depth between the bilge well and the stiffener. As the mechanism is shown in Fig. 2, the longitudinal stress due to longitudinal bending exerts downward force to pull down the longitudinal stiffener at the bracket toe, inducing additional bending moment to the longitudinal stiffener. In such a case, softer bracket toe only improves very local stress concentration just around the bracket toe, but it does not work to reduce the exerted additional nominal bending stress.

This means that depending on the ratio of the stiffener depth to the bilge well depth, and also depending on the magnitude of longitudinal bending stress in way, softer bracket toe and T-type longitudinal may not be a fundamental solution to avoid this type of cracks. In some cases, structural modifications as shown in Fig. 3 may be necessary.

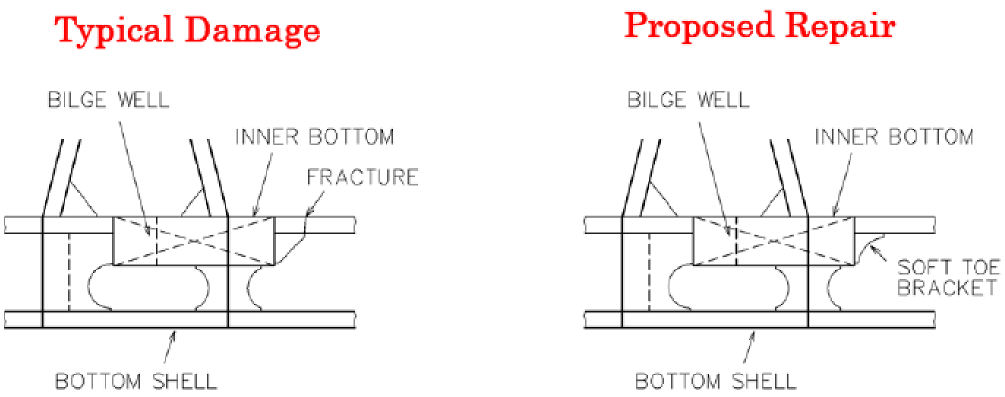

Fig.1 Example of Crack around Bilge Well

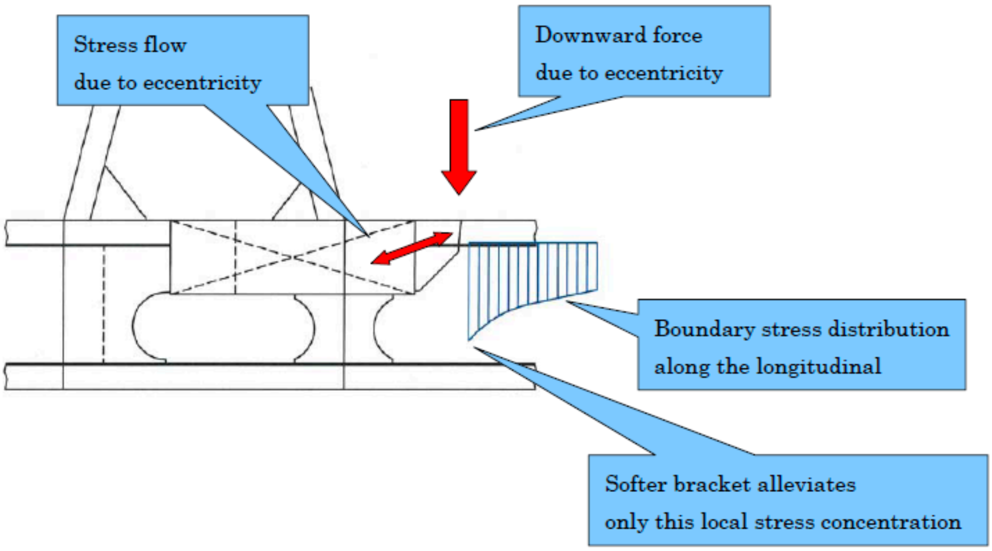

Fig.2 Cause of Crack around Bilge Well

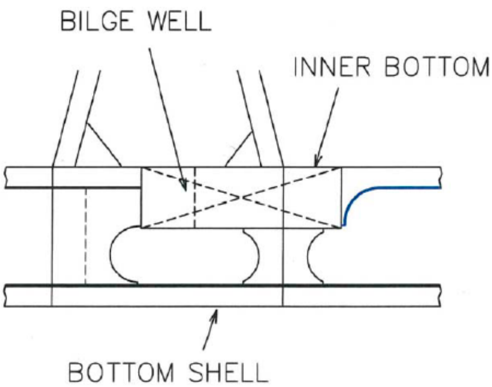

Fig.3 Example of Countermeasure

Similar damages can sometimes be observed, for example, in way of the underneath reinforcement for hose handling cranes. Typical pattern is shown in Fig. 4 [2]. As shown in the right figure in Fig. 4, the boundary stress is linearly distributed along the longitudinal stiffener, and the local stress increase at the bracket toe is very small. This means that the bracket is already soft enough, and another different countermeasure is necessary to avoid this damage.

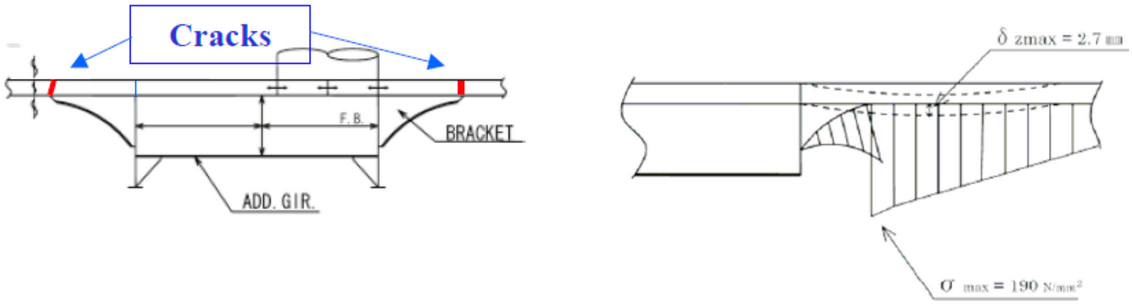

Fig.4 Damage Example of Partial Upper Deck Girder

One of the very effective countermeasures is to remove the scarphing brackets. When the brackets are dispensed with, the position where the stiffener is pulled down comes very close to the position of transverse frame, that is, the supported point. As a result, the additional bending stress due to the difference of the depth becomes very small (almost disappears) as shown in the right figure in Fig. 5 [2]. So that this arrangement works, it is necessary to make the longitudinal stiffener continuous through the transverse frames, and the additional girder to be put on the longitudinal stiffener.

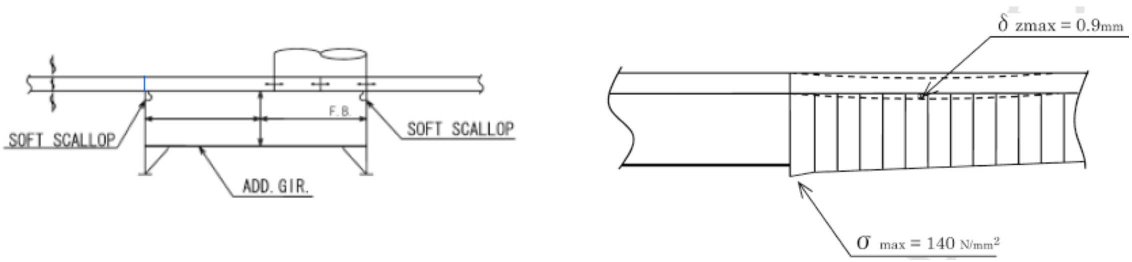

Fig.5 Partial Deck Girder Arrangement without Brackets

When we look into the Common Structural Rules for Double Hull Oil Tankers (CSR-O/T) [3], we find many sentences to stress the importance of structural continuity, such as “Suitable scarphing arrangement are to be made to ensure continuity of strength and the avoidance of abrupt structural changes”, for example in Section 8, 1.6.5. Simply according to this statement, the arrangement in Fig. 4 must be stronger than the arrangement in Fig. 5. However, the fact is that contrary to the expectation the arrangement in Fig. 5 is stronger.

Application of CSR-O/T brought us general thicker scantlings and increased hull girder section modulus, which will result in lower probability of damage. However, the rational design in true sense can only be accomplished by profound understanding of actual structural behavior, and by the application of most suitable solution to each different situation, such as Fig. 3 and Fig. 5. Suitable scarphing arrangement must be selected based on effective parameters such as the ratio of the different depths, exerted stress range in way and so on. Of course, arrangement with continuous longitudinal stiffener and without brackets as shown in Fig. 5 is an effective means in many cases. This kind of efficient and at the same time robust design is accomplished only by experienced designers’ insight into the structural behavior and experienced shipyards’ know-how, i.e. design standards. Experienced shipyards have thousands of pages of hull structural design standards. The designers’ keen intent, deep insight and excellent ability bring about such efficient and robust structural design, and it does not suit the prescriptive nature of the Classification Rules.

3 Slot Cut-out Strength through Three Generations

The structure around slot cut-out is one of the most critical locations within ship hull structures. For several decades, the industries have experienced several kinds of damages, and in response to the damages, design methods and rules have evolved, learning many lessons from the damages [4].

In this chapter, we first look back upon the typical past damages around the slot cut-out and their countermeasures. Then, the effectiveness of CSR-O/T is reviewed for all the types of the slot cut-out damages.

3.1 First-generation Cracks

The first-generation cracks around the slot cut-out appeared more than 40 years ago [5, 2]. Most common cracks were at the root of the web stiffener (connection to the longitudinal stiffener; Crack No.1 in Fig. 6), and propagated along the welding between the web stiffener and the longitudinal stiffener. They were in some cases accompanied by other cracks as shown in Nos. 2, 3, 4 and 5 in Fig. 6.

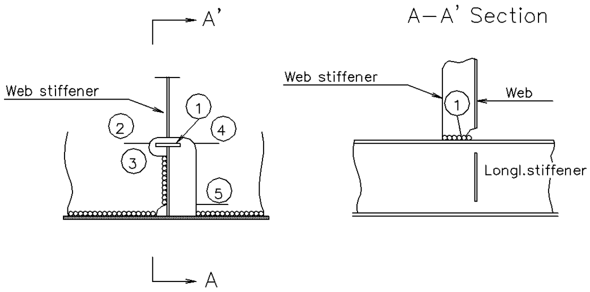

Fig. 6 Typical Damages of the First-generation

Thorough investigations were carried out then, and it was found that in addition to the insufficient scantling of web stiffeners, shear force on the primary supporting member caused tensile stress at the root of the web stiffener, and that depending on the direction of the slot cut-out, it superposed the local stress exerted by the longitudinal stiffener. Fig. 7 illustrates this mechanism. The force *W* causes tensile stress at the root of the web stiffener. Transverse web shear force *F* in slot B also causes tensile stress, but in case of slot A, it exerts compressive stress at the root of the web stiffener, canceling the stress exerted by the force *W*. Damages were accelerated in case of slot B configuration.

Now the root cause is revealed, we can select appropriate countermeasures to overcome this problem.
1. Most direct countermeasure is to increase the size and thickness of the web stiffener and/or the transverse web plate. Addition of backing brackets also works effectively. Stress is reduced in accordance with the nominal sectional area given.
2. Most effective countermeasure is to add collar plate as hatched in Fig. 8. By equilibrating shear forces from the both sides of the longitudinal stiffener, the transverse web shear force does not incur stress at the root of the web stiffener any more.
3. Most wise countermeasure if possible, is to direct the slot cut-out to the direction where the stress exerted by the force from the longitudinal stiffener (*W*) and the stress exerted by the transverse web shear force (*F*) cancel each other. Possibility depends on the construction processes.

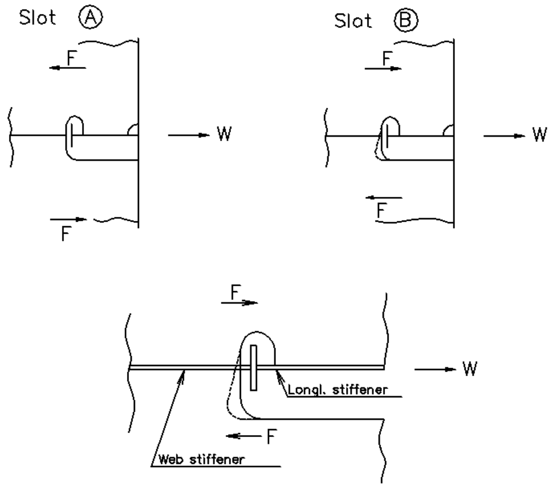

Fig. 7 Action of Shear Force to Slot Cut-out

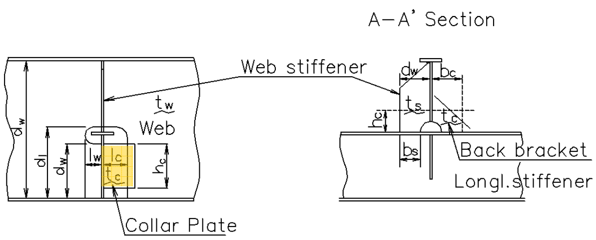

Fig. 8 Countermeasures of First-generation Cracks

3.2 Second-generation Cracks

The second-generation cracks appeared about 20 years ago, long after the first-generation cracks disappeared [6, 2]. They were characterized by the propagation into the longitudinal stiffeners as shown in Fig. 9. Many cracks of this type were observed in way of side longitudinals in the vicinity of the full load water line of VLCC's. Application of higher tensile steel and L shaped longitudinal stiffeners resulted in increased stresses on the longitudinal stiffeners, and caused the cracks. Countermeasures were to decrease stress by increased scantling and application of T shape to the longitudinal stiffeners, and soft heel and toe of the web stiffener at the connection to the longitudinal stiffener.

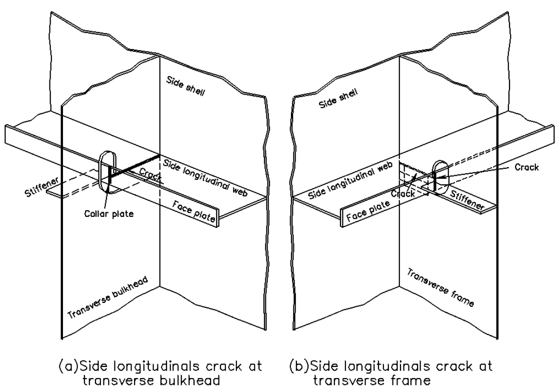

Fig. 9 Second-generation Cracks into Longitudinals

3.3 Third-generation Cracks

Even though all the countermeasures for the first and second-generation cracks were taken, small number of cracks was still sometimes observed around the slot cut-out [4, 2]. An example is shown in Fig. 10. These cracks are characterized by the occurrence only around the slot cut-out, not accompanied by the cracks characteristic to the first and second generation cracks. We call this the third-generation cracks.

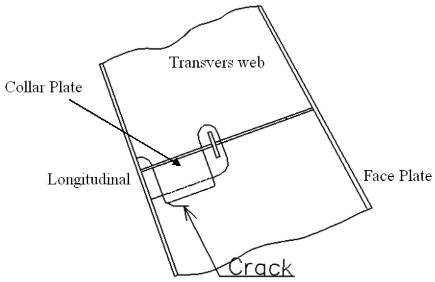

Fig. 10 Third-generation Cracks of Slot

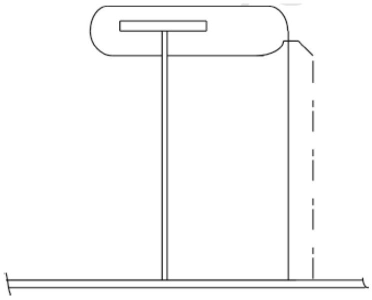

Fig. 11 Softly Shaped Collar Plate

Investigation into this type of cracks was carried out in reference [4]. It was found that:

1) Cracks tend to occur at some critical locations where the shear stress variation on the primary member web is high and the static stress is tensile at the round welding at the connection between the collar plate and primary supporting member web. In this case, softly shaped collar plate, attaching skin plate as shown in Fig. 11 is an effective countermeasure. Arrangement of large web stiffener does not work to reduce this stress.
2) Frequent loading-unloading cycles in shuttle service may cause cracks around slot cut-out, especially in case of longitudinal stiffener without web stiffener connection, where relatively higher stress around the slot is exerted by the loading from the longitudinals. We should be careful that softly shaped collar plate is not effective to the load from the lontitudinals. Effective countermeasure is simply to add web stiffeners, and adequate fatigue strength evaluation against the relevant loading-unloading cycles.

3.4 Review of Slot Rules in CSR-O/T

CSR-O/T stipulates two kinds of requirement for the strength of slot cut-out. One is the stress criteria due to the load from the longitudinal stiffener (Section 4, Ch.3.4 Intersection of Continuous Local Support Members and Primary Support Members), and the other is the fatigue life criteria for the so-called second-generation cracks (Appendix C Fatigue Strength Assessment).

Applicability to first-generation damage

In Section 4, Ch.3.4 of CSR-O/T, strength of connection between the transverse web and intersecting longitudinals is stipulated with regard to the direct stress in way of the web stiffener, and the shear stress in way of the shear connection including the collar plates. Only the load from the longitudinals is accounted for, and the shear forces on the transverse web is not considered. As we described in the previous chapter, the first-generation cracks are strongly influenced by the shear force on the transverse web. Because this effect is not taken into account, designs under only CSR-O/T criteria do not effectively cover the first generation damages.

Applicability to second-generation damage

In Appendix C of CSR-O/T, the fatigue strength of the longitudinals is comprehensively evaluated. Effects of many factors such as relative deformation of the transverse webs, L-shaped longitudinals, local structural detail, etc. are taken into account. Therefore, we can assume that CSR-O/T effectively works to prevent the second generation cracks.

Applicability to third-generation damage

As an effective rule description to the third-generation damage around the slot cut-out, CSR-O/T only stipulates its recommended contour shape of slot cut-out in case of the arrangement without web stiffener connection in Fig.C.1.11 of Appendix C.

However, the rule accounts for only the bending stress of the longitudinals (axial stress of the flange plate) as a base for fatigue strength assessment, in spite of the fact that the stress around the slot cut-out is related to the reaction force at the connection between the transverse web and the longitudinals, not to the bending stress of the longitudinal.

As we reviewed the characteristics of the third-generation slot damages in 3.3, the shear force on the transverse web can be the dominant factor of damages. In such cases, web stiffeners do not work to alleviate exerted stresses, and the recommended contour shape of slot cut-out of CSR-O/T, especially its softly shaped collar plate should be applied even in case that the web stiffener is attached, irrespective of the CSR-O/T requirements. In addition, frequent loading-unloading cycles may lead to damages, especially in case of the arrangement without web stiffener. In such cases, the recommended contour shape of slot cut-out in Fig.C.1.11 of CSR-O/T is hardly effective.

Considerations

Prescriptive Rules by nature account for limited conditions and loads, and we cannot expect prescriptive Rules to be fully comprehensive, to cover daily improvement and new ideas on design. The goal is to design robust and efficient structure. To achieve this goal, the designers should devote all their energies to fully understand the actual structural behavior under various loads.

“I am deeply impressed by the happy dispensation of Nature. And, it brings beneficence to those who have insight into it.” Dr. Mano wrote in his paper, where he explained the characteristics of the first-generation slot damages [7]. However, if only simple and prescriptive Rules govern, such happy dispensation will not work any more.

4 Extensive Structural Analysis Using Stress Response Function Method

4.1 SPB-HULL System

IHI Marine United Inc. developed its “IHI-SPB” (Self-supporting Prismatic IMO type ‘B’) LNG cargo containment system more than twenty years ago. This containment system offers a high level of structural reliability warranted by extensive and detailed structural and fatigue analysis all over the tank. Since then, LNG carriers, LEG carriers, LPG carriers/FSO/FPSO have been constructed with SPB cargo containment system, and are continuing successful service records without structural damages to the tanks [8, 9, 10].

The exhaustive structural analysis technology cultivated in the SPB tank design bore fruit as the “SPB-HULL” system, developed by the company as an extensive and comprehensive structural analysis system, which is now applied to any kind of ships [11]. The slogan was to “Comb all over the structure exhaustively, and do not permit any water leakage of one drop from the net of our assessment.”

“SPB-HULL” system consists of the following two strength analysis methods.

Equivalent regular wave method

In this method, the extreme environmental condition expected for 25 years return period is evaluated by long-term prediction based on the frequency response function (FRF) of ship motion. After the extreme condition for each dominant load parameter, e.g. pitching maximum condition, is evaluated, equivalent regular wave representing the extreme condition is determined. And then, the stress analysis for the equivalent regular waves is performed. The flow chart of this method is shown in Fig. 12.

This method is very useful for the initial design stage because of the less number of stress analysis cases, i.e. normally 10 or 20 cases. However, the possibility to miss the extreme condition for some structural part is remaining.

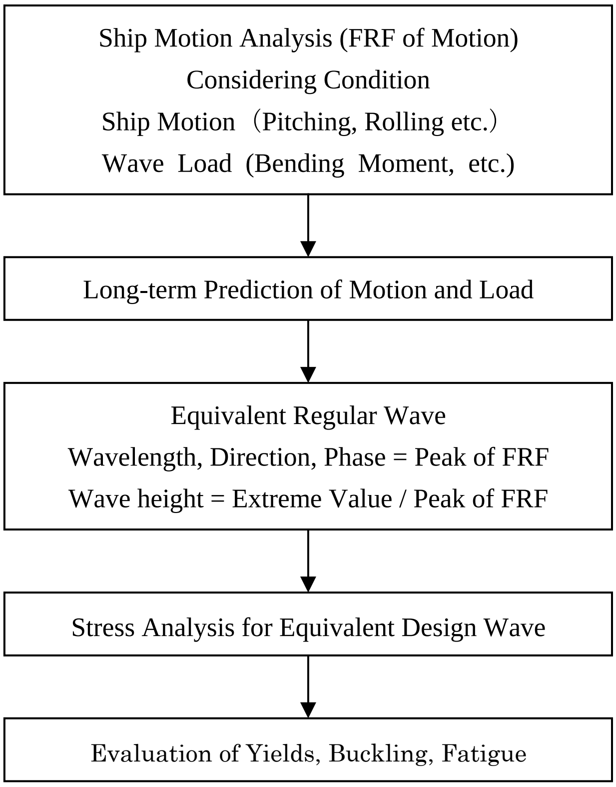

Fig. 12　Design Flow of Equivalent Regular Wave Method

To ensure the strength of all parts of hull structure, following more extensive analysis method is applied.

Stress response function method

In this method, extreme stress of every structural part expected for 25 years return period is evaluated by long-term prediction based on FRF of stress. Structural analysis is carried out for every combination of wavelength, direction and phase, and stress response function is evaluated along all over the finite elements of the hull exhaustively, thus this method assures sufficient strength all over the hull. The flow chart of this method is shown in Fig. 13.

4.2 Design by SPB-HULL System

In following sections, design of double hull oil tanker hull structure based on Stress Response Function Method is described.

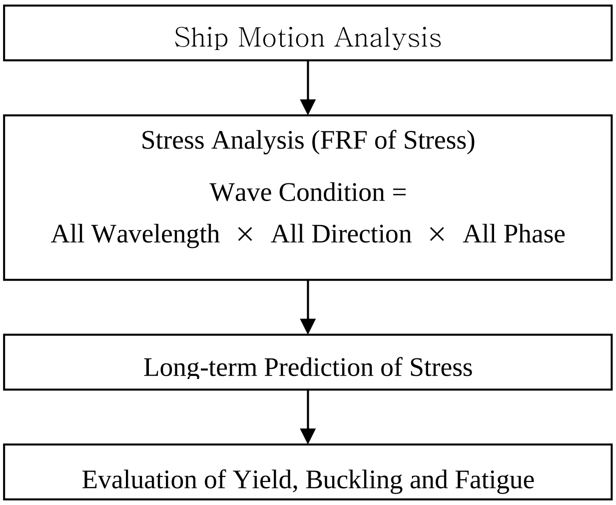

Fig. 13 Design Flow of Stress Response Function Method

Finite element model

As for the structural design, different finite element models are used according to the design stage and objects. At first, stress analysis using whole ship coarse mesh finite element model is performed to find global high stress zones and critical areas. Fig. 14 shows an example of the coarse mesh whole ship model. The mesh size of this model is basically transverse spacing. Fig. 15 shows an example of zooming model. The mesh size is about plate thickness at the critical location for fatigue evaluation.

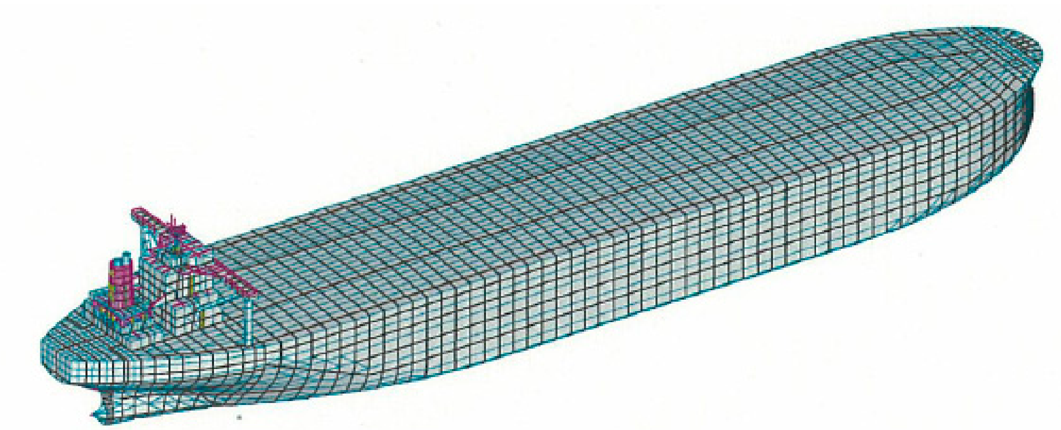

Fig. 14 Coarse Mesh Whole Ship Model

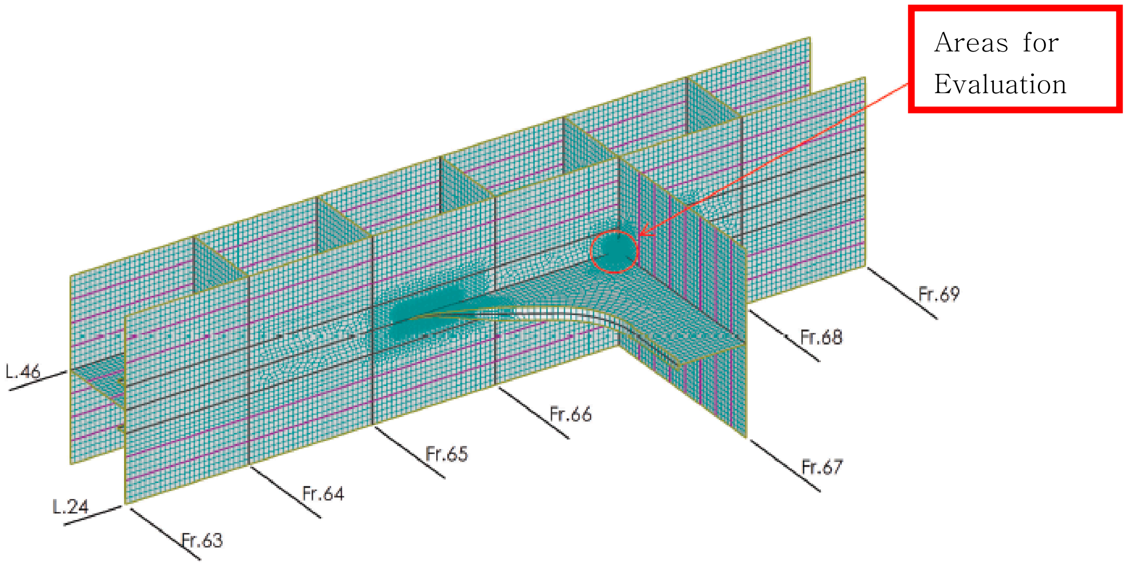

Fig. 15 Example of Zooming Model

Stress response function calculation

As explained above, the structural analysis is carried out for every combination of wave conditions. As for the oil tanker design, structural analysis for approximately 4,600 loading cases is performed.

Table 1 shows the calculation cases of structural analysis corresponding to the ship motion analysis.

Table 1 Calculation Cases of Ship Motion Analysis

Item	Case No.
Wave Direction	24
Wave Period (Wave Length)	32
Wave Position (Phase)	6

In each loading case, wave pressure load, inertia load of hull structural weight and cargo oil pressure taking account of the acceleration are included.

Fig. 16 shows an example of wave pressure load on the shell of whole ship model

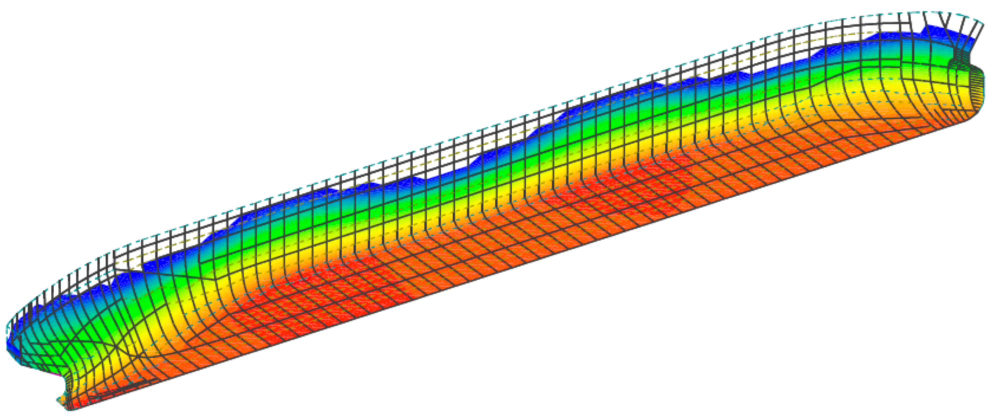

Fig. 16 Wave Pressure Load

From the results of all calculation cases, stress response functions for every element are obtained. Fig. 17 shows an example of the stress response function.

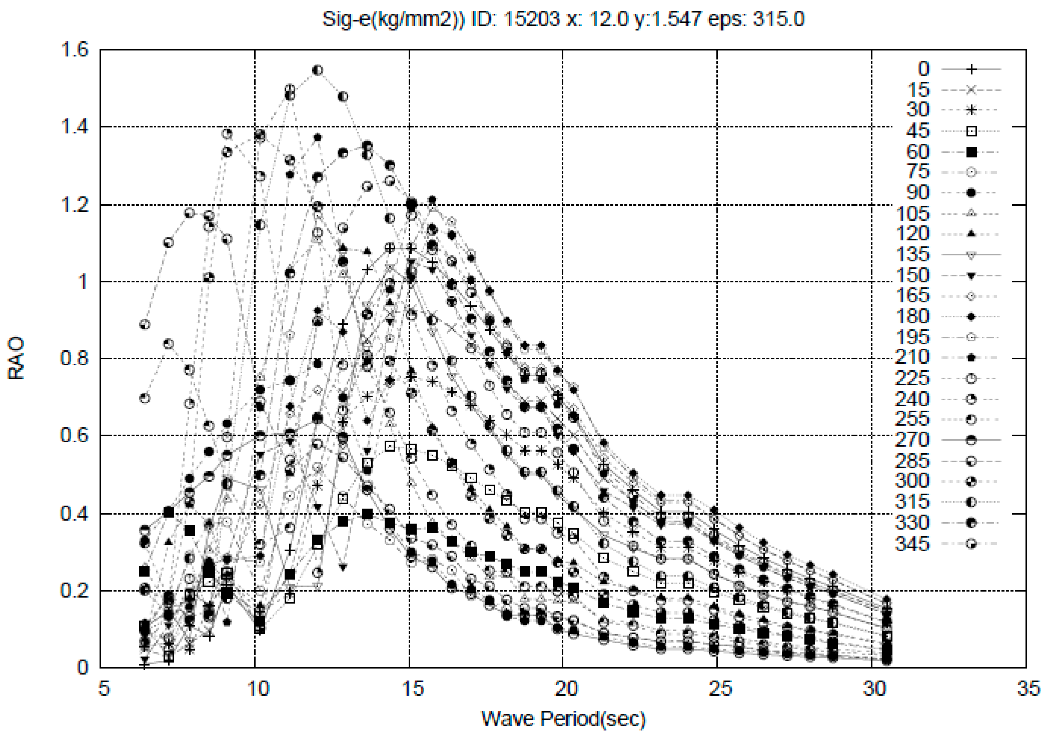

Fig. 17 Example of Stress Response Function

Stress response function calculation

Long-term prediction using stress response function is carried out for 25 years return period at North-Atlantic Sea.

The result of long-term prediction of coarse mesh whole ship model is shown in Fig.18.

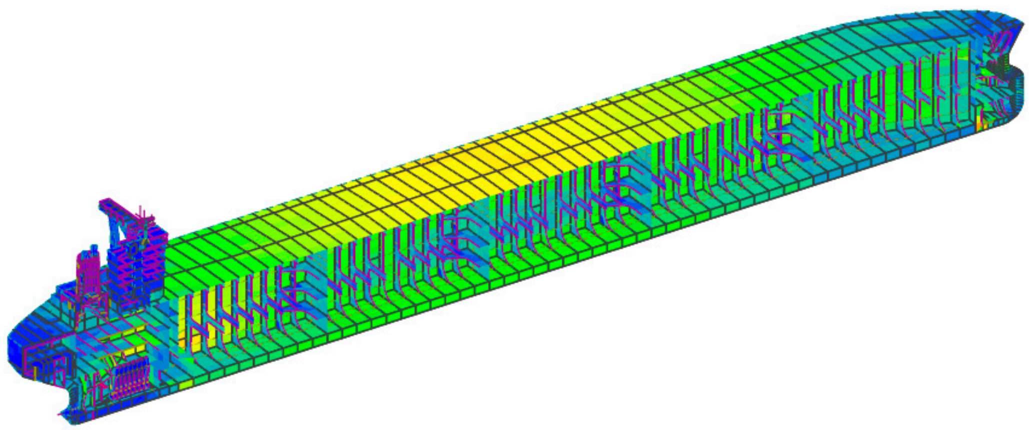

Fig. 18 Long-term Predicted Stress (Coarse Mesh Whole Ship Model)

Evaluation of yield and fatigue

Overall structural elements are combed through, and critical areas are identified. Fig. 19 shows an example of thus identified high stress area on the 4th deck plan in engine room construction. It was found out that because of relatively thin transverse frame in way, the subject structure is rather a "horizontal-main" structure, and the loads gathered at the strut connecting port and starboard horizontal girders. Appropriate reinforcement at the design stage is possible using such thorough investigations.

Fig. 20 shows an example of identification of high stress zone. It is a horizontal girder plan in the hold part. After identification of high stress zone, those areas are subject to further zooming analysis to assess fatigue strength as shown in Fig. 15.

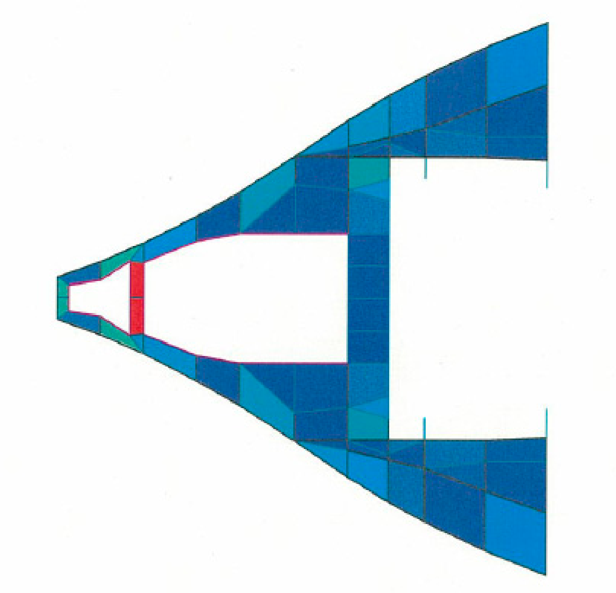

Fig. 19 Example of Identified High Stress Area (Engine Room)

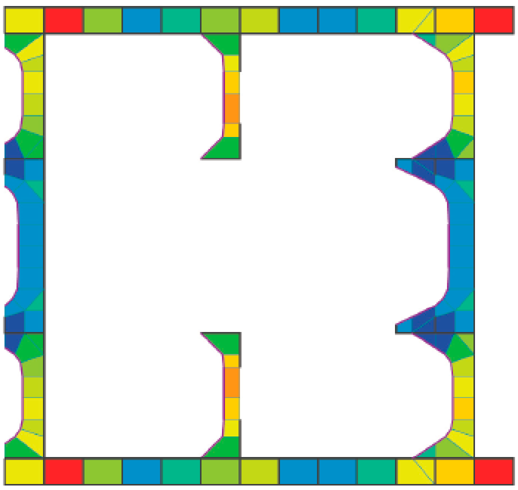

Fig. 20 Example of Identified High Stress Area (Hold Part)

4.3 Considerations about "SPB-HULL"

We have just briefed the procedure of "SPB-HULL" system. Structural design is a successive improvement and introduction of new ideas in association with the rapid economical and environmental change. Then, structural behavior sometimes transcends our experiences, and when we failed to understand the actual change of structural behavior, structural damages may occur. Prescriptive Rules are by nature not useful to cope with such problems. Even ordinary structural analysis such as equivalent regular wave method deals with only limited number of loading cases, which are considered to be critical based on past experiences. Therefore, it is still considered not perfect to prevent unexpected failure proactively and efficiently.

Extensive structural analysis by Stress Response Function Method of "SPB-HULL" system deals with all the wave direction, wave period and phase, combs all the hull structure exhaustively, and thus achieves more reliable hull structure, preventing unexpected failure proactively.

The amount of computation is tremendously huge, but thanks to computational technology nowadays such as parallel computing, it has become practically available.

5 Conclusion

1) CSR introduced increased hull scantlings, and thus safety level has been upgraded.
2) However, due to its prescriptive nature, considerations of some aspects of very detailed structural behavior are left to designers. By considering and understanding such structural behavior, equivalent or more robust structural design can be achieved with less hull steel.
3) As examples of such structural details, longitudinally successive girders / stiffeners with different depths and slot cut-out arrangement were discussed. Some examples how to prevent damages which are not covered by CSR-O/T were shown.
4) On the other hand, in addition to such approach depending on designers' insight and ability, progress in computational technology allows us to carry out exhaustive finite element analysis, combing all the hull structural elements under all the wave direction, wave period and phase. "SPB-HULL" system is applied to all the new designs in IHI Marine United Inc., and is contributing to the enhanced safety of our ships.
5) The goal is to achieve robust and efficient hull structure. Prescriptive Rules only help achieving this goal in an already experienced and well-established structural arrangement. To achieve the goal in more efficient way and in the field of novel engineering, the designers' insight and profound understanding into the structural behavior and the "SPB-HULL" exhaustive finite element analysis are a pair of wheels, both working closely together.

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