Overview of Changes and Comprehensive Revision of Part C of the Rules for the Survey and Construction of Steel Ships

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1. INTRODUCTION

Part C of the Rules for the Survey and Construction of Steel Ships (hereinafter, Part C), which constitutes the technical rules of ClassNK (hereinafter referred to as "the Society"), provides the requirements for the hull construction and equipment of ships except those to subject to CSR (IACS common structural rules), including container ships, ore carriers and liquefied gas carriers, etc., and is a compilation of the technologies and experience related to hull structures that the Society has cultivated over the course of approximately 100 years of ship classification services.

The Society established five basic strategies in the five-year medium-term management plan which started in 2017, and decided to carry out a comprehensive revision of Part C in a manner that corresponds to one of those strategies, "Promoting research and development activities."

To promote this revision, the Society launched a large number of joint research projects in cooperation with universities and research institutes to conduct research and development of element technologies related to design loads, corrosion and yield, buckling and fatigue strength required in order to develop new structural rules. In addition, the Society also build a dedicated team for simultaneously conducting research, development of rules and consequence assessments, which require an enormous amount of work, with young engineers affiliated with the shipyards and shipping companies along with regular staff participating in this project. In 2019, full-scale discussions on the proposed comprehensive revision were conducted in the Sub-technical Committee, which consists of engineers from related industries as well as scholars and experts, at meetings held by the Society, and finally, the comprehensive revision to Part C was approved at the First Technical Committee meeting held in January 2022.

This report explains the transition of the Society's structural rules since they were first issued in 1921 and describes the positioning of this comprehensive revision from the viewpoint of the transition of the rules to date.

2. CHANGES OF STRUCTURAL STRENGTH RULES

2.1 Issuance of Rules for the Survey and Construction of Steel Ships

The first Rules for the Survey and Construction of Steel Ships, which serve as a basis for the judgment criteria in ship classification surveys, were issued in 1921. When our services resumed after World War II, the new Rules for the Survey and Construction of Steel Ships was issued with contents greatly different from those of the old Rules. Nevertheless, a look at the table of contents of the Rules for the Survey and Construction of Steel Ships issued in 1925 (see Fig. 1) which is the oldest extant version, reveals that many vestiges of the earlier Rules remain in the present Part C. In both the old and the new Rules, the chapters describing the requirements for various structural members such as upper deck and bottom plating are arranged in the order in which those members are constructed according to the construction method used prior to the adoption of block construction, and these chapters make up the greater part of the structural rules. Following the chapters concerning those structural members, the old Rules provided a chapter describing the requirements for oil tankers. Since an oil tanker has a small freeboard, and the loads acting on its structure is relatively large. As it also has a longitudinal bulkhead and its structural type is greatly different from that of a general cargo ship. The rules at that time adopted many empirical formulae using principal particulars such as L, B and D as the parameters, and special formulae for oil tankers which is different from those for general cargo ships were required. Since rivet connections were widely used during that period, the old Rules also described the requirements for the distance of rivets, etc. to prevent leakage of cargo oil.

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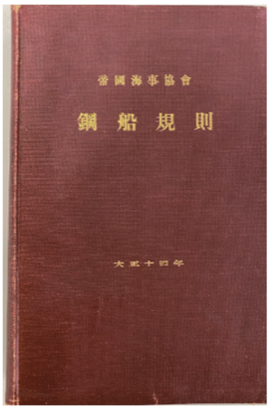

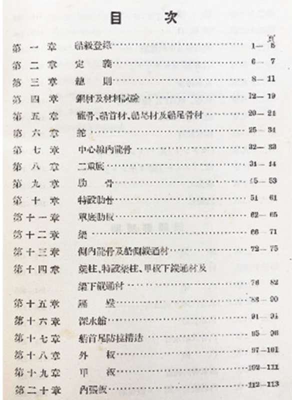

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Fig. 1　Rules for the Survey and Construction of Steel Ships by Teikoku Kaiji Kyokai (issued in 1925)

2.2　Transition from Empirical Formulae to Theoretical Formulae

Table 1 summarizes the major revisions related to structural strength made in Part C over the past 70 years. Here, revisions related to rudders, hull equipment, materials and welding were omitted.

In the rules of the 1950s, formulae for determining scantling were used for members that could be regarded as simple beams, such as stiffeners, in the same way as in the current Rules. However, many of the formulae for shell plating, girder plates, etc. were empirical formulae as a function of principle particulars such as L, B and D, that were derived from the actual scantling of the ships built in the past, or comparisons with the rules of other ship classification societies (see Fig. 2). As approaching the present day, more rational scantling formula based on appropriate load and strength capacity models were adopted. (see Table 2).

Table 1　Major revisions of NK rules for structural strength

Time	Content of revision
1921	Issuance of first edition of the Rules for the Survey and Construction of Steel Ships.
1949	First issuance of Rules for the Survey and Construction of Steel Ships by Nippon Kaiji Kyokai (renamed from Teikoku Kaiji Kyokai following World War II).
1959	Introduction of requirements considering slamming load.
1961	Introduction of theoretical formula-based shell plating requirements.
1963	Introduction of buckling strength requirements for girder webs.
1972	Introduction of longitudinal bending moment based on long-term prediction.
1973	Creation of new Chapter 31 “BULK CARRIERS.” (Introduction of grillage structure assessment by equivalent plate panel)
1974	Reorganization of structural requirements into Part C of the Rules for the Survey and Construction of Steel Ships. Introduction of strength assessment method based on direct strength calculation.
1980	Substantial revisions using wave pressure based on long-term prediction.
1983	Creation of new Chapter 32 “CONTAINER SHIPS.”
1987	Partial incorporation of UR S11 (longitudinal strength).
1989	Introduction of requirements for buckling under combined loads.
1993	Creation of new Chapter 29A “DOUBLE HULL TANKER.” (Introduction of fatigue strength requirements for longitudinal stiffeners)
1999	Introduction of bulk carrier safety-related requirements. (Introduction of requirements for strength in event of flooding, etc.)
2001	Issuance of Guidelines for Tanker Structure. (Introduction of net scantling assessment, equivalent design wave method, fatigue strength assessment for girders, Ultimate hull girder strength assessment)
2006	Creation of new Part CSR-B and CSR-T.
2016	Creation of new Part CSR-B&T. Substantial revision of requirements for container ships. (Introduction of requirements considering whipping load)

船型	L	B	D	d	d/L	船底外板 肋骨構造方式	船底外板 S	船底外板 t NK	船底外板 t LR	船底外板 t Ship	船底外板 t 案	船側外板 S	船側外板 t NK	船側外板 t LR	船側外板 t Ship	船側外板 t 案s	船側外板 t 案/$\sqrt{s}$
凹 1 D^k	44	7.8	3.8	3.4	.0772	T	560	9.46	9.81	10	9.47	560	8.39	8.54	9	8.5	7.86
〃	48	8.8	4.2	3.76	.0783	T	540	9.98	9.72	10	9.56	540	8.60	8.47	9	8.57	8.12
〃	60	9.7	5.5	4.8	.0800	T	600	11.51	11.40	10 11	11.34	600	10.02	9.93	10	10.13	9.40
〃	62	10.4	5.5	4.85	.0782	T	600	11.69	11.61	11	11.40	600	10.18	10.11	10	10.16	9.55
〃	64.5	10.2	5.4	4.75	.0736	T	600	11.82	11.80	10	11.36	600	10,28	10.26	10	10.10	9.74
〃	65	10.2	5.4	4.75	.0731	T	600	11.88	11.85	11	11.36	600	10.31	10.30	11	10.13	9.78
〃	65	10.4	5.2	4.55	.0700	T	660	12.20	12.45	11.50	12.08	660	10.58	10.85	10.5	10.69	10.14
平漁船	66.33	10.5	5.5	4.8	.0724	L	650	10.26	9.68	11	10.32	600	10.54	10.39	11	10.10	9.89
凹 1 D^k	67	10.8	5.7	4.8	.0716	L	650	10.32	9.70	11	10.33	610	10.33	10.51	11	10.26	9.97

Fig. 2 Comparison with other ship classification societies and actual scantling published in NK journal

Table 2 Formulae for determining thickness of bottom shell plating

Period	Rule formula
1960	When L is not less than 110m, $\left\{0.54 + 10.7\left(\frac{L}{100}\right)\right\}\left\{1 + 0.025\left(\frac{L}{11} - D_s\right)\right\}$ (mm) D_S: Depth (above strength deck) of ship
1961	$1.44 C_d S\sqrt{L} + 2.5\ \ (mm)$ $C_D = 1 + 7\left(\frac{d}{L} - 0.06\right)$ S: Spacing of longitudinals
1974	$3.64CS\sqrt{\frac{d + 0.035L'}{1.66 - f_b}} + 2.5\ \ (mm)$ C: Correction coefficient of 1.0 to 1.07 depending on L f_b: Utilization factor of longitudinal strength on ship's bottom

The 1960s was a period when the size of cargo ships, especially tankers, increased dramatically. The NK journal published in 1972, when periodical survey of those large cargo ships in service had begun, contained the following description: "Investigations of the actual damage of ships revealed that damage caused by increased longitudinal bending stress on the ship hull is extremely rare, and in more cases, forces such as the wave-induced force acted on local hull structures, causing damage such as buckling and cracking due to stress concentration." The formulae for longitudinal strength and stiffeners represented by a simple beam model can respond to the significantly larger size of these ships, but the empirical formulae for plate members and girder webs based on actual scantlings of past ships were difficult to deal with. The volume of cargo holds also increased as a result of the increase in ship size, heightening the relative importance of the strength of the girder members in holds, but it became impossible to cope with the deformation and stress generating by the responses of complex indeterminate structures by using the empirical formulae. Therefore, many complex formulae applicable to various indeterminate structures were developed at that time, such as adopting a method for obtaining the burden rate of shear force acting on longitudinal and transverse girders by replacing grillage structures such as double bottom structures with equivalent panels.

2.3 Advent of Long-Term Prediction and Direct Strength Calculation

In the 1970s, strength assessment technologies, which are the most important even today, appeared in Part C. One of those technologies was a design load estimation [4] based on long-term prediction. It then became possible to obtain the maximum expected values for wave pressure, wave-induced longitudinal bending moment, etc. during service life of ships by a technique combining the strip method, which makes it possible to calculate ship motion and pressure acting on the hull, and short-term prediction and long-term prediction based on the science of statistics. The empirical formulae used until that time were replaced by this approach, making it possible to develop more widely applicable and more rational requirements.

Another important technology is direct strength calculation of cargo hold structures by the finite element method, as illustrated in Fig. 3. When rule formulae are used to deal with grillage structures and indeterminate problems such as subjected to forced displacement, the formulae would become too complex and substantial errors may occur in modeling. However, in the direct strength calculation method, the actual structures are replaced by appropriate beam elements and shell elements, enabling assessment with much higher accuracy than in the past. In the case of shell elements, the local stress generated on girders having complex shapes, such as transverse rings, can also be calculated with high accuracy.

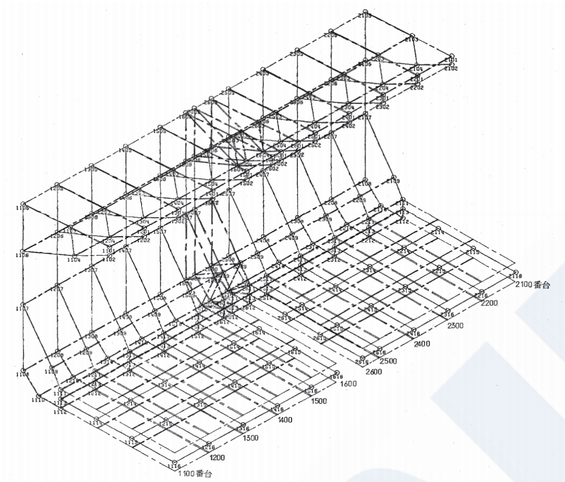

Fig. 3 FE model created in 1970s

2.4 To More Theoretical and Rational Rules

Although it was thought that development of more theoretical and rational rules, which is one of the goal of this comprehensive revision, can be significantly advanced by applying the two above-mentioned technologies, no major revisions had been made since the 1980s, except the revision that wave pressure based on the long-term prediction was applied. On the contrary, since the 1990s, a larger number of revisions have related to structural safety measures introduced by the IMO and IACS, such as the establishment of IACS Common Structural Rules (CSR).

Although there are many reasons why the development of the rules has not progressed, the two problems described below are considered to be large factors.

One of the problems is thought to be the relatively large load values obtained by the long-term prediction method. Fig. 4 shows the results of long-term predictions of the wave-induced vertical bending moment used for longitudinal strength requirements, which served as the technical background for the revision of the Rules in 1972. At that time, it was already known that the maximum expected value during the service life of a ship corresponds to an exceedance probability of 10^{-8} level. However, a formula for deriving the moment corresponding to the exceedance probability of 10^{-5} level was adopted for the reason that it takes into account the effects of weather routing, speed reduction and veering. At the time, some adjustment to actual scantling was necessary because the allowable stress for longitudinal bending stress was taken as approximately 150 N/mm^2 (currently 190 N/mm^2).

From around that time, some ship measurement projects were carried out for the purpose of surveying the actual conditions of ship operation and encountered sea state, but limited data were only obtained from a few ships and it was impossible to see a full picture of the actual conditions.

The second factor was that long-term prediction makes it possible to obtain the maximum expected values of each load component such as wave-induced longitudinal bending moment, wave pressure, accelerationat each position, but the correlation among the load components is completely unknown. In ship design, it is necessary to consider simultaneously-occurring loads combined on all load components. Various studies [5)-7)] were conducted in connection with this problem in the past, and the research results were utilized to develop the equivalent design wave method, which was adopted for the first time in the "Guidelines for Tanker Structures" [8)] issued by the Society, and was also adopted subsequently in CSR.

The equivalent design wave method focuses on the characteristics that the expected value with an extremely low probability of occurrence in the long-term prediction of hull structure response is caused by a very limited number of designated short-term seas (or regular waves of designated wave directions or wave lengths) and using some combined load cases that reproduce those short-term seas to evaluate the strength of hull structures.

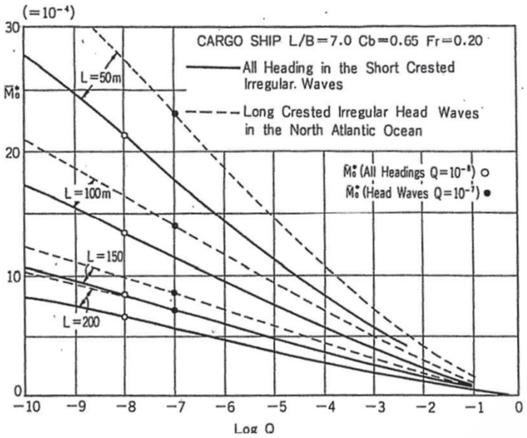

Fig. 4 Long-term prediction results of wave induced vertical bending moment

3. NEW PART C OF THE RULES FOR THE SURVEY AND CONSTRUCTION OF STEEL SHIPS

3.1 Composition of Chapters of New Part C

As previously described in section 2.1, the structure of the chapters of the current Part C has not changed substantially from that of the Rules issued in the 1920s. The chapters specifying the requirements for structural members mainly for general cargo ships make up the greater part of the Rules, followed by exclusive chapters for ship types. At the subordinate level of each chapter for ship type, there are sections concerning structural members such as bottom structures and side structures. Thus, the Rules are composed in a so-called nesting style. This is one factor which reduces the readability of the Rules.

Unlike the period when the original Rules was issued, today long-term predictions of loads and the equivalent design method can be used to indicate the expected load values at various locations and acceleration in long-term prediction and considering the simultaneity of those loads. In addition, generalized strength capacity models can be used not only for the local strength of plates and stiffeners, but also for primary supporting members such as girders and stringers. This means that the necessity dividing chapters by structural members has been reduced.

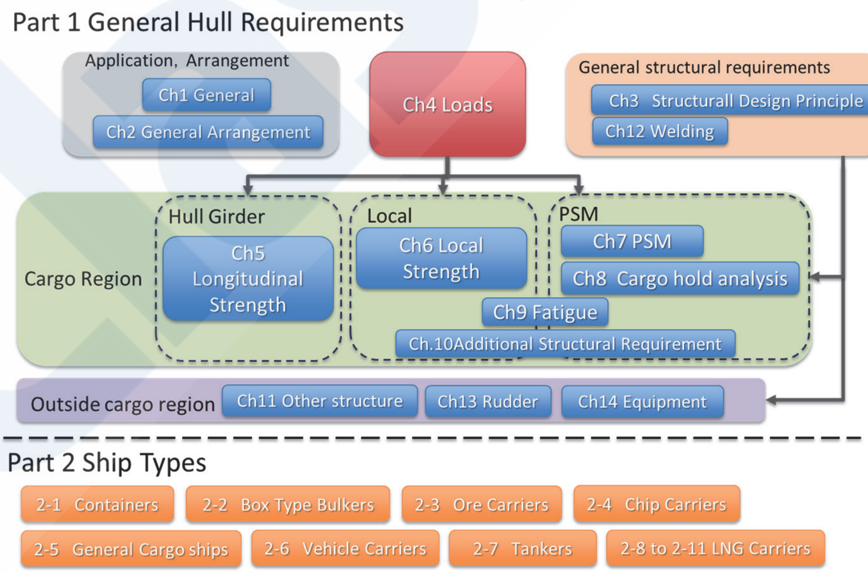

Fig. 5 Composition of chapters of new structural strength rules

Based on these circumstances, considering the readability of the Rules, the ease of understanding for designers familiar with CSR, the new structural rules were developed with the chapter composition shown in Fig. 5.

The essential parts of the Rules are the chapters on the hierarchical levels of structures in terms of strength, such as local strength, strength of primary supporting members and longitudinal strength, and the categories concerning strength assessments such as load and fatigue. The requirements for the cargo types and its loading and additional requirements for structures specific to ship types are specified in Part 2.

3.2 Design Load

In the new Part C, the design load continues to be based on the long-term prediction method and the equivalent design wave concept described previously in section 2.4, and it is now possible to derive more realistic load values by considering the non-linear effect and the effect of operational factor.

In the development of the load formulae, the physically meaningful formulae derived from the two-dimensional potential theory were simplified to obtain more applicable and more accurate estimation formulae [9) 10)]. Furthermore, a wave load analysis was conducted by the 3D panel method, which is best-balanced in terms of estimation accuracy, reliability and calculation cost and is widely used at present, and based on the results, a series of calculations of short-term predictions and long-term predictions was carried out to verify and adjust the developed load formulae.

Nonlinear effects due to changes in the submerged parts of ships in large waves, etc. have been obtained as factors for respective equivalent design waves [11)] from the results of a series of analyses using tank experiments and the nonlinear 3D panel method.

For the effects of operational factor, the long-term prediction values for major hull responses are determined from the wave scatter diagram based on the encountered sea states obtained from AIS (Automatic Identification System) data from several tens of thousands of ships, and the factors [13)] are specified from the ratio of the obtained values to the long-term prediction values derived from the wave scatter diagram defined in IACS Rec. 34 [12)], which had been used from an early date.

By using this factor, it is possible to estimate the load values acting on hull structures more accurately and derive scantlings with less deviation from the actual scantlings.

3.3 Corrosion Additions and Improvement of Accuracy of Strength Criteria

Methods for achieving higher accuracy were targeted not only for design loads, as described in section 3.2, but also for corrosion additions and strength criteria for yield, buckling and fatigue to make it possible to perform strength assessments more in line with the actual phenomena.

For the corrosion additions used in the new structural rules, values corresponding to various corrosion environments were obtained by statistically analyzing enormous volumes of data obtained from thickness measurements conducted at the time of surveys of in-service ships.

Although corrosion additions determined by this method have also been adopted in CSR, in the new Part C, the quality of maintenance in recent years premised on the Enhanced Survey Programme (ESP) was reflected in the corrosion additions by collecting the thickness measurement data for statistical analysis mainly from ships constructed in the 1990s and later. As a result, locations of ship structures such as ballast tanks, where improved maintenance quality has reduced corrosion, and members such as the inner bottom plating of dry cargo ships, where corrosion has not been reduced, are clarified as numerical values.

Efforts were also made to define the strength criteria for yield, buckling and fatigue so as to be more directly related to damage. For example, for the scantling formulae for the lateral pressure of plates and stiffeners, formulae based on the initial yield strength and rigid plasticity theory and the accompanying empirically-defined safety factors had long been used.

In this development, nonlinear FE analyses, in which various levels of pressure were loaded/unloaded, were conducted for plates and stiffeners in order to investigate the level of strength criteria where no residual deformation occurs, and simple formulae for deriving the criteria were developed [14) 15)]. Appropriate safety factors were added to these simple formulae to derive the formulae for scantlings with a clear correspondence to damage.

In buckling strength assessments, while using physically meaningful formulae as much as possible as in the case of the load formulae, an approach that makes it possible to estimate the collapse strength after elastic buckling with high accuracy was adopted [15)]. Requirements that consider the effects of load redistribution after local buckling of a plate panel on surrounding structures in indeterminate structures such as hull structures were also partially incorporated to provide criteria having a higher correlation with actual damage.

For fatigue strength assessments, repeated loading closer to actual conditions was set based on the information on ship courses obtained from the AIS data of several tens of thousands of ships [16)], and requirements with a clear correlation with actual damage cases were adopted, for example, by setting safety factors based on the probability of occurrence of fatigue damage in an entire ship structure.

4. CONCLUSION

The concept of the new Part C is now quite close to the ideal image of structural rules conceived from the time when long-term prediction technology developed in the 1970s, and it may be said the most important factor in its development was the big data obtained from the AIS data and plate thickness measurement data.

As digital twin-related technologies progress and are widely adopted in the future, quantitative measurement and use of the various events that occur while ships are in service will become possible, and it will also be possible to obtain more knowledge in connection with the sea conditions which ships actually encounter and their complex nonlinear structural responses than ever before, allowing an accurate elucidation of the causes of damage accidents, etc.

The new Part C was developed with the aim of enabling strength assessments based on reproduction of the sea conditions actually encountered by ships and the condition of hull structures after ships are commissioned, together with strength criteria based on actual damage. Accordingly, the knowledge revealed by digital twin-related technologies can be reflected relatively easily in the Rules, and further improvement of the safety and rationality of the Rules can be expected in the future.

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