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Research Article

Analysis of Hull Girder Ultimate Strength and Residual Strength Based on IACS CSR-H

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In order to express the safety level of hull structures, IACS Common Structure Rules of Bulk Carriers and Oil Tankers (CSR-H) makes new requirements of hull girder ultimate strength. Compared with original CSR (i.e., CSR-OT and CSR-BC), partial safety factors of hull girder ultimate strength in CSR-H have been partly modified, and new requirements of residual strength have been added in the rules for hull safety after grounded/collided damage. This paper compares the rule requirements of ultimate strength in CSR-H and CSR-OT/CSR-BC and explains the technical background of rule requirements. The hull girder ultimate strength is mainly analyzed by SMITH method in rule requirements due to fast and stable calculation results. This paper also uses nonlinear finite element method (NFEM) to explain the critical influence factors for hull girder ultimate strength implied in the rule requirements. Based on 5 typical Bulk Carriers and 4 typical Oil Tankers, the influence of hull girder ultimate strength and residual strength in CSR-H has been evaluated for ship building industry. The actual ship evaluation results can be used to instruct the new CSR-H ship design.

1. Background

The CSR rules proposed by International Association of Classification Societies (IACS) have brought about significant influence on the procedure of ship design and building of Bulk Carriers and Oil Tankers. CSR rules are divided into two parts, that is, Common Structure Rules of Double Hull Oil Tankers (abbreviation CSR-OT) [1] and Common Structure Rules of Bulk Carriers (abbreviation CSR-BC) [2]. Because CSR-OT and CSR-BC are complex rule systems and their development time is very short and urgent, some technical points in these rules are subjected to disputation of ship industry. Especially for the common part of CSR-OT and CSR-BC, the two rules have not always given the same requirements. Although the ship industry has given some proposal of rules improvement and update, they would prefer that IACS can make harmonized rules for Bulk Carriers and Oil Tankers.

In order to satisfy the industry expectations, IACS promises to harmonize the differences between CSR-OT and CSR-BC and draft Common Structure Rules of Bulk Carriers and Oil Tankers (abbreviation CSR-H) [3] based on the same technical routes and methodologies. The safety level implied in CSR-H will not be lower than original CSR-OT and CSR-BC. At the same time, International Maritime Organization (IMO) has proposed new regulations for Bulk Carriers and Oil Tanker, i.e., Goal Based New Ship Construction Standard (GBS) [4, 5]. So CSR-H should satisfy the GBS function requirements.

After several years work of IACS society members, the CSR-H rules were approved by IACS council on 18th December 2013. CSR-H will be applied on Bulk Carriers having a length of 90 m or above and double hull Oil Tankers having length L of 150 m or above, which is contracted for construction on or after 1st July 2015. IACS rules set for Bulk Carriers and Oil Tankers, including CSR-H rules, URs

(Unified Requirements), and Recommendations, cover all the IMO GBS function requirements, such as human element considerations, structural redundancy, and structural strength.

Hull girder ultimate strength belongs to the 3rd function requirement of IMO GBS and residual strength is the 5th function requirement. The rule requirements of hull girder ultimate strength are covered both in CSR-OT and CSR-BC, but there are large differences between these two rules. The concept of residual strength is only mentioned in principle, but the calculation methods and evaluation criteria are not required in CSR-OT and CSR-BC. In order to satisfy GBS requirements, CSR-H should add the rule requirements of residual strength, which could assure the hull safety after collision or grounding damage in this rule.

ISSC summarized the recent research results about residual strength of ship and offshore structures after collision and grounding damage [6, 7]. Amante et al. [8] investigated the residual strength of a semisubmersible platform column damaged by a supply vessel collision and estimated the safety margin associated with the column structural capability after the collisions. Paik et al. [9] developed empirical formulas for residual strength of double hull Oil Tankers of the form of Residual Strength vs. Damage Index (R-D) diagrams. Kim et al. [10] used a similar approach to develop R-D diagrams and empirical relations for container ship designs with grounding damage. Choung et al. [11] analyzed the effect of neutral axis rotation on hull girder ultimate strength.

Based on the IACS CSR-OT requirement for hull girder ultimate strength, Xu et al. [12] carried out reliability assessment of a tanker using the model correction factor method. It is shown that using semiempirical response models including the important mechanical features with respect to the bending capacity of hull girder, the reliability evaluation can be performed with a limited number of nonlinear FEM (less than 10) promoting the application of advanced response and reliability methods to complex structures. The nonlinear FEM results prove that CSR incremental-iterative method can provide conservative results of hull girder ultimate strength.

Based on the IACS CSR-OT requirement for hull girder residual strength, Hussein and Guedes Soares [13] carried out reliability and residual strength of double hull tankers. Different damage scenarios at side and bottom were considered with different damage sizes to define a lower limit of strength, which might be accounted for during design. The residual strength is calculated using incremental-iterative method. Reliability of the damaged ships is calculated considering the increase in the still-water bending moment due to damage and the loss in ultimate strength.

Amlashi and Moan [14] carried out hogging ultimate strength analysis of a bulk carrier hull girder under alternate hold loading condition. The significant double bottom bending in empty holds in AHL due to combined global hull girder bending moment and local loads is researched. The local loads on double bottom substantially reduce the ultimate strength of the hull girder. The implication of using different design pressures based on CSR and DNV rules on the hull girder strength is assessed. The FE results can be used as a basis for establishing simplified methods applicable to practical design of ship hulls under combined loading.

Witkowska and Guedes Soares [15] also studied ultimate strength of locally damaged panels. The damage is in the form of a local imperfection and represents a dent that could be caused by a fall or strike of an object. The influence of several parameters has been studied to establish their interaction with the presence of the local dent. The large panel is compared with smaller transverse model made of three plates and with a single plate model in order to evaluate the effects of adjacent plates and define the minimum size of the model necessary to obtain proper results. Saad-Eldeen et al. [16] studied ultimate compression strength of high damaged plates resulting from dropping objects, grounding or collision. The effect of dent depth, dent shape, and dent size is studied. An expression to estimate the average reduction of ultimate strength of highly damaged steel plates, subjected to compression loading as a function of the residual breadth ratio, is also developed.

Alfred Mohammed et al. [17] carried out design safety margin of hull girder ultimate strength under vertical bending and torsion combined loads. The results show that the vertical bending moment capacity of the hull girder is reduced when torsion is incorporated. The design extreme values of principal global wave-induced load components and their combinations in irregular seaways are predicted using a cross-spectral method together with short-term and long-term statistical formulations. Consequently, the margin of safety between the ultimate capacity and the maximum expected moment is established. Shi and Wang [18] studied the similar model for hull girder ultimate strength under combined loads of bending and torsion. The similar model of actual ship was derived based on the thin-walled beam theory. A mathematical model optimizing the similar model was set up to improve the design scantlings. The ultimate strength consistency of the actual ship and similar model are validated by nonlinear FEM under the action of bending and torsion, so the similar model can be used in experiment to test the actual ship ultimate strength.

In case of design rule, previously Pre-CSR & CSR design have been compared by Paik et al. [19]. Recently, Wu et al. [20] have clearly reviewed previous design rule (CSR) and new rule (CSR-H) on effect of structural design and scantlings. The effects of corrosion suggested by Pre-CSR, CSR, and CSR-H on ultimate hull girder strength are also recently investigated by Kim et al. [21]. In addition, in the present study CSR vs. CSR-H can also be covered for the comparison purpose.

In this paper, the rule requirements of ultimate strength and residual strength in CSR-H are compared in detail with CSR-OT and CSR-BC, and the technical backgrounds for making the rule requirements are also explained. The hull girder ultimate strength is mainly analyzed by SMITH method in rule requirements because of fast calculation and time saving. This paper also uses nonlinear finite element method to explain the critical influence factors for hull girder ultimate strength implied in the rule requirements. In addition, 5 typical Bulk Carriers and 4 typical Oil Tankers are sampled for ship building industry and the influence of hull girder ultimate strength and residual strength in CSR-H has been evaluated for actual ships.

2. Rule Requirements Comparison between CSR-H and CSR

2.1. Hull Girder Ultimate Strength. CSR rules (including both CSR-OT and CSR-BC) introduce the design concept of ultimate state, local hull members are permitted to produce plastic buckling/yield deformation, and hull girder ultimate strength should be evaluated under extreme wave condition. Before reaching the hull girder ultimate strength, the hull girder bending moment including static water moment and wave moment may lead to nonlinear deformation in hull members; that is, the plating, stiffeners, and longitudinal girders of deck or bottom in tension area may produce local plastic deformation and compression area may produce plastic buckling deformation. Therefore, from the design point, plastic deformation and stress redistribution in structure members are necessary to be evaluated for hull girder ultimate strength. Reasonable structure scantlings and static water bending moment should be designed so as to maximize the utilization of hull girder ultimate strength.

Comparison between CSR-OT and CSR-BC shows that there are some differences in rule requirements of hull girder ultimate strength. CSR Oil Tankers only permit the ship design of double side and double bottom, so these ships have strong hogging bending capacity due to compression stress acting on double bottom and relatively weak sagging bending capacity due to compression stress acting on single lay of deck structures. In CSR-OT, only sagging ultimate strength is required to be verified in seagoing condition, but no requirements about hogging ultimate strength or harbor condition. In CSR-BC, hogging and sagging ultimate strength are both required to be verified in seagoing, harbor, and flooding conditions, and especially the flooding condition is special important condition for bulk carrier safety considering history marine casualties. The detail comparisons between CSR-OT and CSR-BC rule requirements are listed in Table 1.

Evaluation criteria of hull girder ultimate strength are expressed in partial safety factors, which have been calibrated by reliability analysis, to cover undetermined influence factors. The evaluation criteria is shown as follows [3]:

$$\gamma_S M_{SW} + \gamma_W M_{WV} \leq \frac{M_U}{\gamma_R} \tag{1}$$

where

M_{SW} denotes still-water bending moment;

γ_S denotes partial safety factor of still-water bending moment;

M_{WV} denotes wave bending moment;

γ_W denotes partial safety factor of wave bending moment;

M_U denotes hull girder ultimate strength;

γ_R denotes partial safety factor of hull girder ultimate strength.

Compared with CSR-OT and CSR-BC, the changes of rule requirements of hull girder ultimate strength in CSR-H are mainly reflected as follows:

(1) The rule requirements of Oil Tankers have added analysis conditions.

(2) For the calculation of hull girder ultimate strength, one step method has been removed to prevent inconsistent results from different methods.

(3) For partial safety factor of hull girder ultimate strength, a new double bottom factor γ_{DB} has been added in the rule.

In CSR-H, partial safety factor of hull girder ultimate strength $\gamma_R=\gamma_m \cdot \gamma_{DB}$. γ_m covers the uncertainty of material, geometry, and strength and its value is taken as 1.1, which is the same as the partial safety factor of hull girder ultimate strength in CSR-OT and CSR-BC. The double bottom factor γ_{DB} covers the reduction influence of double bottom deformation on hull girder ultimate strength. For empty cargo hold under alternative loading condition, there are big differences between sea water pressure of ship outer bottom and cargo pressure of inner bottom, so the double bottom may produce relatively larger deformation and the bottom plating in the center may be subjected to biaxial compression stress including longitudinal and transverse direction. The bottom deformation and biaxial compression stress would both reduce buckling strength of local panel in double bottom, which would further reduce hull girder ultimate strength [22].

2.2. Hull Girder Residual Strength. Collision and grounding accidents are the main reasons for ship hull damage, fracture, and sinking, which will simultaneously induce catastrophic consequence, such as liquid cargo leakage, environment pollution, and life casualties. In order to reduce the loss induced by ship accidents, the collided/grounded ship should maintain some residual strength to prevent the collapse failure of whole hull girders and also the damaged ship can sustain the flooding water to provide enough time for saving personnel on board.

Residual strength is the 5th function requirement of IMO GBS. The concept of residual strength only is mentioned in principle in CSR-OT, which permits considering the post-buckling capacity and plastic yielding strength. However, the calculation method and evaluation criteria are not given in CSR-OT and CSR-BC requirements. In order to satisfy GBS requirements, CSR-H has added new requirements of residual strength to prove hull safety after collision/grounding in rule aspect.

The first aspect for the evaluation criteria of residual strength is the reasonable definition of collision/grounding damage scope. Based on IMO statics of ship accidents [23], the probability distribution characteristic of collision/grounding damage scope is determined, including collision height in vertical direction, collision penetration depth,

Table 1: Rule comparison of hull girder ultimate strength.

	CSR-OT	CSR-BC	CSR-H
Ship length	150m or above	150m or above	150m or above
Analysis conditions	Seagoing	Seagoing, harbor, flooding	Oil Tanker: seagoing, harbor Bulk Carrier: seagoing, harbor, flooding
Scope	Mid	Cargo and engine area	Cargo and engine area
Hogging/sagging	Sagging	Hogging & sagging	Hogging & sagging
Still water bending moment	Allowable still water bending moment; Maximum sagging bending moment of still water.	Allowable still water bending moment	Allowable still water bending moment; Maximum sagging bending moment of still water only for oil tanker.
Wave bending moment	Same as UR S11	For seagoing, Same as UR S11; For flooding, reduction as 0.8 times; For harbor, reduction as 0.4 times.	For seagoing, Same as UR S11; For flooding, reduction as 0.8 times; For harbor, reduction as 0.4 times.
Ultimate strength calculation	One step SMITH method Nonlinear FEM	SMITH method	SMITH method Nonlinear FEM
Corrosion addition	$0.5t_c$	$0.5t_c$	$0.5t_c$
γ_s	1.0	1.0	1.0
γ_w	1.2	1.2	1.2
γ_R	1.1	1.1	$\gamma_R=\gamma_m \cdot \gamma_{DB}$ $\gamma_m=1.1$ For hogging, $\gamma_{DB}=1.25$ for empty cargo hold of BC-A bulk carrier; $\gamma_{DB}=1.1$ for other cargo holds For sagging, $\gamma_{DB}=1.0$;

Table 2: Collision/grounding damage scope.

Collision	Single side	Double side
Height	0.75D	0.60D
Depth	B/16	B/16
Grounding	Bulk carriers	Oil Tankers
Height	Min(B/20 and 2m)	Min(B/15 and 2m)
Width	0.60B	0.60B

grounding width in transverse direction, and grounding penetration height. Compared with local structures such as plating, stiffener, and panel strength, ultimate strength and residual strength of hull girder both belong to the whole ship structures. From the view of consistent rule requirements, the failure probability of residual strength should be equivalent to that of hull girder ultimate strength. Therefore, based on structure reliability analysis, the damage scope of collision/grounding and partial safety factors in evaluation criteria are determined [24]. The damage scope of collision/grounding in CSR-H is listed in Table 2.

The evaluation criteria of residual strength are required as follows:

$$\gamma_{SD} M_S + \gamma_{WD} M_W \leq \frac{M_{UD}}{C_{NA}} \tag{2}$$

where

γ_{SD} denotes partial safety factor of still-water bending moment after damage; $\gamma_{SD} = 1.1$, which covers the increment of bending moment due to flooding.

γ_{WD} denotes partial safety factor of wave bending moment after damage; $\gamma_{WD} = 0.67$, which covers only one week exposure period on the sea after ship damage.

M_{UD} denotes residual ultimate strength after deducting the damage structural members in collision/grounding accident.

C_{NA} denotes rotation coefficient of neutral axis after damage; $C_{NA} = 1.1$ for collision and $C_{NA} = 1.0$ for grounding. For collided ships, the structural members of one side in damage scope would not contribute to the hull girder ultimate strength, so the cross section of hull girder would not be symmetric and neutral axial of the cross section would rotate in some degree. However, the calculation method of ultimate strength in CSR-H has not considering the influence of neural

Table 3: Boundary conditions used in NFEM.

Position	Displacement constraint			Rotation constraint		
	δ_X	δ_Y	δ_Z	θ_X	θ_Y	θ_Z
Fore end plane	Coupling	Coupling	Coupling	-	Coupling	-
Aft end plane	Coupling	Coupling	Coupling	-	Coupling	-
Independent point A	Fixed	Fixed	Fixed	Fixed	Fixed	-
Independent point B	-	Fixed	Fixed	-	Fixed	-

Note: independent point A and point B are defined in FE model, of which position can be located at the intersection point of neutral axis in cross section.

axis rotation, so the evaluation criteria add the coefficient of neural axis rotation.

3. Ultimate Strength Analysis of Hull Girder

3.1. Incremental-Iterative Method. The incremental-iterative methods of CSR-OT and CSR-BC are harmonized into CSR-H, including element type, meshing, load-displacement curve of element, and calculation procedures, which are almost consistent in these rules. Based on plane cross-section assumption, hull girder section is divided into a series of stiffener element, plating element, and hard corner element, and several critical failure types are assumed for each type element. The stiffener element under compression may produce beam-column buckling, torsion buckling, and web buckling. The plating element under compression may produce plating buckling. Other types of element under compression or tension will produce idealized elastic-plastic failure. Based on the concept of effective attaching plating, average stress-strain curve of each failure type is provided in CSR-H.

The incremental-iterative method assumes that hull girder failure occurs in adjacent strong frames. Only longitudinal stress is considered, biaxial stress and shear stress are neglected, and the effect of initial deflection is also not directly considered. At the rule level, all the influence factors are covered in CSR partial safety factors. Relatively speaking, the incremental-iterative method has characters of simple calculation procedure and stable calculation results.

3.2. Nonlinear Finite Element Method. For ultimate strength calculation method, CSR-H requires that nonlinear finite element method (abbreviation NFEM) can be used for an alternative method, but the evaluation criteria of hull girder ultimate strength should be specially considered. Only general requirements about this method are listed in principle in CSR-H. Detailed implementation procedure is a gap and left to classification societies, which implies that nonlinear finite element method is relatively complex and cannot be easily implemented by ship designers in present stage.

NFEM is a powerful tool to solve the problems of complex engineering structures. Hull ultimate strength analysis involves material nonlinearity and large deformation nonlinearity. NFEM can be used to accurately evaluate the effects of various factors on ultimate strength, which are mainly including model longitudinal scope, element type, mesh size, material constitutive model, boundary condition, initial deformation, weld residual stress, lateral pressure, and plastic buckling [25].

Table 4: Amplitude of initial deformation.

Initial deformation	Maximum allowable value(mm)
Whole deformation of stiffened panel	$l/1000$
Local deformation of plating	$s/200$
Lateral deformation of stiffener web	$l/1000$

Note: l denotes the length of stiffened plating between frames, and s denotes the width of stiffened plating between stiffeners.

Boundary conditions in NFEM in NFEM are given in Table 3.

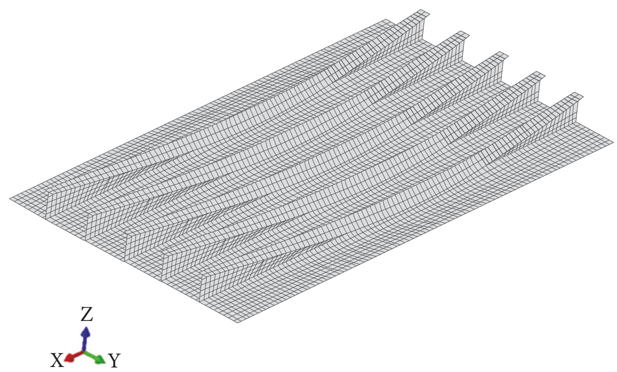
3.3. Effect of Initial Deformation on Ultimate Strength. Based on ISSC conclusion report [26], the initial deformation of hull structures should generally consider the whole deformation of stiffened panel, plating local deformation, stiffener lateral deformation, and so on. The mode and amplitude of initial deformation in hull structures should be accurately simulated, especially out-plane deformation due to welding or fabrication, so the considered deformation can trigger the most dangerous failure mode of hull girder collapse and the minimum value of hull girder ultimate strength can be obtained. The general initial deformations are shown in Figure 1, such as whole deformation of stiffened panel, local deformation of plating, and lateral deformation of stiffener web.

The NFEM listed in previous paper [25], including element type, meshing density, model extent, and calculation method, is also used here to calculate the ultimate strength of hull girder. Then the effect of initial deformation on ultimate strength is analyzed. For actual ships, the initial deformation of structure members should be limited within the allowable value of industry standards, such as IACS Rec.47 [27]. In this paper, the maximum allowable value of initial deformations as listed in Table 4 is applied on finite element model, in order to analyze their reduction effect on ultimate strength.

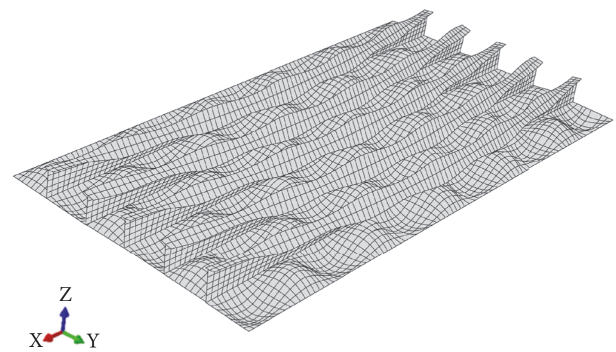
The ultimate strength results calculated by NFEM are listed in Table 5. The reduction effect of initial deformation on hull girder ultimate strength is 1%~8%. Compared with hogging ultimate strength, the initial deformation has bigger influence on reduction of sagging ultimate strength for Bulk Carriers. For Oil Tankers, initial deformation has bigger reduction effect on hogging ultimate strength.

Table 5: Effect of initial deformation on hull girder ultimate strength.

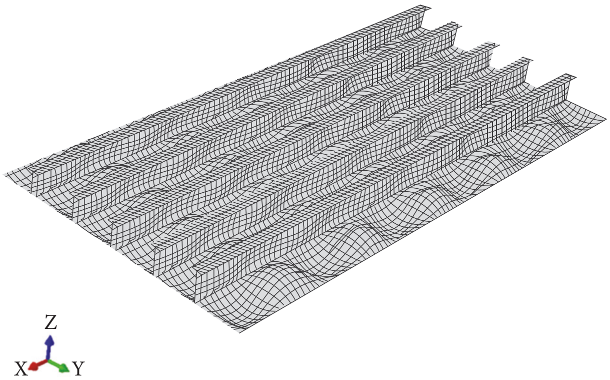
Ship type	Case	Ultimate strength(kN·m) Without initial deformation	With initial deformation	Ratio With/Without
58kW Bulk Carrier	Hogging	8.38E+06	7.98E+06	0.95
	Sagging	-6.78E+06	-6.21E+06	0.92
115kW Bulk Carrier	Hogging	1.15E+07	1.14E+07	0.99
	Sagging	-1.18E+07	-1.10E+07	0.93
115kW Oil Tanker	Hogging	1.11E+07	1.06E+07	0.95
	Sagging	-8.89E+06	-8.59E+06	0.97



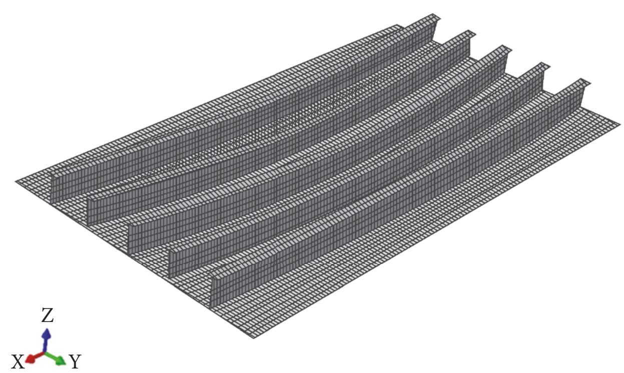
(a) Whole deformation of stiffened panel



(b) Local deformation of plating



(c) Lateral deformation of stiffener web



(d) Combination of aforementioned three deformations

Figure 1: Initial deformation.

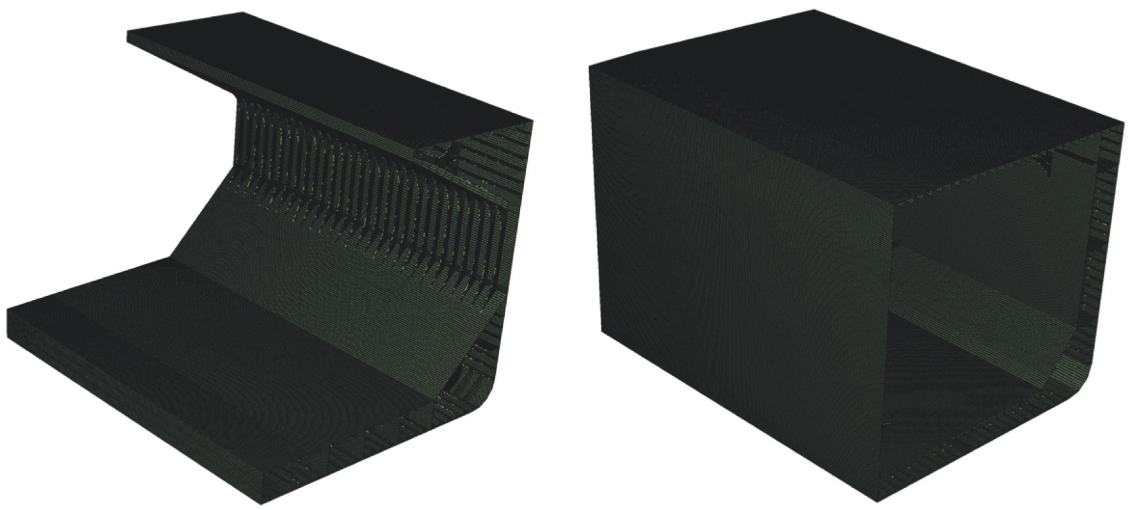
3.4. Effect of Lateral Pressure on Ultimate Strength. In order to analyze the effect of lateral pressure on ultimate strength, the lateral pressure of outer bottom and side shell under different loading conditions should be considered. For empty cargo hold under alternative loading condition, there are big differences between sea water pressure of ship outer bottom and cargo pressure of inner bottom, so the double bottom may produce relatively larger deformation. In NFEM, the longitudinal extent of model should relatively increase, i.e., extending to whole cargo hold between transverse bulkheads, in order to reduce the effect of boundary conditions on double bottom deformation.

All longitudinal continuous structure members and transverse structure members between two adjacent bulkheads are included in FE model. However, the two bulkheads, upper stools and lower stools, are simulated by boundary conditions to simplify the FE model. The initial deformations mentioned in Section 3.3 are also included, which is convenient to convergence of nonlinear calculation. The FE model is showed in Figure 2.

Based on CSR-H rules Pt1Ch4Sec8, the lateral pressure of outer bottom and side shell under full loading conditions, ballast conditions, and alternative loading conditions is separately applied in FE model (Figure 3) . According to loading manuals, a series of different draught is chosen based on the principle of maximum lateral pressure on bottom panels for these three kinds of main load mode. For convention view, dynamic pressure is equivalent to static pressure applied symmetrically on outer shell. The ultimate strength results calculated by NFEM are listed in Table 6. The results show

Table 6: Effect of lateral pressure on ultimate strength.

Ship type	Loading condition under hogging	Ultimate strength(kN·m)		Ratio
		Without lateral pressure	With lateral pressure	With/Without
115kW Bulk Carrier	Full	1.07E+07	9.18E+06	0.85
	Ballast	1.07E+07	9.66E+06	0.90
	Alternative	1.07E+07	8.48E+06	0.79
115kW Oil Tanker	Full	1.04E+07	9.65E+06	0.93
	Ballast	1.04E+07	1.01E+07	0.97



(a) Bulk Carrier (b) Oil Tanker

Figure 2: FE model between adjacent bulkheads.

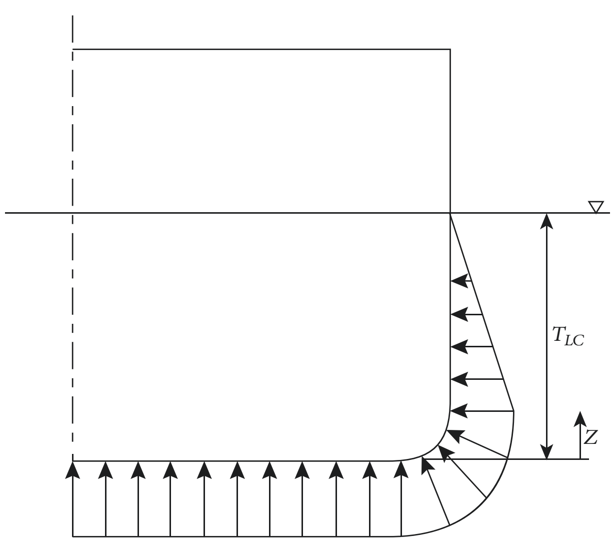


Figure 3: Application of lateral pressure on outer bottom and side shell.

that the reduction effect of lateral pressure under alternative loading condition is about 21%, and the reduction effect under other loading condition is 7%~15%.

3.5. Effect of Neutral Axis Rotation on Residual Strength. For actual ships, cross section of hull girder is generally symmetric, so the neutral axis of the cross section is parallel to horizontal plane. As the external bending moment increases, the hull girder will produce some bending deformation. Even when the longitudinal stress of bottom or deck structures enters into nonlinear stress stage, the position of neutral axis will only move up or down. But for collision damage ships, the cross section will not keep symmetric. Therefore, when the structural elements produce nonlinear deformation under external bending moment, the position of neutral axis will produce translation and rotation movement.

The position of neutral axis can be calculated by following procedures. As conservative assumption, the structural members in damaged scope can be completely deducted from hull girder and the cross section of damaged part is asymmetric. When the external bending moment is small and structural members still remain in elastic stage, the neutral axis, i.e., elastic neutral axis, can be calculated by the scantlings and geometry coordinate of structural members. As the external bending moment increases, some of structural members enter into plastic or buckling stage, the stress distribution of cross section will not be continuous, and the neutral axis, i.e., plastic neutral axis, will produce translation and rotation

Table 7: Effect of neutral axis rotation on residual strength of hull girder.

Ship type	Case	Residual strength(kNm)		Ratio
		Without neutral axis rotation	With neutral axis rotation	With/Without
22.5 kW Bulk Carrier	Hogging	1.84E+06	1.75E+06	0.95
	Sagging	-1.38E+06	-1.26E+06	0.91
64kW Bulk Carrier	Hogging	5.15E+06	4.92E+06	0.96
	Sagging	-3.89E+06	-3.69E+06	0.95

Table 8: Actual ship assessment of bulk carrier ultimate strength.

Ship type	Case	Utilization factor of ultimate strength			Utilization factor of residual strength	
		Seagoing	Harbor	Flooding	Collision	Grounding
BC1	Hogging	0.64	0.58	0.71	0.55	0.44
	Sagging	0.64	0.41	0.77	0.66	0.48
BC2	Hogging	0.84	0.76	0.86	0.67	0.56
	Sagging	0.82	0.84	1.00	0.75	0.59
BC3	Hogging	0.88	0.86	0.86	0.66	0.63
	Sagging	0.88	0.88	0.92	0.84	0.65
BC4	Hogging	0.95	0.89	1.00	0.63	0.68
	Sagging	0.88	0.82	0.92	0.77	0.63
BC5	Hogging	1.00	0.77	0.99	0.71	0.57
	Sagging	0.99	0.76	0.96	0.87	0.68

movement simultaneously. The position of neutral axis at this stage can be determined by the following two conditions:

(1) The combined force in compressed region F_1 and combined force in tension region F_2 have the same amplitude but opposite direction.

(2) The connection line of action point F_1 and F_2 will keep parallel to the action plane of external bending moment M of hull girder.

The calculation results of hull girder residual strength considering the effect of neutral axis rotation are listed in Table 7. The residual strength of hull girder will reduce 4%~9% after considering neutral axis rotation. So if the neutral axis rotation is neglected, the residual strength may be overestimated, which is critical for the safety of damaged ships.

4. Actual Ship Assessment of Hull Girder Ultimate Strength

4.1. Target Ships. In order to analyze the influence of CSR-H rules on ship industry, representative CSR Bulk Carriers and Oil Tankers are chosen to carry out actual ship assessment of hull girder ultimate strength and residual strength. The sample ships generally include the following:

Bulk Carriers: Capesize, Panamax, and Handysize

Oil Tankers: VLCC, Suezmax, Aframax, and Panamax

4.2. Actual Ship Assessment of Bulk Carriers. The actual ships assessment results of bulk carrier hull girder ultimate strength are listed in Table 7. The results show that most of CSR ships can satisfy the rule requirements of hull girder ultimate strength in CSR-H. Because of new partial safety factor of double bottom γ_{DB} in CSR-H, the scantlings of structural members of large Bulk Carriers may slightly increase.

The assessment results of hull girder ultimate strength can be expressed as utilization factor, which is equal to bending moment divided by ultimate strength, i.e., the left part divided by the right part in (1). The utilization factor of hull girder ultimate strength under flooding conditions is relatively large, and the next one is seagoing condition. Because harbor condition only considers 0.4 times wave load, it is almost impossible to be critical load condition.

The utilization factors of ultimate strength in Table 8 are listed as the increase of ship tonnage. The utilization factor gradually increases as the increase of ship tonnage, which predicts that the influence of ultimate strength rule requirements on large bulk carrier safety will become more and more important. Failure mode of hull girder with collision damage after collapse is showed in Figure 4.

The utilization factor of residual strength after collided damage is 55%~87%, and the utilization factor of residual strength after grounding damage is 44%~68%. So CSR Bulk Carriers can satisfy the new addition of residual strength requirement in CSR-H.

4.3. Actual Ship Assessment of Oil Tankers. The actual ships assessment results of oil tanker hull girder ultimate strength are listed in Table 9 as the increase of ship tonnage. The results show that most of CSR ships can satisfy the rule requirements of hull girder ultimate strength in CSR-H. The utilization factor of hull girder ultimate strength under seagoing conditions is relatively large, and the next one is sagging condition under homogeneous loading. The utilization factor gradually

Table 9: Actual ship assessment of oil tanker ultimate strength.

Ship type	Case	Utilization factor of ultimate strength			Utilization factor of residual strength	
		Seagoing	Harbor	Homogeneous loading	Collision	Grounding
OT1	Hogging	0.77	0.50	-	0.63	0.75
	Sagging	0.87	0.52	0.84	0.81	0.71
OT2	Hogging	0.90	0.69	-	0.68	0.77
	Sagging	0.89	0.57	0.89	0.74	0.63
OT3	Hogging	0.91	0.68	-	0.71	0.59
	Sagging	0.96	0.65	0.94	0.84	0.65
OT4	Hogging	0.88	0.66	-	0.67	0.66
	Sagging	0.96	0.61	0.95	0.83	0.68

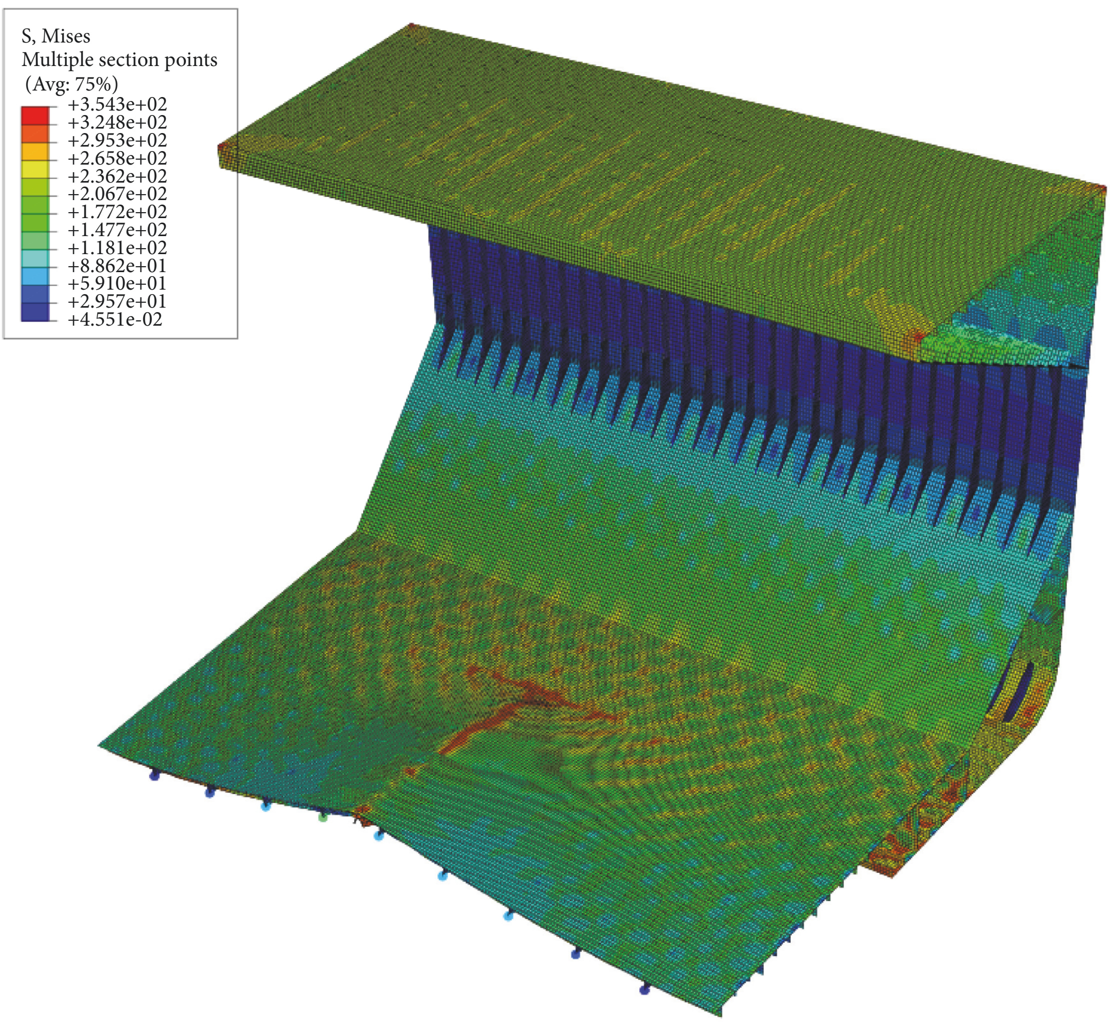


Figure 4: Hogging failure mode of hull girder with damage.

increases as the increase of ship tonnage, which predicts that the influence of ultimate strength rule requirements on large oil tanker safety will become more and more important.

The utilization factor of residual strength after collided damage is 63%~84%, and the utilization factor of residual strength after grounding damage is 59%~77%. So CSR Oil Tankers can satisfy the new addition of residual strength requirement in CSR-H. The new requirement of residual strength will not be a critical design case for enhancing scantlings of hull girder members. However, the damage scope is assumed in the rule requirement, but not based on actual ship damage condition. Residual strength assessment in design stage should conserve enough safety preserve for collision and grounding damage. Residual strength assessment for ship after actual accident should be analyzed case by case, especially considering various damage conditions.

5. Conclusions

The rule requirements of hull girder ultimate strength and residual strength in CSR-H and CSR-OT & CSR-BC are compared in detail, and also the technical grounds of rule requirements are explained. The nonlinear finite element method is used in this paper to analyze the effect of critical factors, including initial deformation and lateral pressure, on hull girder ultimate strength. Finally, the influence of rule requirements of hull girder ultimate strength and residual strength is evaluated on general Bulk Carriers and Oil Tankers in ship industry. Based on the aforementioned research, the following conclusions can be obtained:

(1) The reduction effect of initial deformation assumed in this paper on hull girder ultimate strength is 1%~8%. For Bulk Carriers, the initial deformation has bigger influence on reduction of sagging ultimate strength than hogging condition. For Oil Tankers, initial deformation has bigger reduction effect on hogging ultimate strength than sagging condition. Different type of initial deformation will change the ultimate failure mode and even change the ultimate strength. So initial deformation effect on bending, shear, and torsion of hull girder is worth of analyzing in the future.

(2) For alternative loading condition, the reduction effect of lateral pressure on hull girder ultimate strength under hogging is about 21%. For other loading conditions, the reduction effect of lateral pressure on hogging ultimate strength is 7%~15%. This paper only considered the lateral pressure acting on outer bottom and side shell under water line. For lateral pressure acting on other parts of ship body, it is also needed to be analyzed specially for large or ultra large ships.

(3) The reduction effect of neutral axis rotation on residual strength after collision damage is about 5%. The neutral axis rotation after damage will have some influence on ultimate capacity calculation by SMITH method. The residual strength assessment in CSR-H rules is always assumed the ship floating in vertical position. However, due to flooding of some cabin after damage, the ship may present some heeling rotation.

(4) Owing to the new addition of partial safety factor γ_{DB} about double bottom effect in CSR-H, structural scantlings of hull girder members of large Bulk Carriers may slightly increase. In this view, the CSR-H will enhance the safety margin of large Bulk Carriers. In order to satisfy the requirements of hull girder ultimate strength in CSR-H, the scantlings of double bottom structures will be more conservative than CSR-BC rules.

(5) CSR Bulk Carriers and Oil Tankers can satisfy the new addition of residual strength requirements in CSR-H. The biggest utilization factor of residual strength for these ships calculated in this paper is 0.84, which means that the CSR-H ships have enough residual strength after assumed damage to withstand the still-water and wave loads. Therefore, the new requirement of residual strength in CSR-H will not increase scantlings of hull girder members. However, residual strength assessment for ship after actual accident should be analyzed case by case, especially considering various damage conditions and loading conditions.

Data Availability

The data (such as FE model file and marine structure drawings) used to support the findings of this study have not been made available because the data belongs to ship designer or operator. In this manuscript, the data is analyzed to find the general conclusions, which will be useful for future ship design and rule requirement making.

Disclosure

However, the views expressed in this paper are those of the authors and do not necessarily reflect the official views of affiliations.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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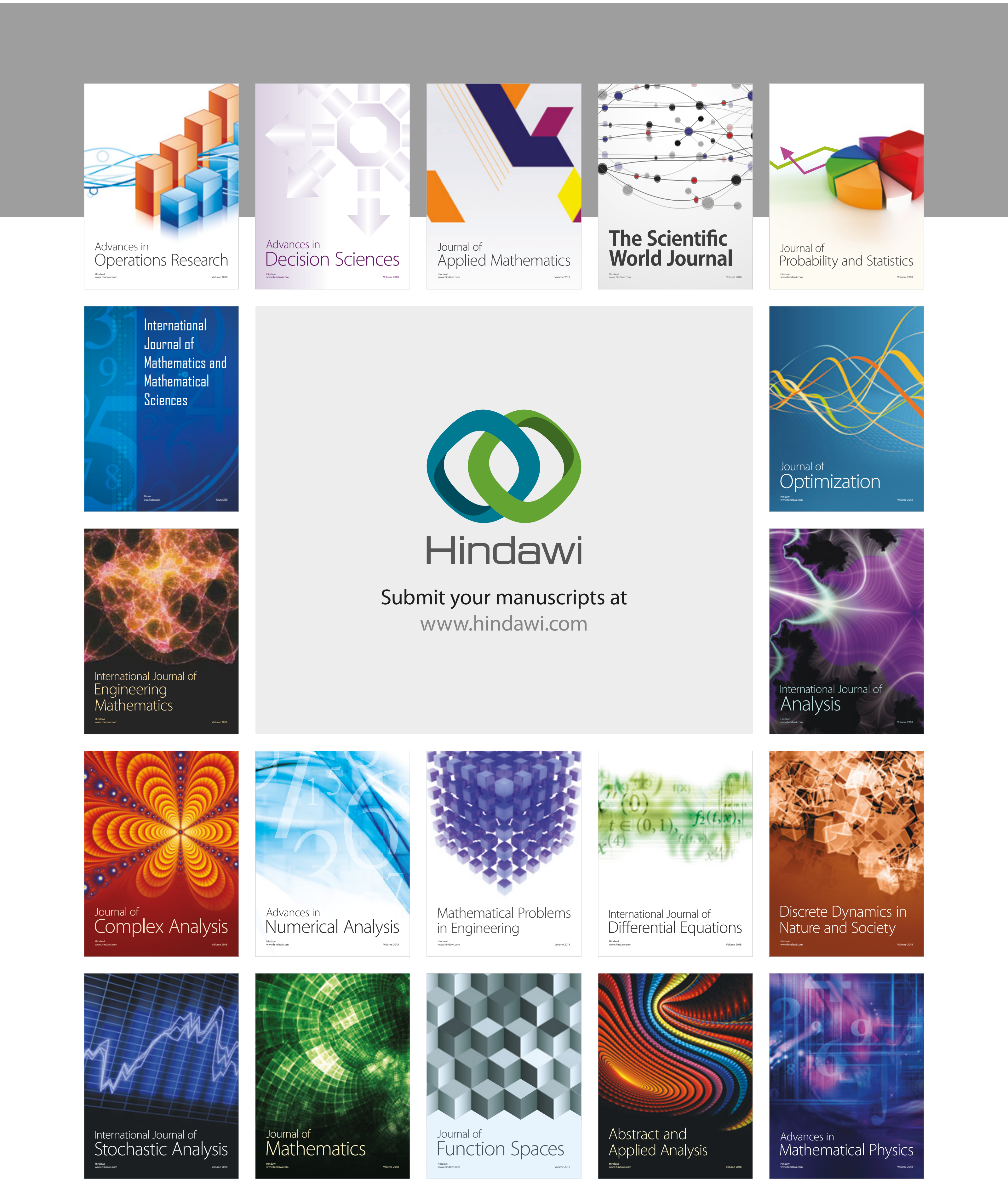
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