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Ultimate strength performance of tankers associated with industry corrosion addition practices

Do Kyun Kim[1,2], Han Byul Kim[3], Xiaoming Zhang[4], Chen Guang Li[5] and Jeom Kee Paik[5]

[1]*Civil Engineering Department, Universiti Teknologi PETRONAS, Tronoh, Malaysia*
[2]*Graduate School of Engineering Mastership, Pohang University of Science and Technology, Pohang, Korea*
[3]*Structure Research Department, Hyundai Maritime Research Institute, Hyundai Heavy Industries Co. Ltd., Ulsan, Korea*
[4]*OPR Offshore Pipelines & Risers Inc., Zhejiang, China*
[5]*The Ship and Offshore Research Institute (Lloyd's Register Foundation Research Centre of Excellence), Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan, Korea*

ABSTRACT: *In the ship and offshore structure design, age-related problems such as corrosion damage, local denting, and fatigue damage are important factors to be considered in building a reliable structure as they have a significant influence on the residual structural capacity. In shipping, corrosion addition methods are widely adopted in structural design to prevent structural capacity degradation. The present study focuses on the historical trend of corrosion addition rules for ship structural design and investigates their effects on the ultimate strength performance such as hull girder and stiffened panel of double hull oil tankers. Three types of rules based on corrosion addition models, namely historic corrosion rules (pre-CSR), Common Structural Rules (CSR), and harmonised Common Structural Rules (CSR-H) are considered and compared with two other corrosion models namely UGS model, suggested by the Union of Greek Shipowners (UGS), and Time-Dependent Corrosion Wastage Model (TDCWM). To identify the general trend in the effects of corrosion damage on the ultimate longitudinal strength performance, the corrosion addition rules are applied to four representative sizes of double hull oil tankers namely Panamax, Aframax, Suezmax, and VLCC. The results are helpful in understanding the trend of corrosion additions for tanker structures.*

KEY WORDS: Corrosion addition; Double hull oil tankers; Age-related degradation; Corrosion maintenance; Pre-CSR; Common structural rules (CSR); Harmonised common structural rules (CSR-H); Time-dependent corrosion wastage model (TDCWM); Union of greek shipowners (UGS).

ABBREVIATIONS & NOMENCLATURES

CSR	Common structural rule	D_s	Ship depth
CSR-H	Harmonised common structural rule	h_w	Web height of stiffener
Pre-CSR	Structural rule applied before CSR	I	Moment of inertia

Corresponding author: *Jeom Kee Paik*, e-mail: *jeompaik@pusan.ac.kr*

TDCWM	Time-dependent corrosion wastage model proposed by Paik et al. (2003a)
UGS	Union of greek shipowners
M_{u_net}	Ultimate hull girder bending moment at net scantling
B_s	Ship breadth
b	Breadth between longitudinal stiffeners
b_f	Breadth of flange
C_b	Block coefficient
L_s	Ship length
M_u	Ultimate hull girder bending moment
a	Length of stiffened panel
B	Breadth of stiffened panel
t	Plate thickness
t_f	Flange thickness
t_w	Web thickness
σ_Y	Yield strength

INTRODUCTION

Corrosion is an important age-related degradation problem that has a great impact on the service life of marine structures. Since the 1950s, the construction time of ships and offshore structures has been significantly reduced by the development of welding and maintenance technology. With maintenance technology advancing at a fast growing rate, the structural failure due to in-service damage is decreasing. These advances, along with other technical developments, have extended the lifespan of ships and offshore structures by two or three times.

Historically, various technologies for preventing corrosion have been suggested, such as corrosion addition, coating, cathodic protection, ballast water deoxygenation, and chemical inhibition (Paik and Melchers, 2008). Of these technologies, coating and corrosion addition are the two most widely adopted technologies by ship designers and builders to protect structural members from corrosion degradation because of their cost effectiveness, simple practicability, and relevance.

Before the introduction of CSR, corrosion addition rules were developed and maintained by individual classification bodies, a period known as pre-CSR. To achieve robust and safer ships, the IACS adopted CSR for oil tankers and bulk carriers on 1st April 2006, at which the corrosion additions for oil tankers and bulk carriers were specified (IACS, 2006a; 2006b). However, the CSR for oil tankers and bulk carriers were developed independently by different teams using different technical approaches. During the review of the CSR, industry stakeholders urged the IACS to harmonise the key technologies used to derive the rules. The IACS agreed and was committed to develop a harmonised version of the rules (IMO, 2012). The new structural rules are known as CSR-H (IMO, 2012), as shown in Fig. 1. The outcome of the verification will be effective soon.

The CSR-H is made up of common "general hull requirements" for both ship types, and separate parts for "ship-type specific" requirements applicable to oil tankers and bulk carriers, respectively (Kim and Cheng, 2012). The rules on the corrosion additions for each ship type are expected to be located in the "ship type specific" parts, and corrosion additions can be defined for a range of cargo hold circumstances for each ship type.

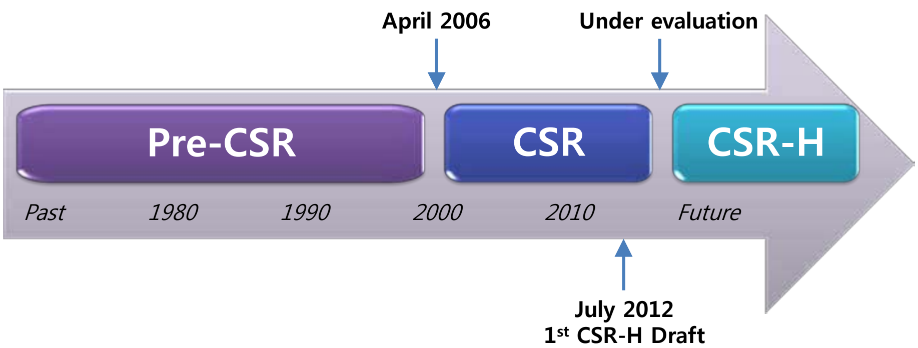


Fig. 1 Overview of corrosion addition rules (DNV, 2005; IACS, 2006a; 2006b; IMO, 2012).

This study investigates the historical trend of corrosion additions for double hull oil tankers and their effect on the ultimate strength performance of hull girders. For comparison, two other corrosion models namely UGS model, a new corrosion model suggested by the UGS and the time-dependent corrosion wastage model are also examined. Many Greek shipowners have called for larger corrosion additions. However, no action has hitherto been taken to change the current corrosion addition rules. This matter has led to the UGS developing an increased corrosion addition model (Gratsos et al., 2009; 2010). Four representtative classes of double hull oil tanker structures, namely Panamax, Aframax, Suezmax, and VLCC, are used to trace the general trend in corrosion addition effects. In addition, bulk carriers have been considered to draw the general tendency using similar procedure as present study by Kim et al. (2014b). The insights obtained in this study will help in understanding the trend in corrosion additions for double hull oil tankers and their effect on the ultimate strength performance.

GENERAL CORROSION ADDITIONS FOR TANKERS

Trend in corrosion addition rules for ship design

The CSR for corrosion additions were specified for double hull oil tanker and bulk carrier structures in early 2006 for several reasons (IACS, 2006a; 2006b) as follows:

- To reflect the experience and resources of all the classification societies (IACS members) in a set of unified rules.
- To remove the confusion surrounding the corrosion additions of different classification societies.
- To achieve a 25-year design life.
- To apply the net thickness approach to ultimate strength analysis for stiffened panels and the half corrosion addition approach for hull girders.

The historical trend in corrosion additions for each structural member for double hull oil tankers is presented in Fig. 2. The figure shows that there is no difference between the CSR and CSR-H, but the CSR corrosion additions are much greater than the pre-CSR corrosion additions. It seems that the specified CSR corrosion additions are sufficient, and thus the same additions have been included in the CSR-H. Of course, the approach between pre-CSR and CSR is originally differing from each other. The pre-CSR has adopted the net-scantling approach for ultimate strength analysis of stiffened panels and half corrosion addition deduced scantling approach for ultimate strength analysis of hull girders. However, the structural scantlings have been changed due to the different strength capacity requirements when the CSR was originally introduced in 2006, as shown in Fig. 3.

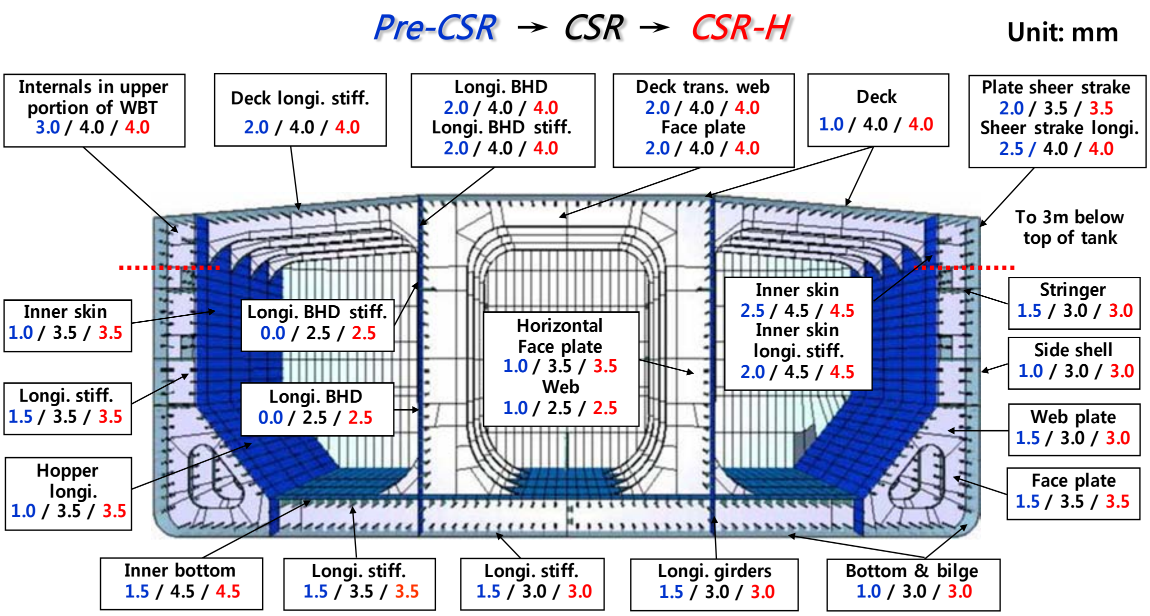


Fig. 2 Changes in corrosion addition rules for double hull oil tanker structures (DNV, 2005; IACS, 2006a; 2006b; IMO, 2012).

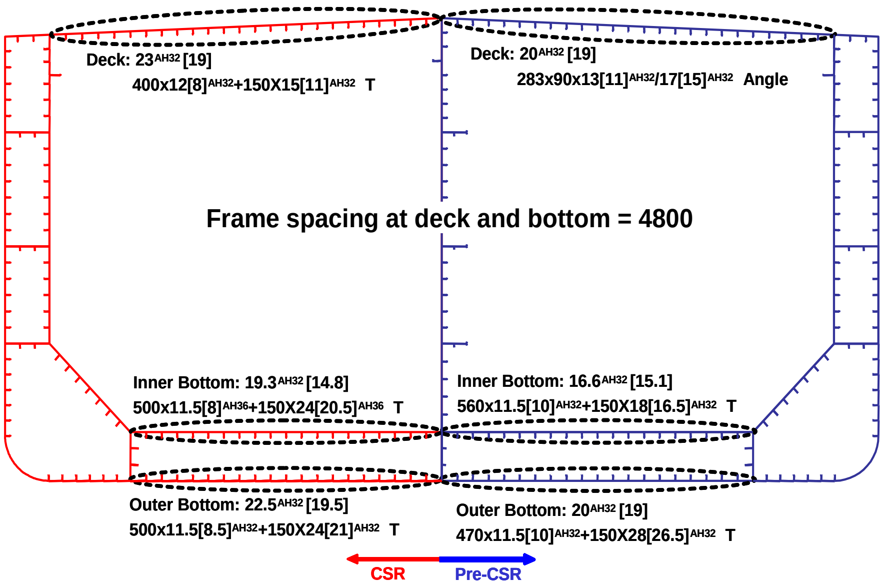


Fig. 3 Comparison of structural scantlings of a Suezmax class double hull oil tanker's mid-ship section in pre-CSR and CSR designs (bracket indicate the net thickness) (Paik et al., 2009).

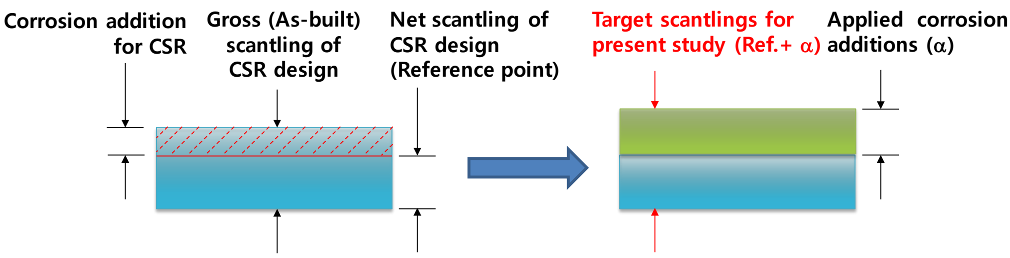


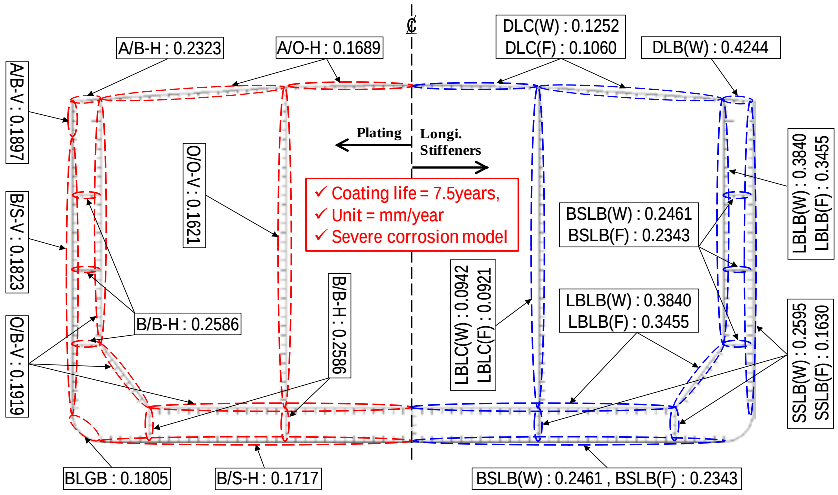
Fig. 4 Applied corrosion additions with structural reference scantlings (net scantlings) (Note: gross scantling = net scantling + full corrosion addition, half corrosion addition deducted scantling = net scantling + half corrosion addition).

Four types of double hull oil tankers designed using the IACS CSR method are employed to avoid complex structural design selection problems. The net scantlings in the CSR design are taken as the reference scantlings in the present study, as shown in Fig. 4.

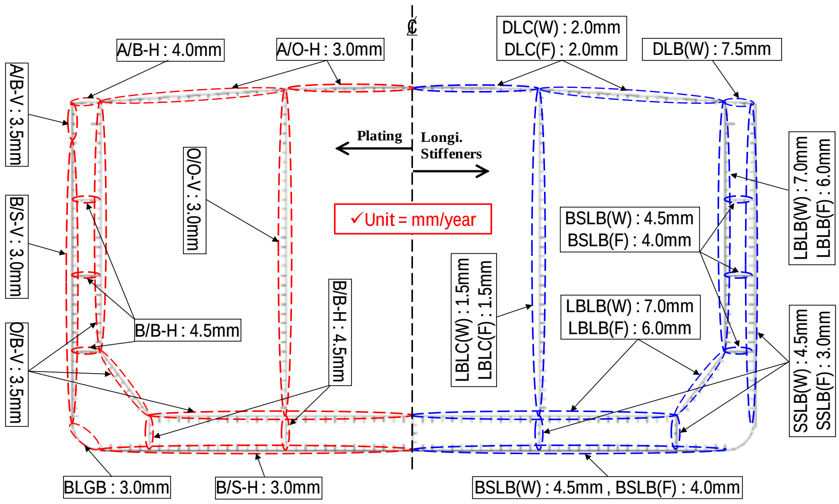
Other corrosion addition models

The TDCWM for ships and offshore structures (Paik et al., 2003a; 2003b; 2004; Guedes Soares et al., 2008) was deducted from the results of statistical analyses using real corrosion measurement data. As mentioned previously, two types of corrosion models (CSR and CSR-H) were also proposed based on real measured time-variant corrosion wastage. But, other types of TD-CWM have been developed by researchers.

Recently, more refined time-dependent corrosion wastage model techniques have been proposed by Paik and Kim (2012) and applied to the various structures such as subsea well tube (Mohd Hairil and Paik, 2013) and subsea gas pipeline (Mohd Hairil et al., 2014). For the condition assessment of corrosion damaged structures, Paik et al. (2003a) developed two types of TDCWM for tankers that cover average and severe cases. Kim et al. (2012a; 2012b) performed an ultimate strength comparison study of hull girders and stiffened panels using the CSR corrosion addition and the average TDCWM. Their results showed that the difference in ultimate hull girder strength between the two corrosion models at the 25 years (net) scantling was around 10-20%. Recently, Kim et al. (2014a) investigated an ultimate hull girder strength of corroded Aframax class oil tanker under grounding damage. In the comparison in this study, a representative severe TDCWM for a double hull oil tanker (Paik et al., 2003a) is applied, as shown in Fig. 5 see Table A.1 for abbreviation used.



(a) Time-dependent corrosion wastage model (TDCWM).



(b) Corrosion addition model determined from TDCWM.

Fig. 5 Corrosion addition model determined from TDCWM for double hull oil tanker (Paik et al., 2003a).

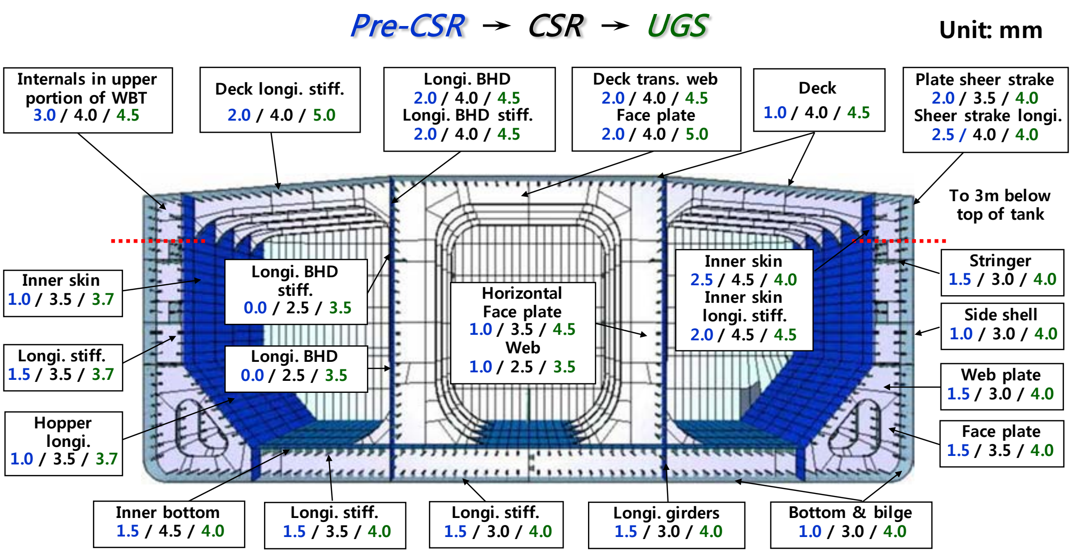


Fig. 6 UGS corrosion addition model for double hull oil tanker with previous rules including pre-CSR and CSR (DNV, 2005; IACS, 2006a; 2006b; Gratos et al., 2010).

Moreover, the UGS suggested a new corrosion addition model (Gratos et al., 2009; 2010), as shown in Fig. 6, that reflects their experience of double hull oil tanker structures to reduce maintenance costs. The model meets with opposition from other shipowners who have confidence in the current maintenance of their ship.

Fig. 6 presents the UGS corrosion addition models for each structural member against other pre-CSR and CSR corrosion addition rules. The UGS corrosion additions are around 0.2 *mm* to 1.0 *mm* greater than the CSR corrosion additions. The UGS corrosion model is also considered here in investigating the effect of corrosion additions on the ultimate strength performance of double hull oil tanker structures.

ULTIMATE STRENGTH ANALYSIS

Hull girders

In the structural analysis of ships, global scantling check (hull girder) and local scantling check (stiffened panel) are performed sequentially.

Applied examples for hull girders

Four sizes of double hull oil tankers (Paik et al., 2012b) are selected as representative vessels to investigate the general trend in corrosion addition effects. The principal dimensions of each ship are illustrated in Table 1. The ALPS/HULL (2013) progressive hull collapse analysis program is used for the hull girder ultimate strength analysis. The details of ALPS/HULL program are described in Hughes and Paik (2010) and benchmark studies have been performed to verify its accuracy and efficiency (Paik et al., 2012a).

Table 1 General mid-ship section information with principal dimensions of the target structures with net scantlings (reference point as illustrated in Fig. 4).

Tanker type	L_s (*m*)	B_s (*m*)	D_s (*m*)	C_b	I (m^4)	N.A. (*m*)
Panamax	219	32.24	20.65	0.817	276.67	9.10
Aframax	239	43.80	21.00	0.832	413.05	9.55
Suezmax	261	48.00	23.20	0.843	627.35	10.38
VLCC	320	60.00	30.50	0.845	1589.54	12.95

Vertical bending moments including hogging and sagging, which are the dominant loads for ships during operation period, are considered in the ultimate strength analysis for the gross scantlings, half addition scantling, and net scantlings of the ship. Only the average levels of initial distortions, which are performed by plate initial deflection and stiffener distortion, are considered. The weld-induced residual strength is not considered for hull girder strength analysis according to the CSR (IACS, 2006a).

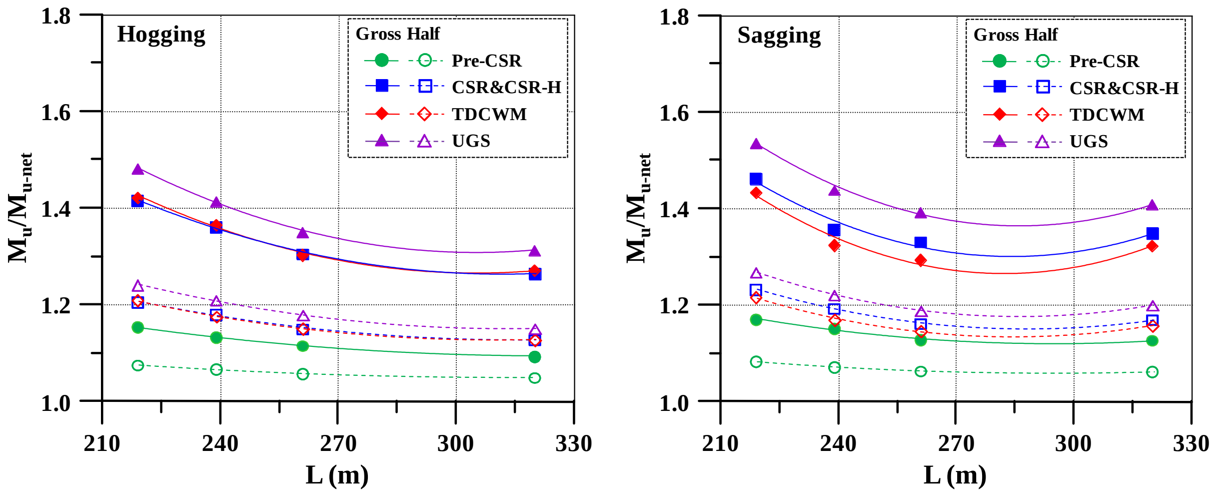
Analysis results of hull girders

The ultimate hull girder strength analysis results for the four sizes of double hull oil tanker structures and the five types of corrosion addition models are compared in Figs. A.1 to A.4, respectively. Empirical formulas based on the analysis results are obtained by the curve-fitting approach presented in Fig. 7 and Table 2. It is apparent that the effect of corrosion additions on the ultimate hull girder (longitudinal) strength tends to decrease as the vessel length increases. This effect is because the same corrosion additions per each structural member are applied to all types of double hull oil tanker structures. In terms of the loading conditions, sagging bending moments affect the ultimate hull girder strength more significantly than hogging.

The mean value and Coefficient of Variation (COV) are presented in Table A.2(a) and A.2(b). The empirical formulas can be defined as follows:

$$M_u / M_{u-net} = \xi \left(\frac{L}{1000} \right)^2 + \psi \left(\frac{L}{1000} \right) + \zeta \quad (1)$$

The coefficients are as summarised in Table 2.



(a) Hogging. (b) Sagging.

Fig. 7 Summary of the ultimate hull girder strength analysis results.

Table 2 Coefficients of the empirical formulas under vertical bending moments.

Coefficients		ξ		ψ		ζ		R^2	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
Pre-CSR	Gross	5.4952	8.8491	3.5597	5.2088	1.6696	1.8870	0.9999	0.9862
	Half	2.8228	4.2379	1.7787	2.4945	1.3294	1.4257	0.9968	0.9999
	Net	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000
CSR & CSR-H	Gross	17.963	36.542	11.189	20.726	3.0045	4.2398	0.9983	0.9521
	Half	8.5541	17.339	5.4084	9.9709	1.9810	2.5837	0.9967	0.9987
	Net	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000
TDCWM	Gross	21.639	40.541	13.192	22.853	3.2756	4.4860	0.9956	0.9631
	Half	9.9872	19.335	6.1785	10.984	2.0816	2.6930	0.9998	0.9948
	Net	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000
UGS	Gross	23.780	38.260	14.494	21.848	3.5153	4.4815	0.9992	0.9917
	Half	10.273	20.746	6.4277	11.848	2.1560	2.8667	0.9993	0.9996
	Net	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000

Note: R^2 = coefficient of determination.

In a sagging condition, these empirical formulas cannot be applied to evaluate the residual strength performance when the vessel length is larger than 261.0 *m* (a Suezmax class double hull oil tanker). In this case, a constant value that can be calculated from the average value from the results for Suezmax and VLCC class double hull oil tankers is applied.

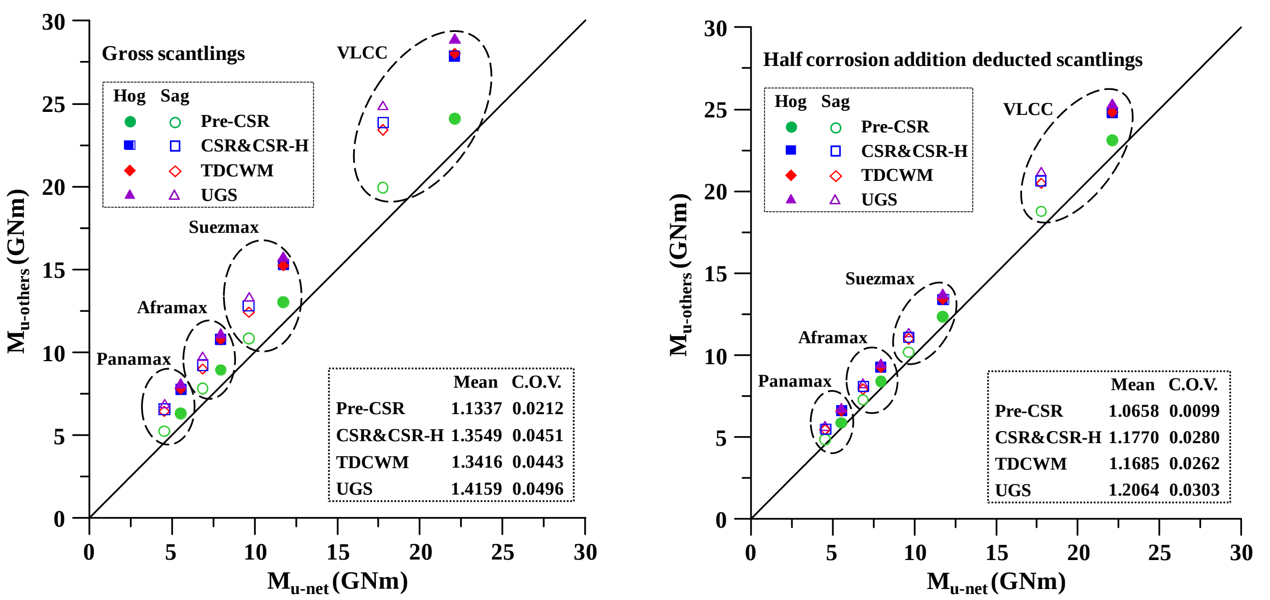
The differences in the mean values are presented in Figs. 8(a) and (b), and more details of the statistical analysis results are given in Table A.2(a) and A.2(b). From the mean values shown in Figs. 9(a) and (b), it is apparent that the ultimate strength capacity of the hull girders can be specified by the following order.

<u>For a hogging condition</u>

$$\text{Pre}-\text{CSR} \ < \ \text{CSR} \ \& \ \text{CSR-H} \ \le \ \text{TDCWM} \ < \ \text{UGS} \tag{2.a}$$

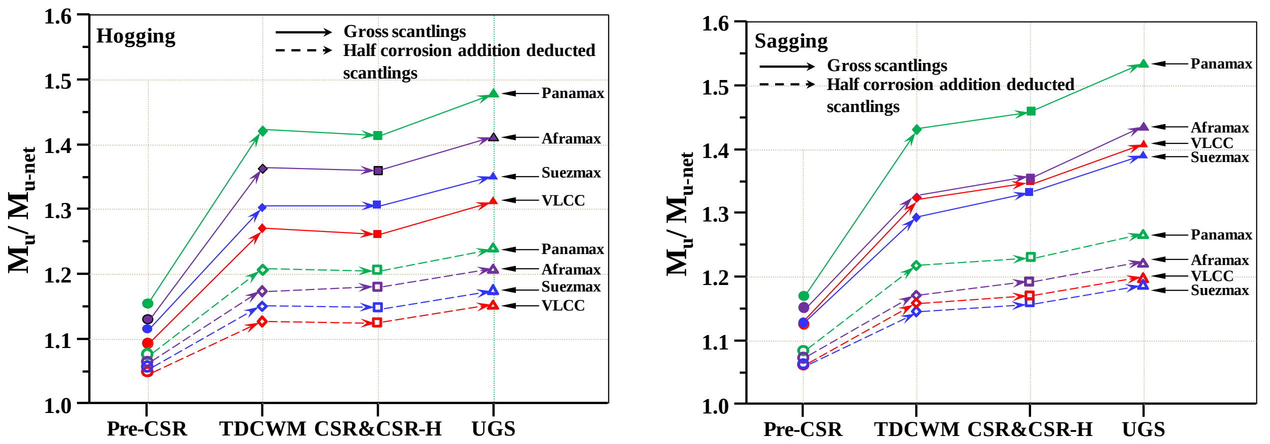
<u>For a sagging condition</u>

$$\text{Pre}-\text{CSR} \ < \ \text{TDCWM} \ < \ \text{CSR} \ \& \ \text{CSR-H} < \text{UGS} \tag{2.b}$$



(a) Gross scantlings. (b) Half corrosion addition deducted scantlings.

Fig. 8 Deviation in the ultimate strength of hull girders between net scantlings and the five corrosion addition models.



(a) Hogging. (b) Sagging.

Fig. 9 Mean values for the ultimate strength of hull girders for double hull oil tankers.

Stiffened panels

The local scantlings are also investigated by applying the ALPS/ULSAP ultimate strength analysis program for stiffened panel. The details of ALPS/ULSAP program have been described in Hughes and Paik (2010) and benchmark studies for stiffened panels have been performed to verify the accuracy and efficiency about the ALPS/ULSAP program (Paik et al., 2012a).

Applied examples for stiffened panels

It is well known that maximum axial compression or tension are applied to the deck, inner bottom, and outer bottom stiffened panel structures, which are located far away from the neutral axis of the ship, as presented in Fig. 10 (Paik et al., 2013). The details of the selected three stiffened panels are presented in Table 3(a) to (d). Schematic diagram of stiffened panel is presented in Fig. 11 and the nomenclatures of the stiffener dimensions are illustrated in Fig. 12.

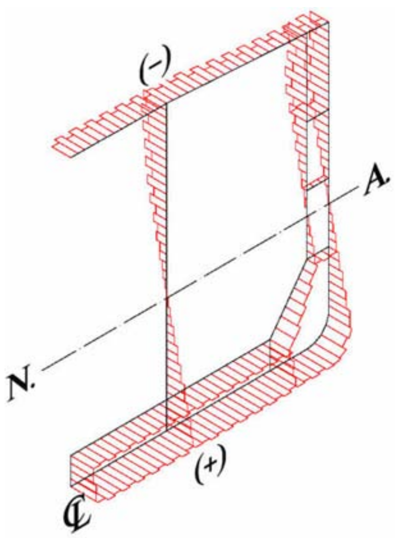


Fig. 10 Longitudinal stress distribution of tanker mid hull at the ultimate limit state (Paik et al., 2013).

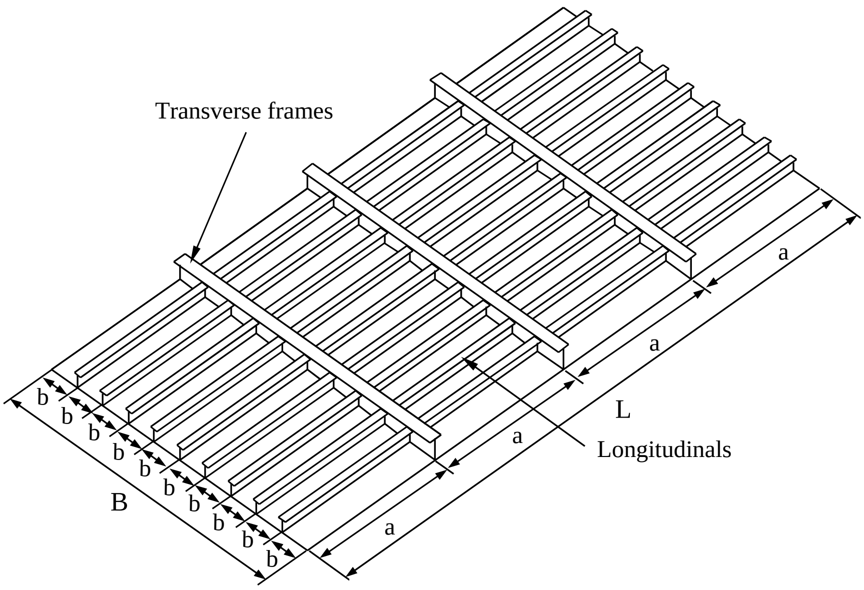


Fig. 11 Schematic diagram of general shape of stiffened panel structure (Hughes and Paik, 2010).

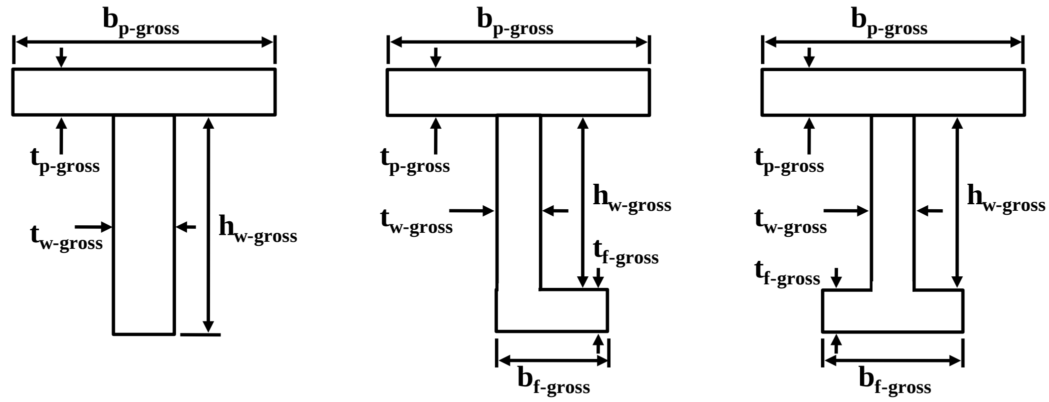
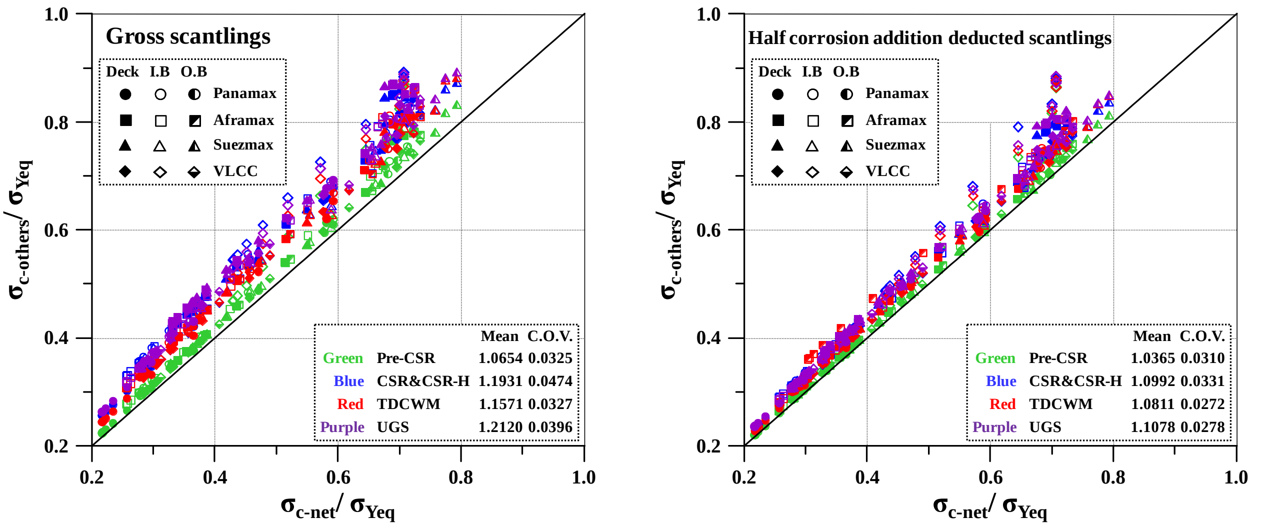


Fig.12 Nomenclature of the stiffener dimensions.

Analysis results for stiffened panels

Fig. A.5 to A.8 show the ultimate strength analysis results of stiffened panels for four types of double hull oil tanker structures subjected to axial or biaxial compression. In case of stiffened panels, the empirical formulas are not presented because the structural scantlings of stiffened panels of each double hull oil tanker show the dissimilar trend. In this regard, only mean values and COV calculations are performed.

The capacity for biaxial compressive action ($\sigma_C = \sqrt{\sigma_{xu}^2 + \sigma_{yu}^2}$) is compared and the obtained results are plotted in Figs. 13(a) and (b) with mean and COV values. The corresponding figures present the trend of the deviation in ultimate limit state of stiffened panels between net scantlings and the five corrosion addition models. The details of statistical analysis results (i.e., mean, standard deviation, and coefficient of variation) are as summarised in Table A.3(a) and A.3(b).



(a) Gross scantlings. (b) Half corrosion addition deducted scantlings.

Fig. 13 Deviation in the ultimate strength of stiffened panels between net scantlings and the five corrosion addition models.

From the mean values shown in Figs. 13(a)-(b), it is apparent that the ultimate strength capacity of the stiffened panels can be specified in the following order and the order of ultimate strength capacity would be linked with Figs. 14(a)-(c).

<u>For deck stiffened panels</u>

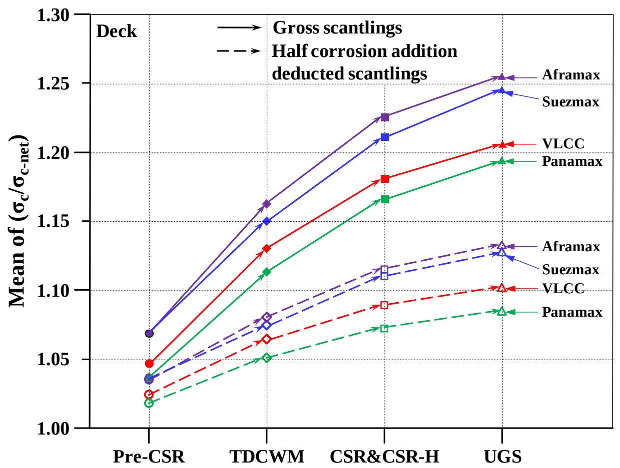
$$\text{Pre}-\text{CSR} \; < \; \text{TDCWM} \; < \; \text{CSR \& CSR-H} \; < \; \text{UGS} \tag{3.a}$$

For inner bottom stiffened panels

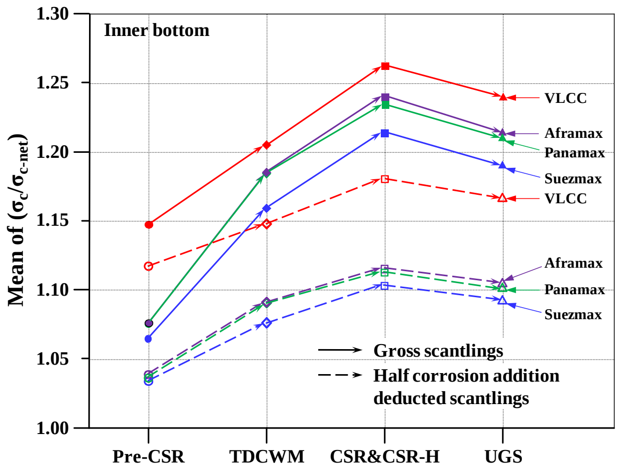
$$\text{Pre} - \text{CSR} \ < \ \text{TDCWM} \ < \ \text{UGS} \ < \ \text{CSR \& CSR-H} \tag{3.b}$$

For outer bottom stiffened panels

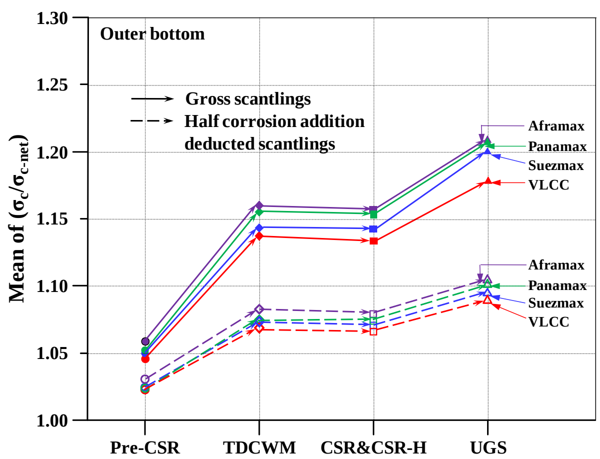
$$\text{Pre} - \text{CSR} \ < \ \text{CSR \& CSR-H} \leq \text{TDCWM} \ < \ \text{UGS} \tag{3.c}$$



(a) Deck stiffened panel.



(b) Inner bottom stiffened panel.



(c) Outer bottom stiffened panel.

Fig. 14 Mean values for ultimate strength of stiffened panels for double hull oil tankers.

Table 3(a) Properties of the stiffened panels of panamax class tanker with net scantlings based on Figs. 11 and 12.

Panamax class tanker	a (*mm*)	b (*mm*)	B (*mm*)	t (*mm*)	Stiff. type	No. of stiff.	h_w (*mm*)	t_w (*mm*)	b_f (*mm*)	t_f (*mm*)	σ_Y(*MPa*)	
											Plate	Stiff.
Deck	3900	830	13280	8	Angle	15	288	7	86	12	315	315
Inner bottom (I.B.)	3900	830	11620	13	Tee	13	404	7.5	146.5	16.5	315	315
Outer bottom (O.B.)	3900	830	11620	13	Tee	13	403	8	147	17	315	315

Table 3(b) Properties of the stiffened panels of aframax class tanker with net scantlings based on Figs. 11 and 12.

Aframax class tanker	a (*mm*)	b (*mm*)	B (*mm*)	t (*mm*)	Stiff. type	No. of stiff.	h_w (*mm*)	t_w (*mm*)	b_f (*mm*)	t_f (*mm*)	$\sigma_Y(MPa)$	
											Plate	Stiff.
Deck	4300	814.58	19550	16.36	Angle	23	388	7.5	96	12	315	315
Inner bottom (I.B.)	4300	815	16300	12.5	Tee	19	424	7.5	146.5	11.5	315	355
Outer bottom (O.B.)	4300	815	16300	16.99	Tee	19	443	8	147	12	315	355

Table 3(c) Properties of the stiffened panels of suezmax class tanker with net scantlings based on Figs. 11 and 12.

Suezmax class tanker	a (*mm*)	b (*mm*)	B (*mm*)	t (*mm*)	Stiff. type	No. of stiff.	h_w (*mm*)	t_w (*mm*)	b_f (*mm*)	t_f (*mm*)	$\sigma_Y(MPa)$	
											Plate	Stiff.
Deck	4800	862	21550	19	Tee	24	404	8	146	11	315	315
Inner bottom (I.B.)	4800	855	17100	14.84	Tee	19	504	8	146.5	20.5	315	355
Outer bottom (O.B.)	4800	855	17100	19.49	Tee	19	503	8.5	147	21	315	355

Table 3(d) Properties of the stiffened panels of VLCC tanker with net scantlings based on Figs. 11 and 12.

VLCC class tanker	a (*mm*)	b (*mm*)	B (*mm*)	t (*mm*)	Stiff. type	No. of stiff.	h_w (*mm*)	t_w (*mm*)	b_f (*mm*)	t_f (*mm*)	$\sigma_Y(MPa)$	
											Plate	Stiff.
Deck	5680	951.19	15218.99	16	Tee	15	404	11	146	15	315	315
Inner bottom (I.B.)	5680	950	10450	23	Tee	10	654	9	171.5	24	235	315
Outer bottom (O.B.)	5680	950	10450	17.45	Tee	10	653	10	197	26	315	315

CONCLUDING REMARKS

This study investigates the trend in corrosion additions in the structural design of ships and the effect of corrosion additions on the ultimate strength performance of four double hull oil tanker structures, namely Panamax, Aframax, Suezmax, and VLCC.

Five types of corrosion addition models, namely Pre-CSR, CSR, CSR-H, TDCWM, and UGS, are applied to investigate the general trend in corrosion additions. The ultimate strength performance of hull girders and stiffened panels are investigated in terms of the gross, half corrosion addition deducted, and net scantlings.

The net scantlings in CSR design are set as the reference scantlings from which the minimum required strength thickness is obtained and to which the additional corrosion additions (margins) of each corrosion models are added, as shown in Fig. 4. Based on these assumptions, empirical formulas are proposed for the ultimate hull girder strength performance of double hull oil tankers for the different corrosion addition rules. But, additional case studies for double hull oil tankers should be performed and considered to develop reliable empirical formulas.

The results are expected to be helpful in evaluating the effect of corrosion additions on the ultimate strength performance of double hull oil tanker structures and to help understand the history of structural design rules on corrosion. Future studies could investigate the effect of corrosion addition models on economics in terms of the consumption of steel and fuel ratio, and the effect of corrosion additions in bulk carriers.

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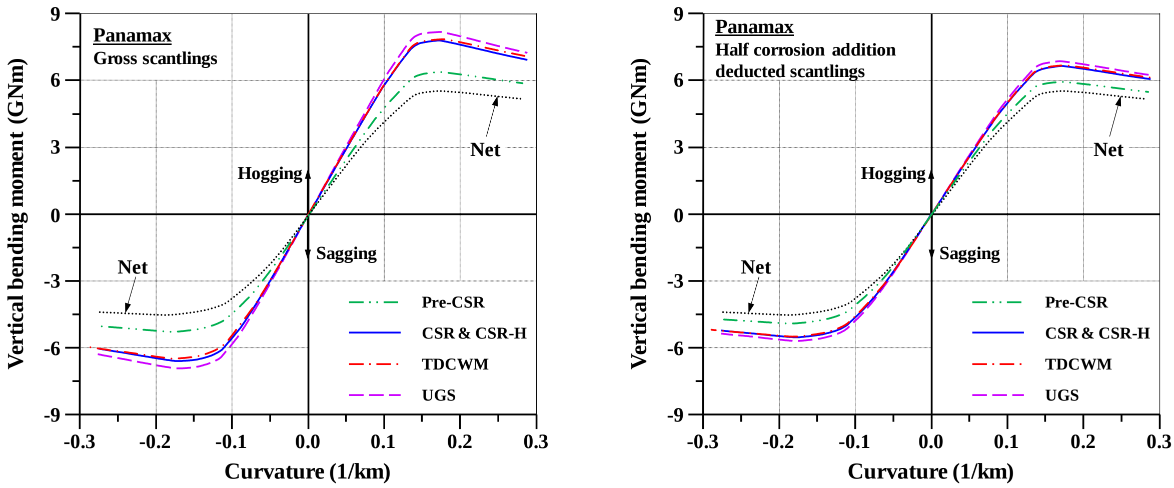
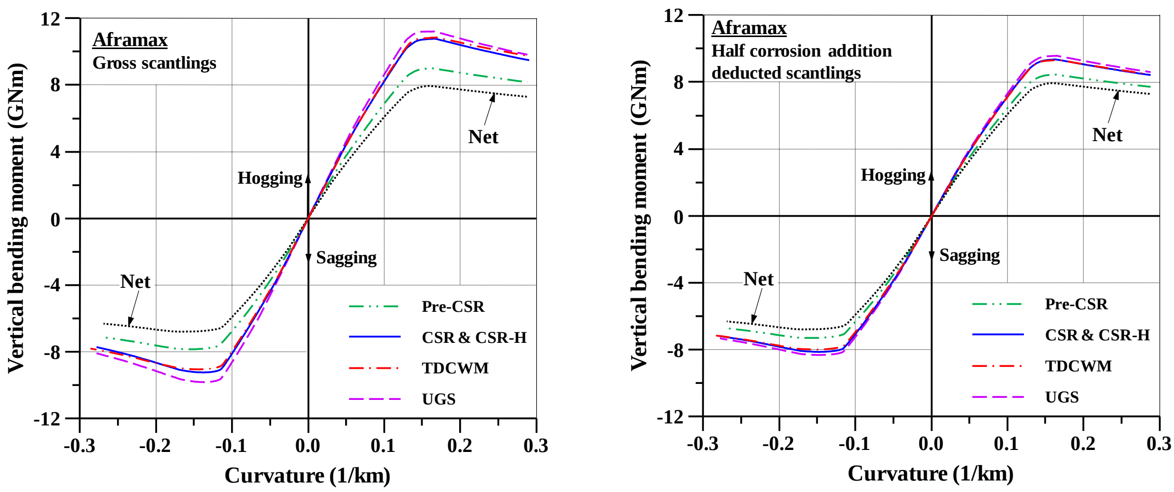
APPENDIX



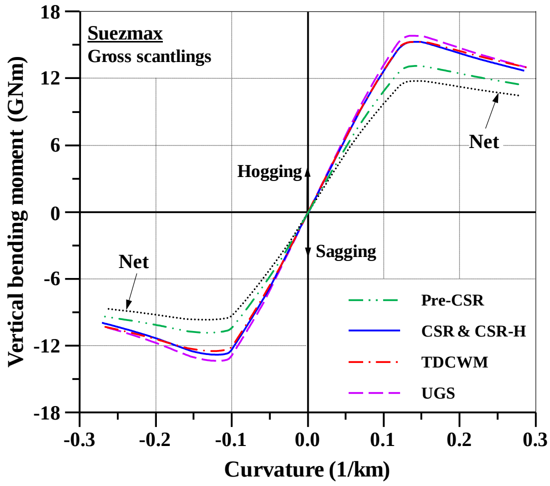
(a) Gross scantlings. (b) Half addition scantlings.

Fig. A.1. Ultimate hull girder strength analysis results of panamax class tanker.

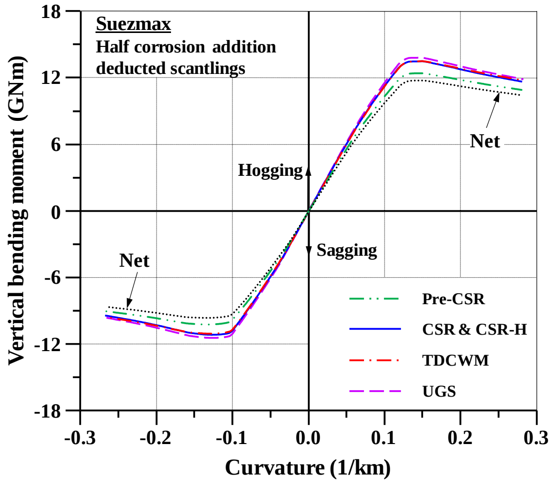


(a) Gross scantlings. (b) Half addition scantlings.

Fig. A.2 Ultimate hull girder strength analysis results of aframax class tanker.

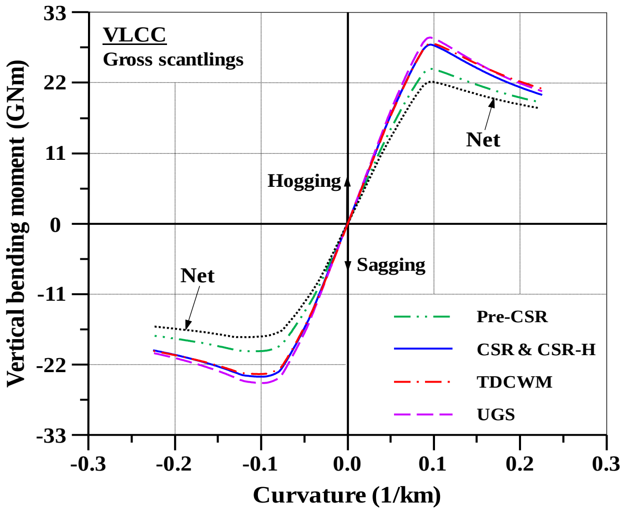


(a) Gross scantlings.

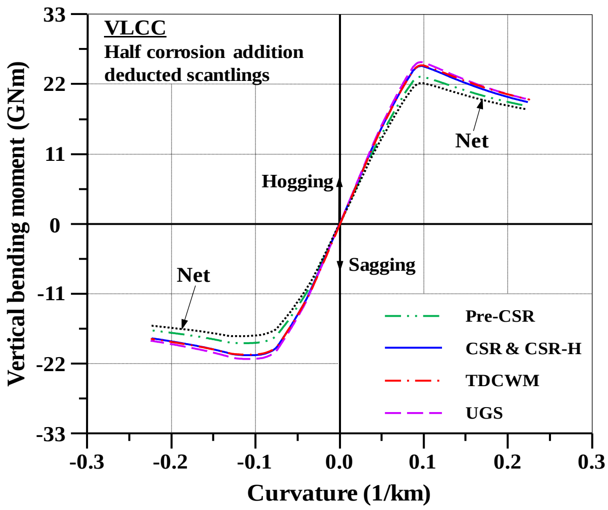


(b) Half addition scantlings.

Fig. A.3 Ultimate hull girder strength analysis results of suezmax class tanker.

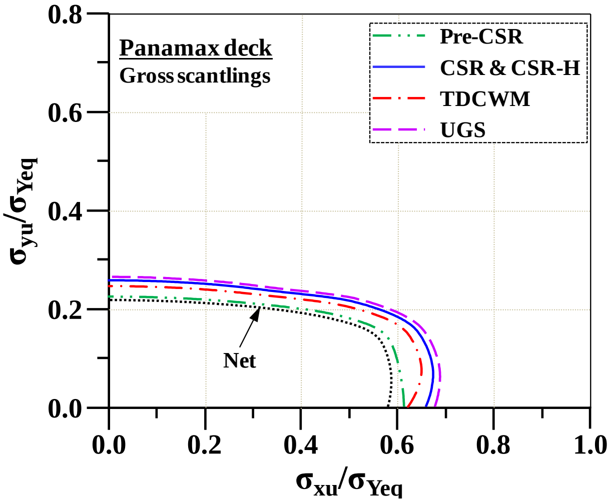


(a) Gross scantlings.

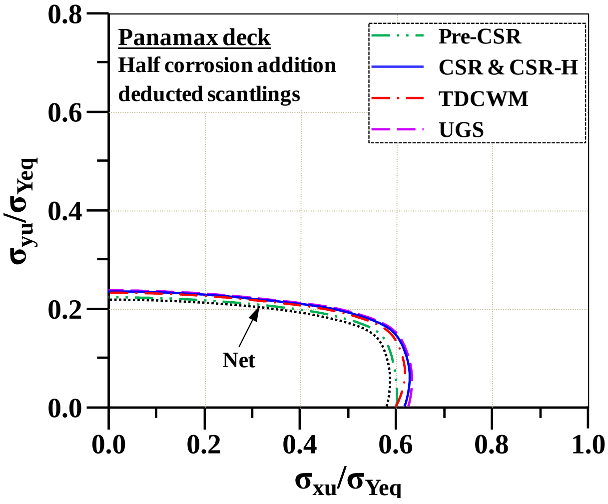


(b) Half addition scantlings.

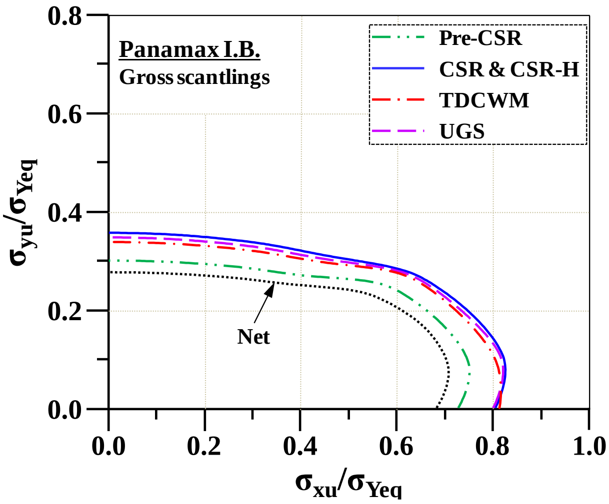
Fig. A.4 Ultimate hull girder strength analysis results of VLCC tanker.



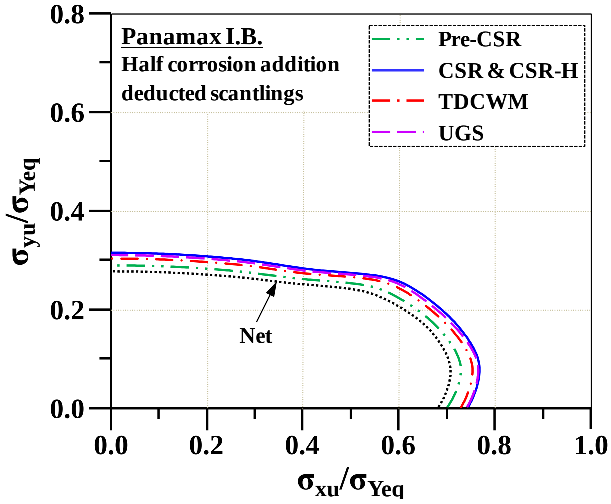
(a) Deck-gross scantlings.



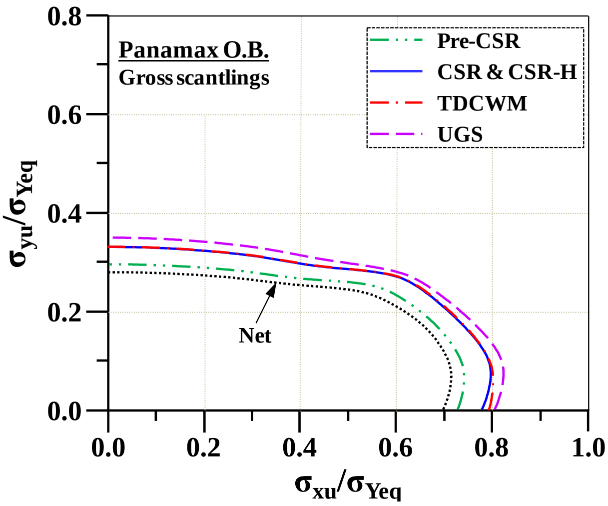
(b) Deck-half corrosion addition deducted scantlings.



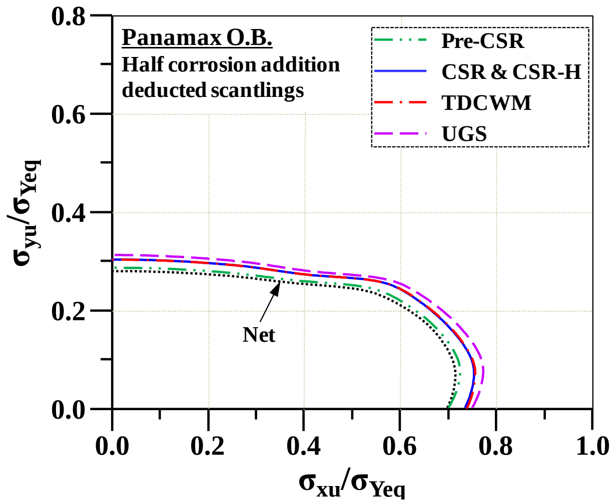
(c) I.B.-gross scantlings.



(d) I.B.-half corrosion addition deducted scantlings.

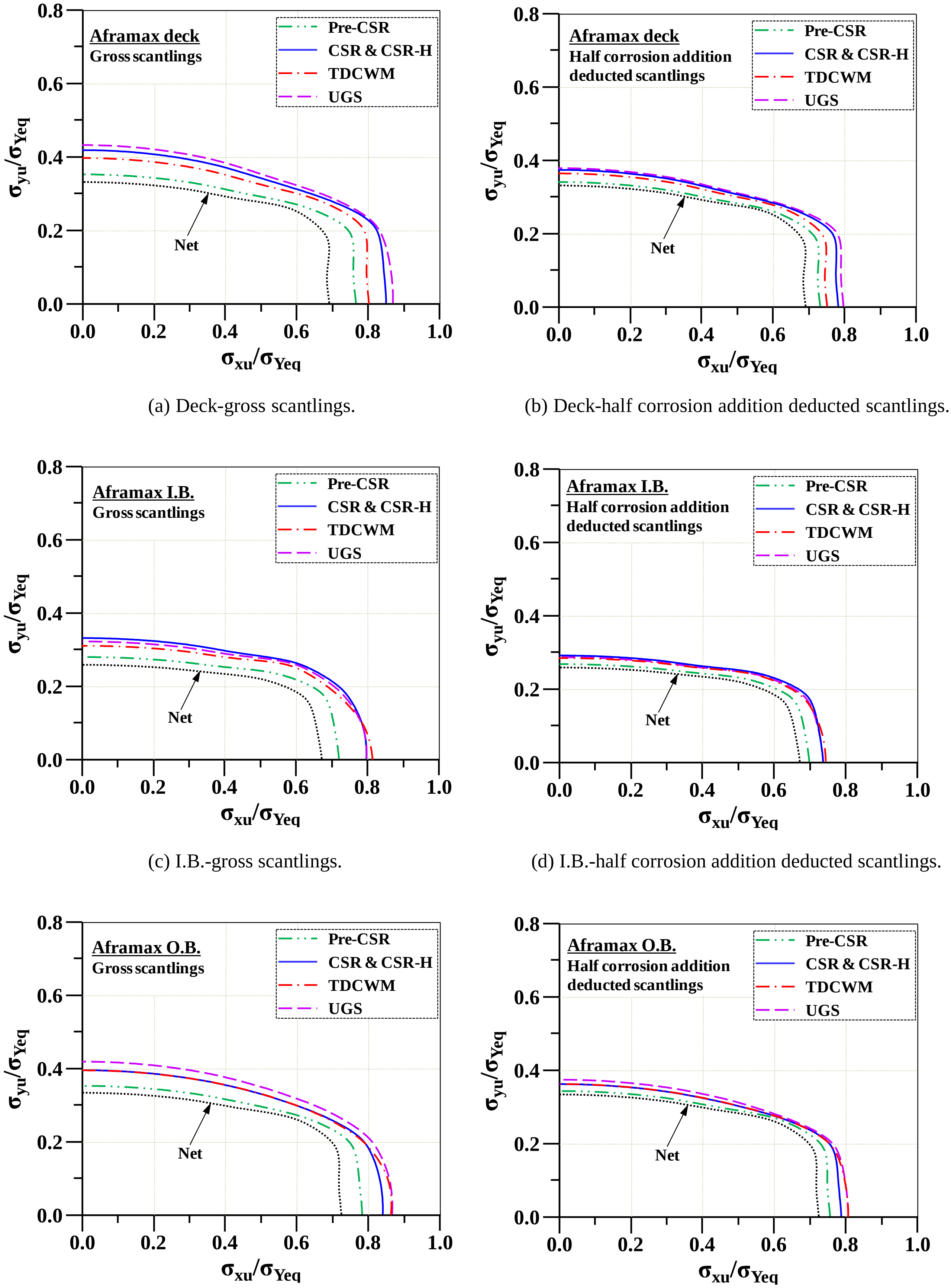


(e) O.B.-gross scantlings.



(f) O.B.-half corrosion addition deducted scantlings.

Fig. A.5 Ultimate stiffened panel strength analysis results of panamax class tanker.



(a) Deck-gross scantlings.

(b) Deck-half corrosion addition deducted scantlings.

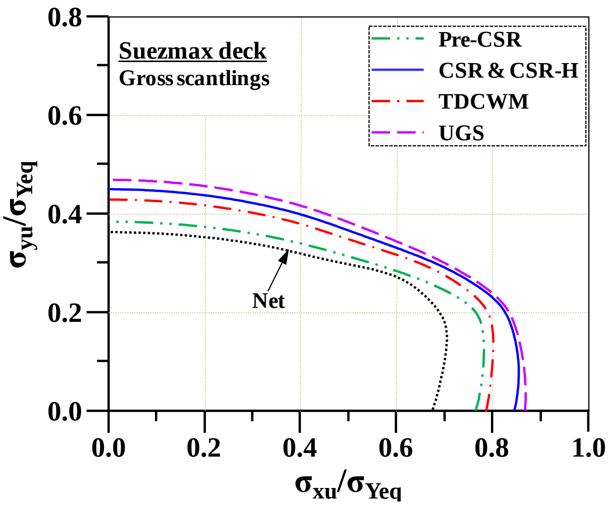
(c) I.B.-gross scantlings.

(d) I.B.-half corrosion addition deducted scantlings.

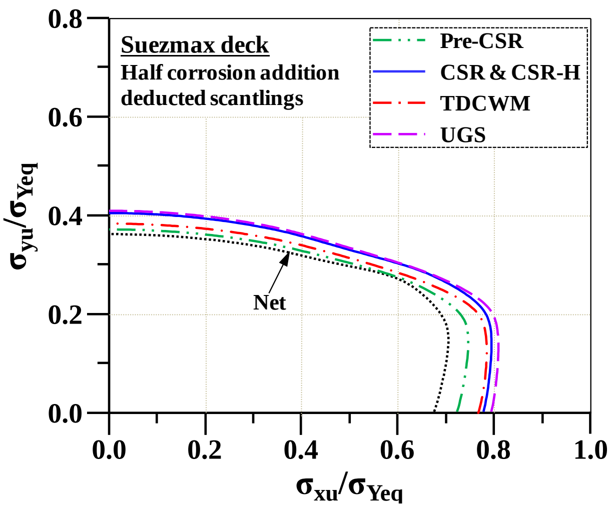
(e) O.B.-gross scantlings.

(f) O.B.-half corrosion addition deducted scantlings.

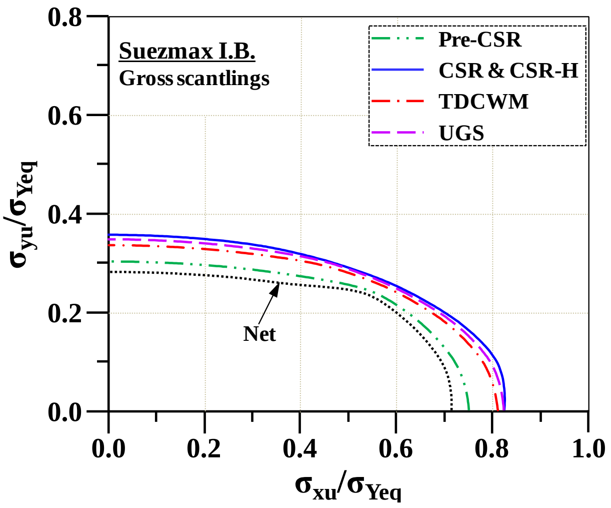
Fig. A.6 Ultimate stiffened panel strength analysis results of aframax class tanker.



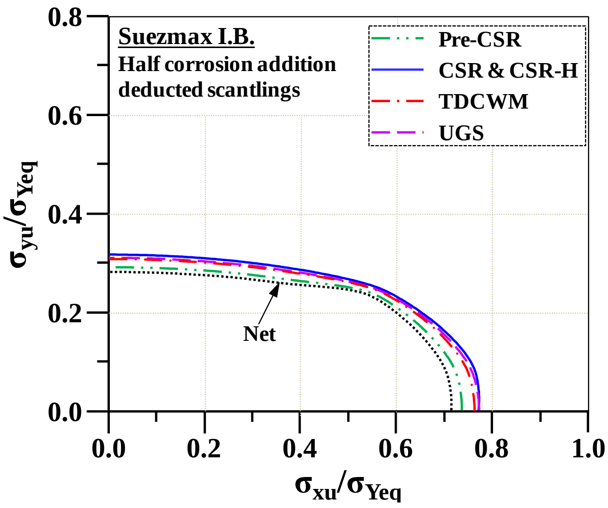
(a) Deck-gross scantlings.



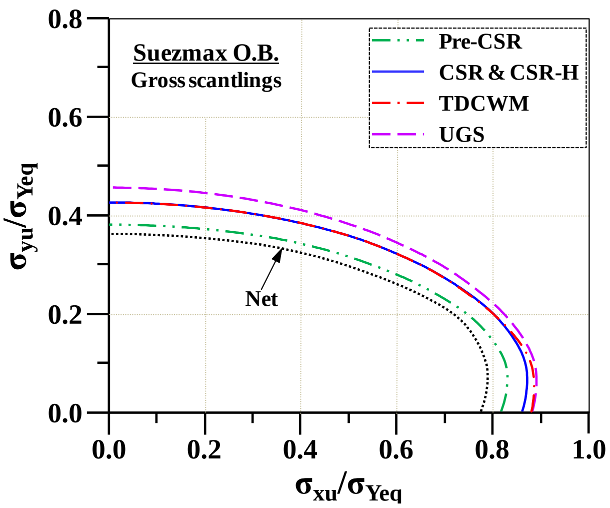
(b) Deck-half corrosion addition deducted scantlings.



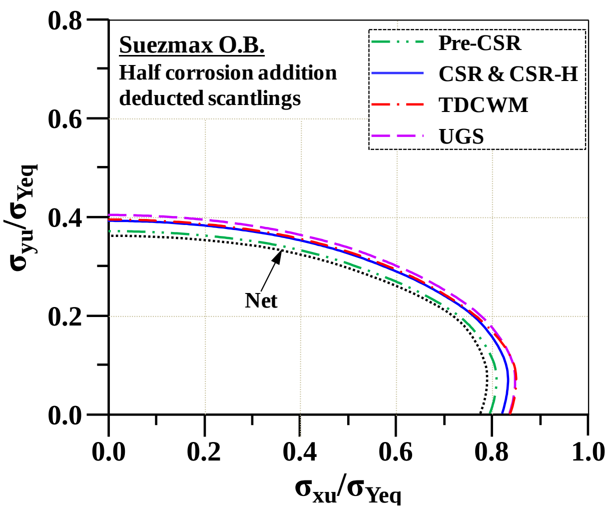
(c) I.B.-gross scantlings.



(d) I.B.-half corrosion addition deducted scantlings.

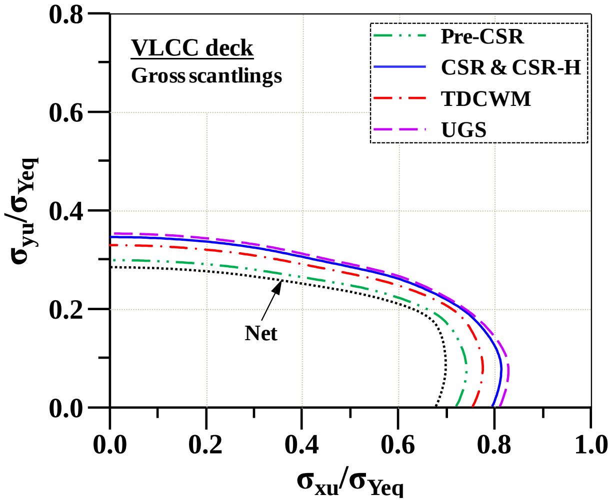


(e) O.B.-gross scantlings.

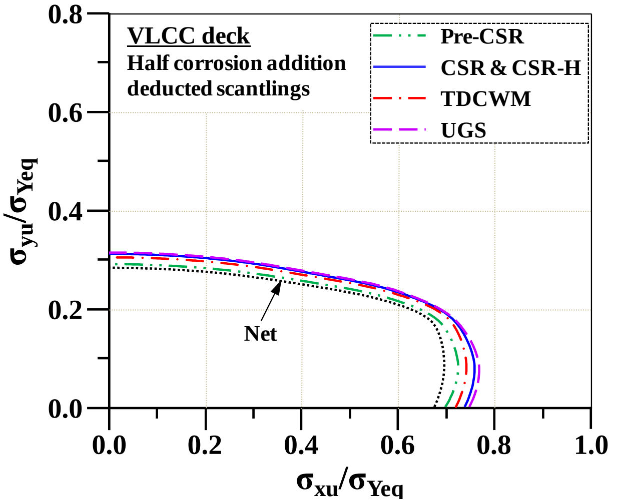


(f) O.B.-half corrosion addition deducted scantlings.

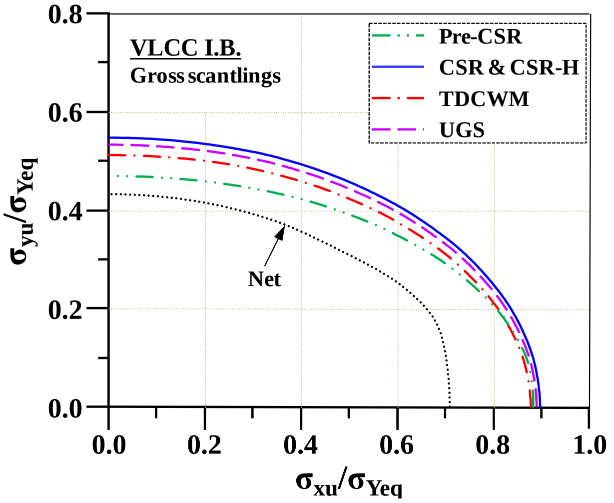
Fig. A.7 Ultimate stiffened panel strength analysis results of suezmax class tanker.



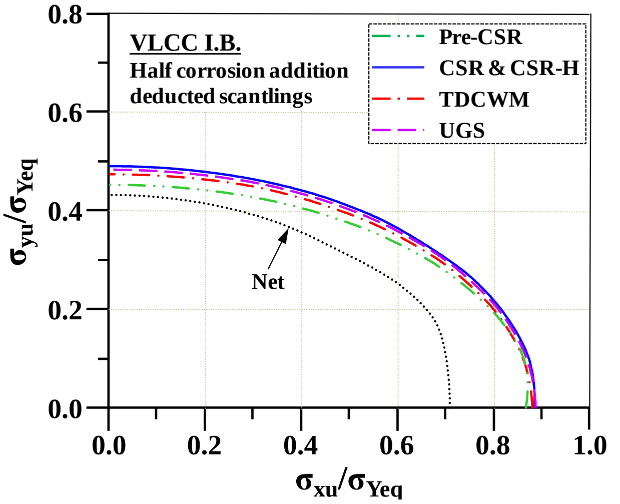
(a) Deck-gross scantlings.



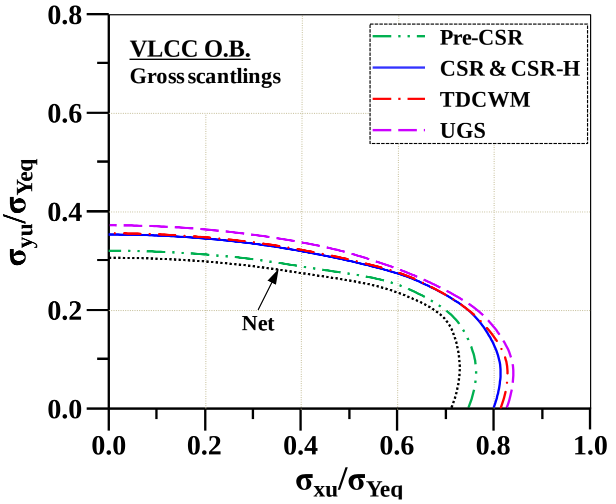
(b) Deck-half corrosion addition deducted scantlings.



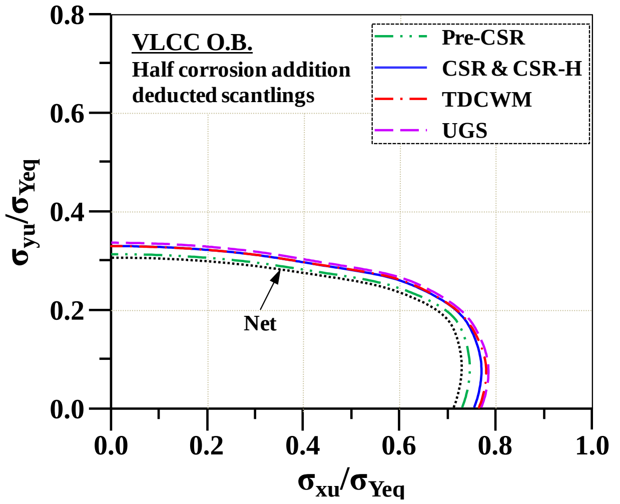
(c) I.B.-gross scantlings.



(d) I.B.-half corrosion addition deducted scantlings.



(e) O.B.-gross scantlings.



(f) O.B.-half corrosion addition deducted scantlings.

Fig. A.8 Ultimate stiffened panel strength analysis results of VLCC tanker.

Table A.1 Abbreviation of midship member presented in Fig. 5 (Paik et al. 2003a).

B/S-H	Bottom shell plating (segregated ballast tank)	SSLB(W)	Side shell longitudinals in ballast tank, web
A/B-H	Deck plating (segregated ballast tank)	SSLB(F)	Side shell longitudinals in ballast tank, flange
A/B-V	Side shell plating above draft line (segregated ballast tank)	LBLB(W)	Longitudinal bulkhead longitudinals in ballast tank, web
B/S-V	Side shell plating below draft line (segregated ballast tank)	LBLB(F)	Longitudinal bulkhead longitudinals in ballast tank, flange
BLGB	Bilge plating (segregated ballast tank)	BSLC(W)	Bottom shell longitudinals in cargo oil tank, web
O/B-V	Longitudinal bulkhead plating (segregated ballast tank)	BSLC(F)	Bottom shell longitudinals in cargo oil tank, flange
B/B-H	Stringer plating (segregated ballast tank)	DLC(W)	Deck longitudinals in cargo oil tank, web
O/S-H	Bottom shell plating (cargo oil tank)	DLC(F)	Deck longitudinals in cargo oil tank, flange
A/O-H	Deck plating (cargo oil tank)	SSLC(W)	Side shell longitudinals in cargo oil tank, web
A/O-V	Side shell plating above draft line (cargo oil tank)	SSLC(F)	Side shell longitudinals in cargo oil tank, flange
O/S-V	Side shell plating below draft line (cargo oil tank)	LBLC(W)	Longitudinal bulkhead longitudinals in cargo oil tank, web
BLGC	Bilge plating (cargo oil tank)	LBLC(F)	Longitudinal bulkhead longitudinals in cargo oil tank, flange
O/O-V	Longitudinal bulkhead plating (cargo oil tank)	BGLC(W)	Bottom girder longitudinals in cargo oil tank, web
O/O-H	Stringer plating (cargo oil tank)	BGLC(F)	Bottom girder longitudinals in cargo oil tank, flange
BSLB(W)	Bottom shell longitudinals in ballast tank, web	DGLC(W)	Deck girder longitudinals in cargo oil tank, web
BSLB(F)	Bottom shell longitudinals in ballast tank, flange	DGLC(F)	Deck girder longitudinals in cargo oil tank, flange
DLB(W)	Deck longitudinals in ballast tank, web	SSTLC(W)	Side stringer longitudinals in cargo oil tank, web

Table A.2(a). Statistical analysis results of hull girder with gross scantlings.

Mu (Gross)			Pre-CSR /Net	CSR /Net	TDCWM /Net	UGS /Net	CSR /Pre-CSR	TDCWM /Pre-CSR	UGS /Pre-CSR	TDCWM /CSR	UGS /CSR	TDCWM /UGS
D/H oil tankers	Hogging	Mean	1.1236	1.3358	1.3400	1.3890	1.1883	1.1920	1.2355	1.0457	1.0838	0.9648
		C.O.V.	0.0229	0.0490	0.0501	0.0530	0.0262	0.0277	0.0304	0.0781	0.0784	0.0034
	Sagging	Mean	1.1437	1.3741	1.3432	1.4429	1.2011	1.1741	1.2612	0.9775	1.0501	0.9309
		C.O.V.	0.0178	0.0428	0.0455	0.0448	0.0277	0.0307	0.0281	0.0046	0.0070	0.0085

Table A.2(b). Statistical analysis results of hull girder with half corroded scantlings.

Mu (Half)			Pre-CSR /Net	CSR /Net	TDCWM /Net	UGS /Net	CSR /Pre-CSR	TDCWM /Pre-CSR	UGS /Pre-CSR	TDCWM /CSR	UGS /CSR	TDCWM /UGS
D/H oil tankers	Hogging	Mean	1.0619	1.1655	1.1649	1.1942	1.0974	1.0968	1.1244	0.9994	1.0245	0.9755
		C.O.V.	0.0105	0.0296	0.0297	0.0323	0.0191	0.0192	0.0218	0.0026	0.0029	0.0031
	Sagging	Mean	1.0697	1.1884	1.1721	1.2186	1.1108	1.0956	1.1390	1.0335	1.0254	0.9619
		C.O.V.	0.0090	0.0264	0.0264	0.0287	0.0175	0.0179	0.0199	0.0876	0.0030	0.0038

Table A.3(a) Statistical analysis results of stiffened panel with gross scantlings.

σ_c (Gross)			Pre-CSR /Net	CSR /Net	TDCWM /Net	UGS /Net	CSR /Pre-CSR	TDCWM /Pre-CSR	UGS /Pre-CSR	TDCWM /CSR	UGS /CSR	TDCWM /UGS
VLCC	Deck	Mean	1.0470	1.1805	1.1301	1.2055	1.1274	1.0793	1.1513	0.9575	1.0211	0.9378
		C.O.V.	0.0095	0.0301	0.0225	0.0345	0.0275	0.0220	0.0317	0.0092	0.0046	0.0137
	I.B.	Mean	1.1466	1.2618	1.2047	1.2387	1.1030	1.0523	1.0824	0.9549	0.9818	0.9725
		C.O.V.	0.0474	0.0150	0.0141	0.0112	0.0552	0.0370	0.0462	0.0186	0.0092	0.0094
	O.B.	Mean	1.0449	1.1331	1.1370	1.1782	1.0843	1.0880	1.1274	1.0035	1.0395	0.9655
		C.O.V.	0.0070	0.0252	0.0243	0.0374	0.0196	0.0181	0.0320	0.0071	0.0126	0.0159
Suezmax	Deck	Mean	1.0687	1.2113	1.1499	1.2448	1.1340	1.0768	1.1655	0.9496	1.0274	0.9244
		C.O.V.	0.0315	0.0344	0.0253	0.0423	0.0356	0.0372	0.0468	0.0135	0.0116	0.0187
	I.B.	Mean	1.0651	1.2140	1.1590	1.1898	1.1391	1.0877	1.1165	0.9555	0.9805	0.9744
		C.O.V.	0.0194	0.0556	0.0403	0.0473	0.0372	0.0213	0.0284	0.0174	0.0101	0.0075
	O.B.	Mean	1.0488	1.1418	1.1428	1.2004	1.0886	1.0895	1.1444	1.0009	1.0507	0.9530
		C.O.V.	0.0075	0.0290	0.0262	0.0491	0.0244	0.0203	0.0446	0.0075	0.0204	0.0258
Aframax	Deck	Mean	1.0688	1.2257	1.1629	1.2546	1.1473	1.0886	1.1743	0.9490	1.0234	0.9274
		C.O.V.	0.0233	0.0326	0.0238	0.0378	0.0363	0.0329	0.0420	0.0112	0.0065	0.0161
	I.B.	Mean	1.0767	1.2395	1.1852	1.2135	1.1511	1.1008	1.1269	0.9570	0.9794	0.9770
		C.O.V.	0.0051	0.0382	0.0218	0.0280	0.0338	0.0199	0.0239	0.0288	0.0121	0.0169
	O.B.	Mean	1.0571	1.1565	1.1597	1.2092	1.0940	1.0969	1.1438	1.0027	1.0452	0.9595
		C.O.V.	0.0137	0.0307	0.0328	0.0408	0.0273	0.0253	0.0391	0.0113	0.0122	0.0206
Panamax	Deck	Mean	1.0367	1.1660	1.1138	1.1934	1.1248	1.0745	1.1512	0.9553	1.0235	0.9334
		C.O.V.	0.0067	0.0168	0.0165	0.0187	0.0193	0.0208	0.0204	0.0068	0.0030	0.0096
	I.B.	Mean	1.0747	1.2341	1.1850	1.2088	1.1479	1.1025	1.1245	0.9610	0.9799	0.9806
		C.O.V.	0.0109	0.0458	0.0295	0.0371	0.0357	0.0199	0.0268	0.0218	0.0095	0.0131
	O.B.	Mean	1.0494	1.1529	1.1547	1.2070	1.0985	1.1002	1.1500	1.0015	1.0466	0.9571
		C.O.V.	0.0071	0.0267	0.0254	0.0391	0.0201	0.0186	0.0328	0.0047	0.0131	0.0152

Table A.3(b). Statistical analysis results of stiffened panel with half corroded scantlings.

σ_c (Half)			Pre-CSR /Net	CSR /Net	TDCWM /Net	UGS /Net	CSR /Pre-CSR	TDCWM /Pre-CSR	UGS /Pre-CSR	TDCWM /CSR	UGS /CSR	TDCWM /UGS
VLCC	Deck	Mean	1.0242	1.0889	1.0644	1.1010	1.0633	1.0393	1.0750	0.9775	1.0110	0.9668
		C.O.V.	0.0060	0.0123	0.0093	0.0145	0.0113	0.0103	0.0130	0.0045	0.0024	0.0069
	I.B.	Mean	1.1166	1.1806	1.1481	1.1658	1.0587	1.0291	1.0452	0.9723	0.9874	0.9846
		C.O.V.	0.0594	0.0357	0.0437	0.0392	0.0263	0.0168	0.0211	0.0141	0.0119	0.0046
	O.B.	Mean	1.0229	1.0662	1.0686	1.0887	1.0423	1.0447	1.0643	1.0023	1.0211	0.9816
		C.O.V.	0.0020	0.0098	0.0091	0.0141	0.0082	0.0074	0.0126	0.0038	0.0044	0.0067
Suezmax	Deck	Mean	1.0351	1.1111	1.0746	1.1268	1.0735	1.0385	1.0885	0.9674	1.0140	0.9541
		C.O.V.	0.0187	0.0202	0.0115	0.0249	0.0103	0.0192	0.0120	0.0147	0.0048	0.0191
	I.B.	Mean	1.0334	1.1037	1.0761	1.0917	1.0678	1.0412	1.0563	0.9752	0.9892	0.9858
		C.O.V.	0.0077	0.0254	0.0188	0.0216	0.0180	0.0112	0.0141	0.0074	0.0050	0.0029
	O.B.	Mean	1.0245	1.0711	1.0726	1.0947	1.0454	1.0469	1.0685	1.0015	1.0220	0.9799
		C.O.V.	0.0039	0.0125	0.0112	0.0175	0.0105	0.0078	0.0155	0.0061	0.0051	0.0099
Aframax	Deck	Mean	1.0359	1.1153	1.0808	1.1316	1.0767	1.0434	1.0924	0.9691	1.0146	0.9552
		C.O.V.	0.0149	0.0171	0.0114	0.0198	0.0132	0.0165	0.0141	0.0091	0.0030	0.0120
	I.B.	Mean	1.0384	1.1151	1.0913	1.1036	1.0739	1.0510	1.0628	0.9788	0.9898	0.9889
		C.O.V.	0.0018	0.0131	0.0085	0.0079	0.0123	0.0082	0.0069	0.0167	0.0068	0.0099
	O.B.	Mean	1.0302	1.0793	1.0822	1.1040	1.0477	1.0505	1.0717	1.0027	1.0228	0.9804
		C.O.V.	0.0073	0.0149	0.0194	0.0218	0.0133	0.0149	0.0208	0.0089	0.0078	0.0117
Panamax	Deck	Mean	1.0181	1.0727	1.0508	1.0840	1.0536	1.0322	1.0647	0.9796	1.0105	0.9694
		C.O.V.	0.0045	0.0066	0.0083	0.0069	0.0092	0.0120	0.0087	0.0041	0.0016	0.0057
	I.B.	Mean	1.0360	1.1126	1.0901	1.1011	1.0738	1.0521	1.0627	0.9799	0.9897	0.9901
		C.O.V.	0.0057	0.0188	0.0129	0.0147	0.0134	0.0096	0.0094	0.0116	0.0049	0.0074
	O.B.	Mean	1.0230	1.0738	1.0741	1.1011	1.0497	1.0500	1.0764	1.0003	1.0254	0.9755
		C.O.V.	0.0059	0.0120	0.0117	0.0146	0.0076	0.0076	0.0099	0.0009	0.0034	0.0040