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Effect of corrosion on the ultimate strength of double hull oil tankers – Part I: stiffened panels

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Abstract. Age-related problems especially corrosion and fatigue are normally suffered by weatherworn ships and aging offshore structures. The effect of corrosion is one of the important factors in the Common Structural Rule (CSR) guideline of the ship design based on a 20 or 25 years design life. The aim of this research is the clarification of the corrosion effect on ultimate strength of stiffened panels on various types of double hull oil tankers. In the case of ships, corrosion is a phenomenon caused by the ambient environment and it has different characteristics depending on the parts involved. Extensive research considering these characteristic have already done by previous researchers. Based on this data, the ultimate strength behavior of stiffened panels for four double hull oil tankers such as VLCC, Suezmax, Aframax, and Panamax classes are compared and analyzed. By considering hogging and sagging bending moments, the stiffened panels of the deck, inner bottom and outer bottom located far away from neutral axis of ship are assessed. The results of this paper will be useful in evaluating the ultimate strength of an oil tanker subjected to corrosion. These results will be an informative example to check the effect of ultimate strength of a stiffened panel according to corrosion addition from CSR for a given type of ship.

Keywords: corrosion; ultimate strength; stiffened panel; double hull oil tankers; common structural rule; time-dependent corrosion wastage model

1. Introduction

Since the establishment of CSR in April 2006, the importance of servicing double-hull oil tankers have increased, although the corrosion addition was much higher than the design even before the introduction of the CSR (IACS 2006a, b, Paik *et al.* 2009). Previous research has compared the performance of ships ultimate strength by investigating the corrosion addition increment.

Crude oil tankers are usually built with a design life of about 25 years. However, recently several accidents have been occurred and resulting the damage in terms of structural part. The lifespan of aging ships depends on the effect of corrosion on plate thickness and fatigue cracks. The effect of

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fatigue has been deeply investigated (Gudze and Melchers 2008, Guo *et al*. 2008, Fricke and Kahl 2005, Kang *et al*. 2010, Paik and Melchers 2008, Poutiainen and Marquis 2006), and fatigue life evaluation methods or fatigue limit standards (DNV 2010, Lotsberg 2006) for ships are well established. In terms of corrosion, a survey rule for hull corrosion criteria by classes have been formulated and repair guidelines for excessively corroded hull members have been suggested, however the research on the effect of corrosion on the ultimate strength of double-hull oil tankers is still limited (Khedmati *et al*. 2011). Since the establishment of the CSR (IACS 2006a, b), all double-hull oil tankers should be designed by considering the effect of corrosion progress. The strength capacity of such tankers is calculated and designed without considering corrosion, and corrosion compensation will be included in the designed plate thickness though corrosion addition.

In this paper, the variation of the ultimate strength behavior of stiffened panels is investigated for four types of double-hull oil tankers. It is based on the time dependent corrosion wastage model (TDCWM) (Paik *et al*. 2003a, b, 2004) which was obtained by statistical analysis from actual measured corrosion data of crude oil tankers. Double-hull oil tankers of the Very Large Crude oil Carrier (VLCC), Suezmax, Aframax and Panamax classes were considered. Stiffened panels of the deck, inner bottom and outer bottom which located far away from the neutral axis of a ship are the elements that are analyzed in this study. The behavior variation in terms of the compression load ratio in the longitudinal and transverse directions of the stiffened panels is investigated. The validity of the CSR corrosion addition is reviewed by analyzing the net scantling of the CSR.

2. Corrosion model

The corrosion of ships and offshore structures begins to propagate once the coating is not effective. According to the current Performance Standard for Protective Coatings (PSPC), the life time of a coating is about 10-15 years. In this analysis, a conservative 10 year coating life is assumed.

There are several types of corrosion, such as uniform, fitting, grooving, and weld metal corrosion (Paik and Thayamballi 2007). This paper focused on uniform corrosion. Corrosion models considering uniform corrosion include the CSR corrosion addition model (IACS 2006a) and the time-dependent corrosion wastage model (Paik *et al*. 2003a, b, 2004) is applied to this paper. An explanation of these two corrosion models is given as follows.

2.1 Time-dependent corrosion wastage model for double-hull oil tanker structures

Paik *et al*. (2003a, b, 2004) presented information on the annual corrosion rate based on actual corrosion data assuming a coating life of 5, 7.5, and 10 years, respectively. The coating process is necessary to prevent corrosion in ships and offshore plant structures. Considering the recent improvements in coating quality, the analysis in this paper was performed based on the annual corrosion data in Paik *et al*. (2003a), which assumes a 10-years coating life for oil tankers. The validity of the CSR corrosion addition is reviewed and examined by applying the corrosion addition to the stiffened panels of oil tankers.

The abbreviations for the member names are defined in Fig. 1 and it also shows the annual corrosion data (mm/year) for each member as well as mean and COV values (Paik *et al*. 2003a). It should be noted in the original paper, the surveyed information is based on a 5, 7.5, and 10 years coating life (Paik *et al*. 2003a), whereas 10-year coating life is assumed in this study.

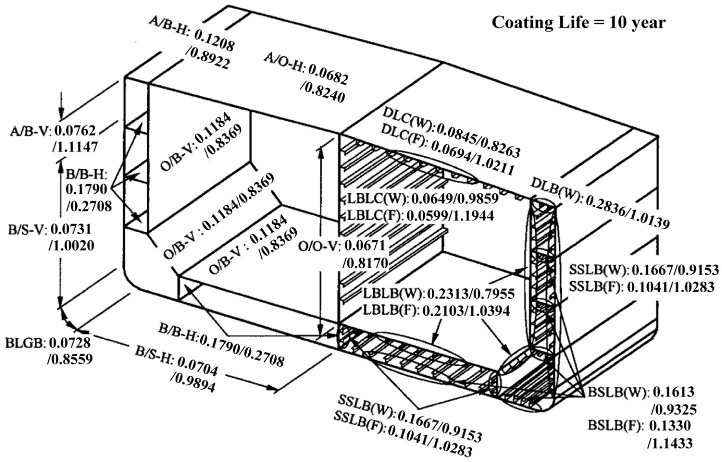


Fig. 1 Mean (mm/year) and COV of the average corrosion rate for the 34 member location/category groups of a double-hull structure considering all corrosion measurement data (Paik *et al*. 2003a)

2.2 Corrosion addition data specified by CSR

The value of the corrosion addition presented in the CSR is illustrated in Fig. 2. The corrosion addition is increased compared with pre-CSR designs (IACS 2006a, Paik *et al*. 2009). For example, for an oil tanker applying the CSR, the corrosion addition of 0.5mm is applied for the member abutting the cargo tank due to oil heating.

The initial state with no corrosion is known as gross (As-built) scantling while the state which corrosion has been generated across the design life of 25 years defines as the net scantling (fully corroded state). In this paper, the ultimate strength of the stiffened panel of an oil tanker is compared and the validity of the corrosion addition in the CSR is reviewed based on the ultimate strength of the stiffened panel and surveyed data on ships in a net scantling state.

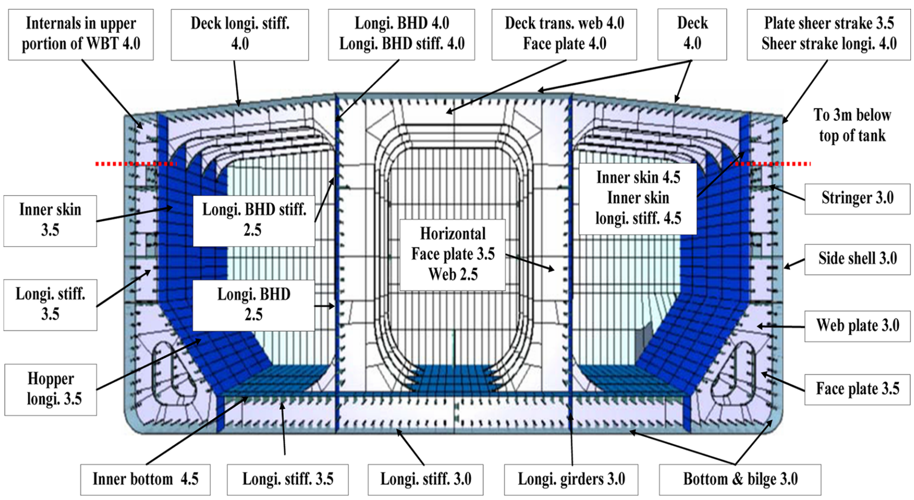
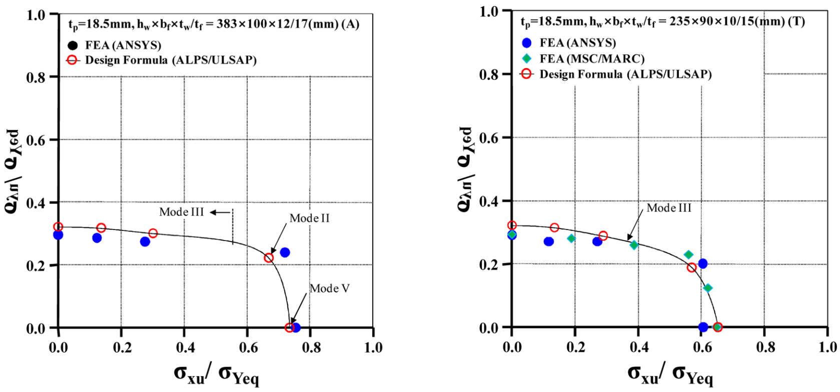


Fig. 2 Corrosion margin values of double-hull oil tanker structures specified by the CSR

3. Applied method – Design formula (ALPS/ULSAP)

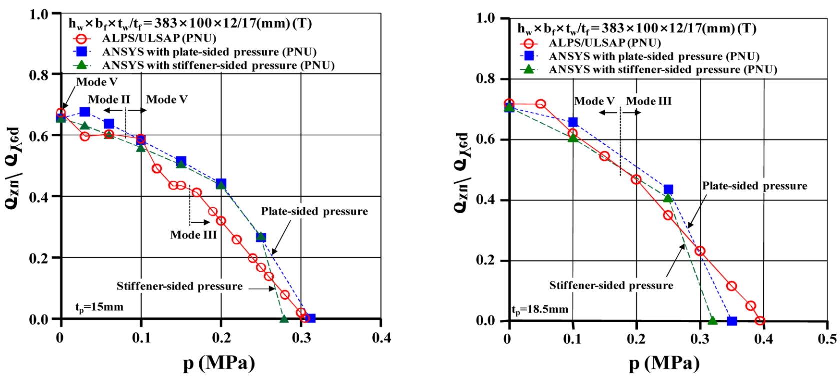
There are several methods to analyze the ultimate strength of stiffened panels, including theoretical, experimental, and numerical methods. Extensive experimental research to analyze the ultimate strength of stiffened panels have been carried out by various researchers (Fujikubo *et al*. 2005, Paik and Melchers 2008, Paik *et al*. 2008), as well as theoretical studies (ALPS/ULSAP 2011, DNV/PULS 2010).

A benchmark study of the ultimate strength of stiffened panels using a numerical method was recently performed (Paik *et al*. 2011). Figs. 3 and 4 presents the results of the previous research on the ultimate strength behavior of stiffened panels modeled as 2 bays - 2 spans (half-one-half model) compared with a numerical method. Based on the comparison results as shown in Fig. 3, results of ALPS/ULSAP shows good agreements with ANSYS nonlinear finite element method. Even if nonlinear FEM gives the better results than others, but considering the efficient computational cost and the reasonable result accuracy, ALPS/ULSAP was adopted as the main tool for analysis of



(a) Angle type (b) T-type

Fig. 3 Benchmark study results using FE analysis and design formula (ALPS/ULSAP) for the ultimate strength of a stiffened panel under biaxial compressive loads (Paik *et al*. 2011)



(a) Plate thickness = 15mm (b) Plate thickness = 18.5mm

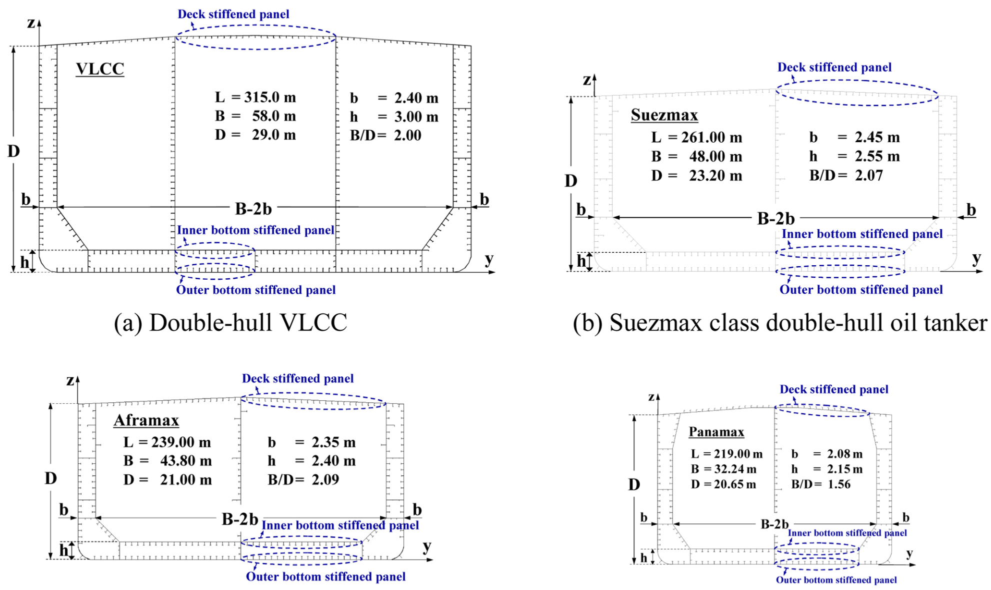
Fig. 4 Benchmark study results using FE analysis and design formula (ALPS/ULSAP) for the ultimate strength of a stiffened panel under axial compression with lateral pressure (Paik *et al*. 2011) stiffened panel of double hull oil tankers in the present study.

Calculation of six types of collapse mode were developed to predict the ultimate strength of the stiffened panel in the ALPS/ULSAP program. The smallest value of analysis result was then defined as the ultimate strength of the stiffened panel. The collapse mode changes according to changes resulted from different loading ratio are shown in Fig. 3. The collapse modes of a stiffened panel are as follows (Paik and Thayamballi 2003, Hughes and Paik 2010).

- **Mode I**: Overall collapse of the plating and stiffeners as a unit
- **Mode II**: Plate-induced collapse (biaxial compressive collapse)
- **Mode III**: Stiffener-induced collapse by beam-column type collapse
- **Mode IV**: Stiffener-induced collapse by web buckling (after the buckling collapse of the plating between the stiffeners)
- **Mode V**: Stiffener-induced collapse by tripping (flexural-torsional buckling of the stiffeners – after the buckling collapse of the stiffeners)
- **Mode VI**: Gross yielding

4. Target structures – stiffened panels of double-hull oil tankers

Double-hull oil tankers are classified by service condition or size of canal. In this paper, four types of double-hull oil tankers – VLCC, Suezmax class, Aframax class and Panamax class – are investigated.



(a) Double-hull VLCC (b) Suezmax class double-hull oil tanker

(c) Aframax class double-hull oil tanker (d) Panamax class double-hull oil tanker

Fig. 5 Structural configurations of the mid-ship sections of various classes of double-hull oil tanker (L = ship length, B = ship breadth, D = ship depth, b = distance between side shell, h = distance between double bottom)

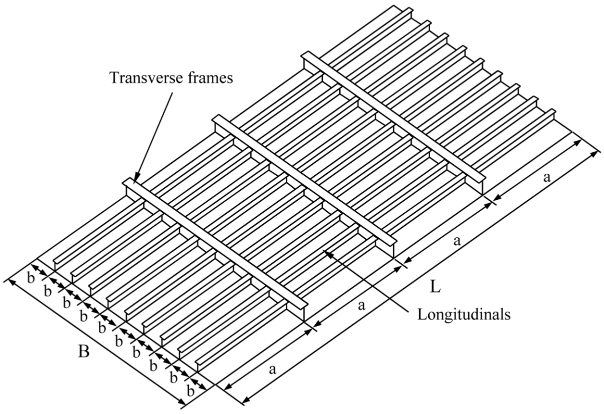


Fig. 6 Schematic of a stiffened panel

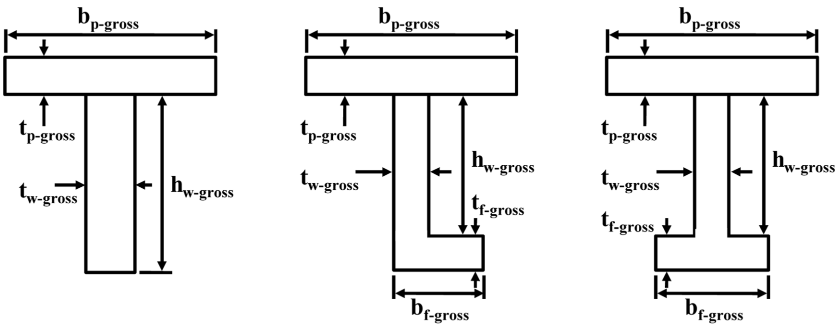


Fig. 7 Nomenclature of the stiffener dimensions, indicating that stiffener height (h_w) is defined by excluding flange thickness (t_f)

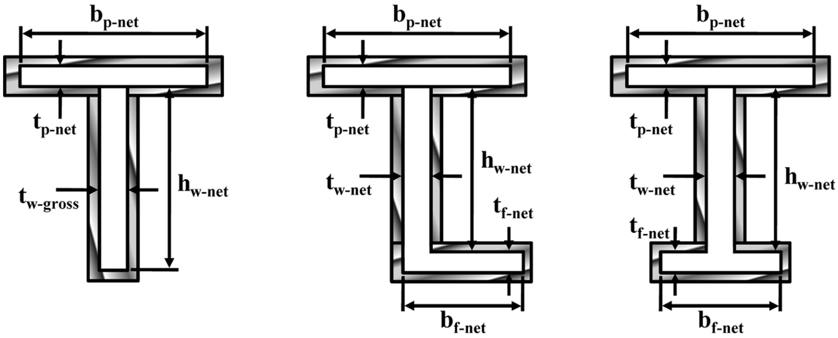


Fig. 8 Schematic of a corroded plate and three kinds of stiffener type – flat, angle, and T-type

Figs. 5(a) to (d) show the stiffened panel, principal dimensions, and mid-ship section data used in this paper. Three types of stiffened panels located at positions far away from the neutral axis at the deck, inner bottom, and outer bottom were selected for analysis.

Fig. 6 schematically illustrates a stiffened panel, which is one of the main structures of ships comprises longitudinal and vertical stiffened panels and plates. The analysis was carried out by one frame spacing, rather than a complete panel. Fig. 7 shows the nomenclature of the stiffener dimensions

Table 1(a) Geometric and material properties of the stiffened panels of a double-hull VLCC (nomenclature from Figs. 6 and 7)

VLCC		a (mm)	b (mm)	B (mm)	t_p (mm)	Stiff-ener type	No. of Stiffener	h_w (mm)	t_w (mm)	b_f (mm)	t_f (mm)	σ_Y (MPa)	
Location	Scantlings											Plate	Stiffener
Deck	0-10 years	4950	815	20750	20.000	Angle	24	283.000	13.000	90.000	17.000	315	315
	15 years				19.659			283.344	12.578	89.653	16.653		
	20 years				19.318			283.688	12.155	89.306	16.306		
	25 years				18.977			284.032	11.733	88.959	15.959		
	CSR - net				16.000			287.000	9.000	86.000	13.000		
Inner Bottom	0-10 years	4800	830	10790	18.500	Tee	12	550.000	12.000	150.000	25.000	315	315
	15 years				17.908			550.822	10.844	148.949	23.949		
	20 years				17.316			551.644	9.687	147.897	22.897		
	25 years				16.724			552.465	8.531	146.846	21.846		
	CSR - net				14.000			553.500	8.500	146.500	21.500		
Outer Bottom	0-10 years	4950	830	10790	21.420	Tee	12	550.000	12.000	150.000	25.000	315	315
	15 years				22.138			500.509	10.694	149.335	23.335		
	20 years				21.786			501.017	9.887	148.670	22.670		
	25 years				21.434			501.526	9.081	148.005	22.005		
	CSR - net				19.490			503.000	8.500	147.000	21.000		

Note: Elastic modulus (E) = 205,800 MPa, Poisson's ratio (ν) = 0.3.

Table 1(b) Geometric and material properties of the stiffened panels of a Suezmax class double-hull oil tanker (nomenclature from Figs. 6 and 7)

Suezmax		a (mm)	b (mm)	B (mm)	t_p (mm)	Stiffener type	No. of Stiffener	h_w (mm)	t_w (mm)	b_f (mm)	t_f (mm)	σ_Y (MPa)	
Location	Scantlings											Plate	Stiffener
Deck	0-10 years	4800	862	21550	23.000	Tee	24	400.000	12.000	150.000	15.000	315	315
	15 years				22.659			400.344	11.578	149.653	14.653		
	20 years				22.318			400.688	11.155	149.306	14.306		
	25 years				21.977			401.032	10.733	148.959	13.959		
	CSR - net				19.000			404.000	8.000	146.000	11.000		
Inner Bottom	0-10 years	4800	855	17100	19.340	Tee	19	500.000	11.500	150.000	24.000	315	355
	15 years				18.748			500.822	10.344	148.949	22.949		
	20 years				18.156			501.644	9.187	147.897	21.897		
	25 years				17.564			502.465	8.031	146.846	20.846		
	CSR - net				14.840			503.500	8.000	146.500	20.500		
Outer Bottom	0-10 years	4800	855	17100	22.490	Tee	19	500.000	11.500	150.000	24.000	315	355
	15 years				22.138			500.509	10.694	149.335	23.335		
	20 years				21.786			501.017	9.887	148.670	22.670		
	25 years				21.434			501.526	9.081	148.005	22.005		
	CSR - net				19.490			503.000	8.500	147.000	21.000		

Note: Elastic modulus (E) = 205,800 MPa, Poisson's ratio (ν) = 0.3.

Table 1(c) Geometric and material properties of the stiffened panels of an Aframax class double-hull oil tanker (nomenclature from Figs. 6 and 7)

Aframax		a	b	B	t_p	Stiffener	No. of	h_w	t_w	b_f	t_f	σ_Y (MPa)	
Location	Scantlings	(mm)	(mm)	(mm)	(mm)	type	Stiffener	(mm)	(mm)	(mm)	(mm)	Plate	Stiffener
Deck	0-10 years	4300	815	19550	20.360	Angle	23	384.000	11.500	100.000	16.000	315	315
	15 years				20.019			384.344	11.078	99.653	15.653		
	20 years				19.678			384.688	10.655	99.306	15.306		
	25 years				19.337			385.032	10.233	98.959	14.959		
	CSR - net				16.360			388.000	7.500	96.000	12.000		
Inner Bottom	0-10 years	4300	815	16300	17.000	Tee	19	420.000	11.000	150.000	15.000	315	355
	15 years				16.408			420.822	9.844	148.949	13.949		
	20 years				15.816			421.644	8.687	147.897	12.897		
	25 years				15.224			422.465	7.531	146.846	11.846		
	CSR - net				12.500			423.500	7.500	146.500	11.500		
Outer Bottom	0-10 years	4300	815	16300	19.990	Tee	19	440.000	11.000	150.000	15.000	315	355
	15 years				19.638			440.509	10.194	149.335	14.335		
	20 years				19.286			441.017	9.387	148.670	13.670		
	25 years				18.934			441.526	8.581	148.005	13.005		
	CSR - net				16.990			443.000	8.000	147.000	12.000		

Note: Elastic modulus (E) = 205,800 MPa, Poisson's ratio (v) = 0.3.

Table 1(d) Geometric and material properties of the stiffened panels of a Panamax class double-hull oil tanker (nomenclature from Figs. 6 and 7)

Panamax		a	b	B	t_p	Stiffener	No. of	h_w	t_w	b_f	t_f	σ_Y (MPa)	
Location	Scantlings	(mm)	(mm)	(mm)	(mm)	type	Stiffener	(mm)	(mm)	(mm)	(mm)	Plate	Stiffener
Deck	0-10 years	3900	830	13280	12.000	Angle	15	284.000	11.000	90.000	16.000	315	315
	15 years				11.659			284.344	10.578	89.653	15.653		
	20 years				11.318			284.688	10.155	89.306	15.306		
	25 years				10.977			285.032	9.733	88.959	14.959		
	CSR - net				8.000			288.000	7.000	86.000	12.000		
Inner Bottom	0-10 years	3900	830	11620	17.870	Tee	13	400.000	11.000	150.000	20.000	315	315
	15 years				17.278			400.822	9.844	148.949	18.949		
	20 years				16.686			401.644	8.687	147.897	17.897		
	25 years				16.094			402.465	7.531	146.846	16.846		
	CSR - net				13.370			403.500	7.500	146.500	16.500		
Outer Bottom	0-10 years	3900	830	11620	16.500	Tee	13	400.000	11.000	150.000	20.000	315	315
	15 years				16.148			400.509	10.194	149.335	19.335		
	20 years				15.796			401.017	9.387	148.670	18.670		
	25 years				15.444			401.526	8.581	148.005	18.005		
	CSR - net				13.500			403.000	8.000	147.000	17.000		

Note: Elastic modulus (E) = 205,800 MPa, Poisson's ratio (v) = 0.3.

of the stiffened panel and Fig. 8 shows the corrosion addition examined in this paper (IACS 2006a, b).

As the corrosion is progressing, the cross-sectional properties of the plate or stiffener will be changed, as shown in Fig. 8. Tables 1(a) to (d) present information on the sectional properties of a stiffener by part of each type of ship.

The nomenclatures are as follows,

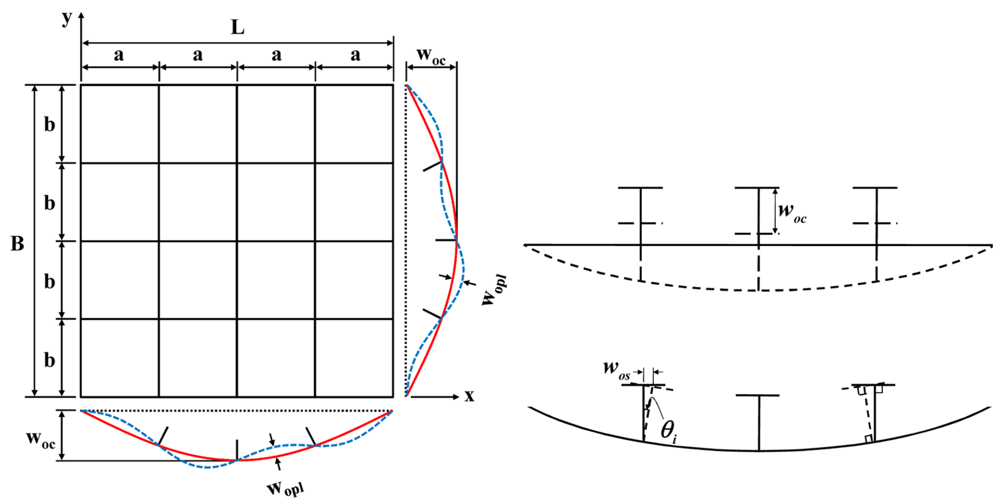
a = frame spacing or plate length, B = total breadth of the panel, t_p = plate thickness, h_w = height of web, t_w = thickness of web, b_f = breadth of flange, t_f = thickness of flange and σ_Y = yield strength of target structures.

5. Initial imperfections and loading conditions

5.1 Initial imperfections

Ships and offshore structures have defects from manufacturing processes such as cutting or welding. There are various types of defects, especially initial deflections and welding residual stresses. In this paper, the average level of residual strength is considered. Initial deflection occurs in two elements; the plate and stiffeners as shown in Fig. 9. There are several ways to determine the initial deflection and there is also exists various initial deflection shapes as shown in Fig. 10. In this study buckling mode shape initial deflection has been adopted. In the case of initial deflection amount, CSR ($w_{opl} = b/200$, $w_{oc} = w_{os} = a/1000$) is usually applied. However, this paper has been adopts following equations considering the thickness reduction due to corrosion as follows (ISO 2007).

$$w_{opl} = 0.1\beta^2 t_p, \quad w_{oc} = w_{os} = 0.0015a \tag{1}$$



(a) Plate initial deflection (b) Stiffener initial distortion

Fig. 9 Initial deflection shape of stiffened panel

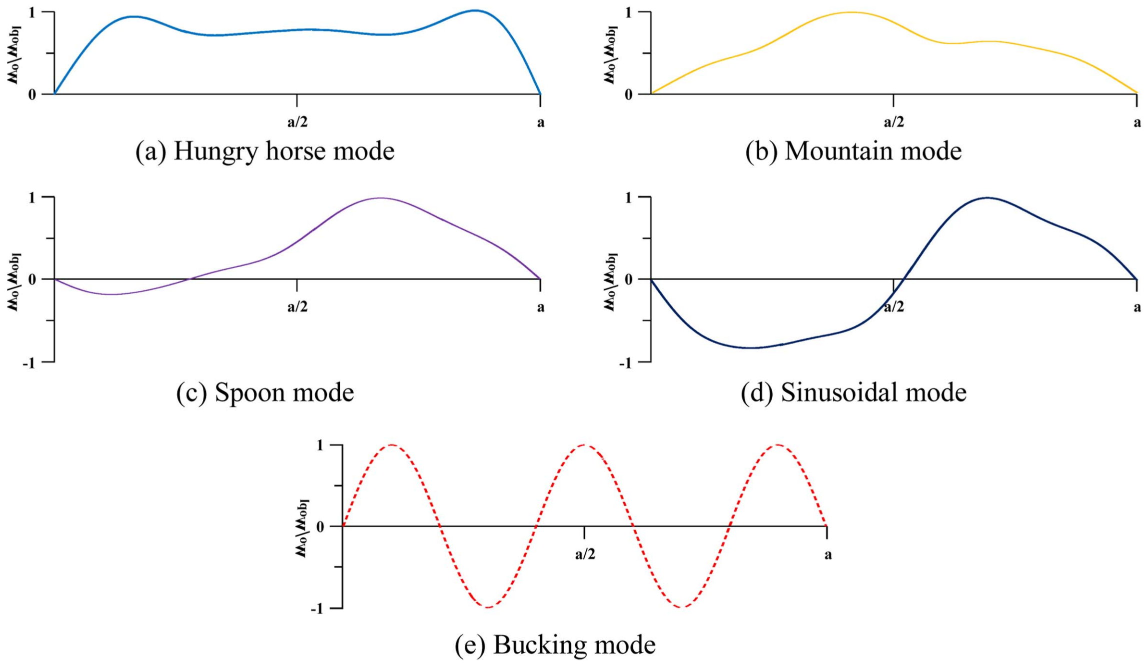


Fig. 10 Several types of initial deflection shape (Paik and Thayamballi 2003)

where,

w_{opl} = the maximum plate initial deflection,

w_{oc} = the column-type initial distortions of the longitudinal stiffeners,

w_{os} = the sideways initial distortion of the longitudinal stiffeners,

β = Plate slenderness ratio $(=(b/t_p)\sqrt{\sigma_Y/E})$.

5.2 Loading conditions

Stiffened plate structures may suffer lateral pressure, in-plane compressive loads, and shear forces. The effects of in-plane compression and lateral pressure are considered in this paper as shown in Fig. 11. In the case of lateral pressure, the data was calculated as in Table 2 based on the static condition. The value of lateral pressure for the stiffened panel from the deck is assumed to be zero, due to the effect of lateral pressure from ship motion effect is too small.

Table 2 Lateral pressure data for the stiffened panels of the four types of double-hull oil tanker

Lateral pressure (MPa)	VLCC	Suezmax	Aframax	Panamax
Deck	-	-	-	-
Inner bottom	0.226	0.190	0.170	0.172
Outer bottom	0.203	0.167	0.147	0.140

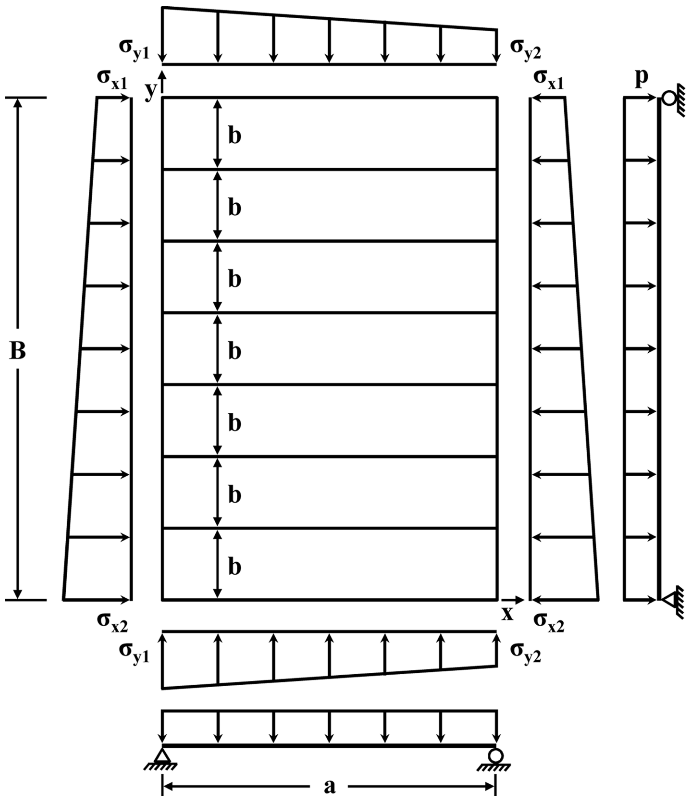


Fig. 11 Applied loads in stiffened panels in this study (Hughes and Paik 2010)

6. Analysis results

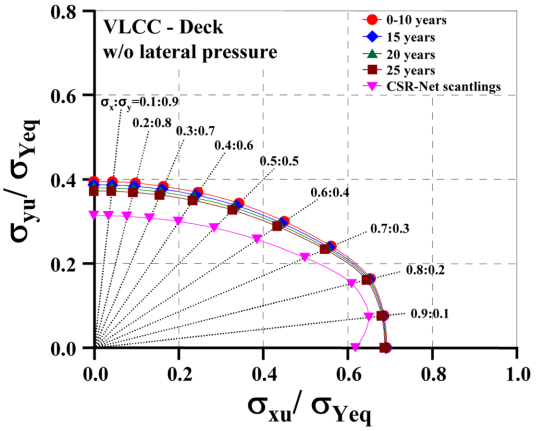
Figs. 12 to 15 show the results of the ultimate strength performance of stiffened panels for the four types of double-hull oil tankers. The CSR model (net scantlings) shows a rapid strength decrease after 25 years compared with the TDCWM. The details of this finding are discussed in the next section.

6.1 Double-hull VLCC

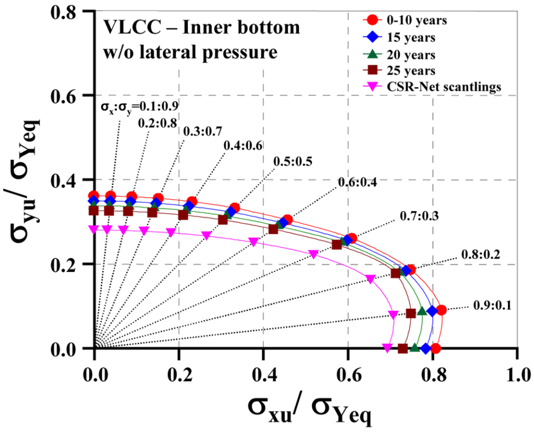
The following figures show the analysis results for the stiffened panel of a double-hull VLCC that take into account the effect of corrosion coupled with in-plane compression and lateral pressure.

6.2 Suezmax class double-hull oil tanker

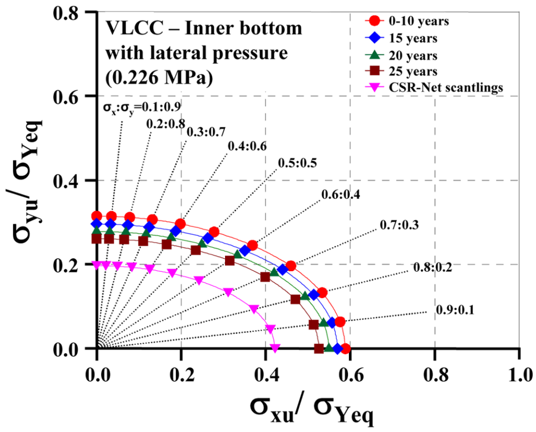
Next, results of the analysis of the stiffened panels for Suezmax class double-hull oil tanker are shown in Fig. 13. It takes into consideration the effect of corrosion coupled with in-plane compression and lateral pressure are shown as follows.



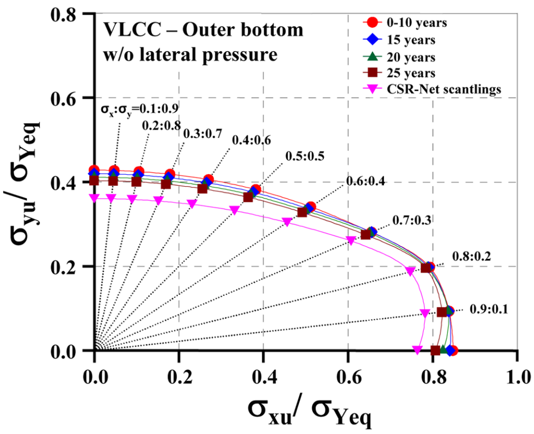
(a) Deck stiffened panel without lateral pressure



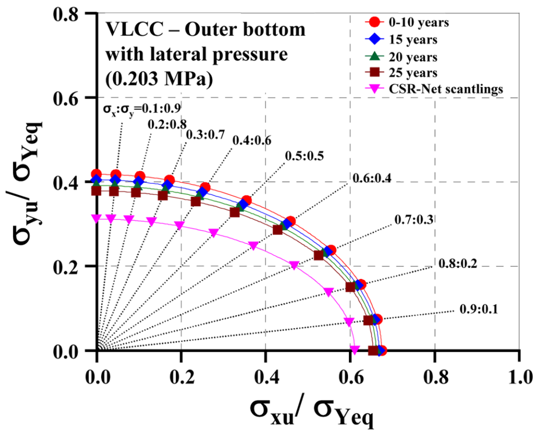
(b) IB stiffened panel without lateral pressure



(c) IB stiffened panel with lateral pressure

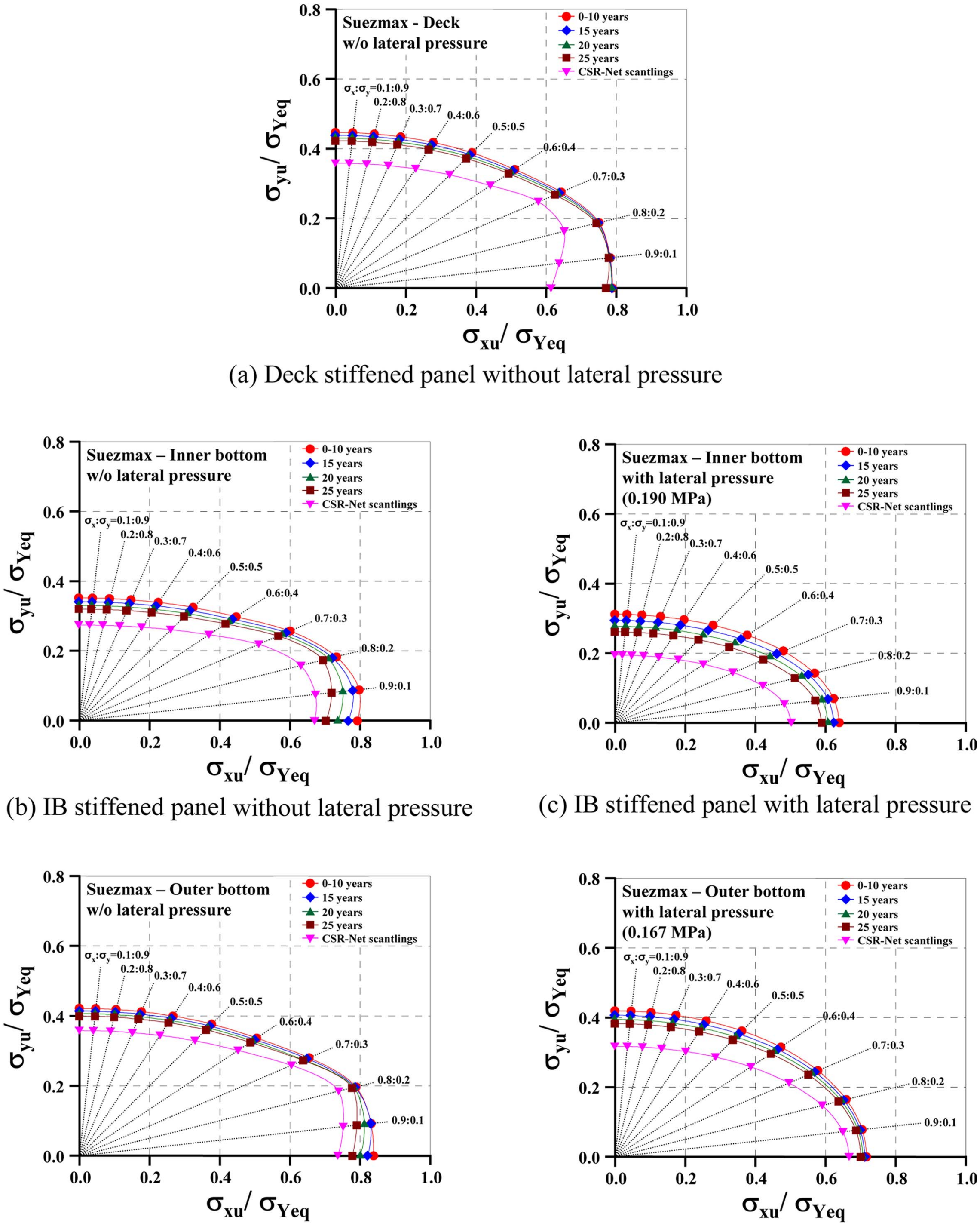


(d) OB stiffened panel without lateral pressure



(e) OB stiffened panel with lateral pressure

Fig. 12 Ultimate strength relationships of the stiffened panels of a double-hull VLCC for each scantling under biaxial compression with lateral pressure



(a) Deck stiffened panel without lateral pressure

(b) IB stiffened panel without lateral pressure

(c) IB stiffened panel with lateral pressure

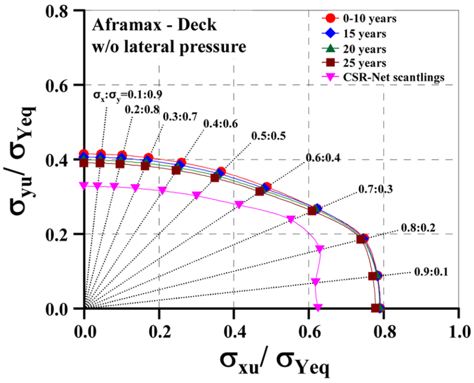
(d) OB stiffened panel without lateral pressure

(e) OB stiffened panel with lateral pressure

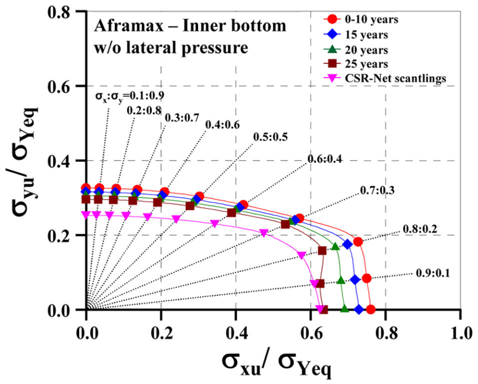
Fig. 13 Ultimate strength relationships of the stiffened panels of a Suezmax class double-hull oil tanker for each scantling under biaxial compression with lateral pressure

6.3 Aframax class double-hull oil tanker

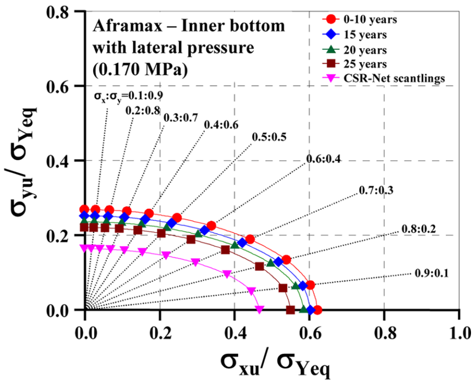
Similarly, the results for the stiffened panels of Aframax class double-hull oil tanker is shown as follows.



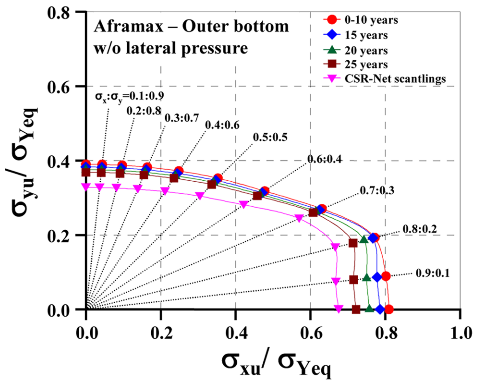
(a) Deck stiffened panel without lateral pressure



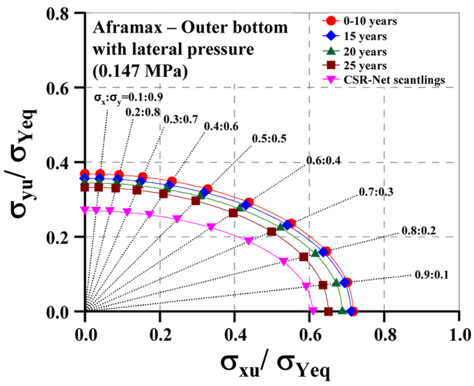
(b) IB stiffened panel without lateral pressure



(c) IB stiffened panel with lateral pressure



(d) OB stiffened panel without lateral pressure

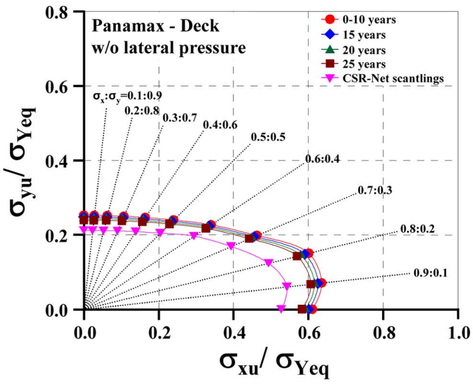


(e) OB stiffened panel with lateral pressure

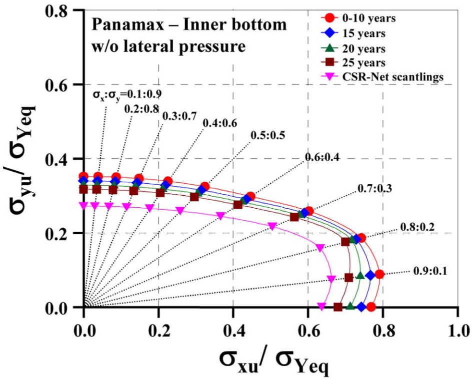
Fig. 14 Ultimate strength relationships of the stiffened panels of an Aframax class double-hull oil tanker for each scantling under biaxial compression with lateral pressure

6.4 Panamax class double-hull oil tanker

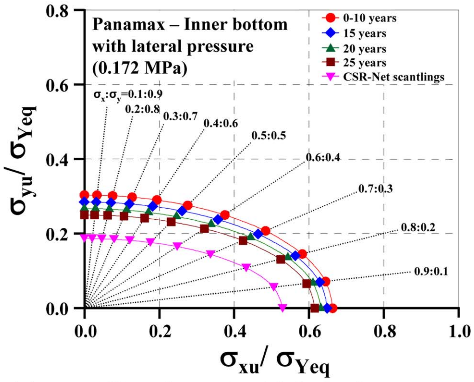
Finally, the results for the stiffened panels of Panamax class double-hull oil tanker is shown as follows.



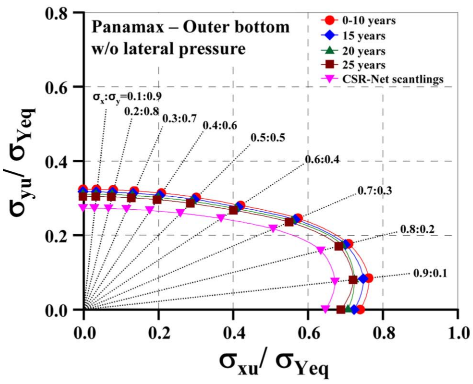
(a) Deck stiffened panel without lateral pressure



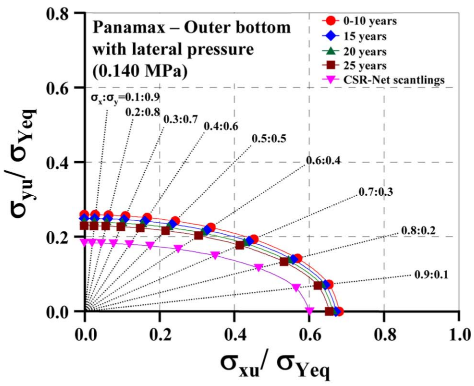
(b) IB stiffened panel without lateral pressure



(c) IB stiffened panel with lateral pressure



(d) OB stiffened panel without lateral pressure



(e) OB stiffened panel with lateral pressure

Fig. 15 Ultimate strength relationships of the stiffened panels of Panamax class double-hull oil tanker for each scantling under biaxial compression with lateral pressure

Table 4(a) Comparison of the results of the collapse mode of stiffened panels without lateral pressure

Collapse Mode	σ_x / σ_y	Deck (years)					Inner bottom (years)					Outer bottom (years)				
		0-10	15	20	25	Net	0-10	15	20	25	Net	0-10	15	20	25	Net
VLCC	1.0 / 0.0	III	III	III	III	V	V	V	V	V	V	III	V	V	V	V
Suezmax		III	III	III	V	V	V	V	V	V	V	V	V	V	V	V
Aframax		III	III	III	V	V	V	V	V	V	V	V	V	V	V	V
Panamax		V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
VLCC	0.9 / 0.1	III	III	III	III	V	V	V	V	V	V	III	III	III	V	V
Suezmax		III	III	III	III	V	II	V	V	V	II	III	III	V	V	V
Aframax		III	III	III	V	V	V	V	V	V	V	V	V	V	V	V
Panamax		V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
VLCC	0.8 / 0.2	III	III	III	III	III	II	II	II	II	II	I	III	III	III	II
Suezmax		III	III	III	III	V	II	II	II	II	II	III	III	II	V	V
Aframax		III	III	III	III	V	V	V	V	V	V	V	V	V	V	V
Panamax		V	V	V	V	V	II	II	II	II	II	II	II	II	II	II
VLCC	0.7 / 0.3	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.6 / 0.4	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.5 / 0.5	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.4 / 0.6	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.3 / 0.7	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.2 / 0.8	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.1 / 0.9	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Suezmax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Aframax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
Panamax		III	III	III	III	III	III	III	III	III	III	III	III	III	III	III
VLCC	0.0 / 1.0	III	V	III	III	III	III	III	III	III	V	IV	III	III	IV	III
Suezmax		III	III	IV	III	III	III	V	III	V	III	III	III	III	III	V
Aframax		IV	III	IV	III	IV	IV	III	III	III	III	III	V	III	IV	IV
Panamax		V	III	III	III	III	III	IV	III	IV	III	III	IV	III	III	IV

Table 4(b) Comparison of the results of the collapse mode of stiffened panels with lateral pressure

Collapse mode	σ_x / σ_y	Deck (years)					Inner bottom (years)					Outer bottom (years)				
		0-10	15	20	25	Net	0-10	15	20	25	Net	0-10	15	20	25	Net
VLCC	1.0 / 0.0	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.9 / 0.1	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.8 / 0.2	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.7 / 0.3	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.6 / 0.4	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.5 / 0.5	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.4 / 0.6	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.3 / 0.7	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.2 / 0.8	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.1 / 0.9	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Suezmax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
Aframax		-	-	-	-	-	III	III	III	V	III	III	III	V	V	V
Panamax		-	-	-	-	-	III	III	III	III	III	III	III	III	III	III
VLCC	0.0 / 1.0	-	-	-	-	-	II	II	II	II	II	II	III	IV	II	V
Suezmax		-	-	-	-	-	II	V	II	II	III	III	II	II	II	III
Aframax		-	-	-	-	-	III	IV	III	II	IV	V	II	III	II	V
Panamax		-	-	-	-	-	III	II	II	II	III	IV	II	II	III	II

7. Discussion

Table 4 show the collapse mode results for the stiffened panels of the four double-hull oil tankers. The collapse mode is depends on the load ratio. In the following sections, the ultimate capacity of the stiffened panels is compared and evaluated. σ_c denotes the capacity of the applicable stiffened panel, and the formula is as follows.

$$\sigma_C = \sqrt{\sigma_{xu}^2 + \sigma_{yu}^2} \tag{2}$$

The time-dependent corrosion wastage and CSR models give different results in terms of the load ratio in the longitudinal and transverse directions after 25 years. The corrosion addition suggested in the CSR has a safety margin of about 3.6-17.5% compared with the design according to surveyed corrosion data based on yield strength. The CSR design applies a sufficiently large safety factor, but it is uneconomical with regard to the excessive corrosion addition, it may result in a reduction of

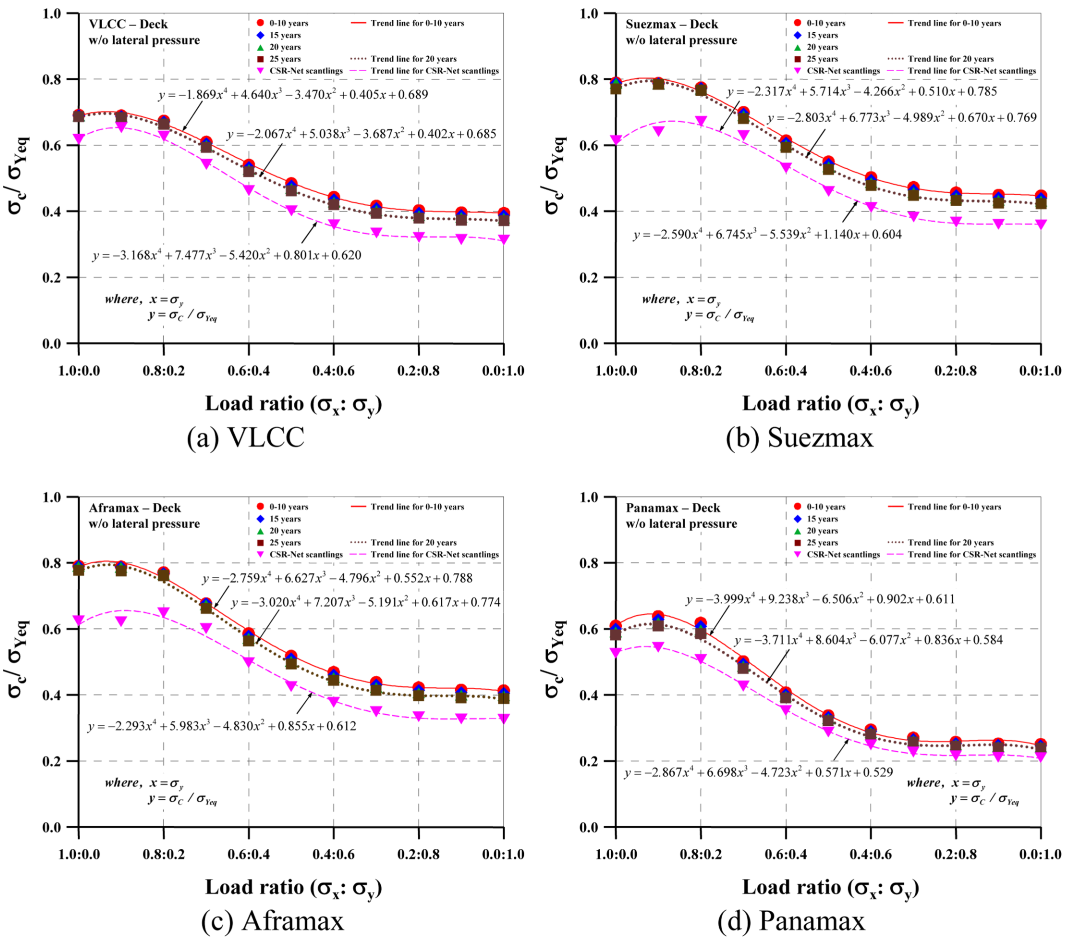


Fig. 16 Ultimate strength relationships of the stiffened panels of the deck of double-hull oil tankers for each scantling under biaxial compression without lateral pressure

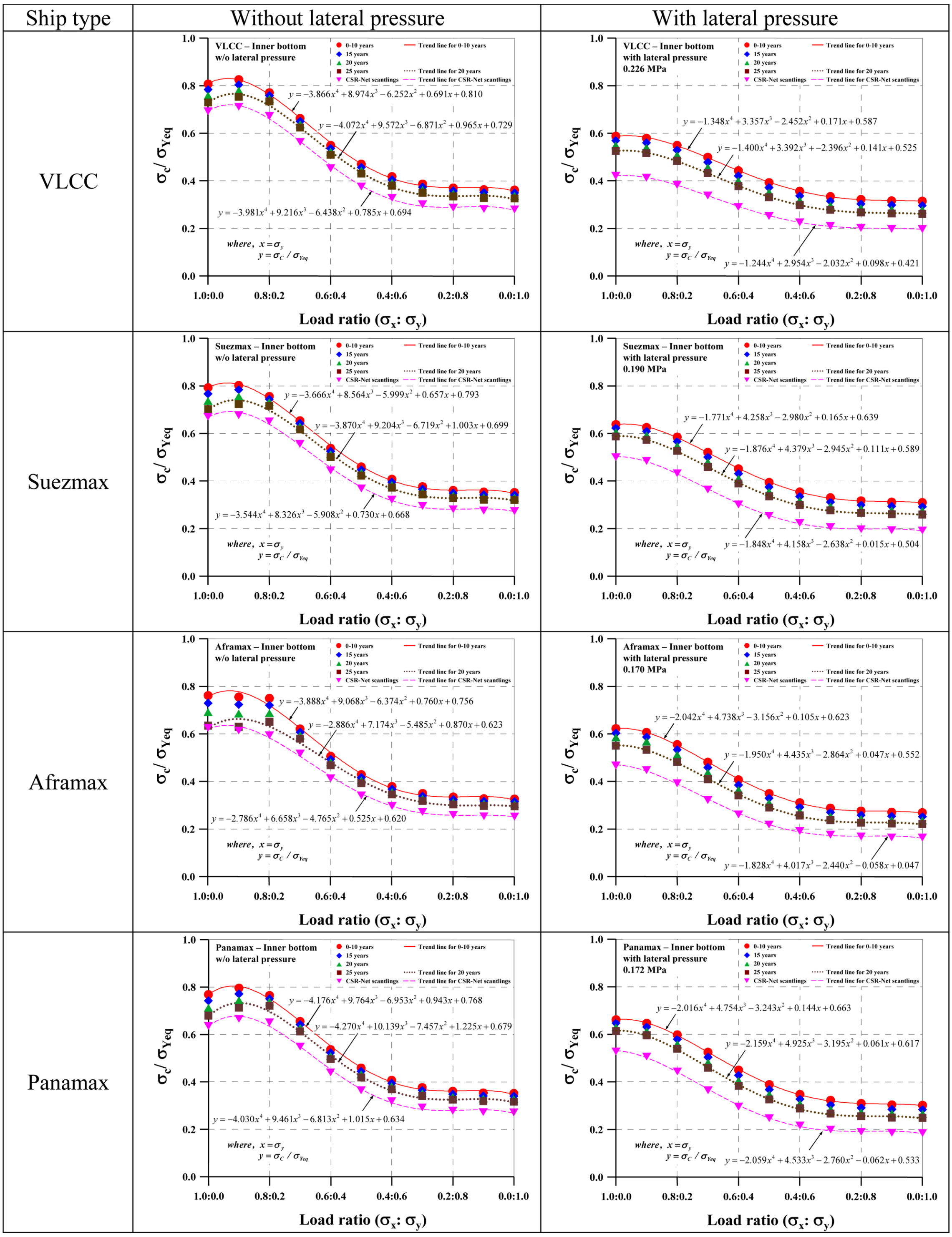


Fig. 17 Ultimate strength relationships of the inner bottom stiffened panel of double-hull oil tankers for each scantling under biaxial compression

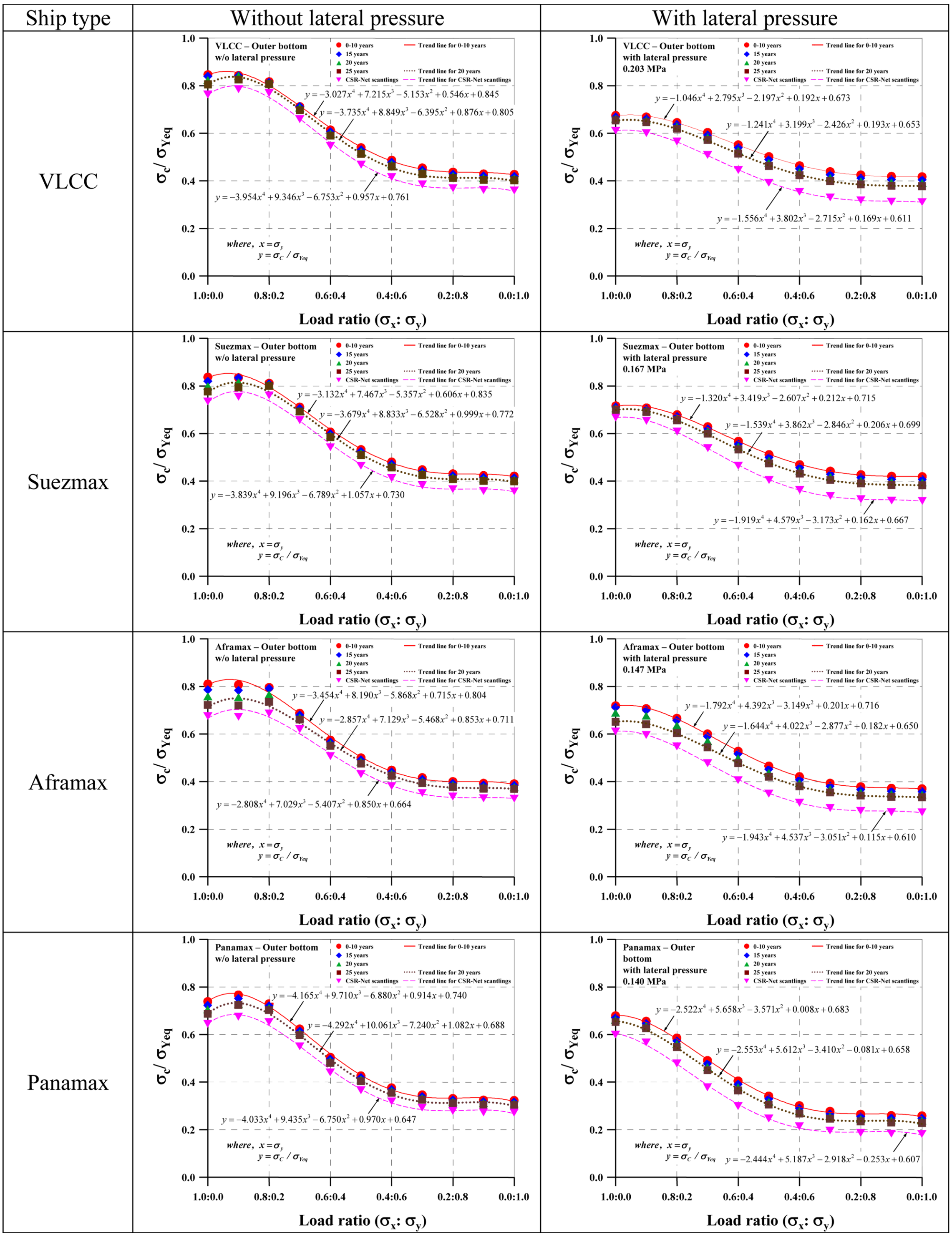


Fig. 18 Ultimate strength relationships of the outer bottom stiffened panels of double-hull oil tankers for each scantling under biaxial compression

Table 5(a) Coefficients of the quartic equation of the trend line related to load ratio versus structural capacity without lateral pressure

Ship type	Location	Age or Scantling	α	β	γ	δ	ε
VLCC	Deck	0 - 10 (As-built)	-1.869	4.640	-3.470	0.405	0.689
		25	-2.067	5.038	-3.687	0.402	0.685
		CSR-Net	-3.168	7.477	-5.420	0.801	0.620
	Inner bottom	0 - 10 (As-built)	-3.866	8.974	-6.252	0.691	0.810
		25	-4.072	9.572	-6.871	0.965	0.729
		CSR-Net	-3.981	9.216	-6.438	0.785	0.694
	Outer bottom	0 - 10 (As-built)	-3.027	7.215	-5.153	0.546	0.845
		25	-3.735	8.849	-6.395	0.876	0.805
		CSR-Net	-3.954	9.346	-6.753	0.957	0.761
Suezmax	Deck	0 - 10 (As-built)	-2.317	5.714	-4.266	0.510	0.785
		25	-2.803	6.773	-4.989	0.670	0.769
		CSR-Net	-2.590	6.745	-5.539	1.140	0.604
	Inner bottom	0 - 10 (As-built)	-3.666	8.564	-5.999	0.657	0.793
		25	-3.870	9.204	-6.719	1.003	0.699
		CSR-Net	-3.544	8.326	-5.908	0.730	0.668
	Outer bottom	0 - 10 (As-built)	-3.132	7.467	-5.357	0.606	0.835
		25	-3.679	8.833	-6.528	0.999	0.772
		CSR-Net	-3.839	9.196	-6.789	1.057	0.730
Aframax	Deck	0 - 10 (As-built)	-2.759	6.627	-4.796	0.552	0.788
		25	-3.020	7.207	-5.191	0.617	0.774
		CSR-Net	-2.293	5.983	-4.830	0.855	0.612
	Inner bottom	0 - 10 (As-built)	-3.888	9.068	-6.374	0.760	0.756
		25	-2.886	7.174	-5.485	0.870	0.623
		CSR-Net	-2.786	6.658	-4.765	0.525	0.620
	Outer bottom	0 - 10 (As-built)	-3.454	8.190	-5.868	0.715	0.804
		25	-2.857	7.129	-5.468	0.853	0.711
		CSR-Net	-2.808	7.029	-5.407	0.850	0.664
Panamax	Deck	0 - 10 (As-built)	-3.999	9.238	-6.506	0.902	0.611
		25	-3.711	8.604	-6.077	0.836	0.584
		CSR-Net	-2.867	6.698	-4.723	0.571	0.529
	Inner bottom	0 - 10 (As-built)	-4.176	9.764	-6.953	0.943	0.768
		25	-4.270	10.139	-7.457	1.225	0.679
		CSR-Net	-4.030	9.461	-6.813	1.015	0.634
	Outer bottom	0 - 10 (As-built)	-4.165	9.710	-6.88	0.914	0.740
		25	-4.292	10.061	-7.24	1.082	0.688
		CSR-Net	-4.033	9.435	-6.75	0.970	0.647

Table 5(b) Coefficients of the quartic equation of the trend line related to load ratio versus structural capacity with lateral pressure

Ship type	Location	Age or Scantling	α	β	γ	δ	ε
VLCC	Deck	0 - 10 (As-built)	-	-	-	-	-
		25	-	-	-	-	-
		CSR-Net	-	-	-	-	-
	Inner bottom	0 - 10 (As-built)	-1.348	3.357	-2.452	0.171	0.587
		25	-1.400	3.392	-2.396	0.141	0.525
		CSR-Net	-1.244	2.954	-2.032	0.098	0.421
	Outer bottom	0 - 10 (As-built)	-1.046	2.795	-2.197	0.192	0.673
		25	-1.241	3.199	-2.426	0.193	0.653
		CSR-Net	-1.556	3.802	-2.715	0.169	0.611
Suezmax	Deck	0 - 10 (As-built)	-	-	-	-	-
		25	-	-	-	-	-
		CSR-Net	-	-	-	-	-
	Inner bottom	0 - 10 (As-built)	-1.771	4.258	-2.980	0.165	0.639
		25	-1.876	4.379	-2.945	0.111	0.589
		CSR-Net	-1.848	4.158	-2.638	0.015	0.504
	Outer bottom	0 - 10 (As-built)	-1.320	3.419	-2.607	0.212	0.715
		25	-1.539	3.862	-2.846	0.206	0.699
		CSR-Net	-1.919	4.579	-3.173	0.162	0.667
Aframax	Deck	0 - 10 (As-built)	-	-	-	-	-
		25	-	-	-	-	-
		CSR-Net	-	-	-	-	-
	Inner bottom	0 - 10 (As-built)	-2.042	4.738	-3.156	0.105	0.623
		25	-1.950	4.435	-2.864	0.047	0.552
		CSR-Net	-1.828	4.017	-2.440	-0.058	0.470
	Outer bottom	0 - 10 (As-built)	-1.792	4.392	-3.149	0.201	0.716
		25	-1.644	4.022	-2.877	0.182	0.650
		CSR-Net	-1.943	4.537	-3.051	0.115	0.610
Panamax	Deck	0 - 10 (As-built)	-	-	-	-	-
		25	-	-	-	-	-
		CSR-Net	-	-	-	-	-
	Inner bottom	0 - 10 (As-built)	-2.016	4.754	-3.243	0.144	0.663
		25	-2.159	4.925	-3.195	0.061	0.617
		CSR-Net	-2.059	4.533	-2.760	-0.062	0.533
	Outer bottom	0 - 10 (As-built)	-2.522	5.658	-3.571	0.008	0.683
		25	-2.553	5.612	-3.410	-0.081	0.658
		CSR-Net	-2.444	5.187	-2.918	-0.253	0.607

the dead weight capacity and increase of CO_2 emissions as well as fuel consumption. Figs. 16 to 18 illustrate the results of the stiffened panel analysis for 10, 15, 20, and 25 years from the As-built states and the CSR net scantlings with trend lines of the load ratios.

The empirical trend line represent the corrosion tendency can be expressed as a quartic equation as follows. Table 5(a) shows the coefficient of fourth order polynomial for As-built and other two types of models considering 25 years marked by $\alpha, \beta, \gamma, \delta, \varepsilon$ neglecting lateral pressure effects. Table 5(b) shows the results including the lateral pressure effect.

$$y = \alpha x^4 + \beta x^3 + \gamma x^2 + \delta x + \varepsilon \tag{3}$$

where, $y = \sigma_C / \sigma_{Yeq}$, $x = \sigma_y$, $\sigma_x + \sigma_y = 1$

Empirical equations as shown in Tables 5(a) and (b) that is based on the limited examples can be applied in typical cases of double hull oil tankers. It is due to the fact that the design of each types of double hull oil tanker structures normally have similar scantlings such as plate thickness, plate breadth and material properties.

8. Conclusions

The results of the present study can be summarized as follows.

1. Analyses of the ultimate strength of the stiffened panels of four types of double-hull oil tankers (VLCC, Suezmax, Aframax and Panamax) were performed and compared using two corrosion models (time-dependent corrosion wastage model and CSR corrosion model).
2. Three types of stiffened panels which are deck, inner bottom and outer bottom were selected for analysis. The ultimate strength capacities according to the two types of corrosion model after 25 years were compared and difference of approximately 3.6-17.5% was found. Again, the CSR rule suggests sufficient corrosion addition to cover the actual amount of corrosion generated, but the value of this corrosion addition is very large. At the same time, reducing of corrosion addition would be economically favorable.
3. The formulation of empirical formula based trend lines of strength variation generated using the ALPS/ULSAP analysis results for stiffened panels by considering the effect of corrosion is formulated. Based on the obtained analysis results, ultimate strength behavior of stiffened panel of typical cases of double hull oil tanker can be easily predicted.

From the results presented in this paper, the effect of corrosion on the ultimate strength of the hull girders of double-hull oil tankers will be performed in Part II.

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