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Effect of corrosion on the ultimate strength of double hull oil tankers – Part II: hull girders

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Abstract. Numerous oil tanker losses have been reported and one of the possible causes of such casualties is caused by the structural failure of aging ship hulls in rough weather. In aging ships, corrosion and fatigue cracks are the two most important factors affecting structural safety and integrity. This research is about effect on hull girder ultimate strength behavior of double hull oil tanker according to corrosion after Part I: stiffened panel. Based on corrosion data of Part I (time-dependent corrosion wastage model and CSR corrosion model), when progressing corrosion of fourtypes of double hull oil tankers (VLCC, Suezmax, Aframax, and Panamax), the ultimate strength behavior of hull girder is compared and analyzed. In case of the ultimate strength behavior of hull girder, when occurring corrosion, the result under vertical and horizontal bending moment is analyzed. The effect of time-dependent corrosion wastage on the ultimate hull girder strength as well as the area, section modulus, and moment of inertia are also studied. The result of this research will be useful data to evaluate ultimate hull girder strength of corroded double hull oil tanker.

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

1. Introduction

Nowadays tankers are usually designed to have a lifespan of around 20-25 years. Various accidents were occurred and reported in corresponding ship structures due to the structural damage by aging problem. The lifespan of aging ships depends on the corrosion rate and the effect of fatigue on plate thickness. The problems of fatigue have been extensively studied (Gudze and Melchers 2008, Kang *et al*. 2010, Lotsberg 2006, Paik and Melchers 2008, Poutiainen and Marquis 2006) and methods for evaluating fatigue life and the fatigue limit standards (DNV 2010) for ships have been established. In corrosion, survey data differentiated by class based on the state of hull corrosion exists. Strong and suggested repair guidelines are available but overall, the research on the

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(a) Panamax class double hull oil tanker (b) Aframax class double hull oil tanker

(c) Suezmax class double hull oil tanker (d) VLCC double hull oil tanker

Fig. 1 Applied four types of double hull oil tankers

effect of corrosion on the ultimate strength of double hull oil tankers is rare.

Since CSR (Common Structural Rules) were established in April 2006 (IACS 2006a, b), all double hull oil tankers have been designed using corrosion addition based on the determination of structural scantling. The evaluation of the longitudinal strength of a ship is calculated based on the performance after 50% deduction of corrosion addition specified by CSR. But it seems that corresponding 50% deducted corrosion addition is an approximate amount of corrosion. In this regards, present study deal with the effect of corrosion on ultimate hull girder strength behavior of double hull oil tankers by applying the actual measured corrosion data. Results are then compared to the CSR results. Paik *et al*. (2003a, b, 2004) suggested time dependent corrosion wastage models (TDCWM) that provide the annual corrosion rate (mm/year) calculated based on the actual measured corrosion data. In this study, focus has been made on comparison in between corrosion models TDCWM and CSR. Four types of double hull oil tankers – VLCC, Suezmax, Aframax and Panamaxare selected for target structures. The vertical and horizontal longitudinal strength and changes in the neutral axis under the vertical bending moment were reviewed. Representative ships are shown in Fig. 1.

2. Double hull oil tanker loss scenarios

Fig. 2 shows the possible causes of oil tanker casualties which can be categorized into three groups: (1) loss of reserve buoyancy (or floating capability), (2) hull girder collapse and (3) loss of stability, initiated either totally or partially by unintended water ingress into cargo holds.

In a large proportion of oil tanker incidents reported, majority of cases involving vessels carrying crude oil. It has been indicated that most of these vessels were over 15 years old, and may have suffered significant defects related to corrosion and fatigue. Reduction of the residual strength and

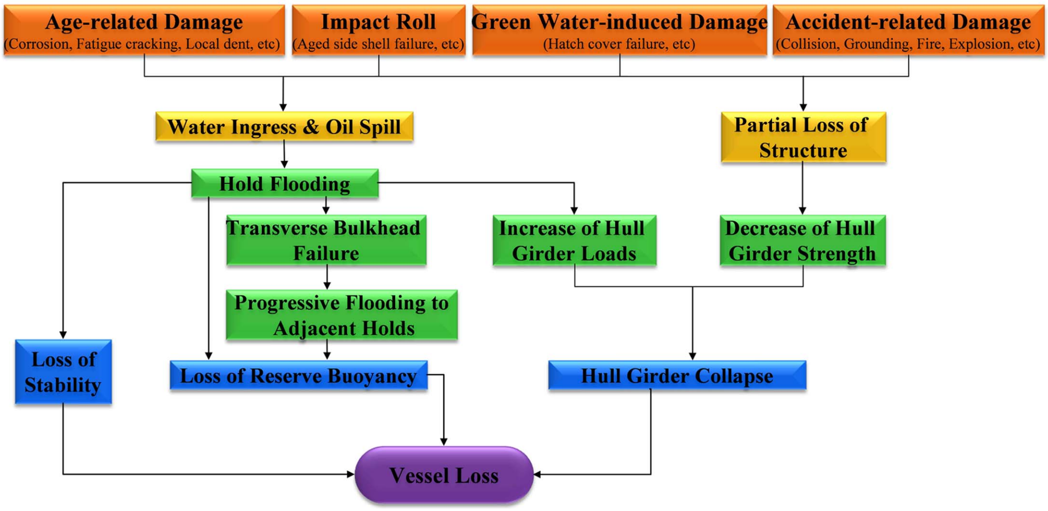


Fig. 2 Ship loss scenarios (Paik and Thayamballi 1998)

an increase of the applied hull girder loads from a flooding event may lead to hull girder collapse. These scenarios, there is the possibility that part of the side or bottom shell forward could be lost due to a combination of circumstances such as a collision accident, a grounding accident, excessive corrosion and fatigue cracking damage, perhaps combined with a sloshing load due to roll in rough sea conditions. These would causeingress of sea water into the cargo holds.

In such postulated accident scenarios, even if the vessel could initially survive with one flooded compartment, the ingress of sea water into a cargo hold could amplify the applied loads, and otherwise lead to vessel loss by progressive flooding. It is particularly happened when the watertight transverse bulkheads are insufficient to withstand the increased pitch motion, whose severity can depend on the cargo density and other characteristics of the vessel. Occasionally some of oil tanker losses were due to progressive flooding after the collapse of watertight bulkheads in a flooded condition. Additionally, with progressive hold flooding, the vessel in some cases could lose stability in rough seas, potentially leading to capsizing.

The present paper is concerned with the possibility and control of hull girder collapse for corroded double hull oil tankers in rough sea and weather.

3. Corrosion model

Coating layers for ships and offshore structures is essential to prevent corrosion damage. In this paper, two models for assessing the effects of corrosion especially over 25 years on ultimate strength behavior are compared. These two models are the time-dependent corrosion wastage model and the CSR corrosion model which is based on uniform corrosion. The validity of the corrosion addition value in CSR is also reviewed. Figs. 3 and 4 illustrate the two types of corrosion models used in this paper.

Fig. 3 shows the mean value of each structural member's corrosion rate obtained using the Weibull distribution function, based on actual measured corrosion data. Paik *et al*. (2003a)

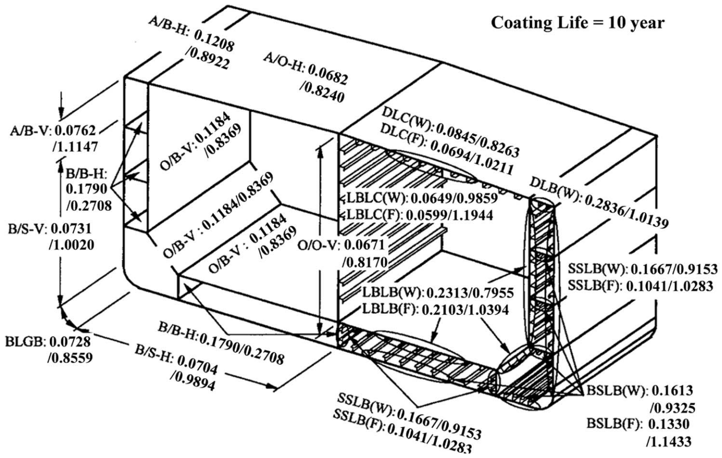


Fig. 3 Mean (mm/year) and COV of the average corrosion rate for the 34 member location/category groups of a double-hull structure considering all corrosion measurement data (Paik *et al*. 2003a)

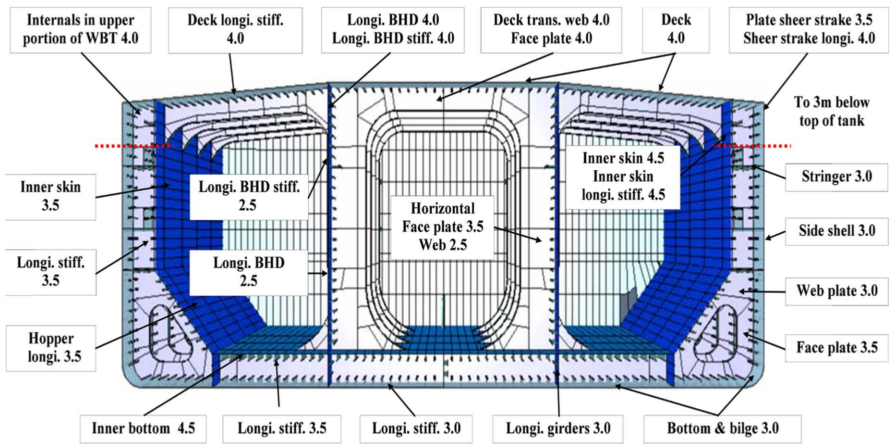


Fig. 4 Corrosion margin values of double hull oil tanker structures (IACS 2006a)

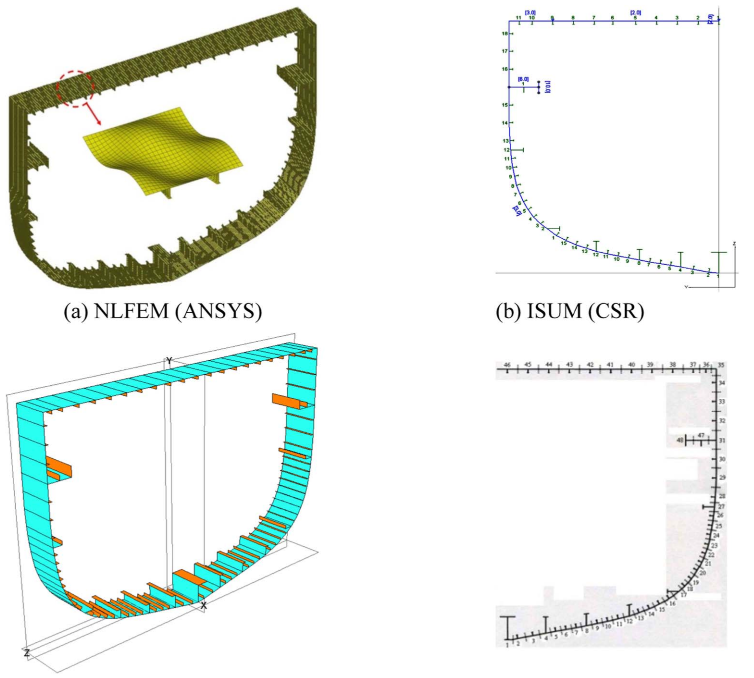
suggested using measured corrosion data based on 5, 7.5 and 10 years corrosion coating life. Coating technology has been developed in the literature (Melchers and Jiang 2006). This study assumed 10-year corrosion coating life.

Fig. 4 represents the corrosion addition value issued by CSR. The initial state of corrosion is defined as gross (as-built) scantling, and the total corrosion in the designed lifespan of 25 years is defined as net scantling. In this paper, the longitudinal strength of oil tankers is compared and the validity of corrosion addition issued by CSR is reviewed based on changes in the longitudinal strength of the ship relative to the observed net (100% fully corroded) scantling state.

4. Applied method – ALPS/HULL (ISFEM)

There are many methods for analyzing ultimate strength of hull girders including theoretical, experimental and numerical methods. Precedent setting research into the ultimate strength behavior of hull girders has been carried out, including the well-known work using a Frigate model by Dow (1991). In addition, theoretical (Caldwell 1965, Paik and Mansour 1995, Paik *et al*. 2011), and numerical (Paik *et al*. 2008, Paik *et al*. 2009, Paik *et al*. 2011, IACS 2006a, b) methods exist.

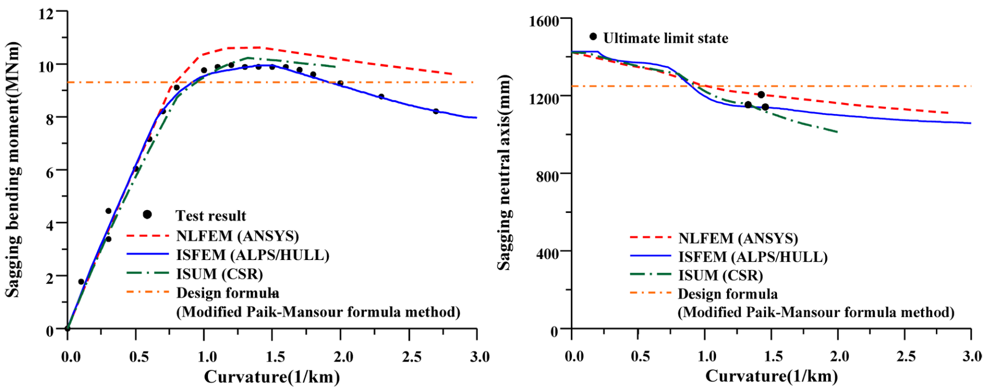
In the numerical category, various approaches exist such as NLFEM (Non-Linear Finite Element Method), ISUM (Idealized Structural Unit Method) or IACS CSR method (IACS 2006a, b) and



(a) NLFEM (ANSYS) (b) ISUM (CSR)

(c) ISFEM (ALPS/HULL) (d) Design formula (Modified P-M mehtod)

Fig. 5 Modeling of Dow's frigate model using various methods (Dow 1991, Hughes and Paik 2010, Paik *et al*. 2011)



(a) Bending moment behavior (b) Neutral axis behavior

Fig. 6 Ultimate strength behavior and neutral axis change of the Dow's Frigate test under a sagging vertical bending moment (Dow 1991, Hughes and Paik 2010, Paik *et al*. 2011)

ISFEM (Intelligent Supersize Finite Element Method) (ANSYS 2010, IACS 2006a, ALPS/HULL 2011). Comparison of the results of these numerical approaches has already been done (Hughes and Paik 2010, Paik *et al*. 2011).

Fig. 6 shows one case from previous research. The behavior characteristics of hull girder ultimate strength was compared and analyzed by applying three methods using the example of a Dow frigate. Three numerical methods and design formula based on already collected experimental data were analyzed (Paik *et al*. 2011). Among these, the result of the ALPS/HULL was similar to the experimental data and others had fairly good agreements and acceptable computational cost. Therefore in this study, the ultimate strength behavior of hull girder-generated corrosion is performed using ALPS/HULL program based on ISFEM (Intelligent Supersize Finite Element Method).

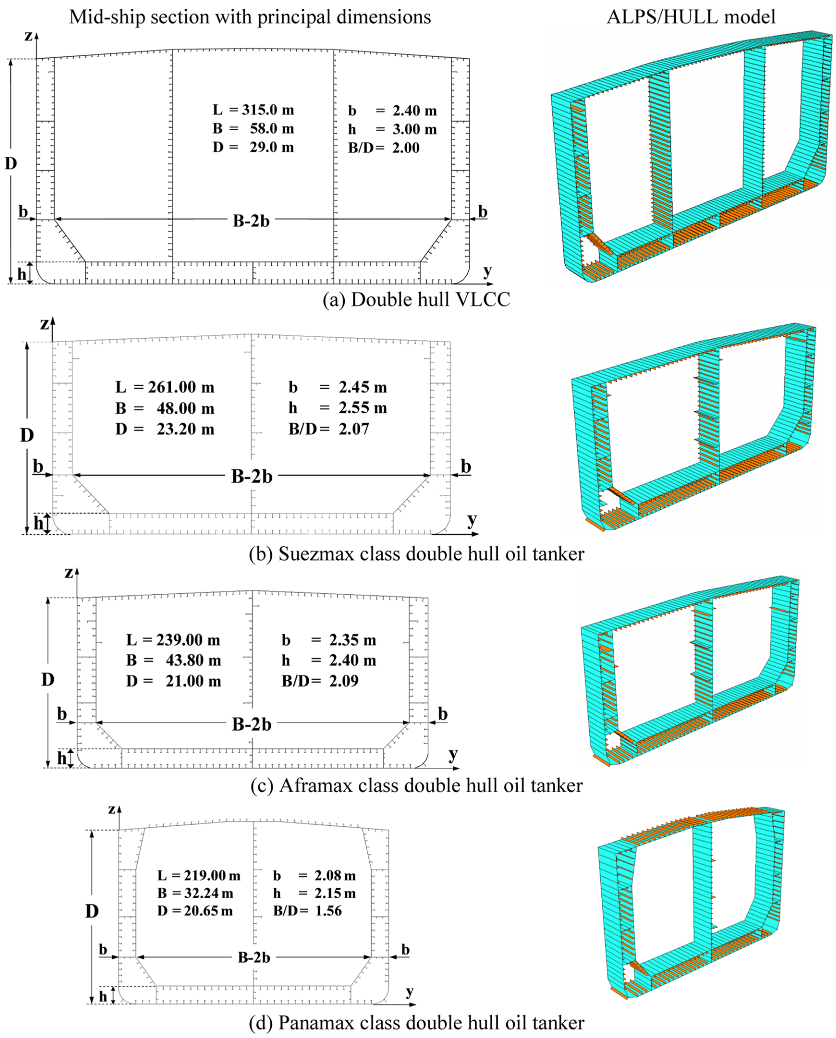


Fig. 7 Structural configurations of double hull oil tanker's mid-ship sections and ALPS/HULL structural models (L = ship length, B = ship breadth, D = ship depth, b = distance between double side shell, h = distance between double bottom)

5. Target structures – double hull oil tankers

Double hull oil tankers are classified by service condition and size of canal. In this paper, four classes of double hull oil tankers, VLCC, Suezmax, Aframax, and Panamax are considered.

Fig. 7 represents the structural configurations of the mid-ship sections used by these ships and the corresponding ALPS/HULL analysis model. The schematic figures and principal dimensions of the selected ship classes are as follows.

Table 1 shows the sectional properties of four types of hull in terms of each corrosion scantling. More details will be covered in the discussion section.

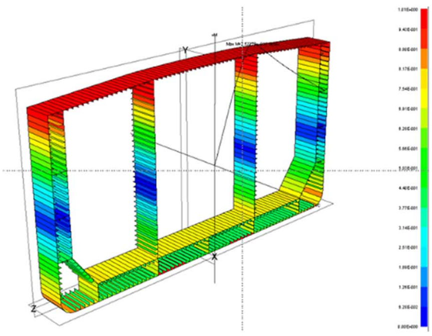
Table 1 Hull cross-sectional properties of the target ships

Oil tanker type	Scantlings		A (m^2)	I (m^4)		S.M. (m^3)		N.A. (m)
				Vertical	Horizontal	Deck	Bottom	
VLCC class	TDCWM	0-10 years	9.593	1349.084	3861.076	72.602	102.063	13.218
		15 years	9.265	1309.085	3718.961	70.604	98.734	13.259
		20 years	8.936	1269.011	3576.670	68.604	95.398	13.302
		25 years	8.677	1236.912	3468.553	66.956	92.815	13.327
	CSR	Gross	9.593	1349.084	3861.076	72.602	102.063	13.218
		Half	8.644	1214.026	3480.617	65.089	92.334	13.148
		Net	7.691	1078.160	3098.452	57.529	82.562	13.059
Suezmax class	TDCWM	0-10 years	7.319	627.354	1980.661	45.517	60.456	10.377
		15 years	7.069	608.6732	1906.224	44.270	58.465	10.411
		20 years	6.815	589.791	1830.496	43.022	56.435	10.451
		25 years	6.560	570.866	1754.673	41.773	54.399	10.494
	CSR	Gross	7.319	627.354	1980.661	45.517	60.456	10.377
		Half	6.592	564.193	1781.473	40.734	54.727	10.309
		Net	5.861	500.802	1581.090	35.950	48.961	10.229
Aframax class	TDCWM	0-10 years	5.847	413.049	1316.832	33.332	43.259	9.548
		15 years	5.625	399.695	1261.964	32.374	41.662	9.594
		20 years	5.403	386.302	1207.029	31.415	40.060	9.643
		25 years	5.180	372.865	1152.028	30.455	38.452	9.697
	CSR	Gross	5.847	413.049	1316.832	33.332	43.259	9.548
		Half	5.222	368.681	1171.752	29.601	38.870	9.485
		Net	4.594	324.031	1026.011	34.458	25.848	9.404
Panamax class	TDCWM	0-10 years	4.523	276.637	576.434	22.041	30.403	9.099
		15 years	4.346	266.692	551.963	21.285	29.241	9.121
		20 years	4.168	256.731	527.455	20.529	28.076	9.144
		25 years	3.990	246.752	502.912	19.771	26.909	9.170
	CSR	Gross	4.523	276.637	576.434	22.041	30.403	9.099
		Half	3.982	242.551	503.253	19.188	26.923	9.009
		Net	3.485	209.655	439.011	23.639	16.403	8.869

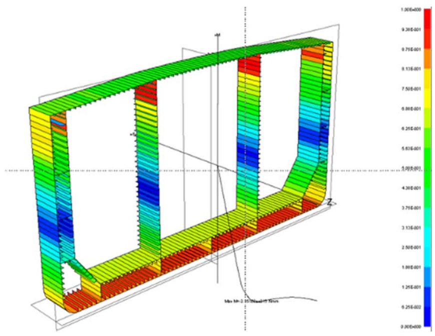
Note: TDCWM = Time dependent corrosion wastage model, A = Hull cross-sectional area, I = Moment of inertia, S.M. = Section modulus, N.A. = Neutral axis position above the baseline, CSR-Net = Net scantlings (100% fully deducted corrosion addition) specified by IACS CSR (IACS 2006a).

6. Results of ultimate hull girder strength calculations

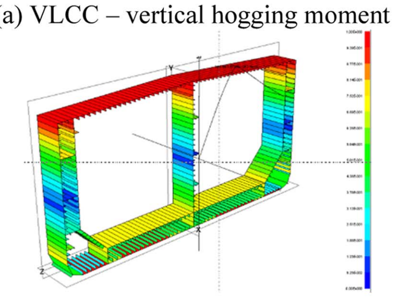
Fig. 8 illustrates the results of the analysis (von-Mises stress distribution) of each double hull oil tanker using the ALPS/HULL program. The same initial deflection formula which used in Part I (ISO 2007) was applied in this study.



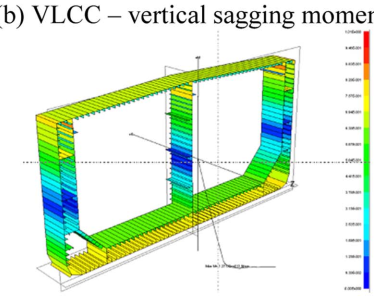
(a) VLCC – vertical hogging moment



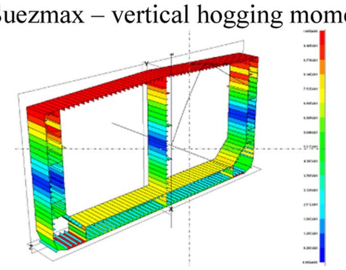
(b) VLCC – vertical sagging moment



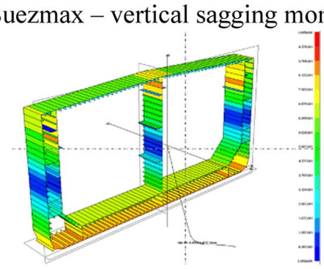
(c) Suezmax – vertical hogging moment



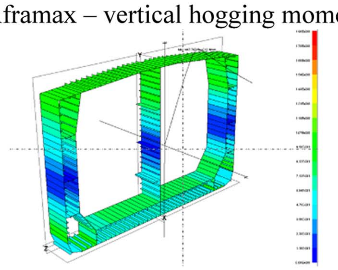
(d) Suezmax – vertical sagging moment



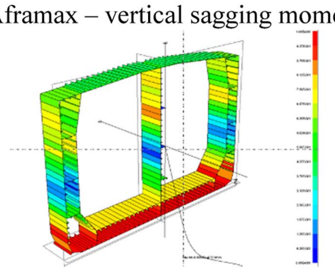
(e) Aframax – vertical hogging moment



(f) Aframax – vertical sagging moment



(g) Panamax – vertical hogging moment



(h) Panamax – vertical sagging moment

Fig. 8 Sample of hull girder calculation result in terms of von-Mises stress distribution for double hull oil tankers under vertical bending moment

6.1 Vertical bending moment

Fig. 9 shows the analysis result of ultimate hull girder strength with change of neutral axis by class in vertical bending moment. Comparison between time-dependent corrosion wastage model and CSR corrosion model will be focused at the 25 years state which is specified by design life of these vessels.

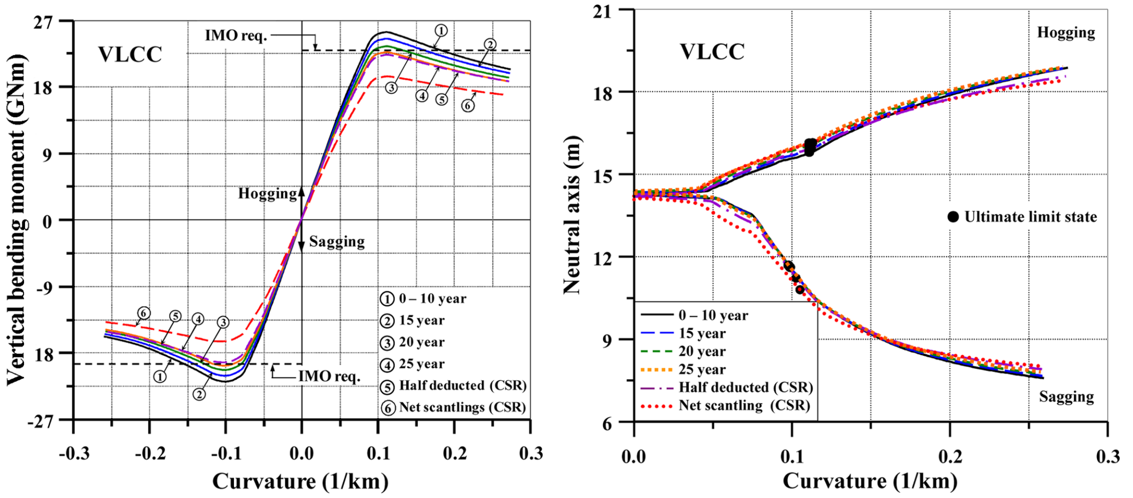


Fig. 9(a) A comparison of the ultimate hull girder longitudinal strength behavior of double hull VLCC with each scantling

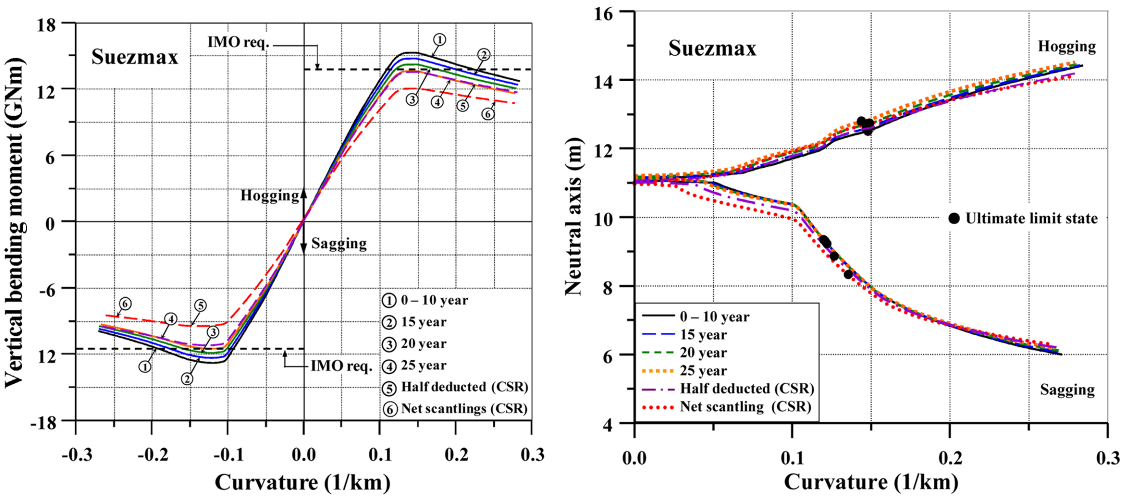


Fig. 9(b) A comparison of the ultimate hull girder longitudinal strength behavior of Suezmax class double hull oil tanker with each scantling

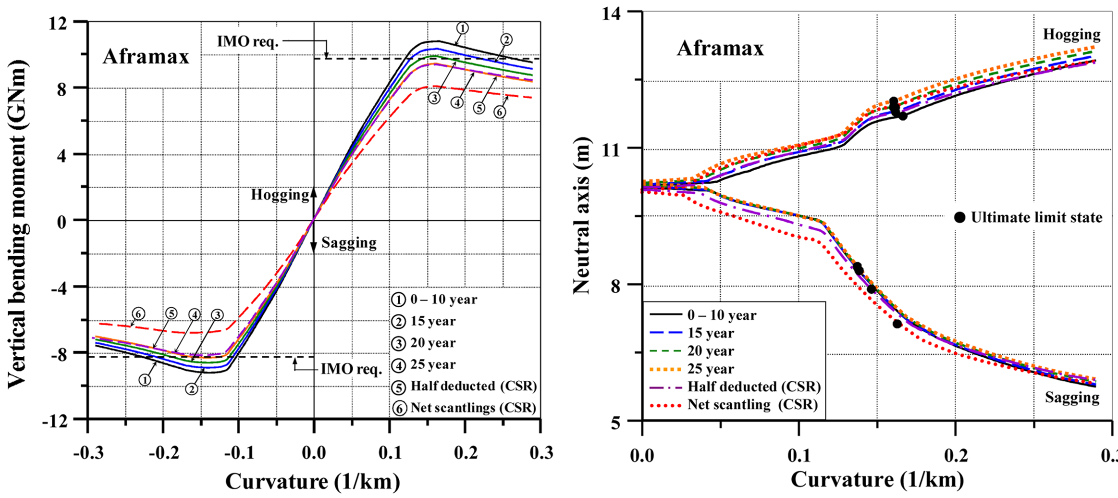


Fig. 9(c) A comparison of the ultimate hull girder longitudinal strength behavior of Aframax class double hull oil tanker with each scantling

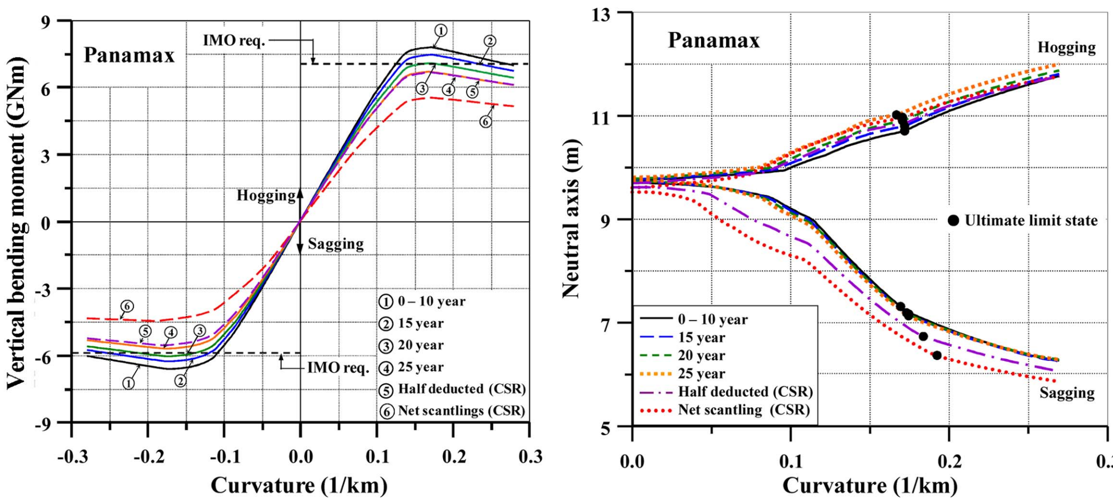
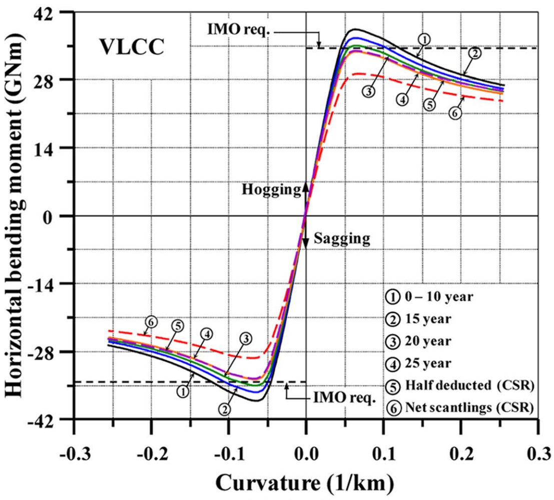


Fig. 9(d) A comparison of the ultimate hull girder longitudinal strength behavior of Panamax class double hull oil tanker with each scantling

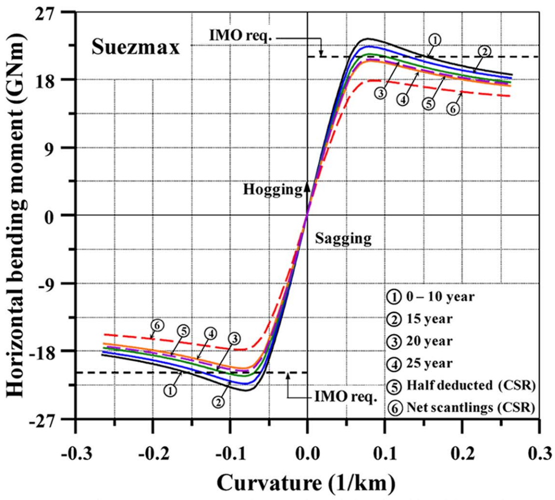
6.2 Horizontal bending moment

The figures below show the results of the analysis of each class of double hull oil tankers in horizontal bending moment. In case of horizontal bending moments, data related to the change of neutral axis is omitted because the physical meaning isn't significant compare to vertical bending moment case. In this section, hogging denotes a center bulkhead to starboard direction and sagging is in the port direction.

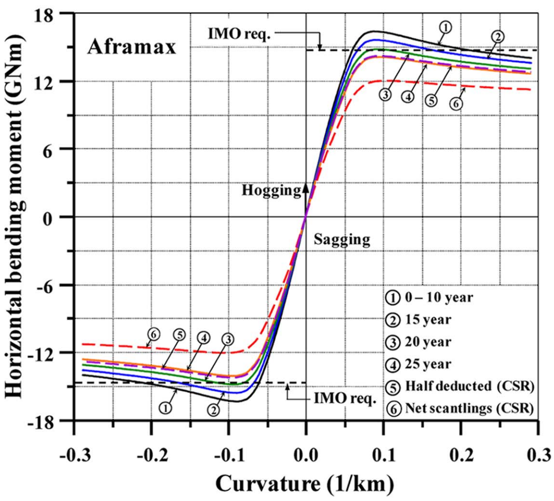
In the case of a ship affected by horizontal bending moment, the change of neutral axis due to



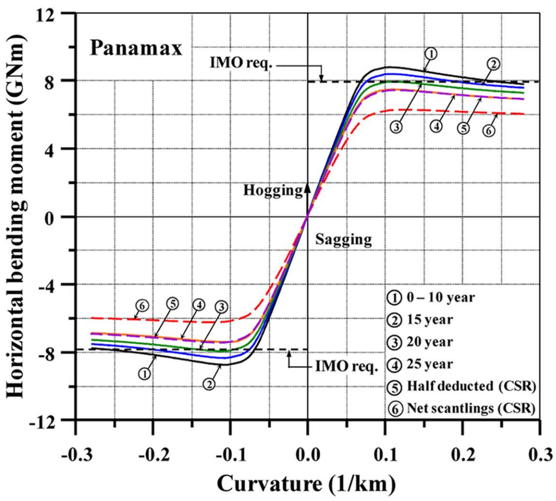
(a) Double hull VLCC



(b) Suezmax class double hull oil tanker



(c) Aframax class double hull oil tanker



(d) Panamax class double hull oil tanker

Fig. 10 A comparison of the ultimate horizontal hull girder longitudinal strength behavior of double hull oil tankers with corrosion

horizontal sagging and hogging moment are almost same. It is due to the fact that symmetrical shape of starboard and port are quite similar based on center bulkhead. For as operating ship, the effect of horizontal bending moment is not significant, therefore the change of neutral axis position caused by horizontal bending moment is omitted in this study.

6.3 Comparison of the four types of double hull oil tanker

The following tables numerically represent the ultimate strength values and neutral axis at the ultimate limit state (ULS).

Table 2 Ultimate vertical bending moment for each ship

V.B.M.		M_u (GNm)							
Scantlings	Ship type	Double hull VLCC		Suezmax class D/H oil tanker		Aframax class D/H oil tanker		Panamax class D/H oil tanker	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
TDCWM	0-10 year	25.331	21.886	15.299	12.828	10.775	9.249	7.788	6.604
	15 year	24.418	21.133	14.754	12.375	10.321	8.948	7.436	6.284
	20 year	23.431	20.384	14.173	11.926	9.864	8.629	7.068	6.041
	25 year	22.700	19.787	13.609	11.481	9.430	8.320	6.691	5.719
CSR	Gross	25.331	21.886	15.299	12.828	10.775	9.249	7.788	6.604
	Half	22.389	19.377	13.514	11.215	9.406	8.109	6.599	5.406
	Net	19.379	16.527	11.756	9.696	8.046	6.822	5.522	4.435

Note: TDCWM = Time dependent corrosion wastage model, V.B.M. = Vertical bending moment, M_u = Ultimate moment, D/H = Double hull, VLCC = Very large crude oil carrier.

Table 3 Ultimate horizontal bending moment for each ship

H.B.M.		M_u (GNm)							
Scantlings	Ship type	Double hull VLCC		Suezmax class D/H oil tanker		Aframax class D/H oil tanker		Panamax class D/H oil tanker	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
TDCWM	0-10 year	38.344	38.348	23.314	23.320	16.358	16.360	8.796	8.771
	15 year	36.554	36.554	22.315	22.325	15.590	15.595	8.353	8.376
	20 year	35.019	35.058	21.341	21.348	14.816	14.838	7.942	7.941
	25 year	33.793	33.803	20.379	20.386	14.075	14.081	7.471	7.416
CSR	Gross	38.344	38.348	23.314	23.320	16.358	16.360	8.796	8.771
	Half	33.840	33.841	20.587	20.594	14.194	14.203	7.422	7.421
	Net	29.340	29.340	17.829	17.833	12.020	12.028	6.244	6.242

Note: H.B.M. = Horizontal bending moment, M_u = Ultimate moment, D/H = Double hull, VLCC = Very large crude oil carrier.

Table 4 Changes in ultimate neutral axis position under vertical bending moment

N.A.		Neutral Axis(mm) under vertical bending moment							
Scantlings	Ship type	Double hull VLCC		Suezmax class D/H oil tanker		Aframax class D/H oil tanker		Panamax class D/H oil tanker	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
TDCWM	0-10 year	15.782	11.544	12.503	9.301	11.679	8.299	10.706	7.314
	15 year	15.901	11.539	12.588	9.237	11.789	8.267	10.813	7.14
	20 year	16.086	11.532	12.716	9.234	11.912	8.241	10.914	7.045
	25 year	16.149	11.532	12.814	9.176	12.03	8.218	11.023	6.913
CSR	Gross	15.782	11.544	12.503	9.301	11.679	8.299	10.706	7.314
	Half	15.919	11.208	12.612	8.874	11.797	7.895	10.868	6.750
	Net	16.148	10.734	12.713	8.325	11.902	7.171	10.95	6.374

Note: D/H = Double hull, VLCC = Very large crude oil carrier.

Table 5(a) Ultimate moment for each ship under vertical bending moment

V.B.M.		M_{Vu}/M_{Vuo}							
Scantlings	Ship type	Double hull VLCC		Suezmax class D/H oil tanker		Aframax class D/H oil tanker		Panamax class D/H oil tanker	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
TDCWM	0-10 year	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	15 year	0.964	0.966	0.964	0.965	0.958	0.967	0.955	0.952
	20 year	0.925	0.931	0.926	0.930	0.915	0.933	0.908	0.915
	25 year	0.896	0.904	0.890	0.895	0.875	0.900	0.859	0.866
CSR	Gross	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Half	0.884	0.885	0.883	0.874	0.873	0.877	0.847	0.819
	Net	0.765	0.755	0.768	0.756	0.747	0.738	0.709	0.672

Note: M_{Vu} = Ultimate vertical moment, M_{Vuo} = Ultimate vertical moment at gross scantling, D/H = Double hull, VLCC = Very large crude oil carrier.

Table 5(b) Ultimate moment for each ship under horizontal bending moment

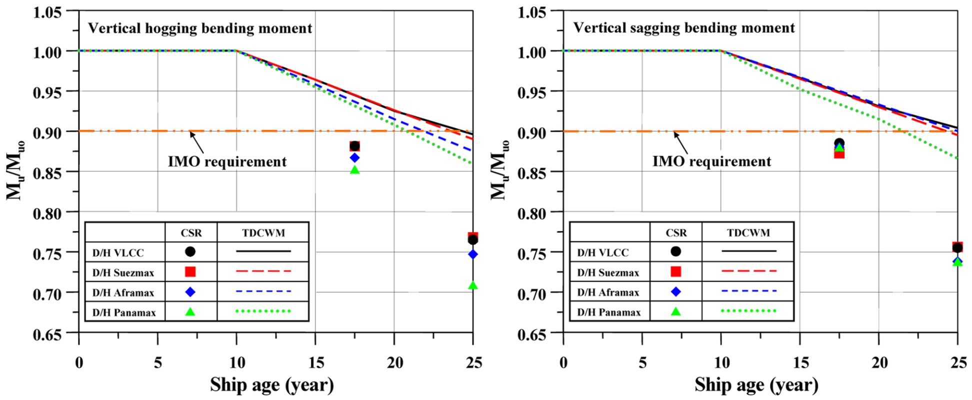
H.B.M.		M_{Hu}/M_{Huo}							
Scantlings	Ship type	Double hull VLCC		Suezmax class D/H oil tanker		Aframax class D/H oil tanker		Panamax class D/H oil tanker	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
TDCWM	0-10 year	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	15 year	0.953	0.953	0.957	0.957	0.953	0.953	0.950	0.955
	20 year	0.913	0.914	0.915	0.915	0.906	0.907	0.903	0.905
	25 year	0.881	0.881	0.874	0.874	0.860	0.861	0.849	0.846
CSR	Gross	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Half	0.883	0.882	0.883	0.883	0.868	0.868	0.844	0.846
	Net	0.765	0.765	0.765	0.765	0.735	0.735	0.710	0.712

Note: M_{Hu} = Ultimate horizontal moment, M_{Huo} = Ultimate horizontal moment at gross scantling, D/H = Double hull, VLCC = Very large crude oil carrier.

Table 5(c) Neutral axis change for each ship

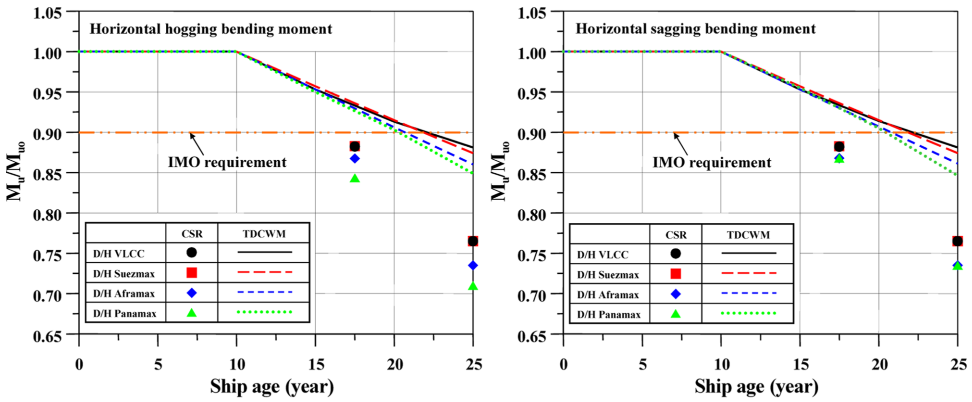
N.A.		Neutral Axis (mm) under V.B.M.							
Scantlings	Ship type	Double hull VLCC		Suezmax class D/H oil tanker		Aframax class D/H oil tanker		Panamax class D/H oil tanker	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
TDCWM	0-10 year	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	15 year	1.008	1.000	1.007	0.993	1.009	0.996	1.010	0.976
	20 year	1.019	0.999	1.017	0.993	1.020	0.993	1.019	0.963
	25 year	1.023	0.999	1.025	0.987	1.030	0.990	1.030	0.945
CSR	Gross	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Half	1.010	0.964	1.009	0.954	1.009	0.951	1.015	0.923
	Net	1.023	0.930	1.017	0.895	1.019	0.864	1.023	0.871

Note: N.A. = Neutral axis, $N.A._{ori}$ = Initial Neutral axis, D/H = Double hull.



(a) Hogging (b) Sagging

Fig. 11 Relationship between ship age and ultimate hull girder bending capacity under vertical bending moment



(a) Hogging (b) Sagging

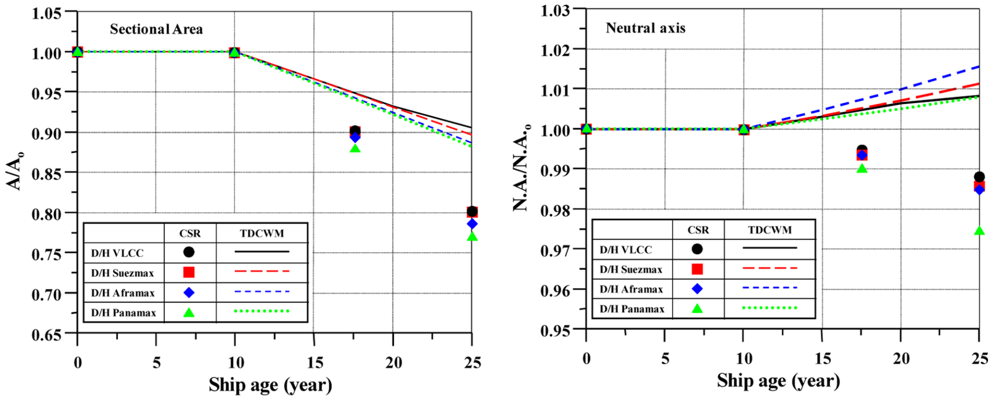
Fig. 12 Relationship between ship age and ultimate hull girder bending capacity under horizontal bending moment

Table 6 Repair periods for double hull oil tankers using time-dependent corrosion wastage model

Repair time (year)		VLCC	Suezmax	Aframax	Panamax
Vertical	Hog	24.3	23.5	21.8	20.8
	Sag	25.9	24.2	24.9	21.6
Horizontal	Hog	22.0	21.8	20.7	20.3
	Sag	22.0	21.8	20.7	20.3

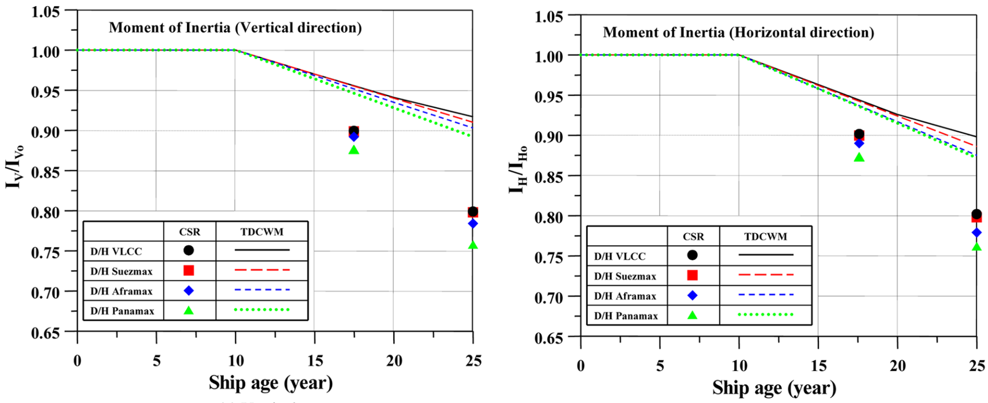
7. Discussions

Tables 5(a) to (c) represents the ratio of ultimate hull girder strength between the previous results and the results of gross scantling measurements (longitudinal strength and neutral axis in as-built



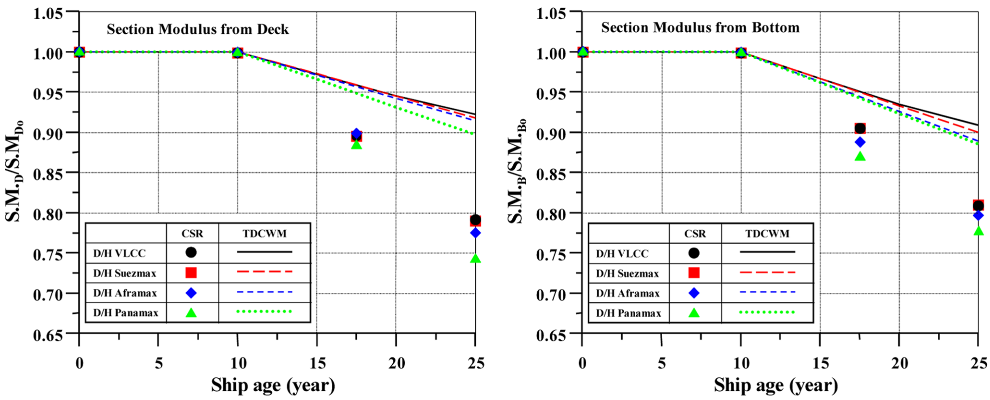
(a) Area (b) Neutral axis (Vertical)

Fig. 13 A comparison of change of cross-sectional area and neutral axis of mid-ship for double hull oil tankers under corrosion rate effect



(a) Vertical (b) Horizontal

Fig. 14 A comparison of changing of moment of inertia for double hull oil tankers under corrosion rate effect



(a) Deck (b) Bottom

Fig. 15 A comparison of changing of section modulus for double hull oil tankers under corrosion rate effect

Table 7 Comparison of strength variation and mid-ship properties of four double hull oil tankers in 25 years state

Ship age = 25 years				VLCC	Suezmax	Aframax	Panamax
Ultimate Bending Moment	V.B.M./V.B.M.(ori)	Hog	As-built	1.000	1.000	1.000	1.000
			TDCWM	0.896	0.890	0.875	0.859
			CSR	0.765	0.768	0.747	0.709
		Difference (%)		13.1	12.2	12.8	15.0
		Sag	As-built	1.000	1.000	1.000	1.000
			TDCWM	0.904	0.895	0.900	0.866
			CSR	0.755	0.756	0.738	0.672
		Difference (%)		14.9	13.9	16.2	19.4
	H.B.M./H.B.M.(ori)	Hog	As-built	1.000	1.000	1.000	1.000
			TDCWM	0.881	0.874	0.860	0.849
			CSR	0.765	0.765	0.735	0.710
		Difference (%)		11.6	10.9	12.5	13.9
		Sag	As-built	1.000	1.000	1.000	1.000
			TDCWM	0.881	0.874	0.861	0.846
			CSR	0.765	0.765	0.735	0.712
		Difference (%)		11.6	10.9	12.6	13.4
Sectional Area	Area/Area(ori)		As-built	1.000	1.000	1.000	1.000
			TDCWM	0.905	0.896	0.886	0.882
			CSR	0.802	0.801	0.786	0.771
	Difference (%)			10.3	9.5	10.0	11.1
Moment of Inertia	$\frac{I_V}{I_V(\text{ori})}$		As-built	1.000	1.000	1.000	1.000
			TDCWM	0.917	0.910	0.903	0.892
			CSR	0.799	0.798	0.784	0.758
	Difference (%)			11.8	11.2	11.9	13.4
	$\frac{I_H}{I_H(\text{ori})}$		As-built	1.000	1.000	1.000	1.000
			TDCWM	0.898	0.886	0.875	0.872
			CSR	0.802	0.795	0.779	0.762
	Difference (%)			9.6	9.1	9.6	11.0
Section Modulus	Deck/Deck(ori)		As-built	1.000	1.000	1.000	1.000
			TDCWM	0.922	0.918	0.914	0.897
			CSR	0.792	0.790	0.775	0.744
	Difference (%)			13.0	12.8	13.9	15.3
	Bottom/Bottom(ori)		As-built	1.000	1.000	1.000	1.000
			TDCWM	0.909	0.900	0.889	0.885
			CSR	0.809	0.810	0.797	0.778
	Difference (%)			10.0	9.0	9.2	10.7

Note: TDCWM = Time-dependent corrosion wastage model, V.B.M. = Vertical bending moment, H.B.M. = Horizontal bending moment, I_V = Vertical moment of inertia, I_H = Horizontal moment of inertia.

state). In the case of the corrosion addition of CSR is applied, majority of professionals bodies agree that this value is large. Therefore, the present analysis of hull girder longitudinal strength is using 50% deducted value of corrosion addition for evaluation as shown in Table 5. In this study, strength analyses of half corrosion addition deducted and net scantlings were also analyzed. Comparison between CSR net scantlings and TDCWM at 25 years old shows the difference of approximately around 10-20% in terms of ultimate longitudinal strength as shown in Table 5. In other words, corrosion addition given by CSR is considering corrosion generated by each part of a double hull oil tanker over 25 years. However, scantling method take into consideration overall evaluation resulting the remaining strength of 10.9-20.4% for each double hull oil tankers.

Table 6 shows the estimate repair time based on IMO requirements (IMO 2003). The hogging moment is more effected by corrosion than the sagging moment. Table 6 shows that the smaller size of double hull oil tankers, the shorter time to repair due to corrosion. Table 6 also shows the repair time of double hull oil tankers under vertical and horizontal bending moment. In the case of CSR half corrosion deducted scantlings, the ship age were assumed as 17.5 years which is calculated from design life (25 years) divide by two.

Figs. 13 to 15 show the results of changes in properties such as sectional area, neutral axis, section modulus and moment of inertia in the initial state based on the results summarized in Table 1. Depending on changes with respect to time, similar trends to Fig. 11 and Fig. 12 except for the neutral axis change is observed. In this case the value of TDCWD's annual corrosion rate (mm/year) on deck side is very small compared to other structural part. In this regards, trends of neutral axis based on TDCWD are going up parallel to increasing age of ship.

Table 7 compares analysis results between the time-dependent corrosion wastage model and the CSR corrosion model at 25 years. The results of sectional area, section modulus, and moment of inertia in the initial state of four kinds of double hull oil tankers are considered. The differences between the two models of corrosion are also presented.

7. Conclusions

The results of this research are as follows.

1. Ultimate longitudinal strength behavior variations on each part of the four classes of double hull oil tankers could be identified by size through annual corrosion data using two different models: time-dependent corrosion wastage and CSR corrosion.
2. As corrosion progress of double hull oil tankers is concerned, the ultimate longitudinal strength of small ship size declines progressively when vertical and horizontal hogging or sagging moments are applied.
3. Using the results of the corrosion analysis, a comparison of time versus behavior of longitudinal strength of double hull oil tankers was made. Based on obtained data, a repair time for servicing the four ship classes could be predicted based on IMO requirements.
4. The difference between the estimation of 25 years double hull oil tankers ultimate longitudinal strength issued by CSR and TDCWM are approximately around 10-20 %. In this case, CSR may result in over design of corrosion addition. Therefore, it will be more economically if this CSR is design with reduction of corrosion addition.
5. In the case of half corrosion deducted scantlings of CSR which is mainly considered at the

design state, the ultimate strength results are quite similar as 25 years results of TDCWM.

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References

ALPS/HULL (2011), "A computer program for progressive collapse analysis of ship hulls", Advanced Technology Center, DRS C3 Systems, Inc., MD, USA (www.proteusengineering.com, www.maestromarine. com).

ANSYS (2010), Version 12.0, ANSYS Inc., Canonsburg, PA, USA.

Caldwell, J.B. (1965), "Ultimate longitudinal strength", *Trans. RINA*, **107**, 411-430.

DNV (2010), *Fatigue Assessment of Ship Structures, Classification Notes*, No. 30.7.

Dow, R.S. (1991), "Testing and analysis of 1/3-scale welded steel frigate model", *Proceedings of the International Conference on Advances in Marine Structures*, Dunfermline, Scotland.

Gudze, M.T. and Melchers, R.E. (2008), "Operational based corrosion analysis in naval ships", *Corros. Sci.*, **50**(12), 3296-3307.

Guo, J., Wang, G., Ivanov, L. and Perakis, A.N. (2008), "Time-varying ultimate strength of aging tanker deck plate considering corrosion effect", *Marine Struct.*, **21**(4), 402-419.

Hughes, O.F. and Paik, J.K. (2010), *Ship Structural Analysis and Design*, The Society of Naval Architects and Marine Engineers, New Jersey, USA.

IACS (2006a), "Common structural rules for double hull oil tankers", International Association of Classification Societies, London, UK.

IACS (2006b), "Common structural rules for bulk carriers", International Association of Classification Societies, London, UK.

IMO (2003), Revised interim guidelines for the approval of alternative methods of design and construction of oil tankers adopted by the Marine Environment Protection Committee of the Organization by Resolution MEPC 110(49), *International Maritime Organization*, London, UK.

ISO (2007), "International standard ISO 18072-1, Ships and marine technology – Ship structures, Part 1: General requirements for their limit state assessment", International Organization for Standardization, Geneva.

Kang, S.W., Kim, M.H., Kim, J.H., Kim, K.S., Kang, J.K. and Heo, J.H. (2010), "An experimental study on the fatigue strength assessment of longi-webconnections in ship structures using structural stress", *Ocean Eng.,* **36**, 1067-1072.

Lotsberg, I. (2006), "Assessment of fatigue capacity in the new bulkcarrier and tanker rules", *Marine Struct.,* **19**, 83-96.

Melchers, R.E. and Jiang, X. (2006), "Estimation of models for durability of epoxy coatings in water ballast tanks", *Ships Offshore Struct.*, **1**(1), 61-69.

Paik, J.K., Kim, B.J. and Seo, J.K. (2008), "Methods for ultimate limit state assessment of ships and ship-shipped offshore structures: Part I (unstiffened panels), Part II (stiffened panels) and Part III (hull girders)", *Ocean Engineering*, **35**(2), 261-286.

Paik, J.K., Kim, D.K. and Kim, M.S. (2009), "Ultimate strength performance of Suezmax tanker structures: Pre-CSR versus CSR designs", *Int. J. Marit. Eng.*, **151**(A2).

Paik, J.K., Kim, D.K., Park, D.H., Kim, H.B., Mansour, A.E. and Caldwell, J.B. (2011), "Modified Paik-Mansour formula for ultimate strength calculations of ship hulls", *Proceedings of MARSTRUCT 2011 Conference*, Hamburg, Germany.

Paik, J.K., Lee, J.M., Hwang, J.S. and Park, Y.I. (2003a), "A time-dependent corrosion wastage model for the structures of single/double hull tankers and FSOs/FPSOs", *Marine Technol.*, **40**(3), 201-217.

Paik, J.K. and Mansour, A.E. (1995), "A simple formulation for predicting the ultimate strength of ships", *J. Mar. Sci. Technol.*, **1**(1), 52-62.

Paik, J.K. and Melchers, R.E. (2008), *Condition Assessment of Aged Structures*, CRC Press, New York, USA.

Paik, J.K. and Thayamballi, A.K. (1998), "The strength and reliability of bulk carrier structures subject to age and accidental flooding", *Trans. Soc. Naval Arch. Marine Eng.*, **106**, 1-40.

Paik, J.K. and Thayamballi, A.K. (2007), *Ship-shaped Offshore Installations: Design, Building, and Operation*, Cambridge University Press, Cambridge, UK.

Paik, J.K., Thayamballi, A.K., Park, Y.I. and Hwang, J.S. (2003b), "A time-dependent corrosion wastage model for bulk carrier structures", *Int. J. Marit. Eng.*, **145**(A2), 61-87.

Paik, J.K., Thayamballi, A.K., Park, Y.I. and Hwang, J.S. (2004), "A time-dependent corrosion wastage model for seawater ballast tanks of ships", *Corros. Sci.*, **46**, 471-486.

Poutiainen, I. and Marquis, G. (2006), "A fatigue assessment method based on weld stress", *Int. J. Fatigue,* **28**, 1037-1046.