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DESIGN AND DYNAMIC BEHAVIORS OF MARINE STRUCTURES

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ABSTRACT

Understanding the dynamic behavior of ships in waves is essential not only for the design of hull structure but also those of equipments and fittings referred in IMO which is the United Nations agency concerned with safety of shipping and protection of the marine environment. Those out fittings such as Emergency Towing Arrangements （ETS）, towing and mooring equipments, doorways and ventilators, hatch covers, miscellaneous openings in freeboard and superstructure decks, windows and skylights are affected by dynamic behaviors of ship in wave.

To design a securing system of container ship, induced loads due to ship motions in the sea should be the most important matters, especially for huge container ships which are recently built for efficiently sea transportation means.

This paper reviews a number of papers by the author on the dynamic tensions of towlines and motion responses of various ships in short crested irregular waves to better understand and discuss the design criteria of out fittings of ships.

Key words: dynamic behavior in waves, design of marine structure, ship motion,

1. INTRODUCTION

To protect the marine environment from pollution as a result of shipping incidents, IMO[1] requires tank ships operating in international to maintain emergency towing equipment on board and to conduct emergency towing drills. The International Convention for Safety of Life at Sea (SOLAS) Chapter 5, Regulation 15.1 requires all tankers of 20,000 deadweight tons and above and built after January 1996 to be fitted with emergency towing arrangements at both ends of the ship. The 75th session of the Maritime Safety Committee (MSC-75) has also adopted Resolution MSC-132(75) on Amendments to the guidelines on emergency towing arrangements for tankers (resolution MSC-35(63)) in 2002.

To provide significant improvements to the structural safety of ships, in particular bulk carriers, following on from recommendations of the United Kingdom Report of the re-opened formal investigation into the loss of the Derbyshire in 1980, IMO MSC-77(2003)[1] has adopted a revised Annex B to the 1988 Load Lines Protocol. The amendments to Annex B include a number of important revisions, in particular to regulations concerning strength and others.

The MSC-80 (2005)[1] has adopted the amendments to SOLAS regulation II-1/3-8 concerning towing and mooring equipment. The regulation will require all ships to be provided with arrangements, equipment and fittings of sufficient safe working load to enable the safe conduct of all towing and mooring operations associated with the normal operation of the ship.

Following the SOLAS amendments, IACS[2] and classification societies of shipping[3] have also improved the safety of ship in waves.

Concerning these issues the author reviews his papers on the dynamic tensions of towing lines and motion response of various ships in short crested irregular waves to understand and discuss the design criteria of out fittings of ships in his paper[4].

Recently very large container ships are built and become more economical ocean transportation means. Very large induced loads on the containers due to ship motions in the sea should be considered for stacking the containers on the ships and their securing systems.

The author also reviews a recent study[5] of motion responses of a mega container ship in short crested irregular waves to give some information for the safety of securing system of huge container ships in the sea.

2. DYNAMIC TENSION OF TOWING LINES

Towing marine structure to the required site in the sea, towing a tanker in salvage operation and others are indispensable in ocean engineering. In calm sea conditions propulsive force is responsible for the motion of the tow system against the tow rope pull and external forces. However, the towing operations become critical with the presence of wind, waves and current.

A study of the dynamic analysis of tension in towline by using the three dimensional lumped mass method is carried out[6]. In the paper a parametric study of the dynamic analysis of tension of towline in the various conditions of amplitude and frequency of motions, pretensions and combination ratios of length of wire and chain are presented.

From the numerical results it is recognized that decrease of period of motion causes increase of dynamic tension, increase of length of portion of chain of total line decreases dynamic tension and increase of initial tension or motion amplitude also increases dynamic tension. And the most effective way to reduce the dynamic tension is to use chain together with wire rope for towline. On the other hand, the length of the towline of wire rope is not so effective to reduce the dynamic tension.

Figure 1 shows the influences of length of chain and motion period on dynamic tensions of lines in case of total length of 1000*m* and motion amplitude of the towline end is 5*m*. From this we can understand that the chafing chain for towing and mooring arrangements is important means to reduce dynamic tensions of lines in dynamic motions.

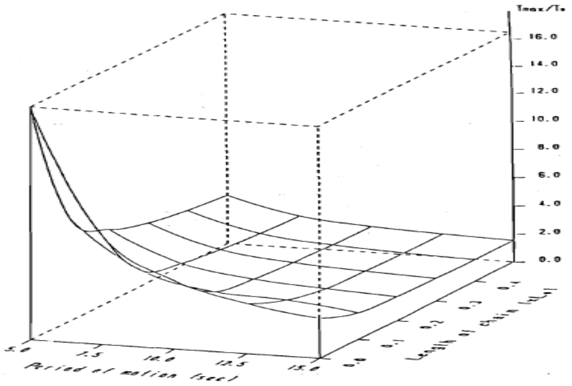

Figure 1 Influences of length of chain and motion period on dynamic tensions of lines

A simulation study on the dynamics response of tanker-tug tow system in the seas is also investigated[7]. Three tankers each of 20,000*dwt*, 100,000*dwt* and 200,000*dwt* have been considered. Two tugs of different pulling capacity of 100*kN* and 400*kN* are assumed for towing operation.

The principal particulars of the tankers are shown in Table 1. The details of the towline used onboard the tankers are also given in the Table 1. These parameters have been determined referring to the equipment number recommended by rules and guidance of NK[3].

The principal particulars of two tugs for the computer simulations are shown in Table2. And the calculating conditions of sea states are shown in Table 3.

Table 2 Principal particulars of tugs

tugs	Length (*m*)	Breadth (*m*)	draft (*m*)	displacement (*tons*)	pull load (*kN*)
A	16.0	6.1	3.0	180	100
B	27.0	10.0	4.0	900	400

Table 3 Calculation conditions of sea states

Beaufort scale	significant wave		wind speed (*knots*)
	height (*m*)	period(*s*)	
3	0.6	5.2	8
4	1.0	6.0	12
5	2.0	7.1	18
6	3.0	7.9	24
7	4.0	8.4	30
8	5.5	8.8	36

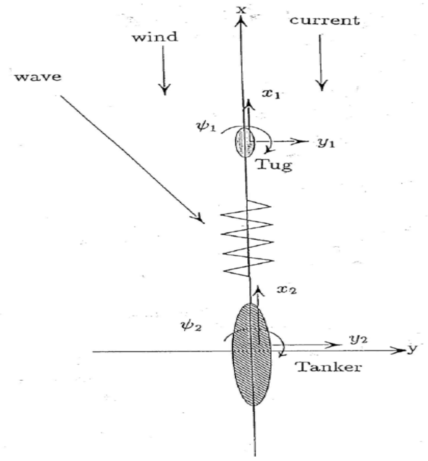

Figure 2 towing configuration in horizontal plane with external force

Table 1 Principal particulars of tankers

Tankers	Deadweight (*tons*)	L x B x d (*m*)	equipment number.	towline		
				length (*m*)	diameter (*mm*)	breaking load(*kN*)
A	20,000	135x21.3x8.6	1570	220	44	941
B	100,000	224x35.9x13.7	3210	280	56	1471
C	200,000	293x47.0x17.3	5500	300	56	1471

Figure 2 shows towing configuration in horizontal plane with external forces. The dynamic response motions in horizontal plane of tug and tanker tow system are simulated by solving the coupling motion equations of surge, sway and yaw of two ships connected by spring in time domain. The environmental forces and moments include wave exciting force, current force and wind force. The motion history of two ships influences the tension variation on the towline. The dynamic tension history is obtained from the non-1inear static characteristics with the horizontal distance of the towline at each time step.

Figure 3 shows (the maximum dynamic tension of towline) divided by (the mean pull of tug) (＝Td/Ts) which are obtained from the tension response for various conditions in time domain. The dynamic tensions on the towline of unit mass of 11*kg/m* with length varying from 500*m* to 1000*m* are shown in the figure for various Beaufort scales. Figure 4 shows the results for tanker C. From this the dynamic towing tensions for the bigger tanker C shows much higher than those for smaller tanker A. It may be considered that the motion response of tanker in the sea affects on the dynamic tension of towline.

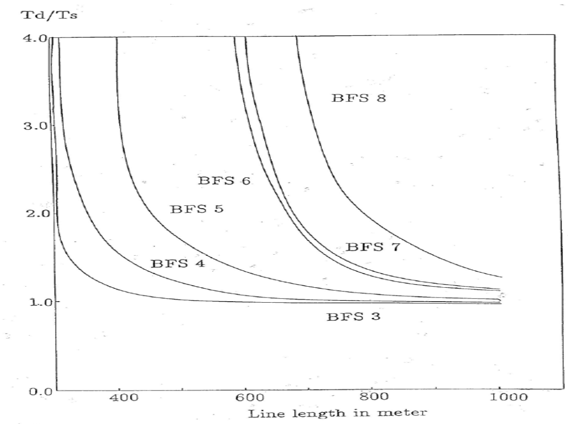

Figure 3 Dynamic tension for tanker A and tug A（mean pull 100*kN*）

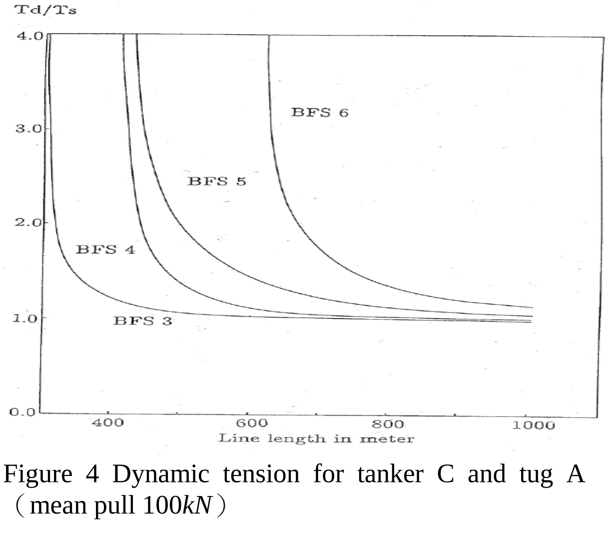

Figure 4 Dynamic tension for tanker C and tug A（mean pull 100*kN*）

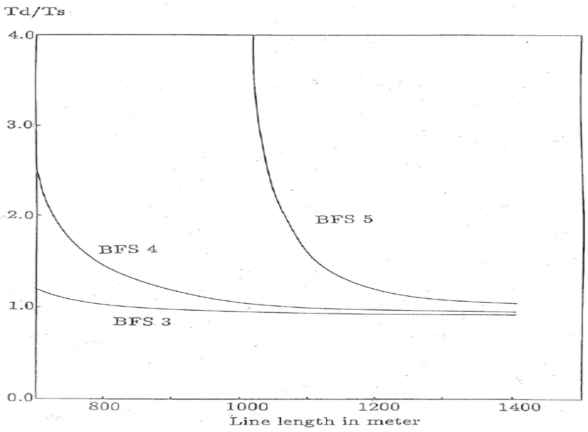

Figure 5 Dynamic tension for tanker A and tug B（mean pull 400*kN*）

The mean value of pull load for the movement of the surface vessels is very sensitive for the dynamic tension of the towline. Figure 5 shows the dynamic tension for tanker A towed by tug B. Due to a higher mean pull load of 400*kN* by tug B the dynamic tension is much increased even in the longer towline by comparing with Figure 3.

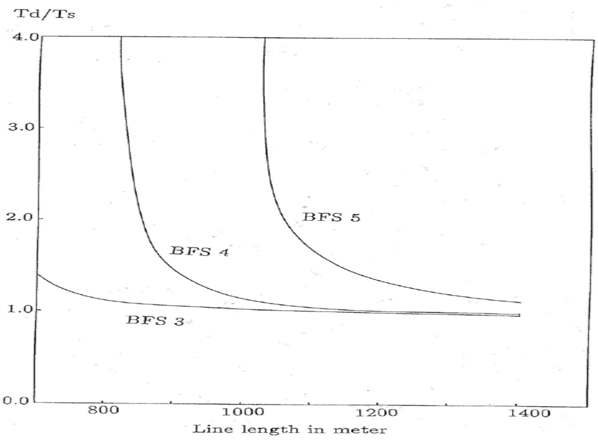

Figure 6 Dynamic tension for tanker B and tug B（mean pull 400*kN*）

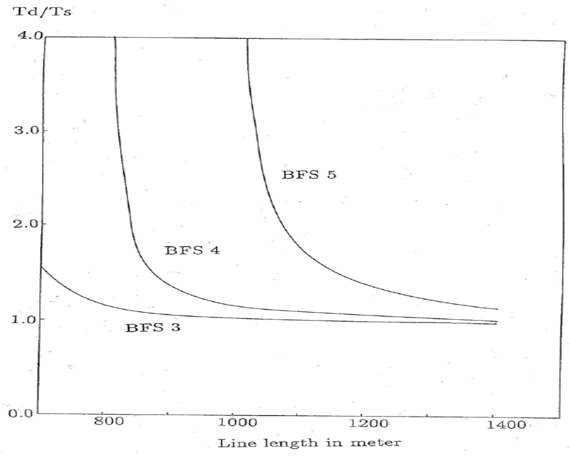

Figure 7 Dynamic tension for tanker C and tug B（mean pull 400*kN*）

In cases of the same tug B（pull load 400*kN*）for tanker B or tanker C no much differences are seen in the dynamic tension as shown in Figures 6 and 7.

From these results it can be seen that during the towing in the rough seas the dynamic tension of towline is much higher than mean pull load by the tug in case of without chain or some shock absorbers for towing wire rope even the length of towline is more than 1000*m*.

To reduce such high dynamic tensions, the additional chain may affect significantly as shown in Figure 3.

From these simulations the dynamic tension increases when, order of sea state is increased, the mean pull is increased and the length of the towline is decreased.

Rules and guidance of NK[3] show the following criteria as shown in Table 4 which are based on IMO guidelines for emergency towing arrangements on tankers. As heavy and long chain have more effective to reduce the dynamic tension of towline in the rough seas, grade 2 chain which is heavier than grade 3 has smaller safety factor for the design load as shown in the Table4. But this may not be definitely considered the dynamic tensions referred in this paper and may be considered corrosion margin and others.

Table 4 design criteria for emergency towing arrangements on tankers

deadweight	Emergency Towing Arrangements	chafing chain nominal diameter, breaking test load	
		grade 2	grade 3
20,000*tons* and over	1,000*kN* type	62*mm*, 2,060*kN*	52*mm*, 2,110*kN*
50,000*tons* and over	2,000*kN* type	90*mm*, 4,090*kN*	76*mm*, 4,300*kN*

3. RELATIVE WAVE HEIGHTS OF SHIPS IN SEVER SEAS

A ship will face various sea states during her voyage in ocean route. So the necessity of accurate predictions of ship motion, wave load, deck wetness and others in these sea state are not only necessary from the view point of seakeeping performance but also from the serious damage of excessive wave load in severe sea state which may even cause sinking of a vessel.

For determination of deck load and bottom slamming force, relative wave height may be considered as an essential parameter. A parametric study on relative wave heights of ships in short crested irregular waves are carried out[8,9]. In the paper linear potential theory has been used to describe the fluid motion and 3-D Green function method with forward speed has been used to determine hydrodynamic forces for surface ship advancing in waves. The time domain simulations of relative wave heights of typical container ships, bulk carriers, pure car carriers (PCC) and general cargo ships in short crested irregular waves have been carried out for sever sea states as shown in Table 5. Empirical roll damping has been taken into account in time domain analyses of motion responses of ships. The short crested irregular waves are generated by using ISSC wave spectrum and directional distribution function of cosine square. And for ensuring longer time simulation of the random sea waves, unequal frequency spacing method is used.

Table 5 Sea State for Numerical Simulation

sea state	mean period (*s*)	significant wave height (*m*)
moderate gale	6	5
strong gale	10	10
hurricane	10	15

As the numerical examples, typical bulk carriers of different sizes are present in this paper. The principal particulars of these ships are shown in Tables 6.

Table 6 Principal particulars of bulk carriers

Items	Bulk-14K	Bulk-140K
LBP (*m*)	120.0	260.0
B (*m*)	18.90	40.20
D (*m*)	10.56	22.18
D (*m*)	7.69	15.58
Δ (m^3)	13783	135661
U (*knots*)	8.0	9.8
C_b	0.790	0.8746
C_w	0.85	0.85
C_m	0.997	0.997
KG (*m*)	5.563	12.20
L.C.G. (*m*)	1.611	3.629
GM (*m*)	1.89	4.02
K_{xx}	34.0 % B	34.0 % B
K_{yy}	26.0 % LBP	26.0 % LBP
K_{zz}	26.0 % LBP	26.0 % LBP

Figures 8~11 show an example of time domain analysis for bulk carrier 140K in a short crested irregular wave for strong gale condition at cursing speed of 9.8 *knots*. Figure 8-10 show the motion responses of heave, roll and pitch in this sea state. Roll motion is induced even in head seas because of short crested irregular waves. Figure 11 shows corresponding relative wave height at forward perpendicular FP position of the ship.

After calculating relative wave height in time domain at side of the main hull, the maximum and the 1/3 highest mean values have been determined along the ship length.

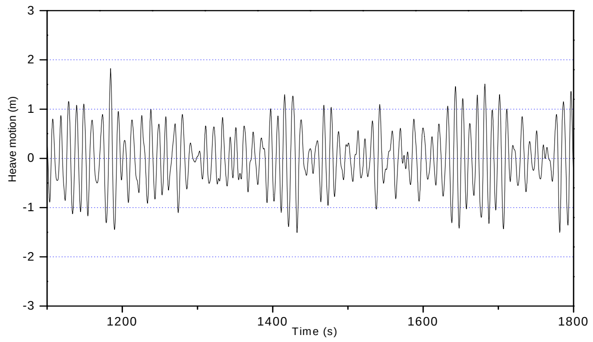

Figure 8 Heave motion of Bulk–140K in strong gale

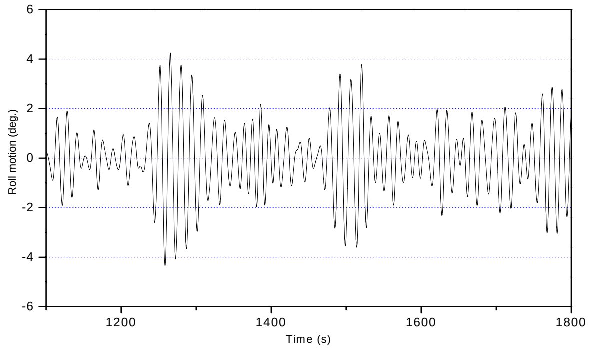

Figure 9 Roll motion of Bulk–140K in strong gale

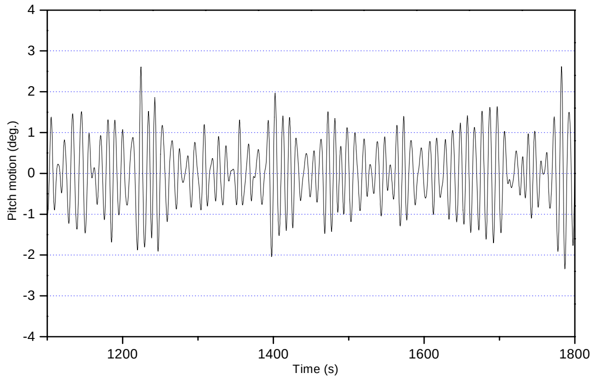

Figure 10 Pitch motion of Bulk–140K in strong gale

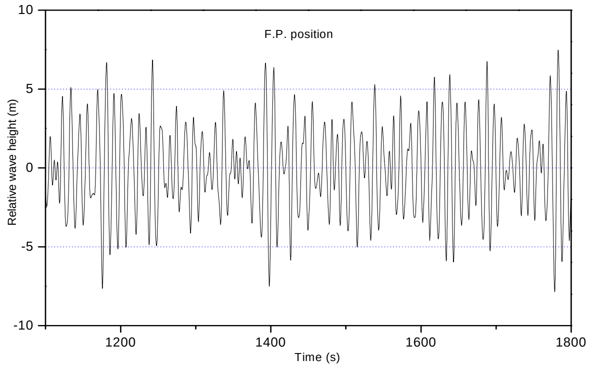

Figure 11 Relative wave height of Bulk–140K at F.P. position in strong gale

The minimum deck load for weather deck is required by rules and guidance of NK[3] as a function of vertical distance from the designed maximum load line to the weather deck at side. From this requirement, we can determine the corresponding height above where the weather deck load becomes zero. This corresponding height for the deck load may be considered as above the maximum relative wave height. The rule also requires closing appliances for the openings of outfitting on deck and where exceeds the some height of openings above the decks, such closing appliances may be omitted. This height for the closing appliances omitted may be considered as above the 1/3 highest mean values of relative wave height. These two kinds of heights are referred to the relative wave heights in various sea states.

Figures 12~14 show the results the maximum and the 1/3 highest mean of relative wave heights along the ship length of Bulk-14K for 3 different sea states.

The small bulk carrier Bulk–14K shows the relative wave heights are below the corresponding height for the deck load and also the height for the closing appliances omitted in moderate gale. But In hurricane the relative wave heights are over the reference heights and bottom slamming may be occurred. In strong gale the maximum values exceed the corresponding height for the deck load at fore and aft and bow slumming may be appeared some times.

Figures 15-17 show the results for the large bulk carrier Bulk–140K. The 1/3 highest mean as well as the maximum value are below the corresponding height for the deck load and also the height for the closing appliances omitted and may not be appeared bottom slamming even in hurricane condition.

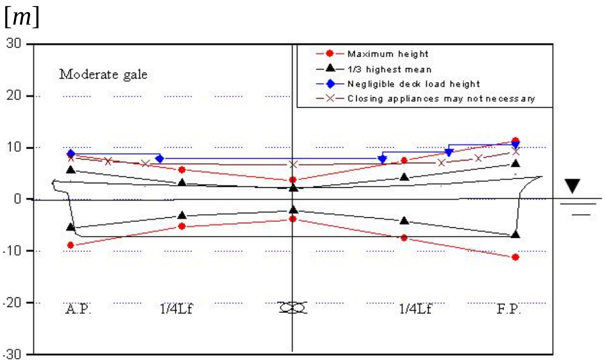

Figure 12 Relative wave height of Bulk–14K in moderate gale

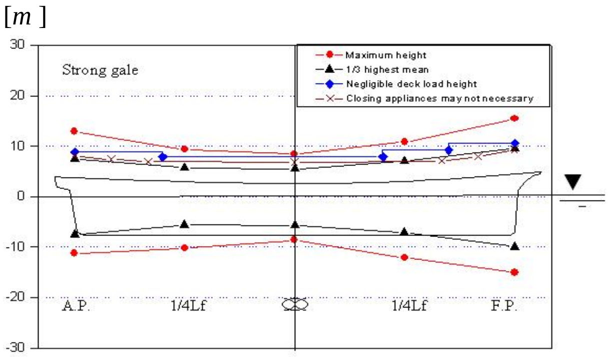

Figure 13 Relative wave height of Bulk–14K in strong gale

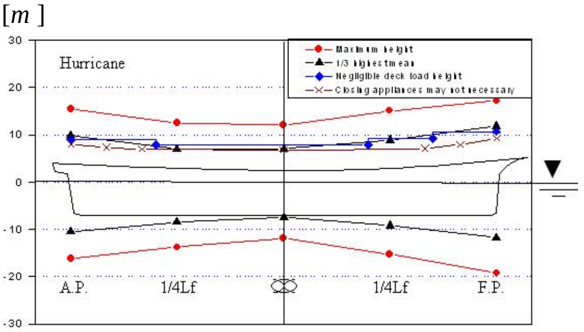

Figure 14 Relative wave height of Bulk–14K in hurricane

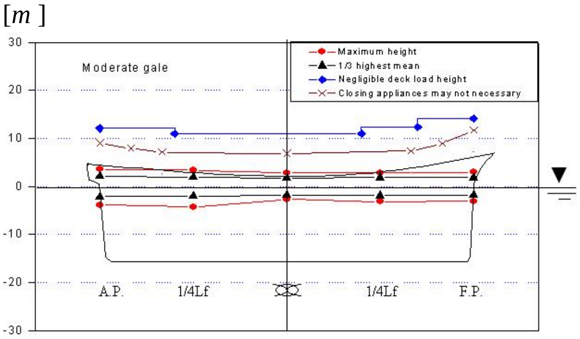

Figure 15 Relative wave height of Bulk–140K in moderate gale

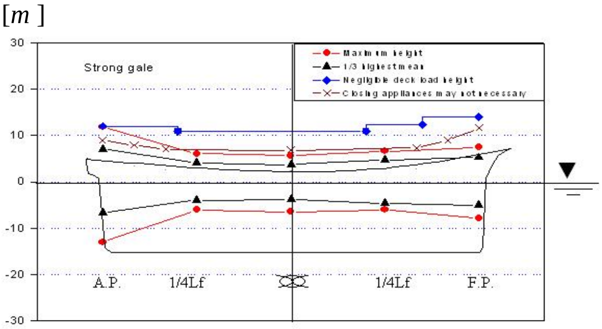

Figure 16 Relative wave height of Bulk–140K in strong gale

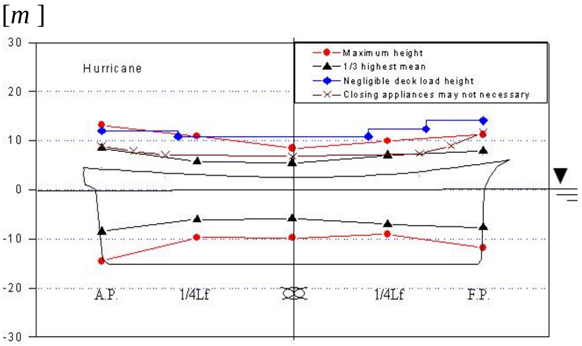

Figure 17 Relative wave height of Bulk–140K in hurricane

From these numerical simulations, except in hurricane condition, the numerical result of the 1/3 highest mean value is almost below the height at where closing appliances are not necessary as well as corresponding height to the minimum requirement of deck load.

IACS S27 “Strength requirement for deck fittings and equipment” gives the velocity of water over the fore deck is 13.5 *m/s* as the applied loading for air pipes, ventilator pipes and their closing devices[2]. This dynamic pressure corresponds to the sea water pressure head of 9.3*m*. And IACS S21 ”Evaluation of Scantlings of Hatch Covers and Hatch Coamings (Rev. 4)” also gives hatch cover load model[2]. By IACS S21, the pressure at the forward perpendicular may be water pressure head 5.0*m* for Bulk-14K and 6.0*m* for Bulk-140K respectively. And the pressure at midship part is 3.4*m* for both of Bulk-14K and 140K. These water pressure heads are close to the heads of corresponding to the 1/3 highest mean values of relative wave height in strong gale for Bulk-14K and in hurricane for Bulk-140K respectively. This may suggest the regulations require more severe sea conditions for the larger ships than the smaller ships.

4. MOTION RESPONSES OF A MEGA CONTAINER SHIP IN SEAWAYS

A ship will face various sea states during her voyage in ocean route. Large motion acceleration of ship in severe sea state may cause serious damages of cargoes and lashing equipments especially for the huge container ships. Since ship motion accelerations in sea ways are functions of ship geometry, mass distribution, ship speed and wave conditions, the assessment of seaworthiness characteristics of a ship requires large number of variations covering all possible wave directions and ship speeds.

In the paper[5], by using the same computer code based on 3D Green function method with forward speed[8,9], some numerical simulations of accelerations due to ship motions in waves are carried out for a typical mega size container ship. The numerical results of the maximum and the 1/3 highest mean of transverse and vertical accelerations along the ship length are determined from the time domain analyses. The principal particulars of the ship are shown in Table 7. The accelerations of ship motion are calculated on the weather deck and the top of containers 15*m* above the deck. The simulations are performed in the hurricane with the significant wave height of 10*m* and mean wave period of 15*s*. All calculations are carried out for the main wave direction of attack angle of 180 *deg* (head sea), 150 *deg* (bow sea) and 120 *deg* (oblique sea).

The numerical simulations of the ship have been also performed in the significant wave height of 10m and mean wave period of 20s. The wave condition of the significant wave with mean wave period of 20s seems to be too large swell in the ocean. DNV and NK may consider the design wave height of 10.75m for the wave period of 15s and 8.28m for 20s respectively.

Table 7 Principal particulars of a mega container ship

LBP	320 *m*
B	42.80 *m*
D	24.40 *m*
D	14.00 *m*
Δ	115,584 m^3
U	24.5 *knots*
C_b	0.602
KG	17.40*m*
L.C.G.	-3.86 *m* (aft)
GMT	2.60*m*
GML	530 *m*
K_{xx}	16.1 *m*
K_{yy}	79.3 *m*
K_{zz}	79.3 *m*

Figures 18~23 show the results the 1/3 highest mean and the maximum of transverse and vertical accelerations on deck height and the top of containers along the ship length at side. In these figures design criteria values by the guidelines for container lashing forces are also shown to compare with the results of numerical simulations in the strong gale. From these numerical results, we can see the maximum values are greater than 2 times of the 1/3 highest mean values at both ends of the ship in the wave condition of strong gale. This may be appeared from beating of coupling motions of roll, sway and yaw for the transverse, and heave and pitch for the vertical accelerations respectively.

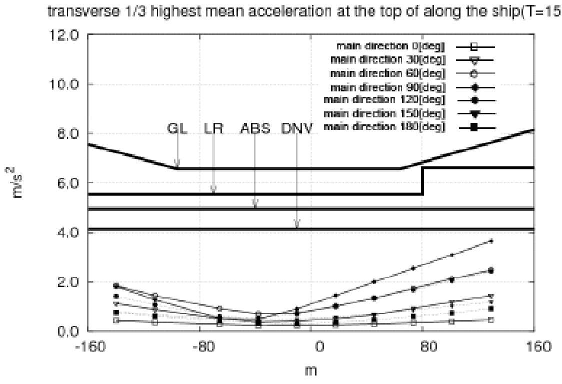

Figure 18 The 1/3 highest mean transverse acceleration at 15m above the deck in the hurricane

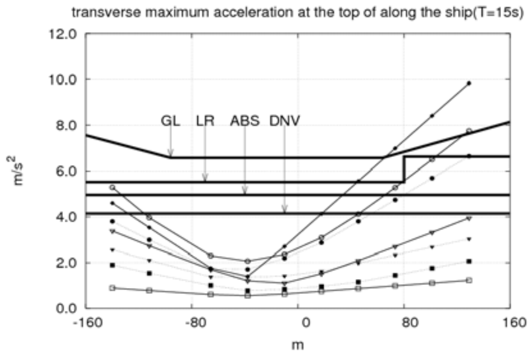

Figure 19 The maximum transverse acceleration at 15m above the deck in the hurricane

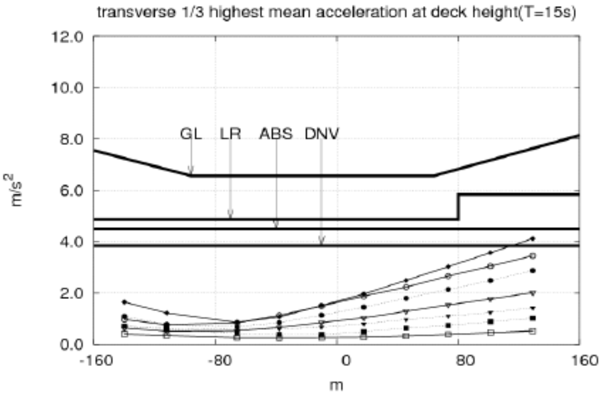

Figure 20 The 1/3 highest mean transverse acceleration at deck height in the hurricane

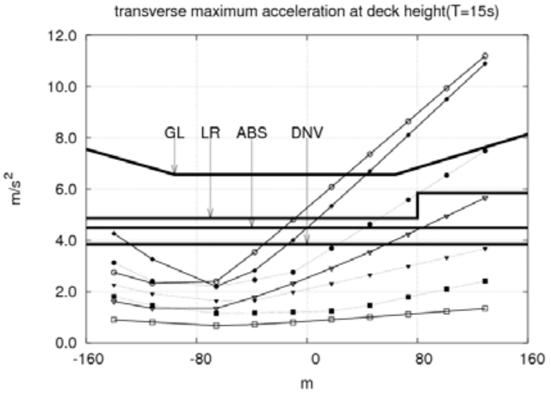

Figure 21 The maximum transverse acceleration at deck height in the hurricane

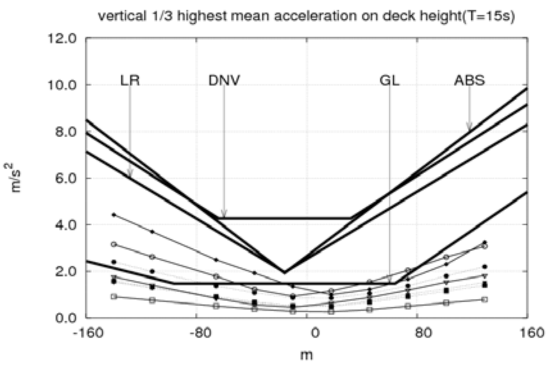

Figure 22 The 1/3 highest mean vertical acceleration in the hurricane

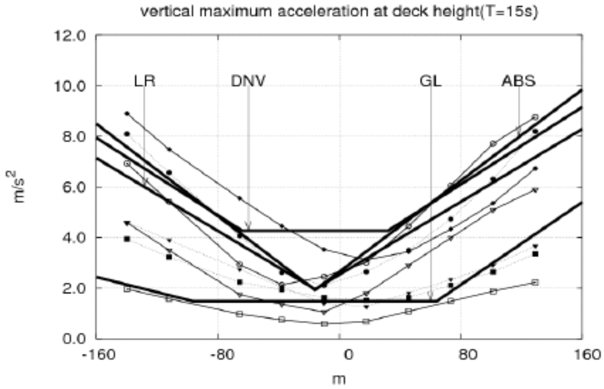

Figure 23 The maximum vertical acceleration in the hurricane

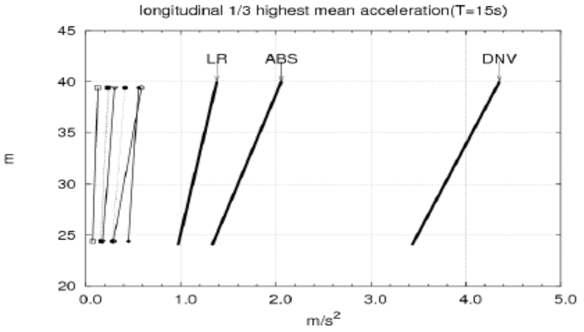

Figure 24 The 1/3 highest mean longitudinal acceleration in the hurricane

We can recognize the transverse accelerations at the bow are larger than those at stern as shown in Figures 18 to 21. The transverse acceleration due to yaw motion is added to those of sway and roll as plus and minus to fore and aft. So that at stern the transverse acceleration on deck is larger than those at the top of containers 15*m* above deck.

The transverse acceleration at forward location of the ship at the mean wave period of 15s is higher than those at the mean wave period of 20s which is more close to the natural period of roll as shown in Figures 26, 27. This is caused by the effect of yaw motion to roll and sway motions at higher frequency than the natural frequency of roll. LR, ABS and DNV may not consider yaw motion in their guidance. Classes may consider the design transverse acceleration at the maximum roll motion at the resonance wave period and the design vertical acceleration at the maximum pitch motion. LR[10] considers the force from wave impact and shipping green seas where the form and proportions of the ship are such that these may occur. In general the design load for the securing arrangements in the forward 0.25LBP are to be suitable for forces increased by 20% except where it can be shown that the containers are adequately protected by break-water or similar structure[10]. Corresponding to this requirement the transverse acceleration by LR is increased by 20% in the forward 0.25 LBP in Figures 18 to 21, 25, and 26.

In huge swell condition, the transverse accelerations by guidance of classes show partially smaller than the maximum values of the simulations as shown in Figure 26, 27. In these huge swell conditions the maximum roll angle reaches 35degrees[5]. We may not need to consider such severe huge swell sea state for the container securing systems.

The vertical accelerations of GL guidelines show lower than the simulation results. GL guidelines show the influence of the container fore to aft for the transverse acceleration and show the same tendency to the simulation results.

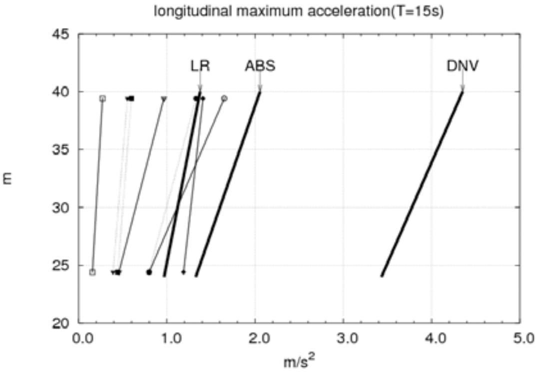

Figure 25 The maximum longitudinal acceleration in the hurricane

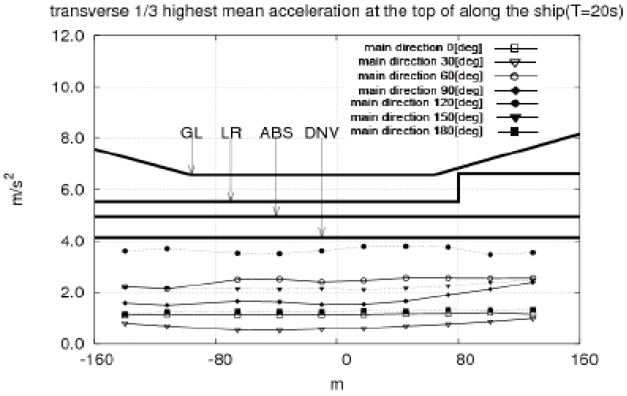

Figure 26 The 1/3 highest mean transverse acceleration at 15m above the deck in huge swell

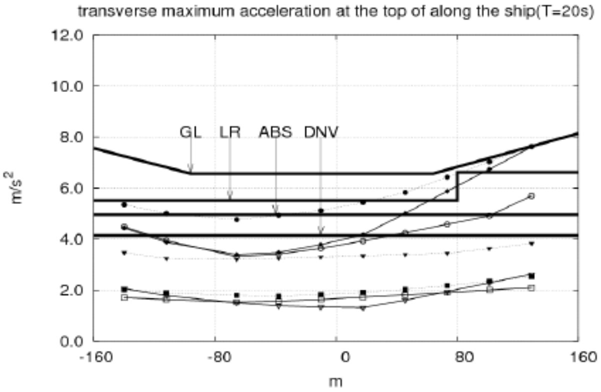

Figure 27 The maximum transverse acceleration at 15m above the deck in huge swell

Though the numerical simulations have been performed only for a typical huge container ship in limited wave conditions, they may suggest that necessity of considering the effect of yaw motion to the transverse acceleration. So the following simplified correction to the guide lines of classes for the container securing systems may be suggested as

$$C = 1 + (x - 0.75L_{BP})/L_{BP} \quad \text{for} \quad x \geq 0.75\,L_{BP}\ .$$

Where, x is longitudinal distance from aft perpendicular to the considered center of gravity of the container.

Due to this correction the design load for the securing arrangements in the forward are to be lineally increased up to 25%. This correction has been applied for NK new guideline[11].

5. CONCLUSION

Though the design criteria of equipments and fittings of ships are not only based on the dynamic behaviors of ships in the sea but also other environmental and functional loads, and so many factors, the author however reviews his papers on studies of dynamic tension of towline and motion responses of ships in short crested irregular waves to understand and discuss these design criteria. The time domain simulations of motion accelerations of a typical mega size container ship in short crested irregular waves have been carried out to compare guidelines of classes.

By the numerical simulation studies, we can see some design criteria are reasonable and may be improved in the consequences of dynamic behaviors of ships in the sea.

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