Development of VLCC without the Cross-tie between Longitudinal Bulkheads ("Cross-tieless Cargo Tank of VLCC")

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Abstract

In the past decades, it has been a standard design of VLCC (Very Large Crude oil Career)to have a cross-tie structure between longitudinal bulkheads in order to support each bulkhead. The cross-tie structure effectively supports the vertical webs on the bulkheads so that the scantlings of adjacent structuresincluding the vertical webs and stringers could be optimized. However, the cross-tie structure is considered as an unstable structure because both of its ends are supported by the middle of the vertical webs on the bulkheads and its ends normally behave independently resulting to large deformation. Therefore, intersection points of the cross-tie and the vertical webs on the bulkheads havealways been exposed to potential damage such as a crack. For this reason, CSR (Common Structural Rules) published by IACS (International Association of Classification Societies) has been continuously defining the strength requirements of the cross-tie structure. In addition, the cross-tie affects the productivity because many scaffoldings and ladders should be provided during block fabrication and erection stage. In order to improve and solve these problems, VLCC without the cross-tie or "Cross-tieless cargo tank of VLCC" has been developed. Instead of the cross-tie, adjacent structures have been reinforced and verified based on IACS CSR Double Hull Oil Tankers Rulesconsidering yield and buckling strengths. Sloshing behaviors of Cross-tieless VLCC were compared to VLCC with the cross-tie and proved that sloshing pressure to cargo tank did not increase significantly. Moreover, the cross-tieless structure has been also verified against vibration and the structure is estimated to be more stable than with cross-tie.

1. Introduction

Steel plated structures such as ship and offshore structures exposed to both hydrostatic and hydrodynamic loads consist of stiffened panel and single or complex girders,also called grillage structures, which are both supported by longitudinal girders and transverse frames [1]. Stiffened panel models locally behave against external force while girder structures should be designed against global load from local behavior of the stiffened panels.

The structure can also be supported by pillars if the girder structures are not sufficient to control the deformation or deflection due to the width of the structure and limitation of girder size. As far as the design of pillar structure is concerned, buckling strength due to axially compressive load on the pillar and the local strength of the connection of pillar and girder should be specially considered.

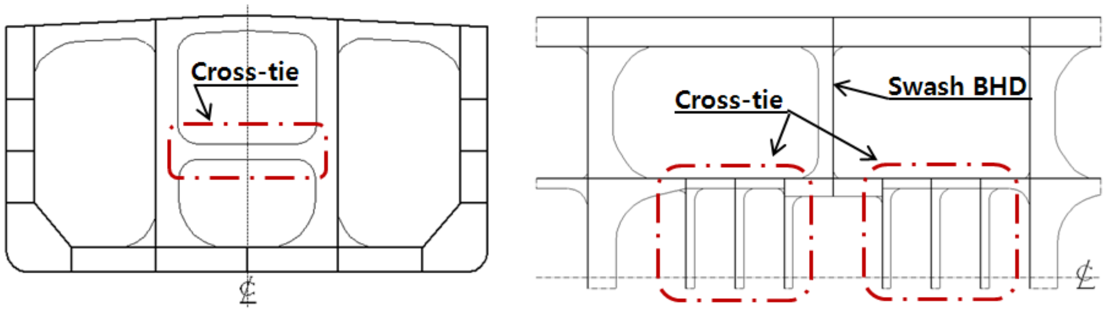
Generally, longitudinal bulkheads as cargo tank boundary oil tankers are built with stiffened panel and vertical web frames, which are main girder structure. In the case of very large vessels such as VLCC or VLOC (Very Large Ore Career), it has been known that the vertical webs on the longitudinal bulkheads are so long that cross-tie structures are normally installed transversely in the middle of center cargo tanks or wing cargo tanks in order to reduce the scantling of adjacent structures such as vertical web frames or stringers.

In way of the connection area between cross-tie and vertical web frames on longitudinal bulkhead, the large and various types of deflection are normally expected due to several tank loading patterns. Moreover, unlike other beam or pillar structures, the cross-tie is unstable because the conditions of both of the end boundaries are not considered asfixed. As a result of the characteristics of its behavior, damage such as fatigue cracks hasoften been reported due to the stress concentration from various types of large deformation. In addition, high place to do fabrication work is inevitable during the production stage of cross-tie structure and a number of portable ladders and scaffoldings are required. Thisworking environment can cause higher probabilityfor human error. If the cross-tie structure collapse due to the mentioned reasons, disaster such as global collapse of longitudinal bulkhead will be unavoidable. So far, the cross-tie structure has been reinforced whenever casualty is reported.

The present paper addresses the development of cargo hold structure design of VLCC without cross-tie also called as"Cross-tieless cargo tank of VLCC (hereafter cross-tieless)". In order to establish acargo tank without the cross-tie, vertical web frames on longitudinal bulkheads and main stringers were reinforced and verified to have adequate strength and stiffnessaccording to CSR. As for the sloshing behavior in the tanks, it is known that cross-tie's role is to reducethe sloshing pressure. This paper also introduces the comparison of sloshing pressure in cargo tank with and without cross-tie in orderto compare the effectiveness in reducing the pressure. In addition, vibration behavior has been studied against unit excitation force in cargo tank with and without cross-tie.

2. Cross-tie structure in VLCC

Cross-ties are defined as large transverse structural members joining longitudinal bulkheads and used to support them against hydrostatic and hydrodynamic loads according to CSR Double Hull Oil Tankers (hereafter CSR) published by IACS [2]. In other words, two longitudinal bulkheads supported by vertical webs would be reinforced by means of cross-tie as a pillar structure. Mostly, cross-tie structures are installed transversely in center cargo tank of VLCC as shown in Fig. 1,otherwise between longitudinal bulkhead and inner hull in both port and starboard wing cargo tanks in some of the previously built vessels.



(a) Typical Trans. Web Section (b) Stringer Plan

Fig. 1 Cross-tie structurein cargo tank of VLCC

According to CSR [2], design concept of cross-tie structure has been addressed based on maximum permissible buckling strength against design axial load on the structure as described equation (2-1)

$$W_{ct} \leq W_{ct\_perm} \quad (2\text{-}1)$$

Where, W_{ct} applied axial load

$= P b_{ct} S$ [kN]

W_{ct_perm} permissible load

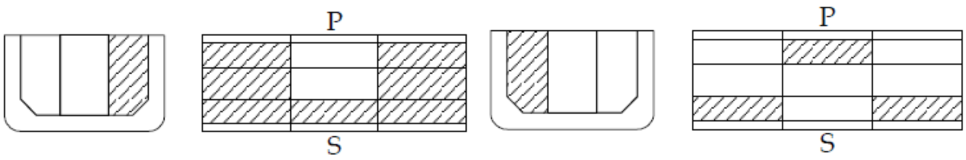
$= 0.1 A_{ct\text{-}net50} \eta_{ct} \sigma_{cr}$ [kN]

P maximum design pressure for all the applicable design load sets being considered in kN/m^2

b_{ct}breadth of design pressure considering arrangement of cross-tie in cargo tank

S primary support member spacing, in m
η_{ct}utilization factor (0.65 and 0.75 for acceptance criteria set AC1 and AC2 respectively)
σ_{cr}critical buckling stress in compression of the cross-tie, in N/mm^2
$A_{ct\text{-}net50}$net cross sectional area of the cross-tie, in m^2

If the cross-tie structure is installed in center cargo tank and the ship's loading manual includes a non-symmetrical loading condition with only one of the wing tanks filled, loading pattern as shown in Fig. 2 should also be consideredwhen finite element analysis for both seagoing and harbor conditionsis carried out.



(a) Loading Pattern A7 (Seagoing) (b) Loading Pattern A12 (Harbour)

Fig.2 Additional loading case for FEA from CSR if cross-tie arrangement in center cargo tank [2]

As aforementioned regarding the characteristic of the cross-tie structure in chapter 1, both ends of the structure are not fixed and behave independently.The relative displacement should be larger and moredisplacement patterns than those of typical beams or pillars in certain loading patterns. This means that stress range value due to repeated loading is higher than other beams or pillars and the possibility of future crack in way of the cross-tie structure cannot beneglected. As shown in Fig. 3, cracks on weld joints of tripping brackets in way of cross-tie end have been reported. The main reason considered is the high cycle fatigue caused by repeated cargo loading during seagoing operation, low cycle fatigue due to cargo loading and unloading or even vibration fatigue.

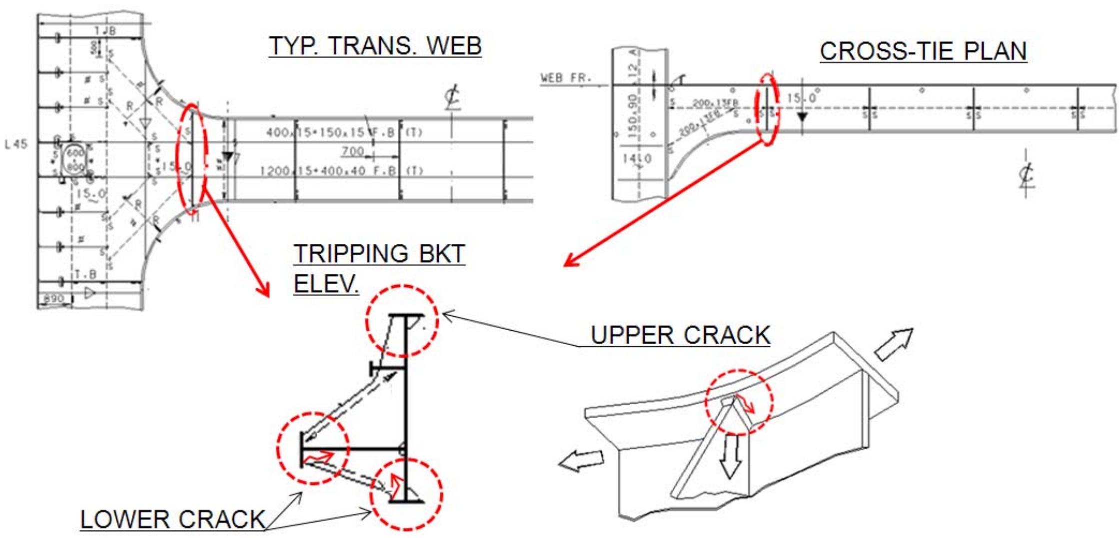


Fig.3 Typical fatigue crack in way of cross-tie and vertical web frames in cargo tank

From the productivity point of view, the cross-tie structure is a very weak point in VLCC. Due to its pillar shape and location, high placesto work in during both fabrication and erection stagescannot be avoided as shown in Fig. 4. Aside from the increased cost due to excessive provision of scaffoldings and ladders, the fabrication of cross-tie structure is not a recommendedpracticeconsidering the safety of the workers. Poor working condition can easily cause human error and quality problems, which leads to aforementioned damage regardless of design problem.

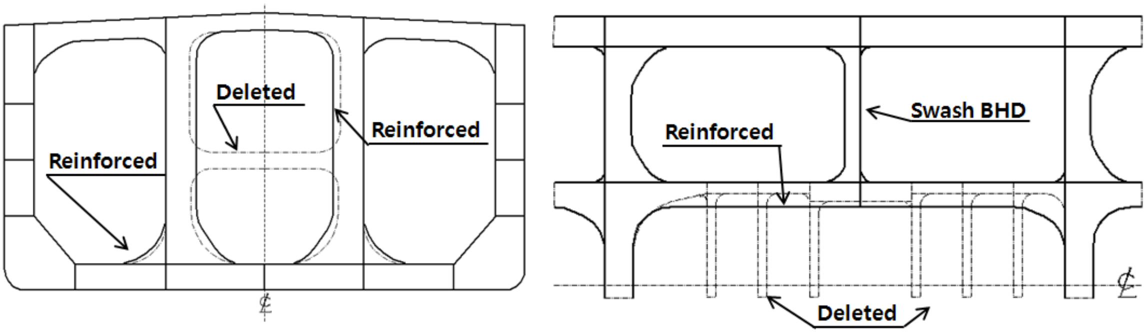
(a) Temporary scaffolding for fabrication stage (b) Temporary scaffolding for erection stage

Fig.3 Example of scaffolding for cross-tie structure installation

3. Development of Cross-tieless cargo tank of VLCC

With the intention of eliminating the problems caused by having a cross-tie, "cross-tieless" cargo tank has been recently proposed and developed by removing the cross-tie and reinforcing vertical web frames, horizontal stringer and adjacent structures in order to compensate for the structural strength as shown in Fig.4.

The design has been carried out in accordance with CSR where therequirements arewell-defined and considered to be more conservative compared to the results of direct calculation of wave loads, etc. There is also no change in the environmental condition of ship operation. Therefore, it is believed that CSR requirements are satisfied in developing the structural adequacy ofthe proposed cross-tieless concept. To verify the structural reliability of the proposed structure, finite element analysis has been performed including buckling check and very fine mesh analysis locally according to CSR procedures. In case of the conventional cross-tie structure, areas prone to fatigue damage,such as the intersection point of cross-tie and vertical web,are very critical to verify the structure with. However, thisfatigue check is not necessary in a cross-tieless cargo tank because the mentionedcritical area is removed in the new structure. It has been known that the internal members in cargo tank have the role of reducingthe sloshing pressure. In this paper, comparison of sloshing behavior was investigated to show how effective the cross-tie structure and reinforced vertical web frames can reduce sloshing pressure in three different types of cargo tanks: a conventional tank with cross-tie, a tank wherethe cross-tie is removed and a cross-tieless cargo tank with increased reinforced vertical web frames. Vibration behavior has also been studied from unit excitation force to prove that cross-tieless cargo tank has more advantages in reducing vibration level in cargo tanks.

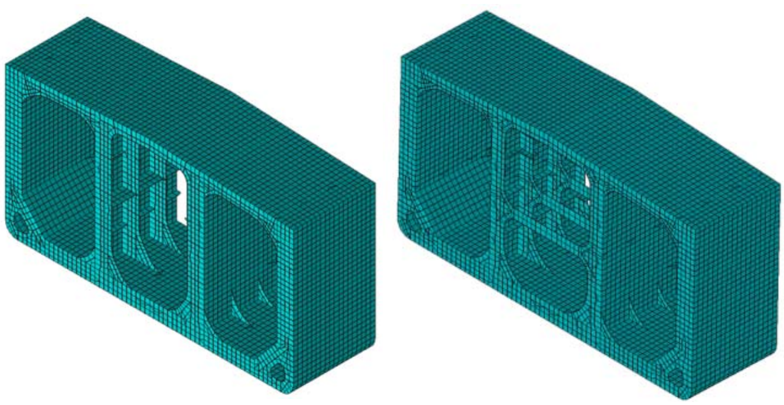


(a) Typical Trans. Web Section (b) Stringer Plan

Fig.4 Cross-tieless cargo tank in cargo tank of VLCC

3.1 Comparison Study in Structural Analysis for Cargo Tank with and without Cross-tie

The assessment technique employed the use of finite element methods for the evaluation of stress as required by CSR [2]. The target finite element model is 0.4L amidship cargo hold area of DSME (Daewoo Shipbuilding & Marine Engineering Co., LTD.) built standard cross-tieless 318,000 TDW Crude Oiler Tanker. The cargo hold has been evaluated by yieldstrength, buckling strength as well as local fine mesh structural strength analysis. In order to verify structural adequacy and reliability of primary structural members for the proposed model, the structure has been compared with the result of finite elementanalysis for conventional cross-tie structure. The analysis was carried out by utilizing the program of SeaTrust-Holdan Ver. 4.62 of Korean Register of Shipping and Nastran solver Ver. 2007 R2. Fig. 5 shows the example of finite element models for both conventional cross-tie and proposed cross-tieless structure respectively. The actual models for finite element analysis have been extended to three (3) full cargo hold models. According to the definition of load case in CSR (Appendix B), cargo tank without cross-tie structure in center cargo tank do not have to be carried out with regards to the loading pattern,in which only one wing cargo tank is fulfilled. However, both models have been evaluated in these loading patterns regardless of cross-tie installation in order to compare the structural behaviors.In order to link into the adequate result of finite element analysis, the procedure of each analysis has been repeated accordingly considering yielding, buckling and local fine mesh analyses respectively.



(a) Cargo Tank without Cross-tie (b) Cargo Tank with Cross-tie

Fig. 5Finite Element Model of Cross-tie and Cross-tieless cargo tank of VLCC

1) Yielding Strength Assessment

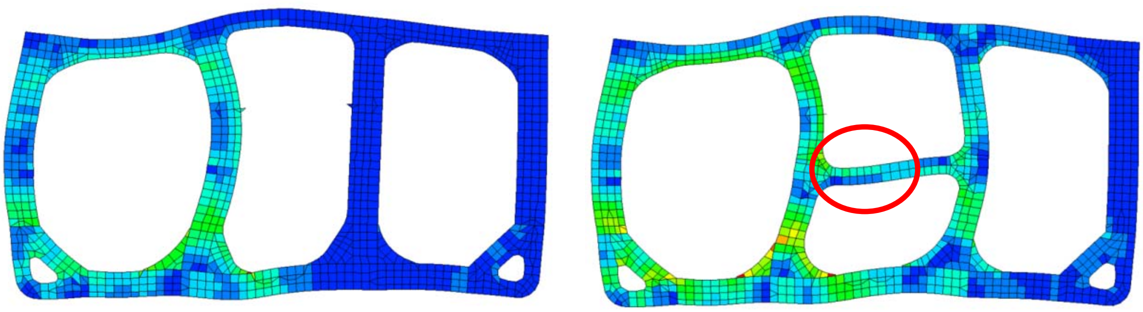
The depth ofexisting vertical web frames was increased by 30% while the scantlings, such as web plate thickness and face plate size havealso been improved. As a result, the vertical web frames has twice stiffness as before, which compensates for the elimination of the cross-tie. Inspection walkway on No. 2 stringer level is replaced to a large stringer structure to reinforce the longitudinal bulkhead by forming a grillage structure.

Fig.6 and 7 show the result of typical stress plot and displacement with regards to CSR load case A12. In case of load caseA12,in which only one wing cargo tank is fulfilled and the wing cargo tank and center cargo tank are empty, cargo internal load in the wing cargo tank can be delivered through the cross-tie for the conventional cross-tie structure. Structural behaviors such as deformation and stress level in way of the connection area between cross-tie and vertical web frames are very criticaland should be specially designed and considered. Proposed cross-tieless cargo tank, on the other hand, consists of a typical grillage structure where port and starboard longitudinal bulkheads behaved independently.

Principal reinforcements for newly proposed cross-tieless cargo tank are as below;

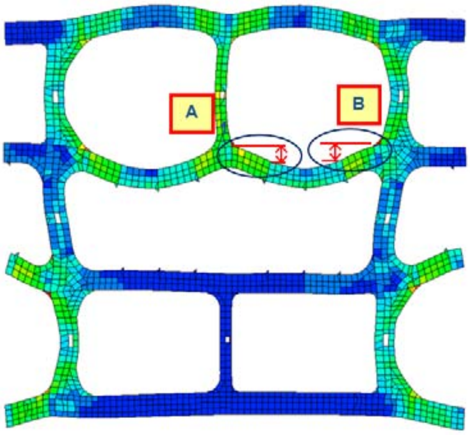
- Depth and thickness of vertical web frames
- Face plate of vertical web frames.
- Large end bracket in way of lower vertical web
- Large stringer on No. 2 stringer plan instead of inspection walkway
- Inner bottom floor thickness in way of lower vertical web
- Swash bulkheadface plate
- No. 1,2 & 3 transverse stringer web thickness and face plate
- Longitudinal bulkhead thickness in way of transverse bulkhead

Most of the adjacent structures should be reinforced to compensate the removal of cross-tie. The joint structure in way of No. 2 stringer plan and lower vertical web frames are increased to become a robust structure.

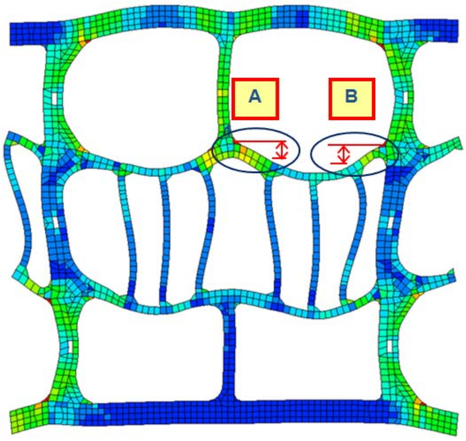


(a) Typical Transverse Web without Cross-tie (b) Typical Transverse Web with Cross-tie

Fig.6 Example of yield stress plot & deformation for cargo tank (Section View, CSR Loading A12)



(a) No.2 Stringer Plan without Cross-tie



(b) No. 2 Stringer Plan with Cross-tie

Fig.7 Example of yield stress plot & deformation for cargo tank (Plan View, CSR Loading A12)

Relative displacement on No. 2 stringer plan between the swash bulkhead and forward frame and between the transverse bulkhead and aft frame are investigated as shown in Fig. 7 and Table 1. As a result, larger relative displacement induces higher stress range for cargo tank loading and unloading as well as higher probability of damage occurrencesuch as fatigue crack and buckling. The deformations of longitudinal bulkheads affect the yield and fatigue strengths of bulkheads stiffeners as well as the strengths of vertical webs and stringers. Hence, the strength and stiffness of the cross-tieless structure is designed to be at least as high as the conventional design but with control on thepure bending deformation and relative displacement of longitudinal bulkheads. Detailed analysis of the structure has been carried out after the pure bending deformation and relative displacement of the longitudinal bulkheads are controlled.According to Table 1, relative displacement of proposed cross-tieless structure is lower than that of a conventional cross-tie structure in the vicinity of swash and transverse watertight bulkheads.This means that the proposed cross-tieless cargo tank is a more sound structure than cargo tank with cross-tie from the stiffness point of view.

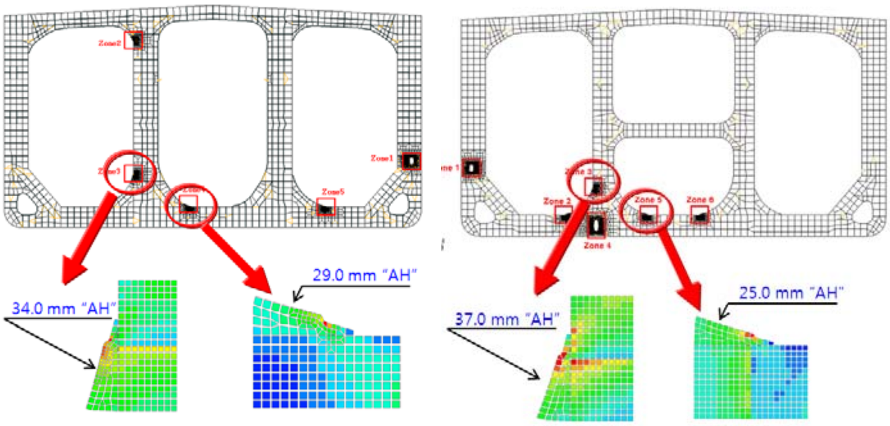
Table 1. Relative displacement from swash or transverse bulkhead to next frames (Unit : mm)

	Coordinate direction	Point A (Swash BHD to next Frame)		Pont B (T.BHD to previous Frame)	
		Cross-tieless	Cross-tie	Cross-tieless	Cross-tie
No.2 STR Plan (L45, Cross-tie)	x	1.8	1.5	2.0	1.5
	y	**16.0**	**18.4**	**14.9**	**21.1**
	z	2.3	2.0	2.3	2.2

2) Buckling Strength Assessment

Buckling strength analysis has also been carried out according to CSR procedure. All primary members throughout the cargo tank have been evaluated using DNV PULS in terms of advance buckling check. Regardless of advance buckling strength check, cross-tie structure should be verified as a pillar against compressive load along the cross-tieconsidering critical buckling stress according to CSR Chapter 10. According to the mentioned chapter in CSR, buckling utilization factor for cross-tie is maximum 75%comparedto other structures, which means that it has to have approximately 25% more margin than the other structures. The utilization factor for cross-tie is known to be adjusted based on the calibration with the sample vessels [3]. It is believed that the reason of the calibration is to reflect the unknown factor for unstable cross-tie structure. As a result of advanced buckling check, the plate of swash bulkhead should be reinforced with buckling carling due to the absence of cross-tie and increased compressive stress on the bulkhead.

3) Local Fine Mesh Assessment
Local fine mesh strength analyses has been carried out according to CSR procedure to verify critical areas such as soft toe, heel of large bracket and structureswith opening nearby with maximum 50x50 mesh size. According to the results, a few bracket end toes or heels of vertical webs and stringers are reinforced compared with the conventional cross-tie structure. However, there is only a slight increase or almost the same thickness in most of the critical areassince the scantlings of the primary members has already been increased and reinforced at the yield strength assessment stage. The examples of local fine mesh analyses model and the results are shown in Fig.8.



(a) Typical Transverse Web without Cross-tie (b) Typical Transverse Web with Cross-tie

Fig.8 Example of local fine mesh model and result for cargo tank (Section View)

3.2 Comparison Study in Sloshing Behavior of Cargo Tank with and without Cross-tie
In this chapter, comparison study with regards to sloshing pressure has been carried out to verify the condition of the primary support members in cargo tanks with or without the cross-tie structure. In order to examine the reduction of efficiency, three (3) model cases have been proposed as below;

- Case.1 Center Cargo Tank with Cross-tie (Conventional Type)
- Case.2 Center Cargo Tank without Cross-tie
- Case.3 Center Cargo Tank without Cross-tie and increased Vertical Web (Proposed Cross-tieless)

Sloshing pressure to longitudinal liquid motion in way of transverse tight bulkhead, P_{slh_lng}has been estimated according toCSR [2] as described in equation <3-1>.

$$P_{slh\_lng} = \rho g l_{slh} f_{slh} \left[0.4 - \left(0.39 - \frac{1.7 l_{slh}}{L}\right)\frac{L}{350}\right] \text{kN}/m^2 \quad \text{<3-1>}$$

Where, ρ density of liquid in the tank in tonnes/m^3, not to be less than 1.025
l_{slh} effective sloshing length, at considered filling height, in m
f_{slh} = 1-2(0.7-h_{fill}/h_{max})^2
h_{fill}filling height, measured from inner bottom, in m
h_{max}maximum tank filling height, measured from inner bottom, in m
L rule length, in m

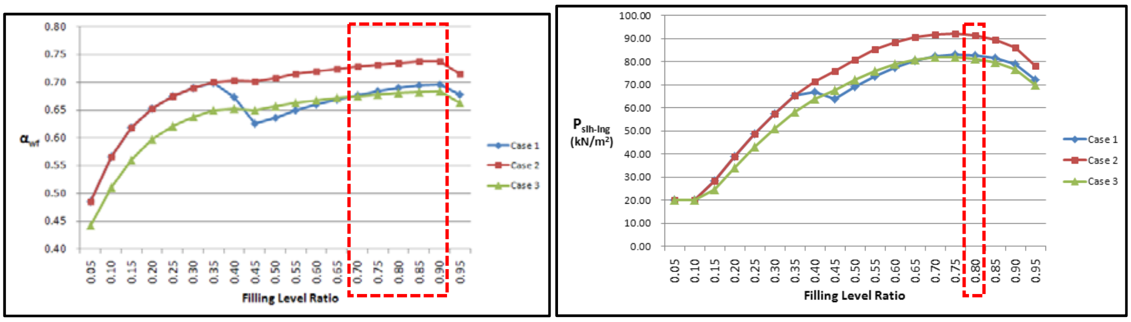
According to CSR, sloshing pressure should be taken as a constant value over the full tank depth and is to be taken as the greater of the sloshing pressures calculated for filling heights from 0.05h_{max} to 0.95h_{max}, in

$0.05h_{max}$ increments. Before CSR, maximum pressure wasdefined at 70% of filling level in certain class requirements [4]. It has been known that the maximum sloshing pressure, however, is normally taken between $0.70h_{max}$and $0.85h_{max}$ due to the maximum effective sloshing length, l_{slh} at other filing levels even though the maximum f_{slh}factor in equation <3-1> is defined at $0.7h_{max}$. Another main factor of sloshing pressure is the total opening area in the transverse section in way of web frames. As far as the variation of sloshing pressure is concerned, smaller total opening area gives lower sloshing pressure because the internal members in cargo tank would be roll of the resistance of sloshing phenomena. The ratio of the total opening area to the total cross sectional area of the cargo tank is defined as transverse web frame coefficient (α_{wf}) as described in equation <3-2> and the coefficient is included in the equation of effective sloshing length, l_{slh}.

$$\alpha_{wf} = \frac{A_{opn\_wf\_h}}{A_{tk\_t\_h}} \quad \text{<3-2>}$$

Where, $A_{opn_wf_h}$total area openings in transverse section i.w.o web frame below considered filling height
$A_{tk_t_h}$total transverse cross sectional area of tank below considered filling height

Transverse web frame coefficient (α_{wf}) with regards to filling level ratio is displayed in diagram form in Fig. 9 (a) and maximum values are calculated between $0.70h_{max}$and $0.85h_{max}$ filling levels. Comparing cases 1 and 3, the coefficient value of case 1 (cross-tie structure) begins with a higher value than that of case 3 (proposed cross-tieless cargo tank). Sloshing pressure to longitudinal liquid motion has been carried out as shown in Fig. 9 (b). Calculated maximum sloshing pressures are 83kN/m^2 and 82kN/m^2 at case 1 and 3 respectively, which are very similar. (Accurately speaking, maximum pressure of cross-tieless is even lower than that of cross-tie). In case 2, wherethe cross-tie is removed, maximum sloshing pressure increased by about 11~12% compared to cases 1 and 3. From what has been discussed above, we can conclude that the reduction efficiency of conventional cross-tie structure and proposed cross-tieless cargo tank is almost the same and both structures are very effective to reduce sloshing pressure compared to case 2. Therefore, there is no effect on any modification in way of transverse watertight bulkhead in cross-tieless cargo tank of VLCC.

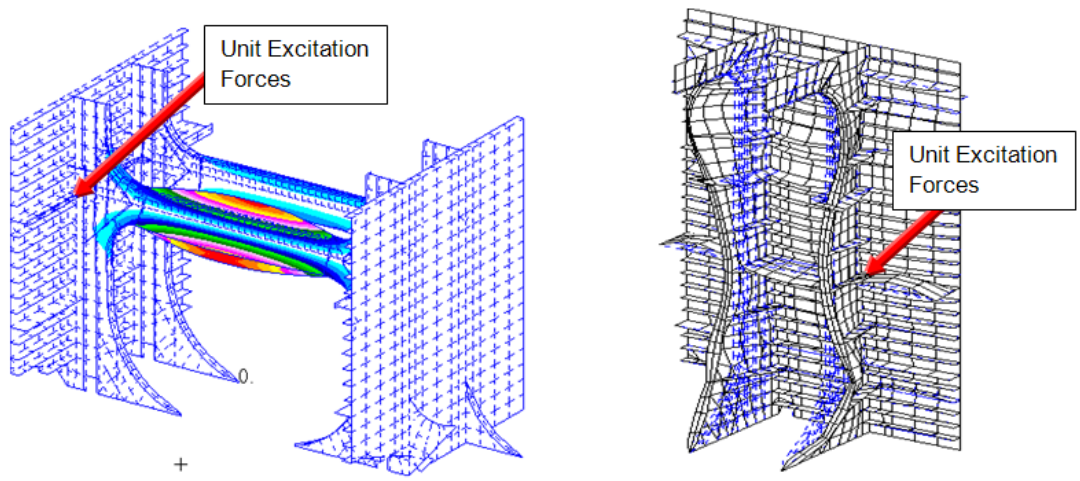


(a) Transverse web frame coefficient (α_{wf}) (b) Sloshing pressure (P_{slh_lng})

Fig.9 Transverse web frame coefficient (α_{wf}) and sloshing pressure (P_{slh_lng}) in terms of filling level

3.3 Comparison Study in Vibration Behavior of Cargo Tank with and without Cross-tie

As the end of cross-tie structures connected to vertical webs are known as one of the main critical points, structural reliability against vibrational excitation force isalso necessary to be carried out in order to manage the risk of crack in the critical area of the conventional cross-tie structure. To do this, the structure has been reinforced according to the result of vibrationcheck as well as yielding and fatigue analyses. Since the critical area is removed in cross-tieless structure, such crack risk management for the new design is not necessary to be analyzedfurther. However, vibration analyses against unit excitation force for both models have been carried out to understand how the cross-tieless structure is relatively more stable than the conventional cross-tie structure. In order to compare vibrational behavior of both structures, unit excitation forces, which are simply defined as 100N for each direction (x, y and z) are appliedto the intersection of No. 2 stringer and vertical webto show the behavioral tendency of the structure. Since unit forces are applied, each absolute value of vibration level itselfdescribed in table 2 isnot meaningful. However, comparative study between these values shows which structure is more reliable from the vibration point of view.As shown in Table 2, the maximum value is calculated in way of cross-tie structure as bending mode vibration phenomena. Although, vibration level of proposed cross-tieless cargo tank in tripping mode on vertical webs is slightly higher than that of a conventional cargo tank with cross-tie, the maximum vibration level (5.04×10^{-2} mm/s) on vertical web of cross-tieless cargo tank is still much lower than the level (1.90×10^{-1} mm/s) on cross-tie structure. Therefore, cross-tieless cargo tank is estimated to be more stable than the cargo tank with cross-tie due to the elimination of risk factor of relatively heavy vibration response from cross-tie.



(a) Bending Mode on Cross-tie (b) Tripping Mode on Vertical Web (Cross-tieless)

Fig.10 Vibration Response in terms of unit excitation force on longitudinal bulkheads

Table 2.Normal mode vibration analysis result for cross-tieless and cross-tie structure.

		Cross-tieless	Cross-tie
Max. Vibration Level (mm/s) against Unit Excitation Force	Bending Mode on Cross-tie	-	1.90×10^{-1}
	Tripping Mode on Vert. Web	5.04×10^{-2}	3.80×10^{-2}

4. Conclusion

The design of cross-tieless cargo tank structure of VLCC has been successfullydeveloped. In this research, the proposed structure has been verified using finite element analysis and comparison with the conventional cross-tie cargo tank structure of VLCC. The effect of sloshing pressure has been also investigated with respect to the modification of primary support member in cargo tank as below;

1) Problem of conventional cross-tie structure, such as expected damage in way of the end connections and low productivity has been investigated and the necessity of removing cross-tie has been studied.

2) Proposed cross-tieless cargo tank structure has been verified from the structuraladequacy point of view. The finite element analysis has been carried out considering yield strength, buckling strength and local

fine mesh structural strength assessment based on CSR finite element analysis procedure. As a result, structural reinforcement has been carried out especiallyon vertical web frames and No.2 stringer structure.

3) Cross-tieless cargo tank has been compared to conventional cargo tank with cross-tie from the sloshing pressure view point. If the cross-tie structure is simply removed without any reinforcement, the pressure is increased by 12%. However, if the vertical web depth is increased, calculated sloshing pressure, which is based on CSR will belower than the pressure from cargo tank with cross-tie. Therefore, any additional effect due to sloshing phenomena is not expected in the vicinity of transverse watertight bulkheadcompared to conventional cargo tank with cross-tie.

4) From the vibration behavior view point, the levels of vibration against unit excitation force have been compared and relatively heavy vibration response is shown at cross-tie structure's bending mode. Maximum vibration level from cross-tieless cargo tank is much lower than the value from that with cross-tie structure.

Based on above research conducted in DSME, domestic and internationalpatents of "Cross-tieless cargo tank of VLCC" has been already registered in several countries such as Korea, Japan, China, United States,and in some European countries.

Reference

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