Comparison Analysis between CSR-OT and CSR-H for Corrugated Bulkhead of Large Product Tanker

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Abstract

Large Aframax product tanker (more than 100k DWT), with centerline longitudinal corrugated bulkheads and transverse corrugated bulkheads in cargo area, is the largest type of product tanker at present. The external draft of Harmonized Common Structural Rules (CSR-H) for Bulk Carriers and Oil Tankers is released for external review. More attentions are paid to the impact of CSR-H on the structure design of corrugated bulkhead of large Aframax product tanker. In this paper, by strength assessment of one 115k DWT product tanker based on CSR-OT and CSR-H, the impact of CSR-H on corrugated bulkhead is discussed.

Keywords：Aframax product tanker corrugated bulkhead CSR-H CSR-OT

1. Introduction

More attentions are payed to the design of corrugated bulkhead of large product tanker today. Corrugated bulkhead is good for saving painting area, washing of tanks, cargo tank volumes controlling, etc. For the product oil with smaller density, the tank volume is even more important than the dead weight. Corrugated bulkhead is used on all the product tankers broadly.

The external draft of Harmonized Common Structural Rules (CSR-H) for Bulk Carriers and Oil Tankers, will bring some impacts on the design of corrugated bulkhead. In this paper, the strength of one 115k DWT product tanker is assessed with rule check and direct strength analysis, comparing the results according to CSR-OT and CSR-H for the design of corrugated bulkhead.

2. Rule Comparison

The comparison about rule contexts between CSR-OT [1] and CSR-H [2] includes local scantling, direct strength analysis and buckling assessment for corrugated bulkhead of oil tanker in this section.

2.1 Local Scantling

Most of rule contexts about local scantling of corrugated bulkhead between CSR-OT and CSR-H are similar. The main differences between them are listed in Table 2.1.

Table 2.1 Differences about local scantling

No.	CSR-H	CSR-OT(1)	Comparison
1	Pt1, Ch3, Sec6, 10.4.3: $d=1000\, l_c/C$. Pt1, Ch3, Sec6, 10.4.5: Span of corrugations (l_c)	Sec8, 2.5.7.4: $d_{cg}=1000\, l_{cg}/15$	C is 15 for tanker, but there may be little difference between l_c and l_{cg}.
2	Pt1, Ch6, Sec4, 1.2.1: C_{CB}	Sec8, 2.5.6.4: C_a	Different for horizontally corrugated longitudinal bulkheads
Note: (1) The latest version (July 2012).			

For most product tanker, the values of l_c and l_{cg} are almost the same, or different not significantly, and the requirement of corrugation depth (d or d_{cg}) could be easily satisfied. So the No.1 difference can be omitted normally. For the tanker without horizontally corrugated longitudinal bulkhead, the No.2 difference can be omitted too.

But for early version of CSR-OT [3], some parameters in Table 8.2.3 are different from that of latest version of CSR-OT and CSR-H. If lower stool is fitted, the only different parameter is the C_i value, which is used to calculate the vertical bending moment, for transverse bulkhead at upper end of l_{cg}. This value is 0.8 in early version of CSR-OT, but 0.65 in latest version of CSR-OT and CSR-H.
Another factor that may influence result is the local design load applied on the corrugation. The static load is same, but the dynamic part may be different. The rule comparison about load is not included in this paper.

2.2 Direct Strength Analysis

The main differences about direct strength analysis (finite element method, yielding assessment) of corrugated bulkhead are listed in Table 2.2. Differences about buckling assessment are list in Table 2.3.

Table 2.2 Differences about direct strength analysis (yielding assessment, midship)

No.	CSR-H	CSR-OT	Comparison
1	Pt1, Ch7, Sec2, 2.4.4: c)	Not noted	The mesh is more accurate in CSR-H for correction of hull girder vertical shear forces.
2	Pt1, Ch7, Sec2, 2.4.4: d)	Not noted	The requirement on element shape and size is more obvious in CSR-H.
3	Pt1, Ch7, Sec2, 2.4.4: e)	Appendix B, 2.2.1.7: (b); 2.7.2.6.	The adjustment of corrugation shape is not allowed in CSR-H, but accepted in CSR-OT which gives special result evaluation.
4	Pt1, Ch7, Sec2, 2.4.4: g)	Not noted	The axial stresses of the dummy rod elements will be evaluated in CSR-H.
5	Pt1, Ch7, Sec2, 5.2.3:Table10; 5.2.4: Yield criteria.	Sec 9, 2.2.5: Table 9.2.1	The corrugation direction is considered in CSR-H, while not distinguishing long. & trans. BHDs; σ_{yd} changed to R_y.
6	Pt1, Ch7, Sec3, 2.1.6: …at the intersection between longitudinal and transverse corrugated bulkheads.	Not noted	The intersection between long. and trans. corrugated bulkheads is considered in local analysis of CSR-H.
7	Pt1, Ch7, Sec3, 3.2.1: (g)	Not noted	The structures listed in (g) are added to screening area in CSR-H.
8	Pt1, Ch7, Sec3, 3.3.1: Table4	Appendix B/3.1.6	Screening factors for corrugated bulkhead are introduced in CSR-H.

More details are shown in rules. Several factors would be focused on in this paper: axial stress of dummy rod elements at the intersection of corrugation web and flange, changed criteria on coarse mesh yielding assessment, and local fine mesh analysis for the intersection between long. and trans. corrugated bulkheads.

2.3 Buckling Assessment

The main differences about buckling assessment of corrugated bulkhead are listed in Table 2.3.

Table 2.3 Differences about buckling assessment

No.	CSR-H	CSR-OT	Comparison
1	Pt1, Ch8, Sec1, 3.3.1: Table1	Sec 9, 2.2.5: Table 9.2.2	Lateral pressure is considered in CSR-H.
2	Pt1, Ch8, Sec4, 3.1.1: overall, flange and web	Sec10, 3.5.2: flange, overall	Corrugation web buckling is considered in CSR-H.
3	Pt1, Ch8, Sec4, 3.2: Reference stress	Not noted	There is no requirement for stress of FEM in CSR-OT
4	Pt1, Ch8, Sec4, 3.4: Local buckling; Pt1, Ch8, Sec5, 3.2	Sec10, 3.5.2.1, 3.2.1, Case1	The cases are more comprehensive in CSR-H.

Details in No.4 difference:
CSR-H: The buckling utilisation factor of flange and web of corrugation is based on the combined axial compressive and shear stresses. The combinations of two normal stresses and shear stress are to be considered. The interaction curve of plate buckling assessment is used with $\alpha=2$ and $\psi=1$.
CSR-OT: Local buckling of a unit flange of corrugated bulkheads is controlled according to the uni-axial buckling of plates, with only case 1 (normal stress along the long side) and $\psi=1$.

3. Local Scantling Analysis

From the comparison in 2.1, there are mainly two factors influencing the local scantling between CSR-OT and CSR-H for vertical corrugated bulkhead with lower stool: Ci at the upper end of lcg for calculating vertical bending moment, and the design loads.
115k DWT product oil tanker, built in Longxue shipyard, is a typical large Aframax product oil tanker, with longitudinal and transverse vertical corrugated bulkheads, and lower and upper stools.
The design loads are calculated on three vertical sections (two ends and middle) for each longitudinal and transverse corrugated bulkhead in one cargo tank of this tanker, shown in Fig. 3.1 and Fig.3.2.
The local scantling results (net required plate thickness along the height) are shown in Fig. 3.3~3.4. The corrugation is mainly rolled by line heat forming.

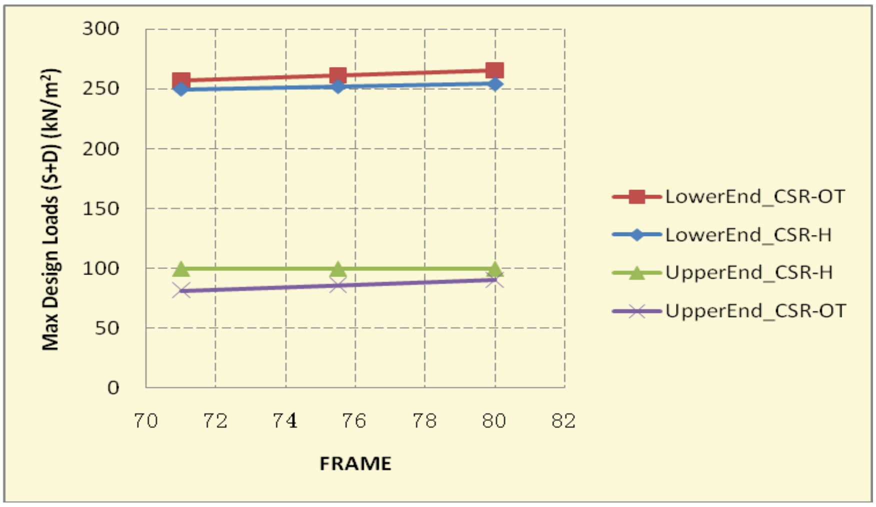

Fig. 3.1 Maximum design loads (longitudinal corrugated bulkhead, No.4 cargo tank)

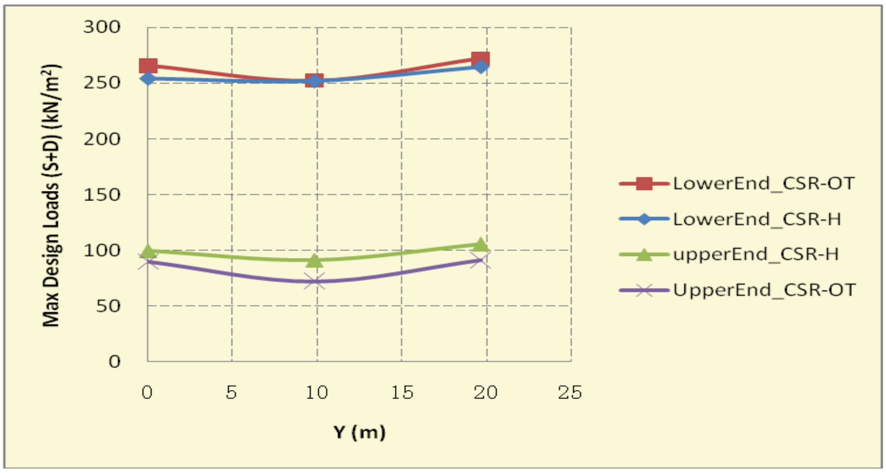

Fig. 3.2 Maximum design loads (transverse corrugated bulkhead, FR80)

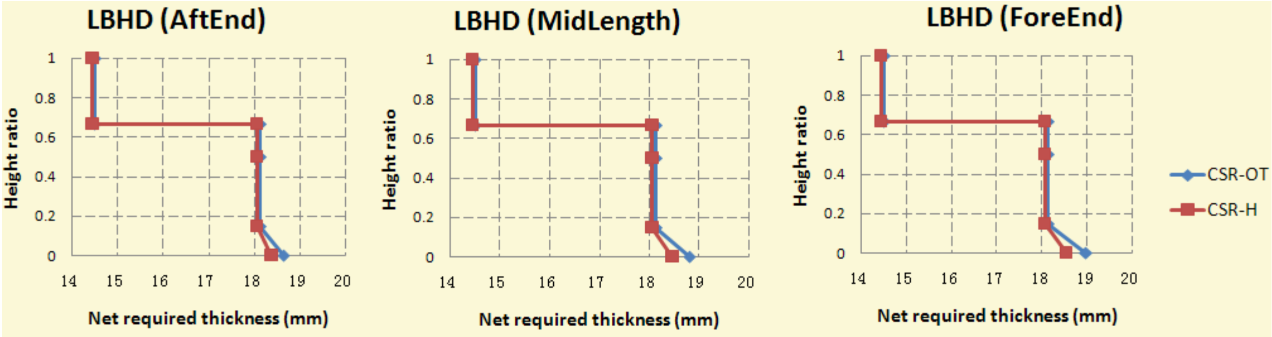

Fig. 3.3 Results for longitudinal bulkhead

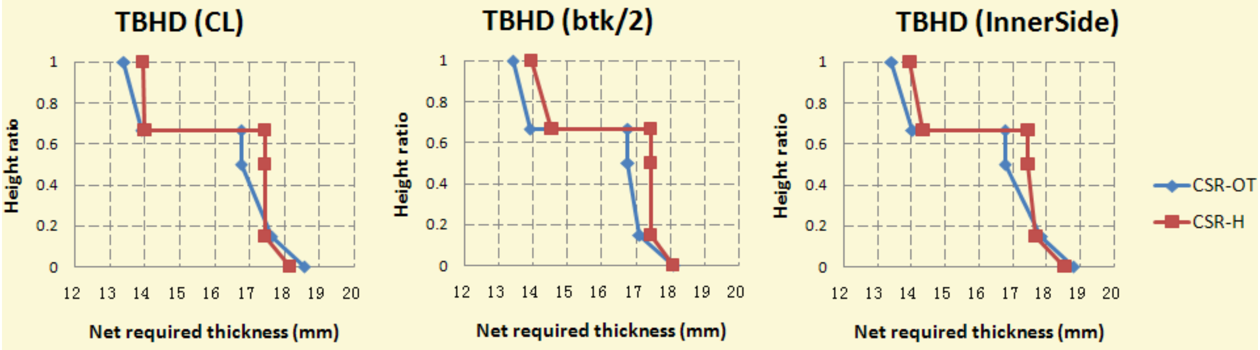

Fig. 3.4 Results for transverse bulkhead

For the longitudinal bulkhead, the results (scantling requirements) in the middle and upper part are very close between CSR-OT and CSR-H, but at the lower end it is lower for CSR-H than CSR-OT. The results at the lower end are determined by the local design loads, which are lower for CSR-H than CSR-OT at the lower end. The results at the middle and upper part are determined by the section modulus requirement, of which the key factor is the average load of lower and upper end at ends of the tank. It can be seen that the average loads of lower and upper end are not different significantly between CSR-OT and CSR-H in Fig.3.1.

For the transverse bulkhead, the results at the middle and upper end are higher for CSR-H than CSR-OT, but at the lower end it is lower for CSR-H than CSR-OT, or similar. Like longitudinal bulkhead, the results at the lower end are determined by the local design loads. The results at the middle and upper end are also determined by the section modulus requirement, of which the key factor is the average load of lower and upper end at the $b_{tk}/2$ vertical section (b_{tk} is the breadth of the tank). It can be seen that the average load of lower and upper end at the $b_{tk}/2$ vertical section is higher for CSR-H than CSR-OT. The results at the position a little higher than 2/3 height of corrugation may be determined by the local design loads at the position.

It is found that the main factor influencing the result is the local design loads. The results at the lower end are normally determined by the local design load at the lower end, and the results at the middle and upper end are normally determined by the average load of lower and upper end. The Ci value can influence the section modulus requirement at the upper end, and have no influence on the results. Because the thickness induced by the section modulus at the upper end shall not be less than 80% of the required thickness at the lower end.

If the local design loads are the same for CSR-H and CSR-OT, it is found that the required thickness results are also the same.

4. Direct Strength Analysis with Coarse Mesh

4.1 General

The cargo tank structural strength analysis of this 115k DWT product tanker is performed both according to CSR-OT and CSR-H. The two FE models are almost the same. The corrugation is to be modelled in accordance with its geometric shape, and the mesh on the stool in way of the corrugations is adjusted correspondingly. There are two elements for typical flange breadth and web height in general. The only different of the two models is that the dummy rod elements with a cross sectional area of 1 mm^2 are modelled at the intersection between the flange and the web of corrugation in the model for CSR-H.

4.2 Yielding Assessment

The most critical results for longitudinal and transverse corrugated bulkhead are shown in Table 4.1 and Table 4.2. The ratio of yield factor shall not be greater than 1.

Table 4.1 The most critical yielding assessment results (longitudinal bulkhead)

	Stress (N/mm^2)	Yield utilization factor (λ_y)	Dominate load case	Permissible yield factor (λ_{yperm})	Yield factor ratio ($\lambda_y/\lambda_{yperm}$)
CSR-OT	253.3	0.804	B3-2 (S+D)	1.0	0.804
CSR-H (shell)	203.1	0.622	B10 (S)	0.72	0.864
CSR-H (rod)	214.86	0.658	B9 (S)	0.8	0.823

Table 4.2 The most critical yielding assessment results (transverse bulkhead)

	Stress (N/mm^2)	Yield utilization factor (λ_y)	Dominate load case	Permissible yield factor (λ_{yperm})	Yield factor ratio ($\lambda_y/\lambda_{yperm}$)
CSR-OT	184.76	0.52	B10 (S)	0.64	0.813
CSR-H (shell)	198.31	0.608	B10 (S)	0.72	0.844
CSR-H (rod)	207.91	0.637	B10 (S)	0.8	0.796

It is found that the assessment results according to CSR-H are a little higher than that of CSR-OT. Although the stress is higher, the assessment results of rod elements are a little lower than that of shell elements due to the different permissible yield factors.

Because of the same mesh and properties, the main factors influencing the results include the load cases and criteria. It is too complex to analyze the load cases. So the analysis of criteria could be performed with the same stress, which is shown in Table 4.3 and Table 4.4. The analysis is only for shell elements, and assumed that the Von Mises stresses are all 100 N/mm^2.

Table 4.3 Yield criteria analysis (longitudinal bulkhead)

	R_{eh} (N/mm^2)	Pressure on one side	Area of stress concentration	λ_y	Load combination	λ_{yperm}	R ($\lambda_y/\lambda_{yperm}$)	R_{CSR-H} / R_{CSR-OT}
CSR-OT	315	Yes	No	0.317	S+D	0.9	0.353	1.046 (1)
CSR-H	315	Yes	No	0.332	S+D	0.9	0.369	
CSR-OT	355	Yes	No	0.282	S+D	0.9	0.313	1.088 (1)
CSR-H	355	Yes	No	0.306	S+D	0.9	0.340	
CSR-OT	390	Yes	No	0.256	S+D	0.9	0.285	1.129 (1)
CSR-H	390	Yes	No	0.289	S+D	0.9	0.322	
CSR-OT	355	Yes	Yes	0.317	S+D	0.9	0.353	0.965 (2)
CSR-H	355	Yes	Yes	0.306	S+D	0.9	0.340	
CSR-OT	390	Yes	Yes	0.317	S+D	0.9	0.353	0.911 (2)
CSR-H	390	Yes	Yes	0.289	S+D	0.9	0.322	

Note:
(1) The value is same for load combination S.
(2) The value is same for the case that the combined pressure is zero.

Table 4.4 Yield criteria analysis (transverse bulkhead)

	R_{eh} (N/mm^2)	Pressure on one side	Area of stress concentration	λ_y	Load combination	λ_{yperm}	R ($\lambda_y/\lambda_{yperm}$)	R_{CSR-H} / R_{CSR-OT}
CSR-OT	315	Yes	No	0.317	S+D	0.8	0.397	0.929 (1)
CSR-H	315	Yes	No	0.332	S+D	0.9	0.369	
CSR-OT	355	Yes	No	0.282	S+D	0.8	0.352	0.967 (1)
CSR-H	355	Yes	No	0.306	S+D	0.9	0.340	
CSR-OT	390	Yes	No	0.256	S+D	0.8	0.321	1.003 (1)
CSR-H	390	Yes	No	0.289	S+D	0.9	0.322	
CSR-OT	355	Yes	Yes	0.317	S+D	0.8	0.397	0.858 (2)
CSR-H	355	Yes	Yes	0.306	S+D	0.9	0.340	
CSR-OT	390	Yes	Yes	0.317	S+D	0.8	0.397	0.810 (2)
CSR-H	390	Yes	Yes	0.289	S+D	0.9	0.322	

Note:
(1) The value is same for load combination S.
(2) The value is same to Table 4.3 for the case that the combined pressure is zero.

The material with Reh=390 N/mm^2, which is not present in this tanker but allowed in the rule, is used for comparing. It could be found that the main factors influencing the results (R_{CSR-H} / R_{CSR-OT}) include material yield stress and area of stress concentration. In general areas, the higher material yield stress is, the more severe for CSR-H than CSR-OT. But in areas of stress concentration, it is opposite. There are more advantages for transverse bulkhead than longitudinal bulkhead in the transition of criteria.

4.3 Buckling Assessment

The local buckling assessment results for longitudinal and transverse corrugated bulkheads are shown in Fig.4.1~4.2. The overall column buckling analysis is not needed for this tanker.

The most critical assessment results for longitudinal and transverse corrugated bulkhead are shown in Table 4.5. The normal stress is signed as positive when compression, and σ_x is the vertical stress.

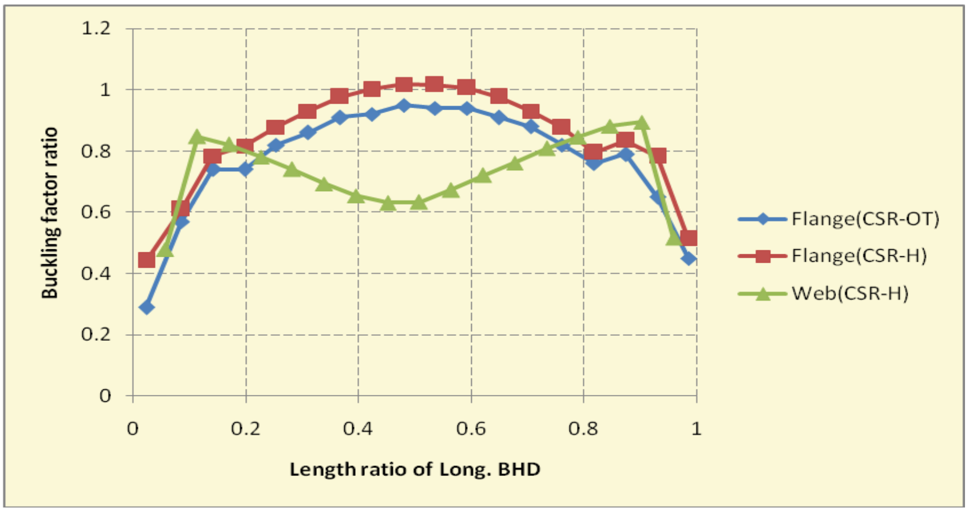

Fig. 4.1 Buckling results of longitudinal corrugated bulkhead (No.4 cargo tank)

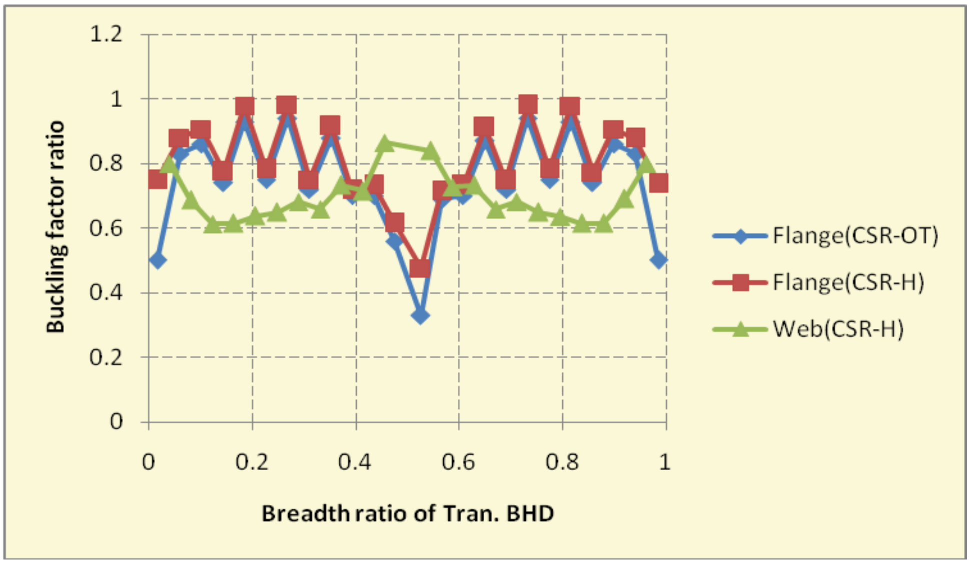

Fig. 4.2 Buckling results of transverse corrugated bulkhead (FR80, from inner side to inner side)

Table 4.5 The most critical buckling assessment results

	Longitudinal BHD			Transverse BHD		
	CSR-OT (flange)	CSR-H (flange)	CSR-H (web)	CSR-OT (flange)	CSR-H (flange)	CSR-H (web)
σ_x (N/mm^2)	181.49	197.03	-7.78	183.28	195.41	-53.35
σ_y (N/mm^2)	11	11.94	-23.29	7.18	7.59	-1.03
τ (N/mm^2)	1.54	4.84	89.04	5.76	4.89	108.5
Buckling factor (η_{act})	0.857	0.916	0.643	0.674	0.707	0.779
Dominate load case	B2 (S+D)	B2 (S+D)	B9 (S)	B11 (S)	B11 (S)	B1 (S+D)
Allowable factor (η_{all})	0.9	0.9	0.72	0.72	0.72	0.9
Buckling Ratio (η_{act}/η_{all})	0.953	1.018	0.894	0.936	0.982	0.865

The result distributions along the breadth of bulkheads are similar: for flanges, the results are higher in middle part than end position, but reverse for webs. Because the scantling requirement of flange is mainly determined by vertical normal stress, which is higher in middle part; the scantling requirement of web is mainly determined by shear stress, which is higher at end of bulkhead. Other factors (e.g. thickness) can also change the results. The buckling factors of web reduce at the ends of longitudinal corrugated bulkhead due to the plate thicknesses increasing.

From the results shown above, it could be found that the buckling factors of flange are higher for CSR-H than CSR-OT, especially for longitudinal corrugated bulkhead (enhanced about 7%). The corrugation scantlings in the middle and upper part are normally determined by the buckling assessment results.

Many factors could influence the results, such as stress (induced by design loads), plate thickness, material, panel breadth, buckling calculation method, etc. For the same model, the main factors include the stress and buckling calculation method. The comparison analysis for flange with same compressive stresses is shown in Table 4.6.

Table 4.6 Comparison buckling analysis of corrugation flange (fixed stress)

	Longitudinal BHD		Transverse BHD	
	CSR-OT	CSR-H	CSR-OT	CSR-H
σ_x (N/mm^2)	197.03		195.41	
σ_y (N/mm^2)	11.94		7.59	
τ (N/mm^2)	4.84		4.89	
Buckling factor (η_{act})	0.931	0.916	0.719	0.707
Allowable factor (η_{all})	0.9		0.72	
Buckling Ratio (ηact / ηall)	1.034	1.018	0.998	0.982

Although σ_y and τ are not considered in CSR-OT, the result may be even larger than that of CSR-H. The formula of actual buckling utilisation factor for corrugation in CSR-H [2] can be written as:

$$\eta_{act} = \frac{1}{\gamma} = \sqrt{\left(\frac{\sigma_x}{\sigma_{cx}}\right)^2 + \left(\frac{\sigma_y}{\sigma_{cy}}\right)^2 - B\left(\frac{\sigma_x}{\sigma_{cx}}\right)\left(\frac{\sigma_y}{\sigma_{cy}}\right) + \left(\frac{\tau}{\tau_c}\right)^2}$$

For the same model, the variables are the three stresses (σ_x, σ_y and τ). When the amplitude of shear stress grows, the factor (η_{act}) will also grow. But it is not correct for σ_x and σ_y if B>0.

5. Local Fine Mesh Analysis

The local fine mesh analysis at the intersection of longitudinal and transverse corrugated bulkheads near lower stool is carried out applied with CSR-OT.
The original gusset plate arrangement is shown in Fig.5.1.

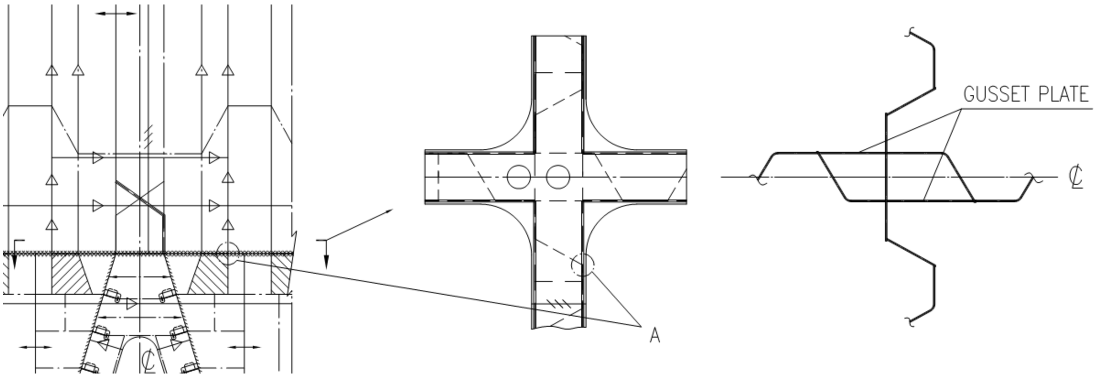

Fig. 5.1 Original gusset plate arrangement

It is found that the local stresses around point A (intersection of corrugation corner and stool plates) are very high (symmetrical location similar), which are shown in Table 5.1. The maximum stresses, although satisfy the criteria of CSR-OT, shall be shaken down considering the potential building problems and cracks. The stress concentricity due to geometry discontinuity is very high around point A. Increasing thickness is not an effective way to solve the problem, as the plate is already very thick. The stresses of similar positions at longitudinal bulkhead are low due to the gusset plates. So the best way to reduce the stress is adding gusset plates.
The modified gusset plate arrangement is shown in Fig.5.2. The maximum stress fringes of two models are shown in Fig.5.3 and Fig.5.4.

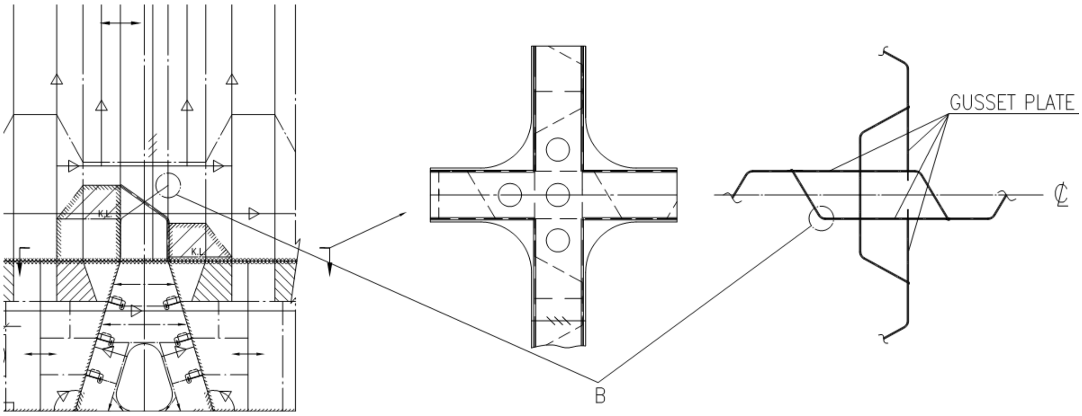

Fig. 5.2 Modified gusset plate arrangement

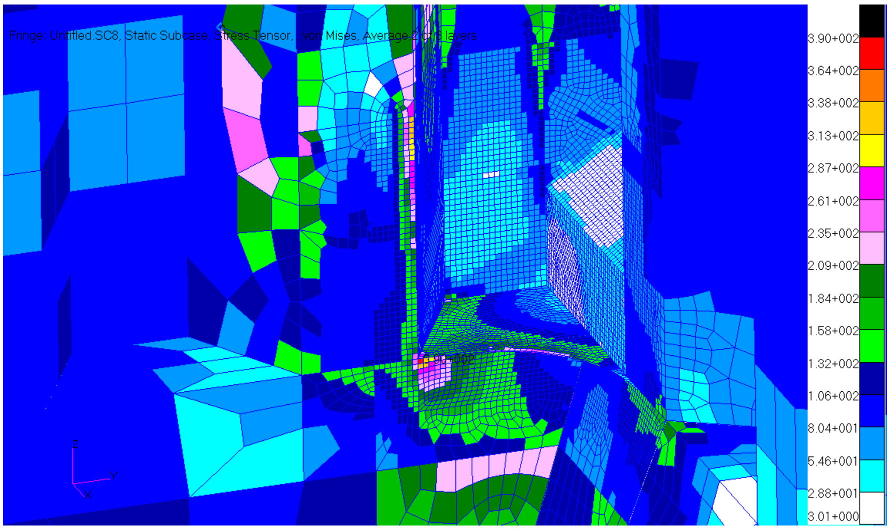

Fig. 5.3 Maximum Von Mises stress of original model

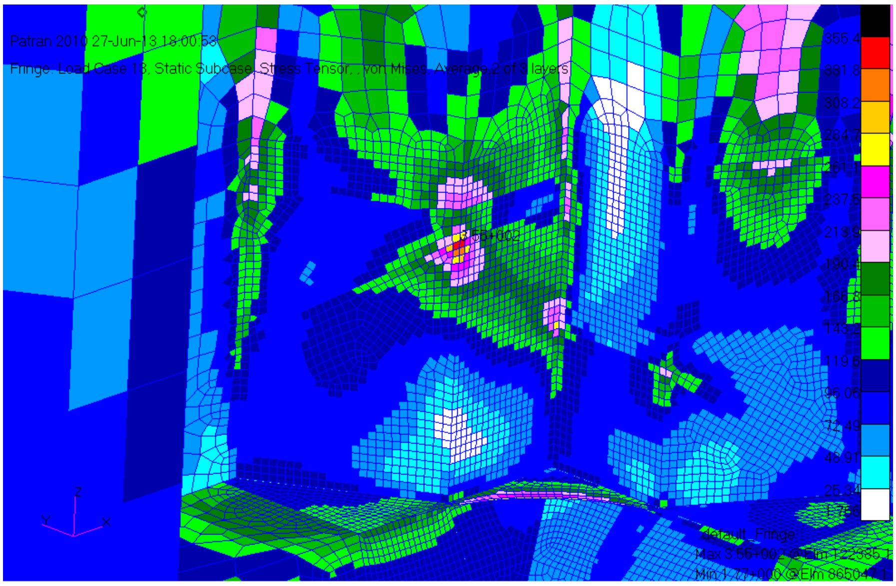

Fig. 5.4 Maximum Von Mises stress of modified model

The maximum stresses (at point A and point B) for the two models are shown in Table 5.1.

Table 5.1 Maximum stresses (N/mm^2)

Location	Model	Load combination S+D		Load combination S	
		Max stress	Allowable stress	Max stress	Allowable stress
Point A	Original	390	451.9	359	391.7
	Modified	201		184	
Point B	Original	335		319	
	Modified	355		334	

The stresses at point A reduce nearly a half after adding gusset plates. Although the maximum stresses at point B (intersection of corrugation corner and shedder plate) is higher than original design, but it still could be acceptable.

The scantling of lowest part of corrugation is determined by the local fine mesh analysis results. Most areas can satisfy the requirement by increasing thicknesses except the area near the intersection of longitudinal and transverse corrugated bulkheads near lower stool.

Considering the stress enhancement for CSR-H than CSR-OT (the stress enhanced about 5% near point A from coarse mesh analysis results), the structural strengthening is necessary.
Further study of fine mesh and fatigue analysis applied with CSR-H is needed.

6. Conclusion

From the structural analysis of corrugated bulkheads of the 115k DWT product oil tanker above,
The conclusion will be shown as following.

(1) The local scantling requirements are similar between CSR-OT and CSR-H, while the design load is the main factor influencing the results.

(2) The results of CSR-H are generally a little higher than that of CSR-OT from the direct strength analysis mainly due to the higher design loads. The new requirements of rod element and web buckling assessment have no influence on the final results in general, but shall also need paying attentions.

(3) In coarse mesh analysis, for general areas (not stress concentration), higher strength steel will give more severe yielding results for CSR-H than CSR-OT, but for areas of stress concentration, it is opposite. There are more advantages for transverse bulkhead than longitudinal bulkhead in the transition of criteria.

(4) The corrugation scantlings in the middle and upper part are normally determined by the buckling assessment results. The buckling assessment results of flange are mainly determined by vertical normal stress, higher in the mid breadth of tank. The buckling assessment results of web are mainly determined by shear stress, higher in the end of tank. The buckling requirement in CSR-H is more complex for corrugated bulkhead, and more comprehensive in total.

(5) The scantling requirements of lowest part of corrugation are determined by the local fine mesh results. More attentions shall be paid to the area around the intersection of longitudinal and transverse corrugated bulkheads near lower stool. The way adding proper gusset plate is more effective than increasing thickness for reducing the maximum stress level of this area.

Reference

[1] IACS. Common Structural Rules for Double Hull Oil Tankers. July 2012.
[2] IACS. Common Structural Rules for Bulk Carriers and Oil Tankers. External Release 1 Apr 2013.
[3] IACS. Common Structural Rules for Double Hull Oil Tankers. July 2010.