

# **Corrugated Bulkheads Designs of Tankers**

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## **ABSTRACT**

Corrugated bulkheads are often used in chemical tankers and product tankers in order to help facilitate cargo tank washing efficiently. Sufficient service records have demonstrated the advantages and contributions to the advanced designs best suited to larger cargo tank capacity arising from the increased demand for the transport of product oils and chemical products. It is obviously important in ship design to proactively learn from satisfactory experience and to reflect feedback from past damage records as an important part of verifying the effectiveness of the application of the latest design technologies. This paper summarizes some of the recent developments in the design of corrugated bulkheads considering the specific limitation of the designs of product and chemical tankers and also shows the impact of scantling and related key design issues.

## **1. INTRODUCTION**

Contamination of cargo is one of the most critical hazards for chemical/product tankers from the viewpoint of safety, the prevention of marine pollution and the quality of products. However, due to the various demands for the transport of products, the type of cargo loaded in each cargo tank may vary with each voyage.

Consequently, ship operators try to minimize the amount of cargo remaining after unloading and carry out cargo tank washing prior to next cargo loading not only to meet the requirements of international regulations but also to meet commercial requirements to maintain the quality of cargo.

To apply complete cargo tank washing, it is most important not to create shadow areas caused by internal structures. The large web frames and stiffeners provided on the boundaries of the cargo tanks easily become complicated shadow objects. Even though the number of cargo tank cleaning machines is increasing, it is very difficult to completely wash the stiffened surfaces with such machines.

To solve this problem, corrugated bulkheads have been applied to chemical and product tankers to convert the cargo tank boundaries into more easily accessible plane surfaces. Such plane surfaces, of course, contribute to minimizing the amount of remaining cargo itself after unloading and also help facilitate easier coating and inspection of corrugated bulkheads as a result.

## **2. 2007 REVISION OF MARPOL ANNEX II AND IBC CODE**

The selection of types of cargo tank bulkheads in the design stage depends on various considerations for ship's design. From the regulatory point of view, when a tanker is designed to carry noxious liquid substances (NLS) under MARPOL Annex II [1] and the IBC Code [2], the maximum quantity of residue permitted after unloading is strictly restricted. Moreover, the cargo tank surfaces must be of a suitable type for effective washing by means of rotary water jets so that the risk of marine pollution by the discharge of NLS after cargo tank washing can be minimized.

The restriction level depends on the pollution categories assigned to each NLS under MARPOL Annex II. Traditionally, smaller tankers having deadweight of less than 20,000t have been registered as product/chemical tankers to carry clean product oils and various NLS, and thus normally have been designed with corrugated bulkheads to fulfil the said requirements. On the other hand, due to the increased demand for the transport of product oils and NLS, the size of

product/chemical tankers has grown becoming over 30,000 DWT recently.

In addition to the increased demand of transportation, the relevant amendments to MARPOL Annex II and the IBC Code concerning the above requirements have entered into force from 1st January 2007. Under these major amendments, the pollution categories for NLS were fully revised including associated requirements, and many NLSs have been re-categorized into higher pollution risk cargoes. For instance, “Vegetable oils” and “Methyl alcohol” are now subject to requirements concerning the maximum quantity of cargo residue permitted, although such requirements were previously not applicable to these cargoes. While “Vegetable oils” and “Methyl alcohol” could previously be transported by oil tankers with stiffened bulkheads before 2007, now they shall be carried by chemical tankers with corrugated bulkheads fulfilling the requirements under MARPOL Annex II and the IBC Code.

As this amendment also accelerated the demand of large size product/chemical tankers with corrugated bulkheads, corrugated bulkheads are now often used in the latest MR tanker designs with 50,000 DWT and are being further extended into the design of larger vessels instead of plane bulkheads with web frames.

### 3. STRUCUTRAL TYPES OF CORRUGATED BULKHEAD

Corrugated bulkheads can be categorized into two main types. One is the “horizontally corrugated bulkhead” and another is the “vertically corrugated bulkhead” as shown in Figure 1 below.

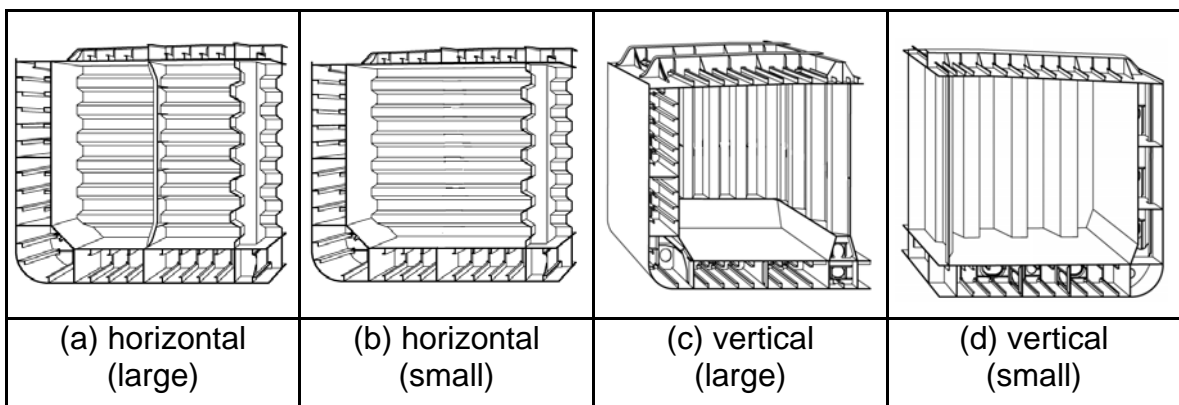


Figure 1: Types of corrugated bulkheads

When the span of corrugation becomes longer in larger vessels, internal vertical webs are provided on horizontally corrugated bulkheads, while upper and/or lower stools are provided on

vertically corrugated bulkheads to shorten the effective bending span of corrugation.

While the horizontally corrugated bulkhead allows the variation of thickness in the direction of the vessel's depth and allows the maximum cargo tank capacity, this design is often applied to easy chemical tankers and product tankers which carry limited products subject to less stringent requirements. In the operation of these ships, the risk of cargo contamination is lower and some internal structures may be accepted. Of course, if internal vertical webs are not required due to shorter corrugation spans, horizontally corrugated bulkheads are also applied to the parcel chemical tankers that are required to carry various kinds of products with complete cargo tank washing. In the case of vertically corrugated bulkhead, although the installation of upper and/or lower stools lead to some loss of cargo capacity, the cargo tank boundary can always be kept a plane surface for complete cargo tank washing.

While it also depends on the shipyard's facility and fabrication procedure, vertically corrugated bulkheads tend to be used rather than horizontally corrugated bulkheads in recent chemical tanker designs. Actually, of the approximately 700 chemical tankers having either corrugated bulkheads and newly registered with our classification society these past 20 years (1990-2009), it was confirmed that about 85% of the corrugated bulkheads designs consisted of vertically corrugated type, while the remaining 15% comprised horizontally corrugated one.

#### **4. TYPES OF CORRUGATED BULKHEADS DAMAGES**

While many successful corrugated bulkheads service histories have been recorded, several damages have been reported and some of which resulting in hazardous damages due to the leakage of cargo into an adjacent compartment. The typical types of damage have been grouped into four main types as shown in 4.1-4.4. However it should be also noted these damage types will not directly link to existing vessels having similar arrangement because such ships have different design consideration/scantling of structural members especially for vessels having good service records.

##### **4.1 DAMAGES CAUSED BY WELDING DEFECTS**

It was reported that cracks were observed in the welding between the vertically corrugated bulkhead and inner bottom plate. As this connection was at the end of corrugation span, the

stress level of welding was very high especially at the corner of corrugation.

It was assumed that the crack initiated as a result of local stress concentration due to overlapping or undercutting of welding at the corner of the corrugation.

#### 4.2 DAMAGES OF SCALLOPS OR BRACKETS TOES AT STRESS CONCENTRATION AREA

It was reported that cracks were observed at the critical area of corrugated bulkhead related structures, notably:

- the scallop at the corner of the lower stool diaphragm just below the vertically corrugated bulkhead
- the bracket toe of the vertical web provided on the horizontally corrugated bulkhead

It was assumed that the cracks were initiated by the stress concentrations resulting from the scallop and shape of the bracket toe.

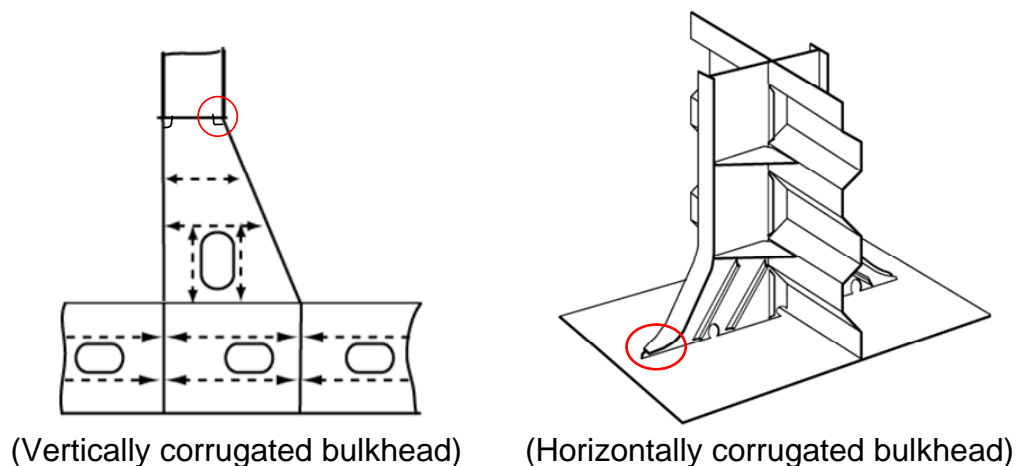


Figure 2: Cracks at scallop and bracket toe.

#### 4.3 DAMAGES DUE TO LACK OF SUPPORTING STRUCTURES

Several kinds of damages which were seemed to be caused by a lack of supporting structures were also reported. These included:

- The connection between the vertically corrugated bulkhead with the inner bottom plate (without lower stool), and
- the connection between the vertically corrugated bulkhead with the lower stool top plate

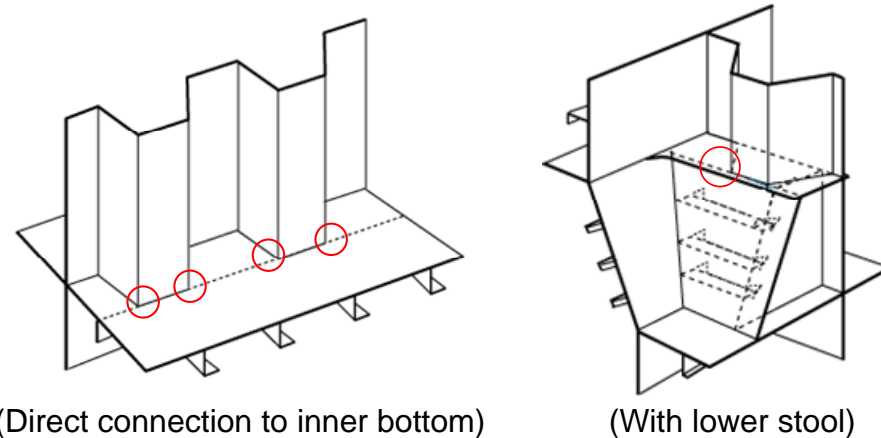


Figure 3: Cracks due to lack of supporting structures.

In case of a direct connection between the vertically corrugated bulkhead and inner bottom plate, both flanges of the corrugated plate should be supported by an adequate backing structure in order to effectively transfer the load. The crack was assumed to be caused by the insufficient load transfer member and rigidity of the backing structure.

On the other hand, if a lower stool is provided, both flanges of corrugated plate can be supported by the stool plate directly. However, some crack damages have been recorded even in these cases. It was assumed that the slanted stool plate was not sufficient to transfer the load in the damaged cases. It was considered that the fitting angle of the supporting structure was also an important factor in effectively transferring the load and to avoiding unacceptable stress concentrations.

#### *4.4 DAMAGES DUE TO LACK OF CONTINUITY (MISALIGNMENT)*

Even though effective supporting structures were provided, some crack damages were recorded at the end connections of vertically corrugated bulkhead. Judging from the details, it was assumed that differences in the thickness and the welding length between the corrugation and its supporting structure was the cause of the damages.

For the purpose of effective transmission of loads from the corrugated bulkhead to the underneath supporting structures, it is considered that the adequate continuity of plate thickness and welding length are also important factor of the design.

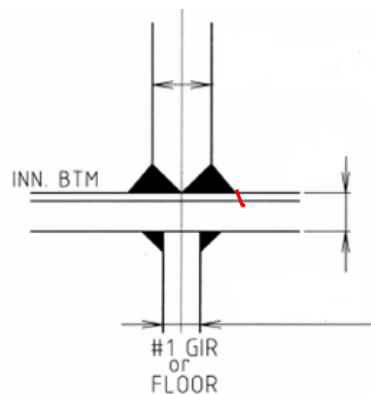


Figure 4: Crack due to lack of continuity.

## 5. DESIGN DEVELOPMENT BASED ON FEEDBACK FROM EXPERIENCES

In order to mitigate any risk of similar damages related to corrugated bulkhead structures, lessons learned from past experience and verification results using the latest design technologies have been incorporated in new designs.

### 5.1 DESIGN OF SUPPORTING STRUCTURES

Considering the effective support of corrugation flanges, floors and girders have been provided just under the corrugation flange in recent designs.

To verify the effectiveness of supporting structure, analysis of selected parameters has been carried out using finite element analysis. Figure 5 shows how the stress of the corner of the corrugated plate will be decreased by providing a rigid supporting structure effectively underneath the corrugation flange.

The conditions of the calculation are shown below.

- Transverse vertically corrugated bulkhead was modelled with relevant supporting structures.
- One side of the corrugation flange was supported by the floor plate.
- Another side of the flange was supported by various types of stiffeners, as shown in Table 1.
- 50mm x 50mm shell elements were used
- Static cargo pressure was set as an out-of-plane load
- Von-Mises stresses at the corner of corrugation were compared to verify the effectiveness of supporting structures

Table 1: Depth of Stiffener for Selected Cases

Case	1	2	3	4	5(*1)
Depth of stiffener/ $d_0$ (*2)	0.31	0.46	0.62	0.92	2.06

\*1: Supporting structure (case 5) is equivalent to floor

\*2:  $d_0$ : Depth of corrugation as shown in Figure 5

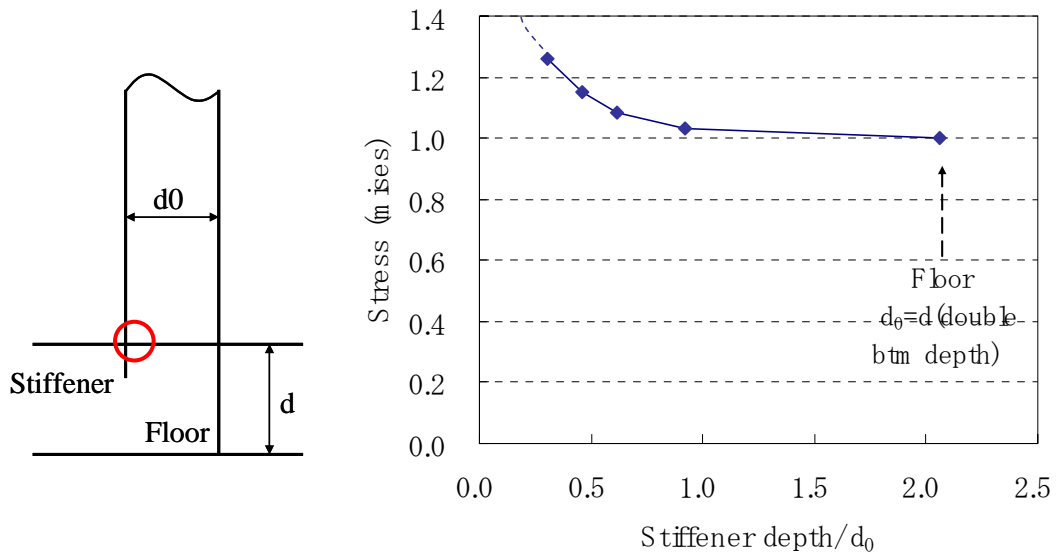


Figure 5: Relative stress by depth of supporting structure.

From this analysis, it was confirmed that:

- Stress at the corner of the end corrugation decreases if a deeper supporting structure is fitted below the corrugation flange.
- When the support depth exceeds half of the depth of corrugation, the stress reduction ratio becomes lower.
- Half of the depth of corrugation depth is considered an effective depth for a supporting structure
- Supporting structure such as floor/girders underneath the corrugation flange are suitable

## 5.2 APPLICATION OF FULL PENETRATION WELDING

To improve the welding at the lower end of corrugated bulkheads, full penetration welding instead of fillet welding has been applied at the corner of the corrugation in recent designs. It is expected that the application of full penetration welding will lower the stress concentration and minimize the risk of cracking at the lower end of corrugated bulkheads.

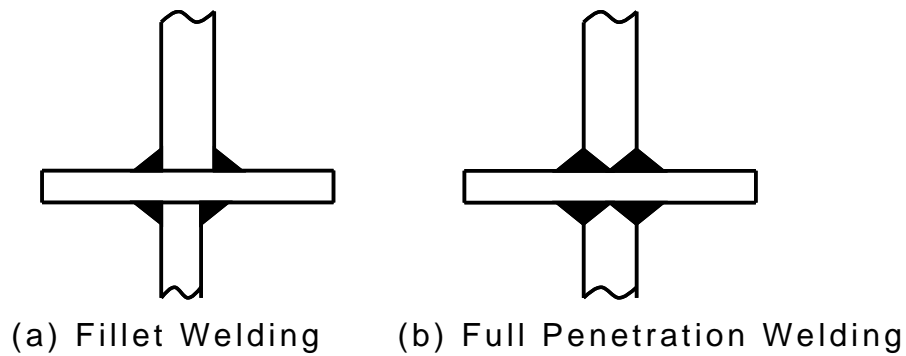


Figure 6: Improvement of welding at lower corrugated bulkhead.

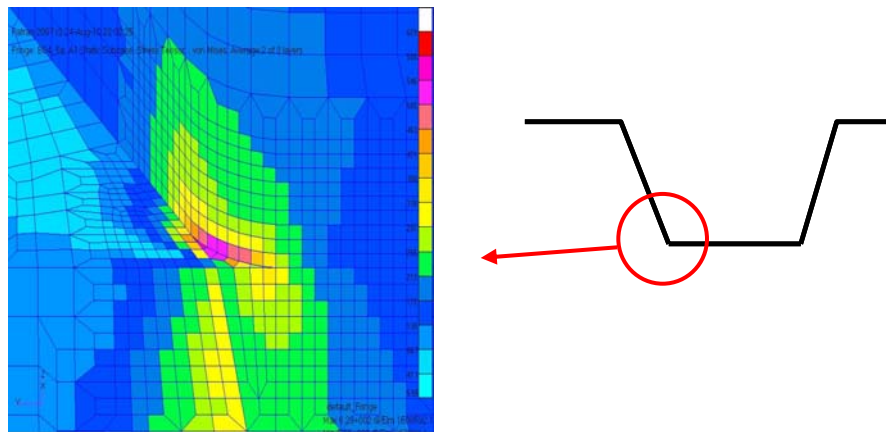


Figure 7: Stress distribution at the corner of corrugation.

Figure 7 shows the stress distribution at the corner of a lower end connection of a vertically corrugated bulkhead using very fine mesh (17mm x 17mm) FEA model reflecting the actual shape of the corner radius. As can be seen in this figure, stress concentrates at the corner of the corrugation and drastically decreases toward the center of the corrugation flange and web. Accordingly, it was confirmed that full penetration welding was effective at the vicinity of the corrugation corner as also shown from the damage experience. Moreover, while the use of fillet welding has some risk of allowing unexpected gaps to remain at the lower end of corrugated bulkhead, full penetration welding is effective in mitigating the risk of stress concentrations caused by unexpected gaps.

To verify the effectiveness of full penetration welding and the effect of gaps in fillet welding, case studies were carried out using very simplified welding model.

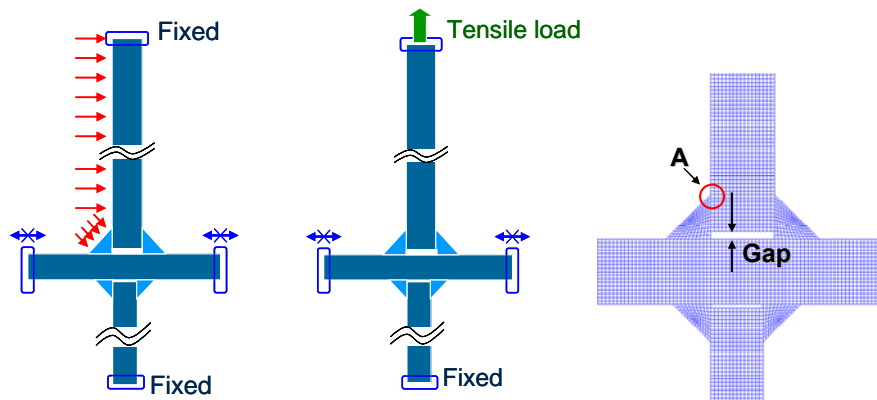


Figure 8: Simplified model of welding and applied load cases

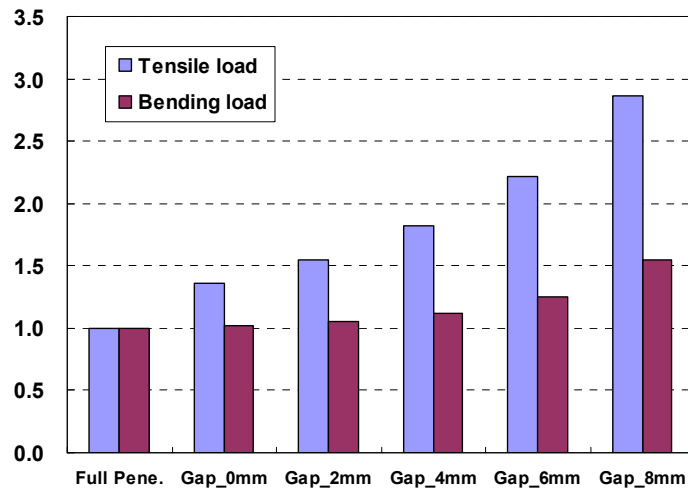


Figure 9: Relative Von-Mises stress at Position A. (Stress of Full Penetration = 1.0)

The result shows sensitive stress concentrations due to gaps caused by tensile loads, while the effect of gaps is not so dominant in stress concentration resulting from bending loads. Considering the combination of loads in the actual condition of such a corrugated bulkhead, it is assumed that the presence of unacceptable fillet welding gaps will result in stress levels at the welding toe (Position A) that are easily 1.3~2.5 times that compared with full penetration welding. It was also observed that higher stress by tensile load occurs at the root due to the reduced throat thickness by gaps. Of course, it is needless to say that such gaps have to be adequately controlled under normal shipbuilding quality standards, however full penetration welding will mitigate the risks of gaps satisfactorily. Moreover, grinder treatment has been applied recently at the corners of corrugations to finish the welding toe smoothly and thereby decrease the stress concentration at the position.

Although it is also effective to remove any welding defects such as undercutting and overlapping completely, such treatment should be applied with care so as not to reduce the throat thickness of the welding beyond unacceptable levels.

### *5.3 OTHER STRUCTURAL ARRANGEMENTS*

Scallops in the diaphragms in way of the connections of the stool sides to the inner bottom and to the stool top plate are normally closed as stress concentration position in recent designs.

As gusset and shedder plates have been commonly applied to the corrugated bulkheads of large bulk carriers to reduce stress concentrations at the lower end connection, case studies using Finite Element Analysis (FEA) to verify the stress levels have been conducted for trial reinforcement using gusset and shedder plates. Although each stress level could be verified together with its effectiveness to lower stress concentrations at the end connection of the corrugated bulkhead, some technical key issues still remain regarding the application of this kind of reinforcement to product/chemical tankers as shown below.

- Adequate arrangement of manholes and air holes is necessary to avoid the formation of any gas pockets in the enclosed space formed by the gusset and shedder plates.
- Welding between the gusset/shedder plate and corrugation needs to be done carefully, since corrugation is normally constructed not by built-up but cold-formed by bending with corner radii.
- When shedder plates cross through the web plate of the corrugation, higher stress concentrations occur at the cross points as shown in Figure 10. To avoid such stress concentrations, which may lead to the cracking and subsequent cargo contamination, supporting brackets or carlings need to be provided on the shedder plates. However those brackets/carlings need to be provided on the backside of the cargo tank in order to allow complete cargo tank washing without any shadow areas. Complicated fabrication in a narrow space is required to weld the brackets or carlings under the shedder plates.
- Non-cross type gusset and shedder plates are preferable to avoid the complicated fabrication described in the above; however, higher gusset plate will create a large enclosed space (void or ballast tank). This would finally leads to a loss of cargo capacity, which is critical in tanker designs.

Utilization of gusset and shedder plates is one of the options for reinforcing the lower end connections of vertically corrugated

bulkheads. However in the actual design of tankers, it is not common to apply this reinforcement, since the designers try to minimize the risk of difficult fabrication, which may lead to defects of welding and loss of integrity, for the safe operation of tankers carrying flammable liquids.

Accordingly, it is recommended not to make the provision of gusset and shedder plates mandatory in tanker designs even if it is required and satisfactory applied in the designs of bulk carriers.

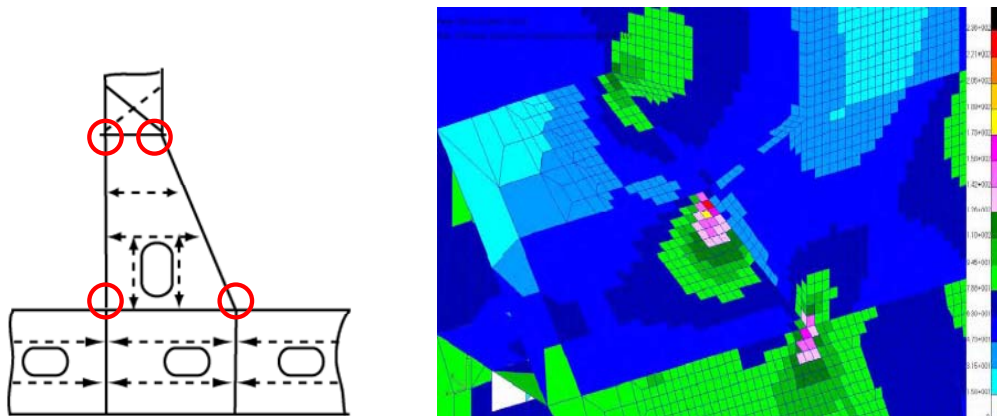


Figure 10: Closed scallops and cross-type shedder plate.

## 6. LATEST RULE REQUIREMENTS FOR CORRUGATED BULKHEADS

Common Structural Rules (CSR) for Double Hull Oil Tankers [3] have been newly applied to double hull oil tankers of 150m length and above and contracted for construction on or after 1 April 2006. As the CSR also cover the structure of corrugated bulkheads, the CSR have been developed to reflect feedback from past damage experiences together with the latest design criteria of finite element analysis (FEA).

### 6.1 REQUIREMENTS OF STRUCTURAL ARRANGEMENT IN CSR

For the adequate structural arrangement considering the continuity of strength, prescriptive requirements of structural arrangement and welding are required by the CSR. For example:

- Ships with a moulded depth equal to or greater than 16m are to be fitted with a lower stool.
- The extension of the stool top plating beyond the corrugation is not to be less than the as-built flange thickness of the corrugation.

- Within the region of the corrugation depth from the stool top plate the net thickness of the stool side plate is not to be less than 90% of that required for the corrugated bulkhead flange at the lower end and is to be of at least the same material yield strength.
- Continuity is to be maintained, as far as practicable, between the corrugation web and supporting brackets inside the stool. The bracket net thickness is not to be less than 80% of the required thickness of the corrugation webs and is to be of at least the same material yield strength.
- Scallops in the diaphragms in way of the connections of the stool sides to the inner bottom and to the stool top plate are not permitted.
- For ships with a molded depth less than 16m, the lower stool may be eliminated.
- Double bottom floors or girders are to be fitted in line with the corrugation flanges for transverse or longitudinal bulkheads, respectively.
- Brackets/carlings are to be fitted below the inner bottom and hopper tank in line with corrugation webs. Where this is not practicable gusset plates with shedder plates are to be fitted.
- Within the region of the corrugation depth below the inner bottom the net thickness of the supporting double bottom floors or girders is not to be less than the net thickness of the corrugated bulkhead flange at the lower end and is to be of at least same material yield strength.
- Brackets/carlings arranged in line with the corrugation web are to have a depth of not less than 0.5 times the corrugation depth and a net thickness not less than 80% of the net thickness of the corrugation webs and are to be at least the same material yield strength.
- Cut outs for stiffeners in way of supporting double bottom floors and girders in line with corrugation flanges are to be fitted with full collar plates.
- Scallops in brackets, gussets plates and shedder plates in way of the connections to the inner bottom or corrugation flange and web are not permitted.
- Full penetration welds are to be used in the lower end of vertical corrugated bulkhead connections.

Considering the verification results in sections 5.1 to 5.3 above, it is considered reasonable and effective to apply the above requirements in order to have satisfactory continuity of strength. As for the welding at the lower end of vertically corrugated bulkheads, application of full penetration welding is required not only at the corrugation corner but also along the parallel portion of the corrugation flange/web. From the view point of the integrity of liquid-tightness, application of full penetration

welding gives higher safety rather than fillet welding also in areas not subject to high stress. However, it is not required to apply edge treatment such as a grinder or additional TIG welding which gives more smoothed surface under the requirements of the CSR.

Considering the recent feedback from damage records and analysis, it is the opinion of most Japanese shipbuilders that full penetration welding should be required only to the corner part of the corrugation, since the stress concentration and subsequent damage records were observed primarily in the limited corner area and no damage record leading to loss of liquid-tightness has been reported at fillet welding of parallel part. Actually it was recent practice before the introduction of the CSR to apply full penetration welding and grinder treatment to the corner part and thus considered satisfactory.

## *6.2 REQUIREMENTS OF FINITE ELEMENT ANALYSIS (FEA) IN CSR*

In addition to prescriptive requirements, the following FEA are required by the CSR in order to verify the scantlings of each corrugated bulkhead and its related structures:

- Overall stress and buckling analysis by coarse mesh (app.800 mm x 800 mm)
- Fine mesh stress analysis of lower end connection of vertically corrugated bulkhead (50 mm x 50 mm)

As it is well known that the level of stress represented at stress concentration areas is strongly sensitive to mesh size, case studies have been done to investigate the impact of the above requirements and criteria in the rules.

Parametric analysis was carried out changing the size of the mesh around the corner corrugation to know the sensitivity of stress levels. The analysis was carried out under the following conditions:

- Vessel size: MR Tanker
- Model size and applied load:  
3 Tank length model, zig-zag loading case
- Type of corrugation:  
Vertically corrugated bulkhead with lower stool
- Net thickness: 22mm (corrugated bulkhead, stool top plate, and stool side plate)
- Design density of cargo:  
0.8, 1.025, 1.3, 1.5, 1.85 (t/m<sup>3</sup>)
- Size of mesh:  
Very fine mesh (17mm x 17mm)  
Fine mesh (50mm x 50mm)

Coarse mesh (615mm x 615mm)

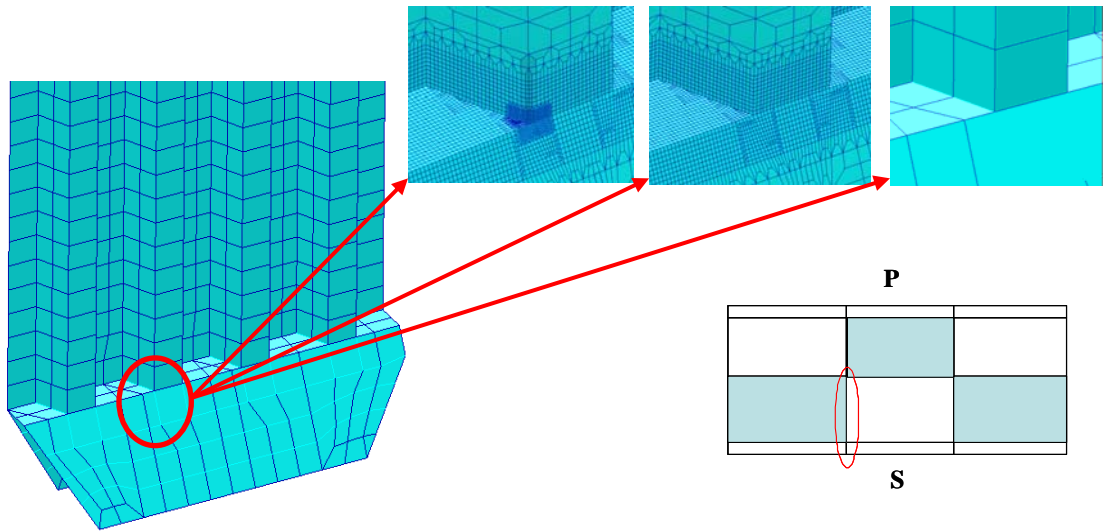


Figure 11: FEA models using different mesh size.

Figure 12 shows the results of the Von-Mises stresses for different size of element, which belongs to the corrugation web and includes the corner of the corrugation. “Distance from corrugation corner” means the distance from the corrugation corner to the center of the evaluated element. (Ex: 25 mm for 50 mm x 50 mm fine mesh.) The results between coarse mesh and fine mesh were derived by the averaged stress using the stress of fine mesh elements in the region.

Five cases of design cargo density were applied as cargo loads. It was subsequently confirmed that the tendency of stress increase was the same regardless of design cargo density.

On the other hand, it was clearly observed that the element stresses of the corrugation corner strongly depend on the size of the mesh, especially in the range below 200mm x 200mm.

As the extent of stress will directly affect the scantlings normally needed for a corrugated bulkhead, it is reasonable and important to define the size of the fine mesh such as 50mm x 50mm commonly used for the evaluation of the stress concentration area.

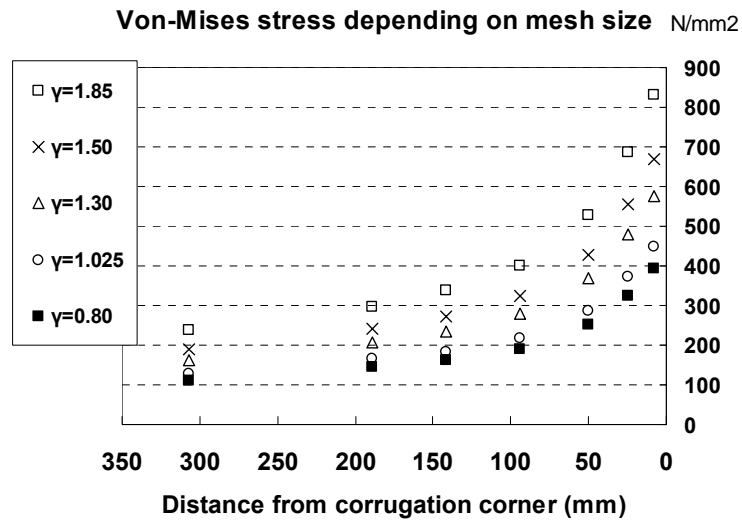


Figure 12: Von-Mises stress of corrugated corner  
( $\gamma$  = cargo density, t/m<sup>3</sup>)

However, at the same time, the following important issues were also reported from various designers to satisfy the criteria of 50mm x 50mm fine mesh analysis in the CSR.

- Considerable scantling increase is required even for designs having satisfactory service experience, if the existing corrugation span is maintained.
- The required scantlings are currently reaching almost the maximum thickness allowable of corrugation due to the bending capacity of the facilities used to fabricate cold-formed corrugate bulkheads.
- Once the thickness exceeds the allowable level, the designers have to modify the span of corrugation by providing upper/lower stools or by modifying the design specific gravity of the cargo tanks to a lower value.
- In each case, of course, a higher level of safety will be achieved by the modified design. However, it will also lead to a loss of cargo capacity followed by higher building costs and operation costs compared with similar designs with demonstrated history of successful service experience.

Considering the above situation in recent ship designs, it is considered necessary to continuously watch the service histories of tankers having corrugated bulkheads and to verify whether the latest rules are really appropriate from the viewpoint of both safety and reliability.

As a minimum, grinder treatment and/or use of anti-fatigue steel should be reviewed possible solutions for helping to keep scantling increases at reasonable levels, if satisfactory

procedures for the design, construction and survey can be established.

## **7. CONCLUSIONS**

Corrugated bulkheads are essential structures for product and chemical tankers and sufficient service records have demonstrated the advantages. In recent designs of tankers, corrugated bulkheads also tend to be applied in larger sized product and chemical tankers currently being built in response to the increased demand for the transport of product oils and chemical products and the amendment of MARPOL Annex II and the IBC Code. Rules and designs of corrugated bulkheads have been improved to cover various complexities of fabrications and operations based on satisfactory service experience together with feedback from damage records and recent design technologies using FEA.

Such feedback is also incorporated in the latest rules covering:

- general structural arrangements
- support structure including its continuity
- full penetration welding, and
- assessment by FEA.

It is needless to say that safety should always be the first priority in the corrugated bulkheads design, which plays a key role in maintaining satisfactory structural integrity without any failures leading to cargo contamination, while at the same time retaining plane surfaces that better facilitate complete cargo tank washing.

However, it has been also reported that considerable scantling increase, which may be beyond the capacity of existing facilities of many yards to fabricate using cold-forming technologies, is required by fine mesh analysis in the CSR. In some cases, designers have modified the initial design to save unacceptable scantling increase even if the design has satisfactory service experience without any damages.

Continuous updating of the rules and designs not only requiring increased thickness but also allowing for the establishment of new technologies should be performed, while watching the valuable service experience of existing designs carefully.

## **8. ACKNOWLEDGEMENTS**

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acknowledge many colleagues and researchers in ClassNK for their contribution to structural analysis and fatigue tests.

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