# Design Development of Corrugated Bulkheads

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## Abstract

Corrugated bulkheads are often used in chemical tankers and product tankers to carry out cargo tank washing efficiently. Sufficient service records have proved the advantage and contribute to the advanced designs corresponding to larger cargo tank capacity due to the increased demand for the transport of product oils and chemical products. It is obviously important in ship design to follow satisfactory experiences and to reflect feedback from past damage records together with the verification based on 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/chemical tankers and also shows the impact of scantling and related key design issues based on the application of the common structural rule (CSR).

## 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, in order to minimize the remaining cargo residue in the cargo tanks, cargo tank washing is applied not only by the requirements of MARPOL Annex II but also by the 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 / product tankers to convert the cargo tank boundaries into more easily accessible plane surfaces. Such plane surfaces help easier coating and inspection of corrugated bulkheads as a result.

## 2. Structural types of Corrugated Bulkheads

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 Figs.1 and 2 below.

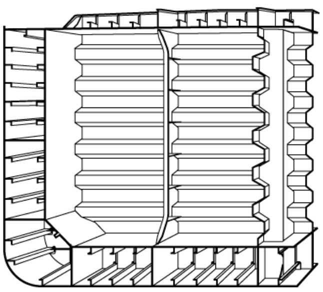


Fig. 1 Horizontally corrugated bulkhead.

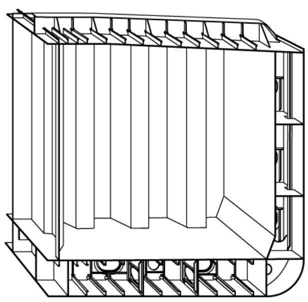


Fig. 2 Vertically Corrugated Bulkhead.

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 designs. Actually, of the approximately 700 chemical tankers having corrugated bulkheads and 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.

## 3. 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 3.1-3.4. 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.

### *3.1 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.

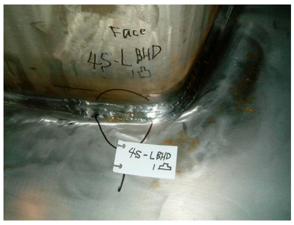



Fig. 3 Crack by welding defects.

### *3.2 Damages of scallops or bracket toes at stress concentration area*

It was reported that cracks were observed at the critical area of corrugated bulkhead related structures, notably:
(a) the scallop at the corner of the lower stool diaphragm just below the vertically corrugated bulkhead
(b) 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.

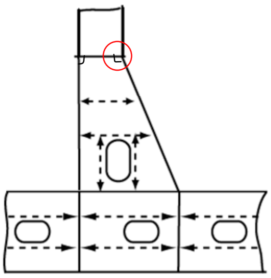


Fig. 4 Crack at scallop
(Vertically corrugated bulkhead).

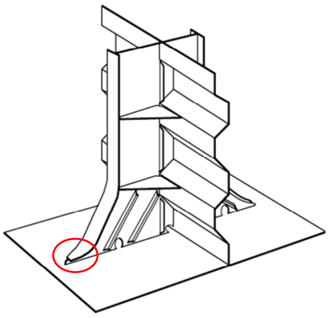


Fig. 5 Crack at bracket toe
(Horizontally corrugated bulkhead).

***3.3 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:
(a) the connection between the vertically corrugated bulkhead with the inner bottom plate (without lower stool), and
(b) the connection between the vertically corrugated bulkhead with the lower stool top plate

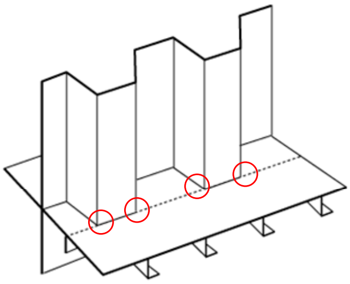


Fig. 6 Direct connection to inner bottom.

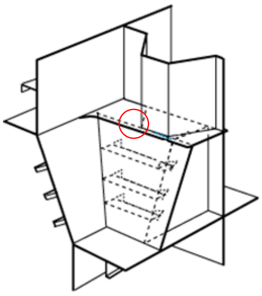


Fig. 7 Connection with lower stool.

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.

***3.4 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.

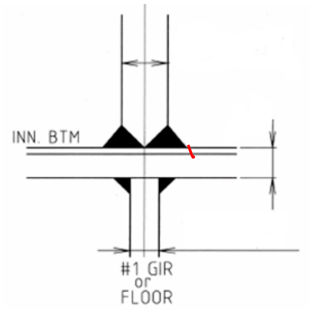



Fig. 8 Crack at corner of corrugation due to lack of continuity.

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.

## 4. Design development based on feedback from damage experiences

### *4.1 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.

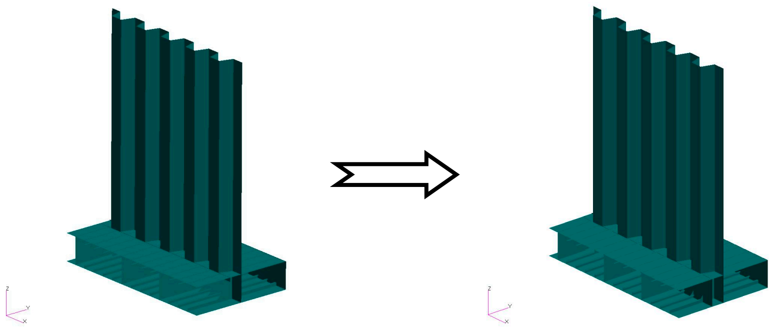


Fig. 9 Upgrade of supporting structure under corrugation flange.

To verify the effectiveness of supporting structure, analysis of selected parameters has been carried out using finite element analysis. Figure 11 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.
(1) Transverse vertically corrugated bulkhead was modeled with relevant supporting structures.
(2) One side of the corrugation flange was supported by the floor plate.
(3) Another side of the flange was supported by various types of stiffeners, as shown in Table 1.
(4) 50mm x 50mm shell elements were used
(5) Static cargo pressure was set as an out-of-plane load

Table 1 Depth of Stiffener for Selected Cases

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

* Case 5: Supporting structure is equivalent to floor
* d0: Depth of corrugation as shown in Fig.10

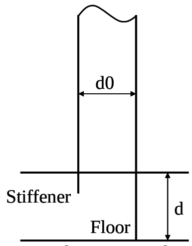



Fig. 10 Definition of parameter.

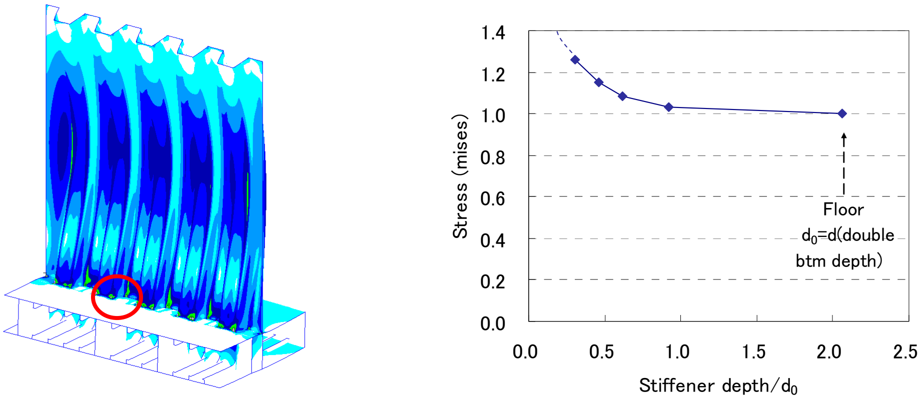



Fig. 11 Evaluation position and relative stress by depth of supporting structure.

From this analysis, it was confirmed that:

(a) Stress at the corner of the end corrugation decreases if a deeper supporting structure is fitted below the corrugation flange.

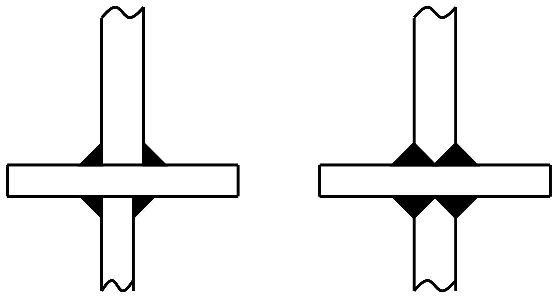
(b) When the support depth exceeds half of the depth of corrugation, the stress reduction ratio becomes lower.

(c) Half of the depth of corrugation depth is considered an effective depth for a supporting structure

(d) Supporting structure such as floor/girders underneath the corrugation flange are suitable

### *4.2 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.



(a) Fillet Welding (b) Full Penetration Welding

Fig. 12 Improvement of welding at lower corrugated bulkhead.

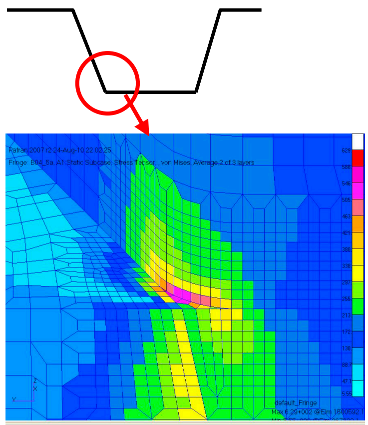
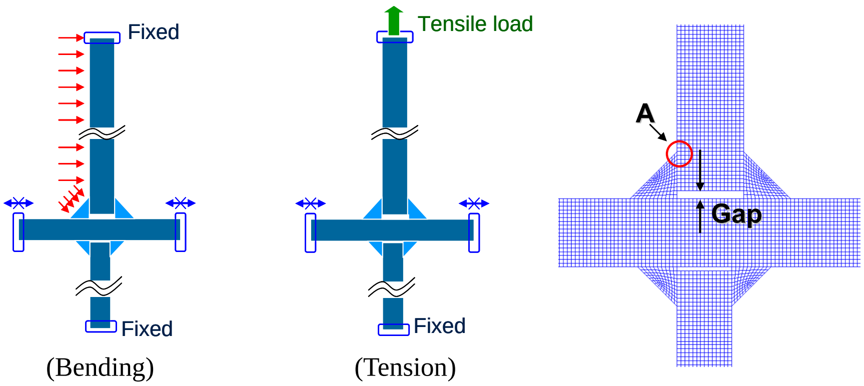


Fig. 13 Stress at corrugation corner.

Figure13 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 experiences.

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

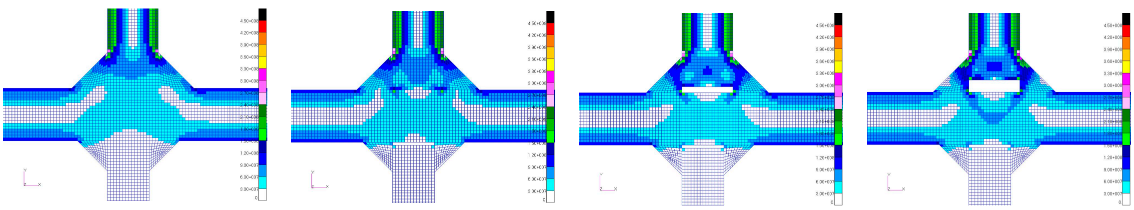



(Bending) (Tension)

Fig. 14 Simplified model of welding and applied load cases.

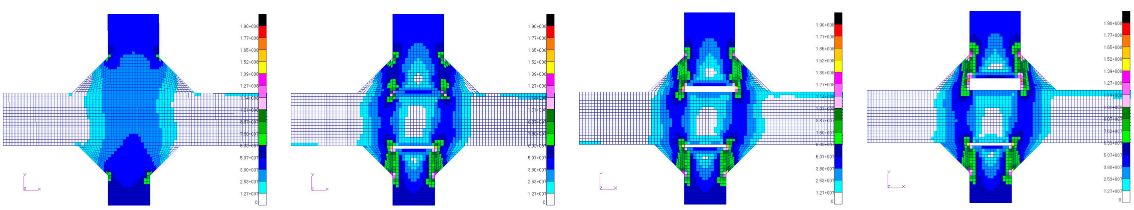
As shown in Figure 14, bending load and tensile load were applied separately to the plate, which was welded by full penetration welding or fillet welding with parametric gaps.

Distributions of Von-Mises stresses caused by the bending load are shown in Figure 15, while those due to the tensile load are shown in Figure 16. The concentrated stress at Position A is summarized in Figure 17 for comparison.



(a) Full Penetration (b) 0mm gap (c) 2mm gap (d) 4mm gap

Fig. 15 Distribution of Von-Mises stress (Bending load).



(a) Full Penetration (b) 0mm gap (c) 2mm gap (d) 4mm gap

Fig. 16 Distribution of Von-Mises stress (Tensile load).

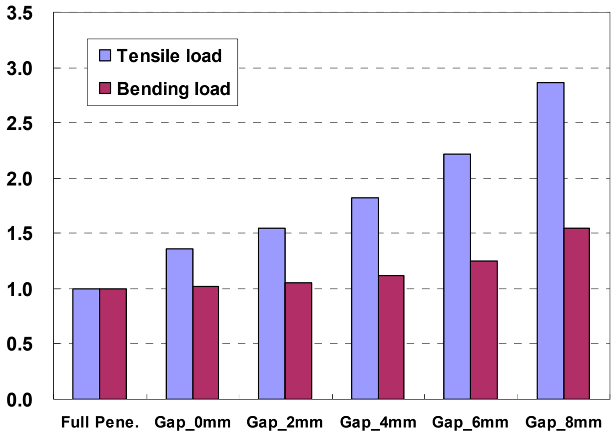



Fig. 17 Relative stress at Position A (Stress of Full Penetration = 1.0).

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 is 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.

***4.3 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.

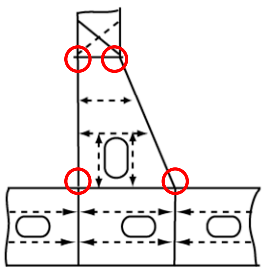
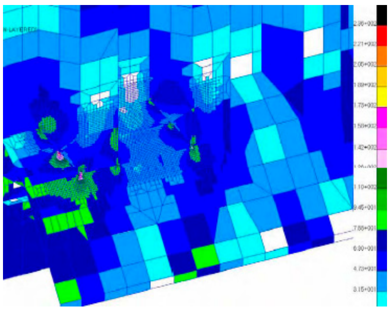


Fig. 18 Closed scallops in the diaphragms.

Case studies have been conducted for reinforcement using gusset and shedder plates, since it has been commonly applied to the corrugated bulkheads of large bulk carriers and its effectiveness can be adequately verified by FEA. 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.

(1) 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.
(2) 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.
(3) When shedder plates cross through the web plate of the corrugation, higher stress concentrations occur at the cross points as shown in Figure 19. 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.
(4) Non-cross type gusset and shedder plates are preferable to avoid the complicated fabrication described in paragraph (3) 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.



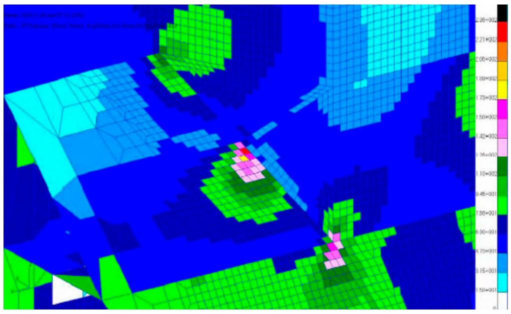


Fig. 19 Arrangement of cross-type shedder plate.

## 5. Latest rule requirements for corrugated bulkheads

Common Structural Rules (CSR) for Double Hull Oil Tankers 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).

### *5.1 Requirements of structural arrangement in Common Structural Rules(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 4.1 to 4.3 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.

### *5.2 Requirements of Finite Element Analysis (FEA) in Common Structural Rules(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:

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

Case studies have been done to investigate the impact of the above requirements.

### *5.2.1 Sensitivity of mesh size around corrugation corner*

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:

(a) Vessel size: MR Tanker
(b) Model size and applied load: 3 Tank length model, B4-1 zig-zag loading case
(c) Type of corrugation: Vertically corrugated bulkhead with lower stool
(d) Net thickness: 22mm (corrugated bulkhead, stool top plate, and stool side plate)
(e) Design density of cargo: 0.8, 1.025, 1.3, 1.5, 1.85 (t/m$^3$)
(f) Size of mesh: Very fine mesh(17mm), fine mesh(50mm), coarse mesh(615mm)

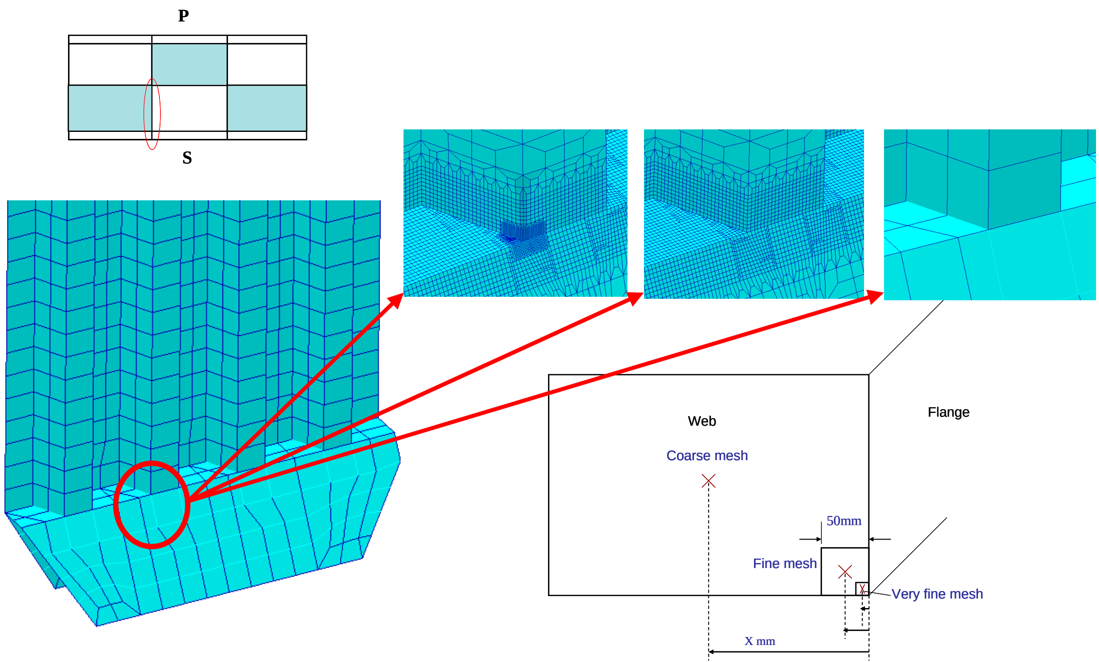



Fig. 20 FEA models of corrugated corner using different mesh sizes.

Figure 21 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.

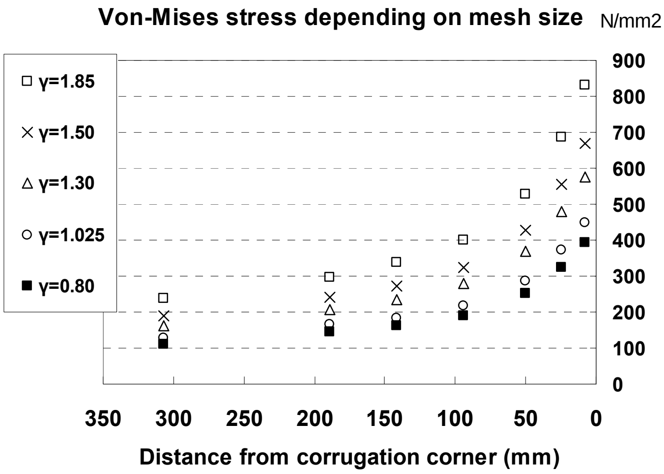



Fig. 21 Von-Mises stresses of corrugated corner depending on mesh size.

### *5.2.2 Impact of Fine Mesh Analysis (50 mm x 50 mm) criteria on scantlings*

In order to investigate the impact on scantlings by the criteria of Fine Mesh, a number of case studies have been conducted on several MR tankers having different scantlings and different service records. These are briefly summarized below:

(a) Ship A: New design vessel which fully complies with the CSR
(b) Ship B: Non-CSR ship with successful service experience without any damage records
(c) Ship C: Non-CSR ships with damage records
(d) Ship C _with brackets: After reinforcement of Ship C without any further damage records
(Brackets provided under corrugation web)

A design cargo density of 1.025 t/m$^3$ was applied for all loading cases as defined in the CSR to investigate the maximum stress at the evaluation elements. As a result, zig-zag loading case B4-5a* gave the highest level of stress of all loading cases. Figure 22 shows the stress distribution along the web and flange of corrugation for this case. (*B4-5a: See the table B.2.4 in Appendix B of the CSR)
From this figure, it was confirmed that:

(1) Stress concentrates at the corner of the corrugation and 100mm to either side of this corner.
(2) Within this area, stress increases drastically towards the corrugation corner.
(3) The stress of the corner elements is app.1.5-2.0 times that of adjacent elements.
(4) The maximum stress of Ship C largely exceeds the criteria, while the coarse mesh stress for the ship is within the acceptable limit.
(5) The maximum stress of Ship B also exceeds the criteria, although the ship has a satisfactory service experience without any damage records.
(6) The maximum stress of Ship C _with brackets also exceeds the criteria, even though the ship has satisfactory service experience after reinforcement.

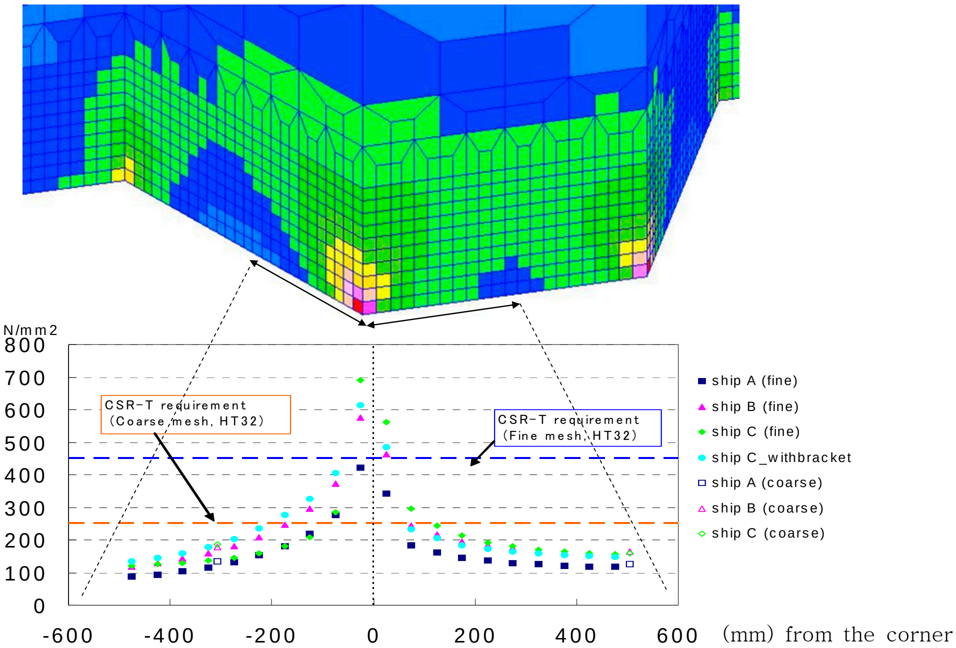



Fig. 22 Distribution of element stress and CSR criteria.

Considerable scantling increase of corrugated bulkhead of Ship A was reported to comply with the criteria at the corner position and similar tendency was observed in other designs needing to comply with the CSR. Taking these impacts by the CSR into account, the following important issues were reported from various designers.

(1) Considerable scantling increase will be required even for designs having satisfactory service experience, if the existing corrugation span is maintained.
(2) 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.
(3) Once the thickness exceeds the allowable level, the designers will 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.
(4) 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.

## 6. Conclusion

Corrugated bulkheads are essential structures for product / chemical tankers and sufficient service records have proved the advantage. 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:
(1) general structural arrangements
(2) support structure including its continuity
(3) full penetration welding, and
(4) 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 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 need to modify 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.

## References

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