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Misalignment effect on stress concentration of thickness mismatched plate structures

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Abstract

The aim of this paper is to numerically simulate the stress concentration response of the weld structures and compare the results with analytical equations performed on the misalignment effect. Different structures numerical models are subjected to tensile load which lead to large stress in local area of welded structures due to the discrepancy of plates thickness. The transitions of unequal thickness plates undertaking the in-plane force could also lead to the local bending. The stress concentration factors were simulated using the finite element method (FEM). For investigations of misalignment welded structures local stress concentration, the effects of geometrical variables, i.e. the cope hole of welded plates connecting zone, the position of structure plane, the slope ratio of unequal plates, the number of components, are systematically considered. Finally, by the comparison of numerical results, the optimized form of structures could be determined.

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1. Introduction

In the processing of manufacturing steel structures, butt-welded joint plays an important role in connecting the different components of welded structures, such as ships, floating offshore platforms, frame structures, shell structures,
wind energy towers. It is also well known that these structures in specific environments are damaged by dynamic cycling loading, which may result in catastrophe disasters. The origin of fatigue failure under millions of cycling force is often places of geometry discontinues. Therefore, the weld joints as the major area of geometry changing are widely studied by structure experts. The mechanical and geometrical properties of welded connections have a strong influence on the fatigue life. In the meantime, the hot spot stress as a function of life prediction, which is nearby the weldment is computed for the fatigue assessment procedure.

In general, stress concentration factor is a dimensionless factor which is used to quantify how concentrated the stress is in a material. It is defined as the ratio of the highest stress in the element to the reference stress. The misalignments due to the plates thickness discrepancy could give rise to the stress concentration when the connections between two different plates are subjected to tension or bending loading. Maddox (1985, 1997) of the UK welding institute investigated the misalignment effect by concluding a series of butt welds misalignment derivation analytic equations which are sensitive to different plates geometry, boundary conditions, and stress levels, subsequently these equations were recommended in fatigue design rules of plants structures such as DNV (2013), BS7910 (2013), Eurocode 3(2005). However, there is still a complicated problem to access the hot spot stress by SCFs with the diversity of structure geometry, dimension and loading conditions. To illustrate the detrimental influence of misalignment derived from geometry change and induced overlarge stress concentration on the fatigue performance of welded structures. Lotsberg (2008) studied the eccentricities during plant thickness transitions and fabrication tolerances of butt-weld joints, and he found that it could be induce the increasing of maximum stress of joints due to the existence of local bending. In addition, the accuracy of Maddox equations for SCFs is improved by correcting the parameters of it.

The present work attempts to study the misalignment effects in a large-scale deck welded structure of bulk carriers compared with the analytical equations. In the meantime, The SCF magnitudes of transverse misalignment butt welds which locate on and back face the structural plane in the deck structures with stiffeners is investigated. Parametric studies on the effects of geometric variables, i.e. the thickness and the thickness ratio of transitions and the length of panels on SCFs are performed.

2. Basic equation for SCFs at butt welds

Eccentricity is more or less inevitable in the welding processing of plated structures and the eccentricity in a butt weld can exert additional SCFs due to adding membrane to local bending stress as illustrated in Fig.1. A simplified misalignment plate is subjected to a transverse force per unit width equal \( N = \sigma_a \cdot t \), where \( \sigma_a \) stands for transverse stress and \( t \) is the plate thickness. The magnitude of local bending stress assumes that the bending moment caused by the transverse load and eccentricity is shared by the two plates. The lengths of these plates are assumed to be equal. The existence of eccentricity \( \delta_m \) is sometimes referred to as fabrication tolerance. A bending moment in the plate at both side of local region is expressed by the equation \( M = N \cdot \delta_m / 2 \), and \( W = t^2 / 6 \) stands for the section modulus of unit width in a plate. Thus, the bending stress formula at the weld region is determined:

\[
\sigma_b = \frac{M}{W} = \frac{N \delta_m / 2}{t^2 / 6} = \frac{3N \delta_m}{t^2} = \frac{3\sigma_a \delta_m}{t}
\]  

(1)

And the SCF at weld toe in Fig.1 can be shown:

\[
SCF = 1 + \frac{3\delta_m}{t}
\]  

(2)
The value of $\delta_m$ is limited to approximately 3mm to 4mm or 0.15t in some recommended rules. According to previous researches, the equation shows good agreement for the equal thickness misalignment plates. However, the existing of eccentricity at butt welds are not only due to the fabrication tolerance, but also the thickness mismatch or angular misalignment. The estimating SCFs are generally discounted by the combination effect of both misalignment types. Maddox (1985,1997) of UK welding institute gave a general equation (3) considering the transverse misalignment, which not only depends on fabrication tolerance, but also influences by unequal thickness.

$$SCF = 1 + \frac{6 (\delta_t + \delta_m)}{t} \frac{1}{1 + \left(\frac{T}{t}\right)^{1.5}}$$

Where $\delta_t$ is the shift in transverse direction of butt welds at thickness transition, and it equals to 0.5(T-t). $\delta_m$ means fabrication tolerance. $T$ and $t$ are the thickness of both sides plates.

The Eq.(3) has been recommended to use for butt welds connections with different thickness in the DNV-RP-C203 (2013) and British Standard BS7910 (2013). In this equation, the SCFs is estimated to obtain hot spot stress from the nominal stress for fatigue analysis.

3. Misalignment butt welds in large-scale plated structures

A designer is unlikely to strengthen all components using the very high strength steel for fabricating ship structures in complex marine environment. It is beneficial that more thickness plates are applied to some critical position to resist fracture by overloading, however these changing could induce misalignment and stress concentration in thickness transition regions. To closely examine local SCFs of the large-scale plated structures caused by thickness direction misalignment, the ship structures including typical components and local shift region as showing in Fig.3 is employed in the following investigations.

3.1. Description of misalignment butt welds panel structures

The overview and transition region models of a ship panel structures are showed in the Fig.2. according to the reality range of ship building platforms. Many of different thickness plates and stiffeners make up the ship cabin structures shown as Fig.2(a). The panel is 27000mm $\times$ 20000mm $\times$ 6000mm, in which the spacing distance between longitudinal stiffeners is uniform 2000mm. Details of the typical components of ship plates structures are shown in Fig.2(b), and it contents four longitudinal stiffeners which connect vertically with different thickness plates. Dimensions of these corresponding plate thickness is in the range 12-25mm. The butt welds shown in Fig.2(c) are located in the thickness transition region with a cope hole. The out-of-plane of the panel is defined as structure plane, while the shift plane of butt welds is reverse side of the structural plane, acted as in-plane transition.
Based on the actual fabrication, the assembly processing from the plates and stiffeners to the deck panel structures is roughly divided into 4 steps. Firstly, all longitudinal stiffeners are welded to different plates forming unit panels with MIG welding from both sides and simultaneous operating. Secondly, it is the assembly of each unit panels using I section stiffeners. Thirdly, transverse stiffeners are welded across the different unit panels. Finally, joints between unit panels are connected by two submerged-arc welding machines simultaneous from the centre of panels.

3.2. The misalignment unit panel structures model

To gain a better understanding of the SCFs changing in the actual misalignment structures, a typical model of unit panel with four stiffeners shown as Fig.3(b) was studied by finite element analysis using elastic theory. The cope hole near the thickness transition region shown in Fig.3(c) is cut to ensure that the stiffeners is clear of the panels butt welds. For the model of unit panel, the fix boundary condition is set at the end of the thick section in longitudinal direction, and the nominal axis stress of 100 MPa is applied at the other end of the thin section. Using the commercial software ABAQUS to perform elastic FE analysis, the C3D8R reduced integration element type was chosen to predict the distribution of SCFs in the misalignment transition region. All FE simulations assumed elastic material properties and nonlinear geometry to obtain possible second order effects.

In this study, different models peak stress values of transition regions were compared to determine FE solution accuracy with analytical equations. From the results of peak stress, the locations are general in the reentrant corners.
of transition region. Therefore, we extrapolate the characteristic stress far from the corner points which determines the peak stress value in the thin plate.

3.3. Effect of cope hole in the misalignment butt weld structures

For the equal thickness plates with a misalignment tolerance in butt weld structures, it has been found that the values of SCFs Eq. (2) is good agreement with numerical results in certain scenarios. However, the relationships of different sizes longitudinal stiffener groups, position of transition regions and cope holes with peak stress in large-scale structures have been not clearly illustrated in design standards. Although, some researchers have reported that longitudinal stiffeners can reduce magnitudes of peak stress in transition regions.

Cope holes left gaps in stiffeners transition region may cause high stress concentration and reduce fatigue strength of local zones (2006). According to design details in panel structures, the SCFs of transition regions not only depend on plate thickness but also on shape of cope holes in stiffeners. In general, the geometric shape of these cope holes is triangle, circle or rectangular. To simulate the effects of cope holes in considered large-scale panel structures by computation, uniformly distributed nominal stress which is 100 MPa is applied to the end of thin plate. Additionally, the effects of altering sizes of rectangular cope holes and the corresponding stress concentration in transition regions were investigated. Specifically, four cases with different cope hole conditions, namely inside without hole, cope hole 1(100mm*30mm), cope hole 2(130mm*50mm) and cope hole 3(210mm*60mm), shown in Fig.3, are employed using FE analysis.

Table 1. The size of holes in the transition zone

<table>
<thead>
<tr>
<th>Case</th>
<th>High</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICH1/OCH1</td>
<td>30 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>ICH2/OCH2</td>
<td>50 mm</td>
<td>130 mm</td>
</tr>
<tr>
<td>ICH3/OCH3</td>
<td>60 mm</td>
<td>210 mm</td>
</tr>
</tbody>
</table>

Structure plane represents a reference plane in fabricating process of ship structures. In order to illustrate the difference in the unequal thickness plates shift regions, the transition region plane was divided into two groups as Fig.3(a) and Fig.3(b), which located inside and outside of structure plane respectively.

Fig. 4 shows the SCFs along the transverse weld inside of structure plane without and with cope hole. It is indicated that the stress concentration is largest near the cope hole and the SCF decreases as the cope hole size increases due to the existence of it. At the same time, the simulation values of SCF decrease gradually far away from the cope hole in the range of 300mm. Away from the variation range, the FEM results of SCFs have a good agreement with the Eq. (3) results. Note that the SCFs without cope hole are significantly cut down in the variation range compared the middle of plate. It shows that the bending stress is increased by constraint from vertical plates with the existence of cope hole.
3.4. Effect of position of structure plane in the misalignment butt weld structures

Fig. 5 shows the SCFs along the transverse weld outside of structure plane without and with cope hole. The SCFs tendency of group Fig. 5 in the transition zone is similar with the group Fig. 4, while the stabilization stage results of simulation in the middle of plate are decreased 11% than the analytical equation results. Considering the constraints of structural plane inside with cope hole coming from the vertical plates is stronger than outside with cope hole, the vertical plates release more bending stress in the transition zone so that the results of structural plane inside with cope hole are larger than another.

3.5. Effect of thickness of butt weld in transition zone

According to the Eq. (3), different stress concentration can be exerted due to the thickness difference of plates in the longitudinal direction. In order to figure out the thickness effect, the ICH1 model is chosen and a fixed slope in
transition in thickness of 1:4 is applied to this model. The thickness range of \( t \) and \( T \) is 12-20mm, 25-34mm, respectively. Nine groups are combined from different thickness plates. Fig6(a) shows the SCFs of different thickness plates combination. The SCF curves of plates combination tends to decrease with the increasing of plates thickness. Fig.6(b) demonstrates comparison results of predicted SCF and analytical SCF from different thickness combinations. As a nominal stress 100Mpa is loaded, the predicted stress concentration values of transition zone have a good agreement compared with analytical results for the nine combinations.

![Fig.6 (a) SCFs of different thickness plates combination, (b) Comparison of predicted SCF and analytical SCF from different thickness combinations.](image)

### 3.6. Slope effect of transition zone between the different thickness

To examine the effect of slope, different slope models were analyzed and compared with calculated results. At the same time, two different thickness plates are chosen to figure out the SCF, which is 20mm and 15mm. These results show slope effect in misalignment transition zone in Fig. 7. The SCFs are gradually decreasing with the slope ratio increasing.

![Fig.7 Slope effect of SCF in transition zones](image)
4. Conclusion

This paper presents the misalignment effect on stress concentration of butt welded joints in plated structures by FE simulations. As the structure shows geometric variations on the mismatched thickness, the hole size surrounding transition zone, the position of structure plane and the slope of thickness transition, a series of geometric models are compared and we can draw the following conclusions from the study:

- The existing of cope hole can influence the peak stress surrounding the transition zone. The increasing of cope hole size results in decreasing of SCF due to the constraint releasing.
- According to the SCFs results of different positions of structure plane, the cope hole inside of structure plane SCFs is higher than outside of structure plane compared with analytical equation result, especially the intersection zone.
- The study of plates thickness combination and the slope of transition indicates that SCFs are sensitive to thickness variation.

References

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