Effect of Joint Details on Fatigue Properties of a Slot Structure

J. G. Youn, H. S. Kim and D. H. Park

Abstract

Effect of the joint details on the stress distribution over a slot structure has been studied in order to improve its fatigue life using a finite element analysis. The joint details of interest are the radius and height of scallop at the stiffener as well as the mis-alignment between the stiffener and longitudinal member. For a slot structure currently used, the stiffener heel is subjected to the maximum stress for a given external load, where is a potential fatigue crack initiation site. The stresses at the stiffener heel and toe decrease both by increasing the scallop radius and more significantly by increasing the mis-alignment, while no notable effect of the scallop height on it is appreciated. A proper combination of these factors makes it possible to reduce the stresses at the stiffener heel and toe, theoretically, more than 50%. This is attributed to the modification of the stress distribution over the slot structure including the transition of the maximum stressed region from the stiffener heel to the slot surface of the transverse web. Such then results in a great improvement of the fatigue life of the slot structure.

Key Words : Slot structure, Scallop, Mis-alignment, Stiffener, Fatigue properties

1. Introduction

Recently, the International Maritime Organization has specified the mandatory application of double hull structure for the chemical carrier of type I, II, and the oil tanker that having the dead weight over 600 tons in order to prevent possible pollution at sea. Compared with a conventional single hull structure, a double hull structure requires many slot connections between the transverse webs and longitudinal members, the so-called slot structures. Slot region of the structure has a complicated structural geometry because it is the junction of the transverse web, the longitudinal member, a collar plate and a stiffener.

Such a complicated structural feature causes stress concentration at this region during operation so that it deteriorates the fatigue life of the slot structure. It is therefore important to secure sufficient fatigue life of the slot structure. To do this, stress concentration within the structures should be minimized through a modification in structural geometry and/or weld geometry for a given cyclic loading [1-4]. Authors' preliminary work on the fatigue properties of some slot structures showed that fatigue crack initiated mainly at the weld toe of the stiffener heel subjected to very high stress for a given loading condition.

It was theoretically reported that the stress at this region could be reduced either by modifying the scallop radius of the stiffener [5] or by the mis-alignment between the stiffener and the longitudinal member [6].

The present study has focused on improving the fatigue life of the slot structure as by minimizing the stress concentration at the stiffener through a modification in joint details.

The joint details of interest are the radius and height of scallop at the stiffener and the mis-alignment between the stiffener and longitudinal member.

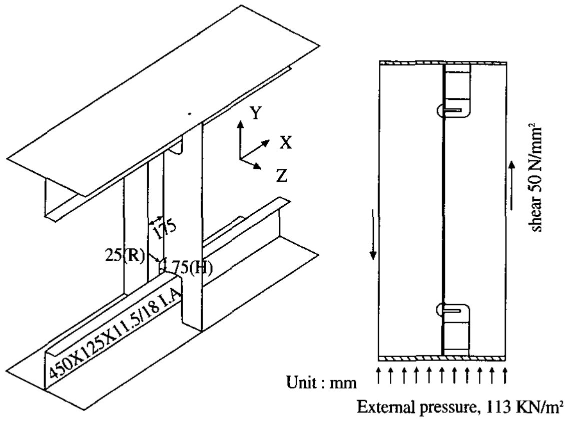
The stress distribution over the slot structure was evaluated by a finite element analysis. Both fatigue and static test on the slot structures having different joint details were performed in order to confirm the stress analysis.

J. G. Youn and *H. S. Kim* are with Hyundai Industrial Research Institute, Hyundai Heavy Industry Co. Ltd., Ulsan, Korea.
D. H. Park is a Professor, Department of Metallurgical Engineering, University of Ulsan, Ulsan, Korea.
E-mail : mrd@hhi.co.kr, TEL : +82-52-230-5511

2. Stress analysis

2.1 General stress distribution

The stress analysis on a slot structure has been carried out in order to evaluate the stress distribution of a slot structure using an analysis program of the commercial finite element (NISA II). The slot structure analyzed has been currently adopted in a 153 K double hull oil tanker. The slot structure was modeled in a full scale of the actual dimension as shown in Fig.1. Model size was corresponding to 1 frame space and 1 longitudinal member of the actual structure. About 8000 elements were generated using the plane stress isoparametric shell element. Finer elements were applied to the structural stress concentration regions expected.



* A point is restrained along Y direction.

Fig. 1 Full-scale model and boundary conditions for stress analysis

The stress concerned in this study is the equivalent stress because the slot structure becomes subjected to combined stresses of tension, bending and shear. The boundary conditions for the analysis were as following. 1) An external pressure of 113 KN/m² was applied to the bottom of the model and mean shear stress acting on the transverse web plate was 50N/mm² as shown in Fig.1. 2) Nodal displacement along both X and Z directions was symmetric. Nodal displacement at the center point of the web plate of the left side transverse was restrained along Y direction for the analysis of shear effect, which was a loading direction.

The Fig.2 shows the deformed feature of the slot structure together with the equivalent stress distribution over the slot structure for the condition given above. Lower longitudinal member is severely bent like a wing and stress acting on the longitudinal member is generally small. Since the junction between the web plate, stiffener and longitudinal member acts as a bending support due to its strong rigidity, no significant deformation is found but very high stresses develop at this junction. This is attributed to the bending moment caused by asymmetric geometry of web plate. The maximum stress is observed at the stiffener heel, that is, at the scallop edge on the flange of the longitudinal member. This location is well known to be a potential fatigue crack initiation site. The stresses both at each corner of the slot and at the stiffener toe are also subjected to very high stresses.

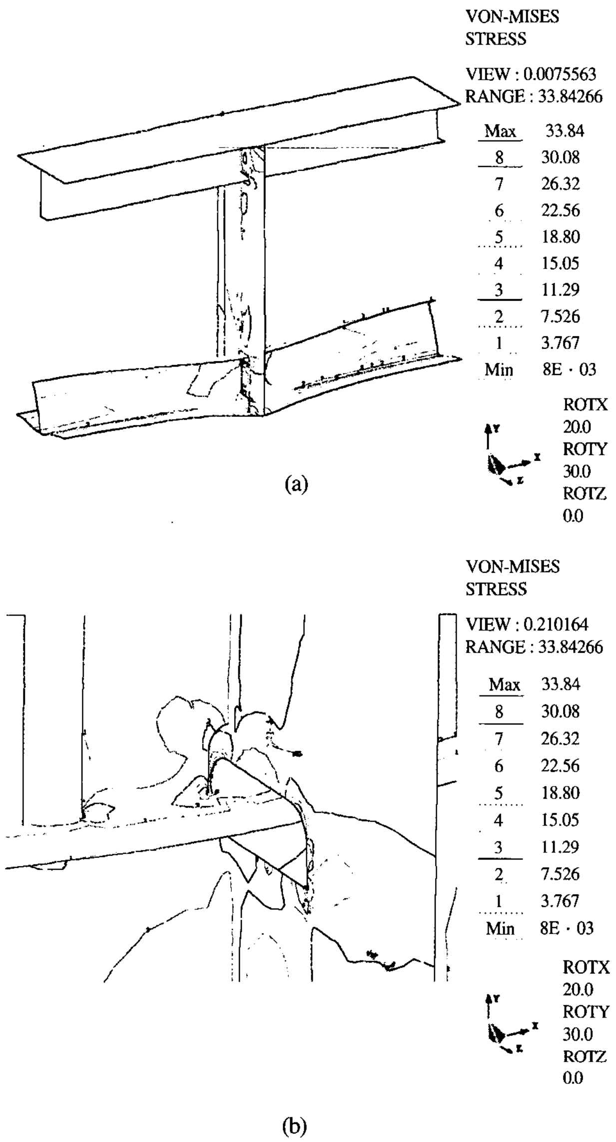


Fig. 2 Equivalent stress distribution over the slot structure currently used: (a) General view and (b) Local view around the slot

2.2 Effect of joint details on the stress distribution

In order to modify the stress distribution particularly the local stress at the stiffener heel observed in Fig.2, effect of joint details on the stress distribution over the slot structure has been investigated. The joint details studied were the radius (R) and height (H) of scallop at the stiffener and the mis-alignment (e) between the stiffener and the longitudinal member as shown in Fig.3. For the analysis, a half of the model given in Fig.1 was employed in order to compare the analysis result with the experimental data. A force of 30 ton was applied to the top of the model as in a three point bending form to simulate the external pressure effect shown in the Fig.1. However, the shear force that was acting on the web plate has not been taken into a consideration in this case therein.

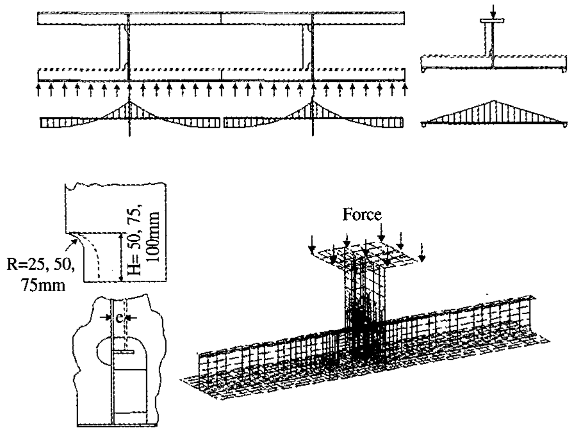


Fig. 3 Half model of the slot structure and geometric parameters for stress analysis

Fig.4 (a) shows the effect of scallop radius (R) on the stress distribution along the stiffener bottom for the slot structure having a scallop height of 75mm without mis-alignment. The stress at the stiffener heel is reduced about 18% from 45 to 37 kg/mm^2 with an increase in the scallop radius from 25 to 75mm. The variation of stress at the scallop toe with scallop radius is relatively small. The location (i. e., stiffener heel) subjected to the maximum stress is not shifted by changing the scallop radius studied. The stress reduction at the stiffener heel caused by increasing scallop radius is compensated with the overall stress increment at the slot surface (see Fig.6).

Effect of scallop height (H) on the stress distribution along the stiffener bottom is shown in Fig.4 (b) for the slot structure having a scallop radius of 50mm without mis-alignment. Although the peak stresses at the stiffener heel and toe for H=100mm are slightly lower than those for H=50 and 75mm, no significant variation of the stress distribution with the scallop height studied is discernible and the maximum stressed region is not also altered.

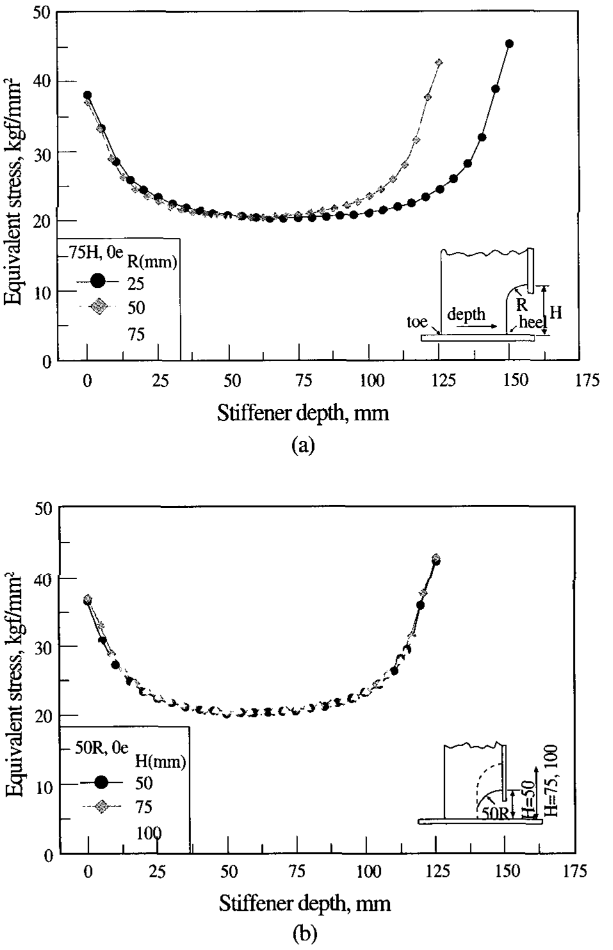
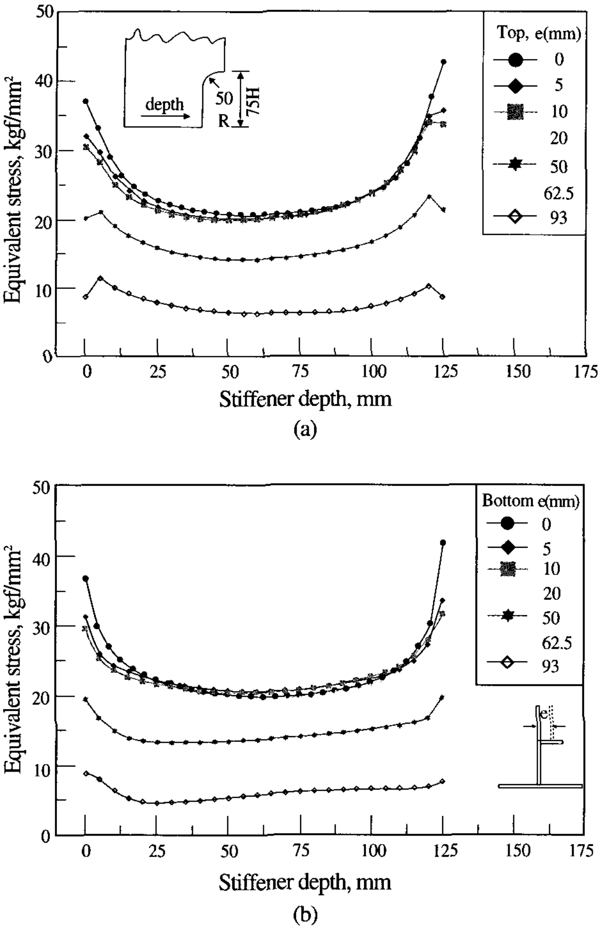


Fig. 4 Effect of joint details on the equivalent stress distribution along the stiffener bottom : (a) Effect of scallop radius (R) for the slot structure with H=75mm and e=0mm, and (b) Effect of scallop height (H) for the slot structure with R=50mm and e=0mm,

Fig.5 shows the effect of mis-alignment (e) on the stress distribution along the stiffener bottom for the slot structure with H=75mm and R=50mm. (It is worthwhile to note that the stress values at both the heel and toe of the stiffener cannot be taken as the real values since they were averaged by the stress value of the adjacent element) The mis-alignment effect on the stress distribution is more substantial than the other geometric factors studied. As the mis-alignment increases, the stresses at the stiffener heel and toe are gradually reduced. The stress at the stiffener heel can be reduced theoretically more than 50% simply by adopting the mis-alignment longerthan 50mm.



(a)

(b)

Fig. 5 Effect of mis-alignment on the equivalent stress distribution along the stiffener bottom for the slot structure with H=75mm and R=50mm : Data from (a) Top surface and (b) Bottom surface of the element

Such a remarkable reduction of the stress is directly attributed to the bending effect of the stiffener under a given loading condition. This results in an overall stress increment and expands the area of highly stressed location at the transverse web plate, more exactly at the slot region (see Fig.6). Bending of the stiffener also causes the stress gradient between the top and bottom surface of the stiffener, that is, along the thickness direction of the stiffener as shown in Fig.5 (a) and (b). The stress obtained at the top surface is generally higher than that at the bottom surface and the stress difference between them increases with an increase in the mis-alignment. The mis-alignment effect on the stress distribution was also confirmed for the slot structures having different scallop geometry (for example, Fig.6).

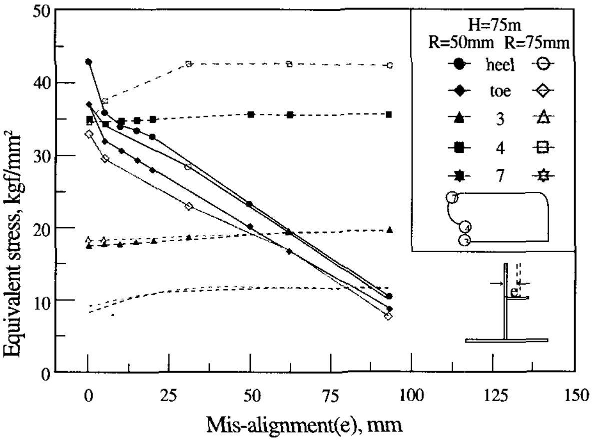
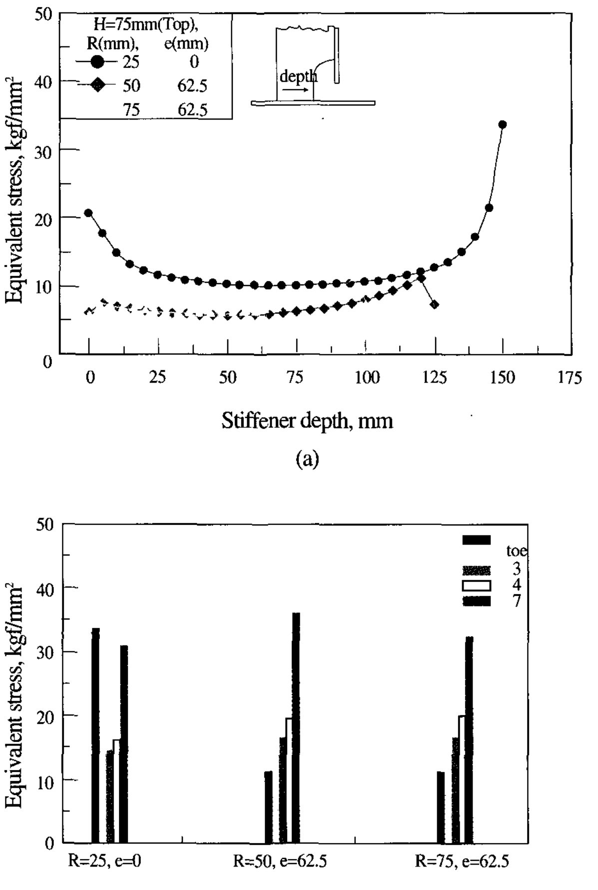


Fig. 6 Variation of local stress around the slot with mis-alignment

In order to understand the reason responsible for the stress reduction at the stiffener bottom, the variation of the local stresses at some critical locations in the slot structure has been analyzed as a function of mis-alignment. As shown in Fig. 6, the stresses at the stiffener heel and toe decrease almost in a linear manner with an increase in the mis-alignment for the slot structures studied. All the stresses at the slot surface increase steadily but increasing the mis-alignment expands the areas subjected to these stresses. Along the slot surface, the highest stress acts on No.4 location where is the top region of the junction between the transverse web plate and the web of the longitudinal member. For the slot structure the location subjected to the maximum stress is then determined by counter-balancing between the stress reduction at the stiffener heel and the stress increment at No.4 location. The shift of the maximum stressed region from the stiffener heel to the slot surface takes place above about the mis-alignment of 10mm for the slot structure (H=75mm and R=50mm) and 2.5mm for the slot structure (H=75mm and R=75mm), respectively. This trend reflects the rigidity of the stiffener. That is, bending effect of the stiffener is predominant for the slot structure having large scallop area.The mis-alignment studied did not significantly deteriorate the buckling strength of the slot structure.

2.3 Stiffener design

Based on the stress analysis results, application of large scallop radius and long mis-alignment to the slot structure is desirable in order to reduce the local stresses at the stiffener heel and toe. In order to confirm the results described in the above section, an additional stress analysis has been carried out for a full-scale model using the same conditions described in the section 2.1. The slot structure analyzed had the geometry of H=75mm, R=50 or 75mm and the mis-alignment of 62.5 mm.



(a)

(b)

Fig. 7 Equivalent stress distribution over the slot structures studied (full scale model) : (a) Along the stiffener bottom and (b) Stress values at various locations

As shown in Fig.7 (a), the stress along the stiffener bottom is clearly lowered for the geometrically modified slot structures, compared with the slot structure currently used (H=75mm, R=25mm and e=0mm). The stress at the stiffener heel of the geometrically modified slot structures is about 11.3 kg/mm^2, which is only 33% of the value (about 33.8 kg/mm^2) observed at the slot structure currently used. Similar result is also found at the stiffener toe.

Slightly higher stresses develop around the slot such as No.3, No.4 and No.7 location as shown in Fig.7 (b) and the maximum stress acts on No.7 location for the geometrically modified slot structure. The maximum stressed location is not corresponding to the result in Fig.6 because of the shear effect at the transverse web plate in this case.

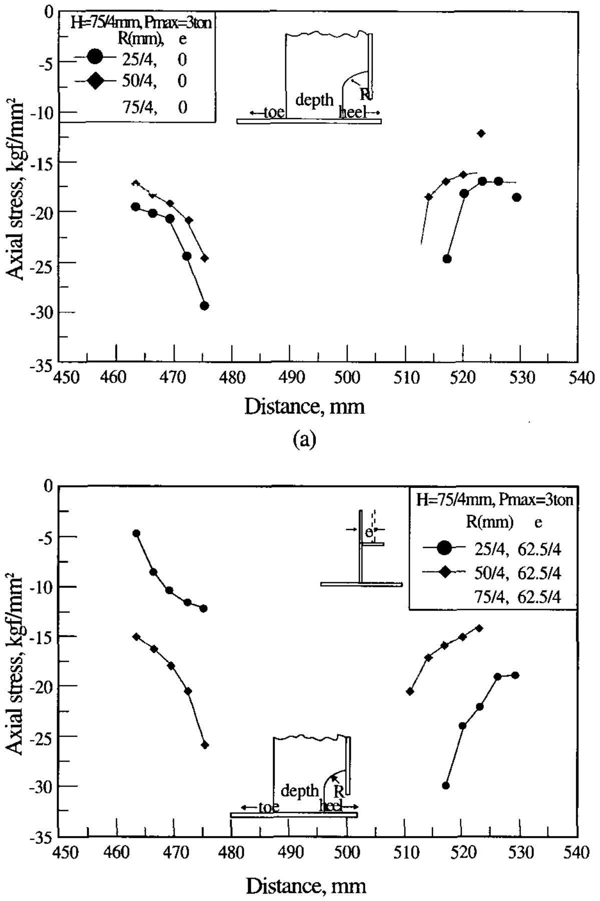
3. Experimental evaluation of stress and Fatigue Properties

3.1 Experimental procedure

The slot structures having the different joint details were made in a quarter scale of the actual dimension given in Fig.1 with the exception of the plate thickness that followed the specimen geometry shown in Fig.3. The thickness was 6mm and 8mm for the plate and the angle, respectively. In order to evaluate the mis-alignment effect clearly, the stiffener was located at the center of the flange of an angle corresponding to the mis-alignment of 62.5mm. The slot structures were made by a fillet welding using a mild steel plate and a FCAW process. The leg length of the fillet weld was 6mm. The stress distribution over the slot structure was evaluated by measuring and converting strain values obtained at various locations under an external load of 3 tons. Two sets of 5 uni-axial strain gauges were attached close to the weld of the stiffener heel and toe over the flange of the angle. The first strain gauge was on the location about 2.5mm away from the weld toe. The tri-axial strain gauge was used in order to measure the local stress at No.4 location of the slot region. Three-point bending fatigue test was carried out under a constant load range with a load ratio of 0.1 and Pmax. of 5 tons. The fatigue crack initiation was monitored using the liquid penetration check every 5x10^4 cycles. The fatigue crack initiation life (Ni) was defined when the surface crack length was about 10mm.

3.2 Stress distribution measured under a static loading condition

Fig.8 shows the effect of joint details around the slot on the stress distribution over the flange of the longitudinal member at the slot structure. The stress value in this figure is an average value from two specimens. Fig.8 (a) shows the effect of scallop radius on the axial stress distribution for the slot structure without mis-alignment. (Actual mis-alignment of the specimen was about 1-2mm). The stresses at the stiffener heel and toe decrease with an increase in scallop radius, which is almost corresponding to the finite element stress analysis.



(a)

(b)

Fig. 8 Effect of joint details on the axial stress distribution near the stiffener bottom : (a) Effect of scallop radius (R) and (b) Effect of mis-alignment (e) for the slot structure as with H=75/4mm

The absolute stress value at the stiffener toe is slightly higher than that at the stiffener heel for each slot structure.

Effect of mis-alignment on the axial stress distribution over the flange of the longitudinal member is shown in Fig.8 (b). For the slot structure having the mis-alignment value of the half-length of the flange width of the longitudinal member, the absolute stress value at the stiffener toe generally decreases in a great extent but that at the stiffener heel increases, when compared with the results in Fig.8 (a). This may be associated with either the further stress concentration caused by the weld geometry such as toe radius and flank angle or with a possible experimental error due to very small space within the scallop. A notable feature in this figure is that the effect of scallop radius on the stress distribution becomes insignificant because of significant effect of mis-alignment on it.

3.3 Fatigue properties

As shown in Fig.9, all the fatigue cracks initiated at the weld toe of either the stiffener heel or the stiffener toe even for the geometrically modified slot structure designed to induce the slot region to be subjected to the maximum stress. That is, the fatigue crack initiation sites were not exactly corresponding to the region expected by the stress analysis. These were coincided with the weld toe subjected to high peak stresses. This emphasizes again on the further stress concentration effect at the weld toe. The fatigue crack propagated along the thickness direction of the flange of the longitudinal member.

Effect of the joint details on the fatigue life of the slot structure is shown in Fig.10. With an increase in scallop radius of the stiffener, fatigue life of the slot structure without mis-alignment increases. This reflects the dependency of the stress concentration at the stiffener heel and toe on the scallop radius as shown in Fig.4 (b). The slot structure having the mis-alignment shows longer fatigue life than the slot structure without mis-alignment for a given scallop geometry.

4. Conclusion

Effect of joint details on the stress distribution over a slot structure has been studied in order to improve its fatigue life using a finite element analysis. The joint details of interest were the radius and height of scallop at the stiffener and the mis-alignment between the stiffener and the longitudinal member.

1) For the slot structure currently used, the scallop heel of the stiffener is subjected to the maximum stress for a given external load. The stress at the stiffener heel decreases with an increase in the scallop radius and the mis-alignment, while effect of the scallop height is not significant.
2) A proper combination of these factors makes it possible for the slot structure currently used to reduce

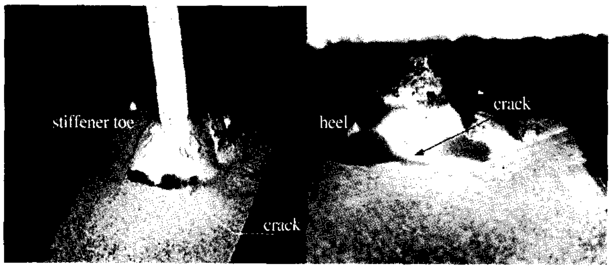


Fig. 9 Fatigue cracking at the slot structures

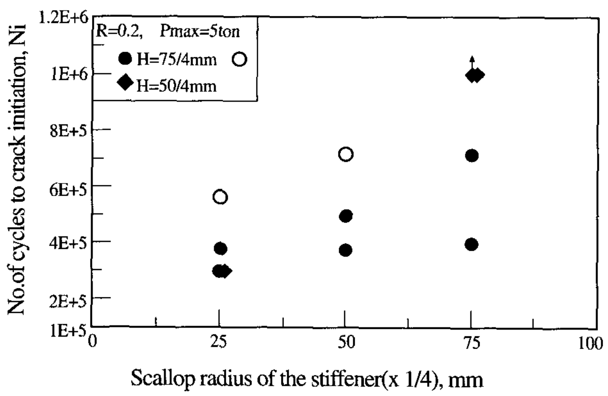


Fig. 10 Effect of joint details on the fatigue life of the slot structure

the stress at the stiffener heel and toe theoretically as over 50%. This is attributed to the modification of the stress distribution over the slot structure including the transition of the maximum stressed region from the stiffener heel to the slot surface of the transverse web.

3) Fatigue crack initiates either at the stiffener heel or at the stiffener toe even for the geometrically modified slot structure.The fatigue life of the geometrically modified slot structure is improved in a great extent, compared with the slot structure currently adopted. This is associated with the significant stress reduction at the stiffener heel and toe.

Acknowledgments

The authors would like to thank Mr. M. C. Youn of the Initial Hull Design Department, HHI for the valuable discussion upon the present work.

References

1. T. R. Gurney: Fatigue of Welded Structures, 2nd ed., *Cambridge Univ. Press, Cambridge,* (1979)
2. S. J. Maddox: Fatigue Strength of Welded Structures, 2nd ed, *Abington Publishing, Abinton,* (1991)
3. J. G. Youn H. S. Kim and D. H. Park : Geometric Effect on the Fatigue Properties of a Stiffened Joint, *Welding in the World,* Vol. 35, No. 4 (1995), pp.262-266
4. J. G. Youn and H. S. Kim : Geometric Effect on the Fatigue Properties of the Side Frame in a Hull Structure, *IIW document XIII-1618-96*
5. M. S. Kim, K. S. Lee, B. C. Kim and C. W. Sohn : A Study of Structural Connectivity between Stiffeners and Longitudinal on Web Frame, *Proceedings of 95 Korea ANSYS User's Conf, Seoul, Korea,* November. (1995), pp.315-324
6. I. Huther, H. P. Lieurade and N. Sayhi : Parametric Study of the Geometrical Stress on Fillet Welded Joint with Longitudinal Attachment, *IIW document XIII-1600-95*