Research on influencing factors of fatigue performance of cruciform welded joints on offshore platforms

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Abstract. In this study, the fatigue life of load-carrying cruciform welded joints under various plate thicknesses and degrees of penetration was performed. The fatigue assessment results showed a significant "thickness effect." The fatigue limit of the 25 mm-thick sample was 13.4% lower than that of the 16 mm-thick fatigue sample. Essentially, the fatigue life of the weld toe does not change with the degree of penetration. Plate thickness is the key factor affecting the fatigue life. The thickness effect is determined by both the stress gradient along the plate thickness and the degree of surface stress concentration. The correction result based on the effective notch stress approach is more accurate than the thickness correction formula in the ABS standard, which underestimates the thickness effect of load-carrying cruciform welded joints and may lead to danger. The penetration ratio a/t affects the fatigue failure position of load-carrying cruciform welded joints. The fatigue design of load-carrying cruciform welded joints can be performed by appropriately increasing the degree of penetration while achieving the damage at the weld toe.

Keywords: Cruciform welded joints, fatigue strength, thickness effect, degree of penetration.

1. Introduction

Structural fatigue is one of the most important concerns in marine ships, and the fatigue life of key nodes in hulls and offshore platforms has always been crucial. Welding is one of the common connection forms in offshore steel structures [1]. As the welding parts are often used at key nodes with geometric discontinuities, their fatigue performance has great engineering significance for the overall fatigue resistance design of steel structures.

As a common structure in ships and offshore operations, fatigue failure in cruciform welded joints usually starts from the weld roots or toes. The crack propagates through the weld or base metal under cyclic loading, resulting in fatigue failure at the joints. Depending on the applied forces, cruciform welded joints can be divided into load-carrying and non-load-carrying cruciform welded joints [2].

Based on the structural stress approach, K Kinoshita et al. [3] studied the influence of the length of the welding leg and gap depth, i.e., the penetration length, on the fatigue performance of non-load-carrying cruciform welded joints. Ngoula et al. [4] corrected the crack propagation behavior of cruciform welded joints by considering the effects of residual stress and weld toe geometry. Liao et al. [5] used three-dimensional numerical simulation to analyze the effect of low temperature on the crack propagation life of non-load-carrying cruciform welded joints. Andud [6] studied the effects of high-frequency mechanical shock treatment on the fatigue life of cruciform welded joints. There are still uncertainties regarding the factors affecting the fatigue strength; therefore, the study of the factors affecting the fatigue performance is crucial in structural design.

In this study, we tested the fatigue performance of load-carrying cruciform welded joints under different plate thicknesses and degrees of penetration, and plotted the S-N curve. The influence of plate thickness and degree of penetration on fatigue performance was analyzed using the values of fatigue limit. Combined with finite element analysis, the influence pattern of plate thickness and degree of penetration on the fatigue strength of load-carrying cruciform welded joints has been discussed in depth.in their paper.

2. Experimental design

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2.1 Material selection

EH36 common steel was selected as the material for offshore platforms. Its material properties and chemical composition are shown in Tables 1 and 2.

Table 1. Chemical composition of EH36(wt.%).

Material	C	Si	Mn	P	S	Cu	Cr	Ni
EH36	0.16	0.28	1.33	0.021	0.011	0.25	0.15	0.29

Table 2. Mechanical properties of EH36.

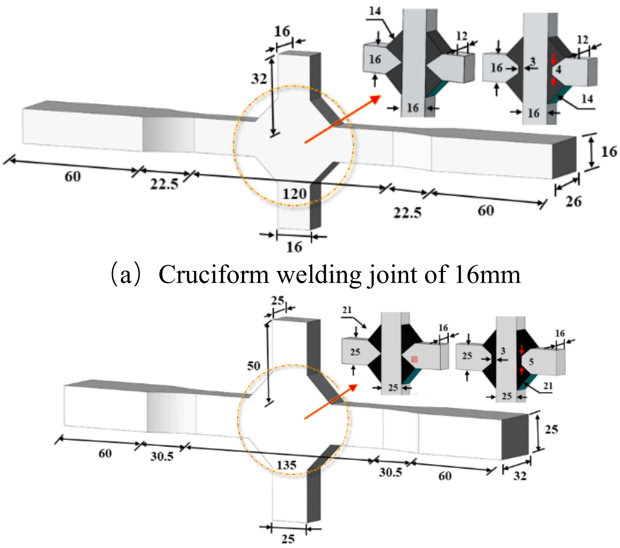
Material	Yield strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Elastic Modulus (MPa)
EH36	347	580	28.5%	2.06×10^3

2.2 Sample preparation

According to the welding manual on common offshore platforms, the welding process uses flux-cored arc welding (FCAW) as the base, and submerged-arc welding (SAW) as the filling and cover. The design of the sample is shown in Figure 1. The thickness of the main plate in the two samples was 16 mm and 25 mm. The joint was a cruciform welding joint processed through wire cutting.

Table 3. Welding processing conditions

Welds	Method	Current (A)	Voltage (V)	Gas	Weld speed (mm/min)
Bottom	GMAW	127-155	18-22	CO_2	170-280
Filled	SAW	400-650	26-33	/	400-600
Cover	SAW	400-650	26-33	/	400-600



(a) Cruciform welding joint of 16mm

(b) Cruciform welding joint of 25mm

Figure 1. Fatigue specimen configurations for cruciform welding joint with different thickness

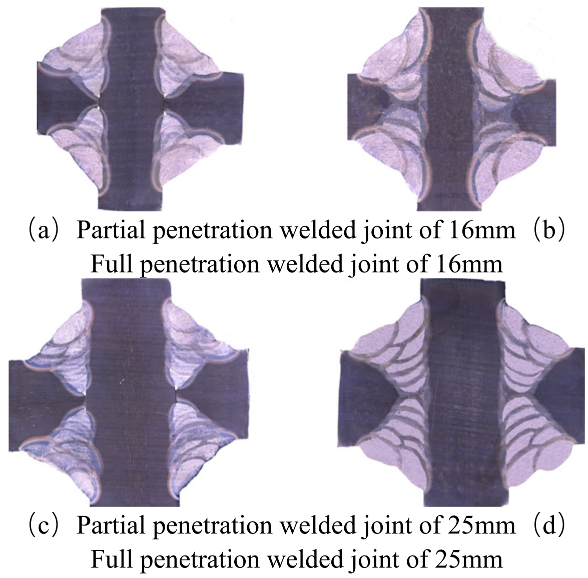
2.3 Test equipment and procedures

Referring to GB/T4337-2015 [7], SDS high-frequency fatigue testing machine was used as the test equipment with a stress ratio R of 0.1. A sine wave was applied through constant amplitude loading with a test frequency of 120 Hz. The frequency of the testing machine decreases when the sample cracks. The test ends automatically when the frequency is lower than 10 Hz, and the crack length is approximately half of the thickness of the main plate. The uniaxial tensile fatigue performance test was performed on four types of samples using the group method. Each group of samples was subjected to fatigue tests at 5 to 6 stress levels.

3. Results and Discussion

3.1 Fatigue macroscopic quality

The cruciform welded joints used in the fatigue tests were polished, and the weld appearance quality was inspected using a macroscopic metallographic approach. The metallographic test is a direct and objective method to assess the quality of weld forming [8], which can be used to observe invisible welding defects. The results of the metallographic test are shown in Figure 2. It can be seen that the welding seam is well formed, and there are no welding defects, such as pores, slag inclusions, and incomplete penetration. We measured the unpenetrated depth and gap size of the partially penetrated welded samples. It was observed that the average unpenetrated length of the 16 mm thick partially melted sample was 4.47 mm with an average gap width of 0.5 mm; and the average unpenetrated length of the 25 mm thick partially melted sample was 4.73 mm with an average gap width of 0.51 mm.



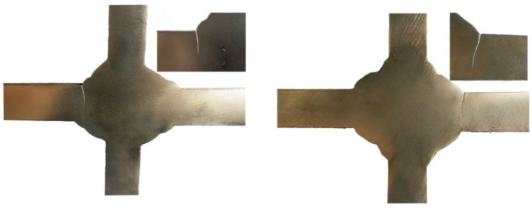
(a) Partial penetration welded joint of 16mm (b) Full penetration welded joint of 16mm

(c) Partial penetration welded joint of 25mm (d) Full penetration welded joint of 25mm

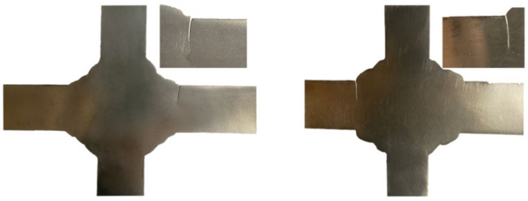
Figure 2. Macroscopic quality inspection results of fatigue specimens.

3.2 Fatigue test results

The failure modes of the load-carrying cruciform welded joints are usually weld root failure and weld toe failure [9]. The experimental results showed that for all the tested samples, the cracks originated at weld toes and propagated along the thickness direction perpendicular to the main plate until the final failure. The fatigue failure mode is shown in Figure 3.



（a） Partial penetration welded joint of 16mm （b） Full penetration welded joint of 16mm



（c） Partial penetration welded joint of 25mm （d） Full penetration welded joint of 25mm

Figure 3. Failure modes of fatigue sample.

According to the results of the fatigue test and nominal stress method in IIW [10] (International Institute of Welding), the test data were processed, as in Eq. (1), to obtain the corresponding median S-N curve. The median S-N curve was determined using the method of least squares, where the slope of the regression was set to 3.0. The fatigue strengths corresponding to the fatigue life of two million cycles were compared.

$$\log\Delta\sigma=-1/m\log N+1/m\log C \quad (1)$$

where $\Delta\sigma$ is the stress range, N is the cycle numbers, and m and C are parameters.

The median S-N curves under the four conditions are shown in Figure 4. Each point in the graph represents the average value of fatigue life at the corresponding stress level. All, but one, data points are well distributed on both sides of the fitting curve or coincide with the curve, which proves the accuracy of the test data.

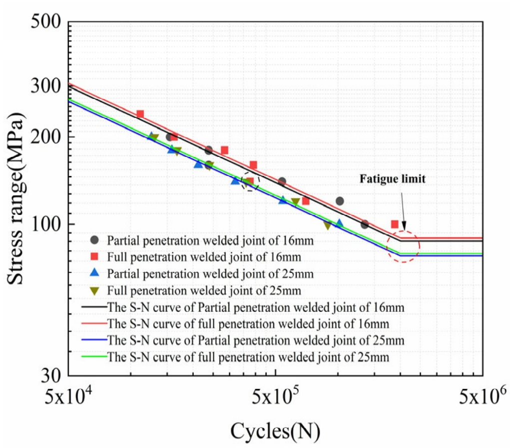


Figure 4. Median S-N curves of different plate thicknesses and penetration degrees.

The fatigue performance of the 16 mm thick cruciform welded joints was significantly better than that of the 25 mm thick cruciform welded joints. The fatigue limits of the partial penetration cruciform welded joints were 86.1 MPa and 77.7 MPa at thicknesses of 16 mm and 25 mm, respectively. The fatigue limits of the full penetration cruciform welded joints at thicknesses of 16 mm and 25 mm were 89.8 MPa and 79.2 MPa; the difference between the fatigue limits of the two was 10.8 % and 13.4 %, respectively. The results showed that plate thickness is a key factor affecting the life as the increase in the plate thickness reduces the fatigue performance of welded joints.

The degree of penetration determines the extent of fusion of the attachment plate and the main plate. Part of the penetration has an unfused area at the junction of the two plates, which causes geometric discontinuity at the weld root and leads to stress concentration. In the load-carrying cruciform welded joint, the weld root and weld toe are the two key weak parts susceptible to fatigue. The degree of stress concentration determines the occurrence of fatigue failure [11], and the strength of stress concentration on the two parts determines the location of fatigue failure.

In our tests, the fatigue failure positions were all located at the weld toes. It can be seen from Figure 4 that the fatigue failure life at the weld toe is essentially the same between the partial penetration and full penetration samples, and their fatigue curves mostly overlap each other. The fatigue limits of the 16 mm thick partial penetration and full penetration cruciform welded joints were 86.1 MPa and 89.8 MPa, respectively. The fatigue limits of the 25 mm thick partial penetration and full penetration cruciform welded joints were 77.7 MPa and 79.2 MPa, respectively. The difference in the fatigue limits of the two was 3.1 % and 1.9 %, respectively.

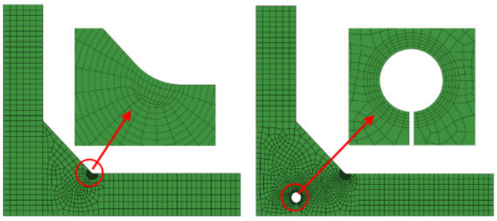
Table 3. Fatigue limit values of welded joints under different conditions

Penetration	Thickness （mm）	Fatigue limit （MPa）
Partial	16	86.1
Full	16	89.8
Partial	25	77.7
Full	25	79.2

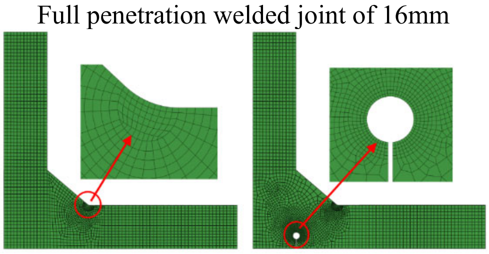
3.3 Influence of plate thickness and degree of penetration

To analyze the influence of plate thickness and degree of penetration on fatigue life further, ABAQUS software was used to model four types of welded joints based on their actual sizes. Owing to the symmetry of the structure, a 1/4 model was established. The stress at the tip of the weld toe had singularity and local micro-constraint effects. A virtual radius of 1 mm was constructed at the weld toe using the effective notch stress method. The effective notch stress method was used as suggested by IIW [10]. It is based on the studies of multiple researchers [12,13], and is published as the guideline. The notch was idealized through the concept of mean stress [14], and the notch stress calculation coefficient was obtained through the local maximum principal stress at the radius based on the simulated reference radius.

Wang Q [15] studied the grid sensitivity of the notch stress method. Notch stress varied with the element sizes when the number of elements was no more than 20, however, it remained almost unchanged when the number exceeded 20. We used a grid size of 0.1 mm for the fatigue weak spot of welding toes and weld roots, and performed the finite element analysis based on the linear elasticity theory. The model and grid refinement are shown in Figure 5. The grid refinement at the weld toe was consistent between the partial penetration and full penetration welded joints; therefore, the grid refinement at the partial penetration weld toe is not shown.



(a) Partial penetration welded joint of 16mm (b) Full penetration welded joint of 16mm



(c) Partial penetration welded joint of 25mm (d) Full penetration welded joint of 25mm

Figure 5. Mesh and FE model for welded joint fatigue samples with different thickness.

The maximum principal stress at the notch was extracted as the notch stress concentration factor, and the results are shown in Table 4.

It can be seen from the results that the increase in the plate thickness leads to a significant increase in the notch stress concentration factor at the weld toe, and the notch stress concentration factor at the weld toe of the partially penetrated welded joint is larger than that of the weld root. Changes in the degree of penetration had no distinct effects on the stress concentration factor at the weld toe, which was consistent with the test results.

Table 4. Results of notch stress concentration coefficient.

Penetration	Thickness (mm)	Notch stress concentration factor	
		Weld toe	Weld root
Partial	16	2.58	2.11
Full	16	2.64	\
Partial	25	2.76	2.24
Full	25	2.81	\

3.3.1 Influence of plate thickness.

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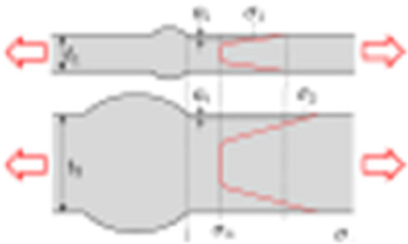

Figure 6. Schematic diagram of thickness effect

ABS standard introduced a thickness correction formula based on statistical results, which corrects the welded structure with a thickness greater than 22 mm in the form of a power function. For untreated welded joints, the correction factor is 0.25.

$$k=\left(\frac{T}{22}\right)^{0.25} \quad (2)$$

Where k is the thickness factor for fatigue strength and T means the real thickness of welded joint.

In the effective notch stress method, owing to the existence of the virtual notch, the notch stress concentration factor is the average stress from the surface to the depth of 1 mm from the sharp notch of the weld toe. The notch stress concentration factor at the weld toe radius includes the change in the degree of stress concentration and stress gradient at the weld toe caused by the increase in plate thickness. The results obtained using the effective notch stress method already cover the thickness effect.

The fatigue test data were processed using the thickness correction formula and the effective notch stress method, as shown in Figures 7 and 8. The figures show three S-N curves under the survival rates of 2.3 %, 50 %, and 97.7 % to reflect the dispersion degree of the corrected results. The corresponding dispersion bandwidth was calculated.

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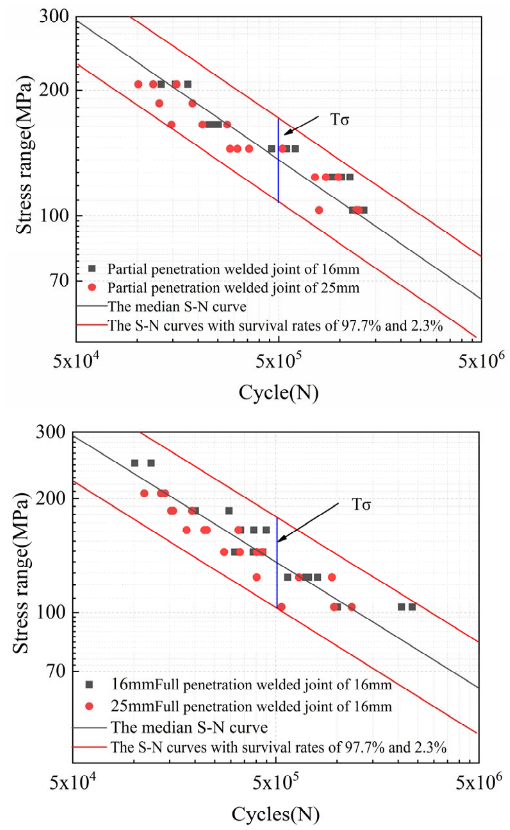
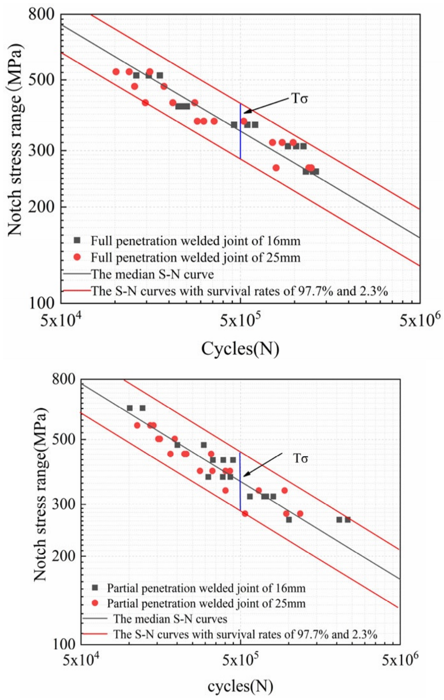


(a) Correction results of partial penetration with different thicknesses (b) Correction results of full penetration with different thicknesses

Figure 7. Correction result of thickness correction formula



(a) Correction results of partial penetration with different thicknesses (b) Correction results of full penetration with different thicknesses

Figure 8. Correction results of effective Notch Stress Method.

Based on the thickness correction formula, the calculated value under the thickness of 25 mm was 1.032. However, as shown in Figure 2, the fatigue life correction results of welded joints are not ideal. The distribution of data points under different thicknesses is relatively discrete. Under high stress, the distribution of data points under different thicknesses is relatively concentrated, whereas under low stress they are relatively discrete. However, they still show a distinct thickness effect. The calculated dispersion bandwidth was $T\sigma_1 = 1{:}1.59$ and $T\sigma_2 = 1{:}1.73$.

Compared with the thickness correction factor, the correction result of the effective notch stress method is more accurate. The distribution of data points under different thicknesses is well patterned. The difference between the test data is small, which effectively aggregates the fatigue life under the two plate thicknesses onto the same S-N curve, as shown in Figure 3. The calculated dispersion bandwidths were $T\sigma_3 = 1{:}1.44$ and $T\sigma_4 = 1{:}1.56$.

The load-carrying cruciform welded joint was enlarged in equal proportion to obtain the fatigue strength reduction curve under different thicknesses. The correction results were compared, as shown in Figure 9.

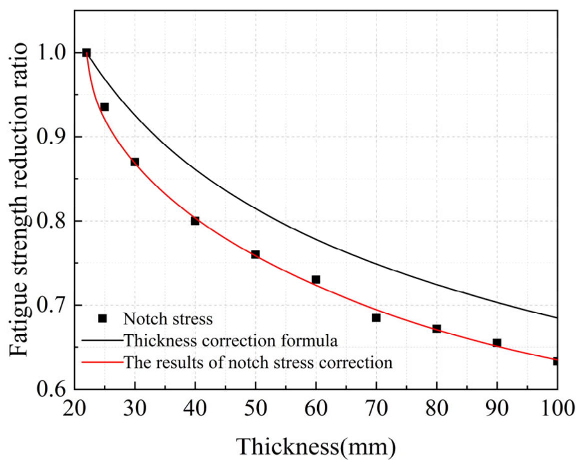


Figure 9. Fatigue strength reduction curve under different thickness.

It was found that the thickness effect of the welded joints enlarged in equal scale was distinct [18], whereas the thickness effect of the welded joints with non-proportional enlargement was ambiguous. In the out-of-plane gusset structure commonly used in the ocean [19], when the thickness of the main plate changes, the thickness correction coefficient index is in the range 0.1–0.14. Toshiaki [20] found that HFMI could effectively improve the fatigue performance of thick plates. The thickness effect is a function of the plate thickness in addition to being the result of the combined effect of various factors, such as the welding structure, joint form, and weld size. It is more accurate to use "size effect" [21] instead of thickness effect.

The thickness effect is determined by the stress gradient along the plate thickness and the degree of surface stress concentration. Compared with non-proportional magnification, proportional magnification leads to an increase in the size of the attached plate and the weld. The surface stress concentration at the weld toe increases, which leads to greater stress gradient along the thickness of the main plate. In the high stress area, the average stress of the proportionally scaled welded joint is greater than that of the non-proportionally scaled welded joint, resulting in significant thickness effect. When the degree of stress concentration at the weld toe in the welded structure is not sensitive to the increase in the plate thickness, even when the plate thickness changes, the stress gradient generated along the thickness direction and the change in the average stress are relatively small.

The notch stress method has a larger correction on the fatigue strength reduction ratio of the load-carrying cruciform welded joints. The calculation result of the thickness correction formula proposed in the ABS standard is underestimated, and there is a certain risk in the fatigue design. Owing to its own characteristics, the notch stress concentration factor includes the influence of welding structure, joint form, and weld geometry, so that the fatigue life can be more accurately corrected when the geometry of the welded structure changes.

3.3.2 Influence of the degree of penetration.

The penetration ratio a/t is defined as the ratio of penetration length ‘a’ to plate thickness ‘t.’ The relationship between the stress concentration factor of the notch at the root and toe of the load-carrying cruciform welded joint and penetration ratio a/t is plotted, as shown in Figure 10.

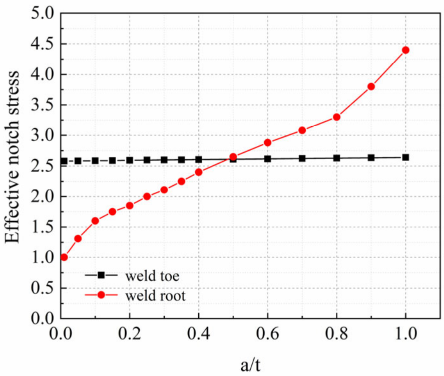


Figure 10. Variation of calculation coefficient of notch stress at weld toe and weld root with a/t.

With an increase in a/t, the notch stress concentration factor at the weld root increases rapidly. The notch stress concentration factor at the weld root is more sensitive to the change in a/t, which increases from 1 to approximately 4.4. The notch stress concentration factor at the weld toe essentially does not change with a/t. The change in the penetration ratio a/t has no distinct effect on the fatigue life at the weld toe of the load-carrying cruciform welded joint.

When $a/t < 0.48$, the stress concentration factor of the notch at the weld toe is considerably higher than that at the weld root. The high stress concentration at the weld toe results in fatigue failure of the weld toe. When $a/t = 0.48$, the notch stress concentration factors at the weld toe and the weld root are equal, and the notch stress concentration factor curves of the two intersect at one point. When $a/t > 0.48$, the stress concentration at the weld root is relatively higher, and the weld root becomes the fatigue failure point. When a/t=1, which is a zero-penetration fillet weld, the notch stress concentration factor at the weld root is considerably higher than that at the weld toe. The effective notch stress method can clearly distinguish weld root and weld toe failure. The results show that the degree of penetration can be appropriately increased while ensuring the fatigue life [22], and the amount of welding consumables can be saved.

4. Conclusion

The following conclusions can be drawn through the fatigue tests of the commonly used load-carrying cruciform welded joints in the ocean under different plate thicknesses and degrees of penetration, as well as the finite element analysis of the influence of the plate thickness and degree of penetration on the fatigue life:

(1) The load-carrying cruciform welded joint exhibited a distinct thickness effect, and the fatigue limit decreased by 13.4%. The fatigue performance of welded joints reduced significantly with the increase in the plate thickness. The degree of penetration had no distinct effect on the fatigue life of the toe of the load-carrying cruciform welded joint. The fatigue limits of the partial penetration and full penetration welded joints differed by only 3%.

(2) The thickness effect is determined by the stress gradient along the plate thickness direction and the degree of surface stress concentration. The thickness correction formula in the ABS standard is not suitable for load-carrying cruciform welded joints. The thickness effect is a function of the plate thickness in addition to being the result of the joint action of various factors, such as welding structure, joint form, and weld size. The effective notch stress method can make an accurate correction for the thickness effect.

(3) The notch stress concentration factor at the weld root is sensitive to changes in the penetration ratio a/t, and the notch stress concentration factor at the weld toe is not affected by the penetration ratio. At $a/t < 0.48$, fatigue failure occurred at the weld toe; and at $a/t \geq 0.48$, the weld root became the most fatigue-sensitive point. While achieving the damage at the weld toe, we can appropriately increase the degree of penetration to save the amount of welding wire.

Acknowledgments

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