Thickness effect of fatigue on butt weld joints

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Abstract

Thickness effect refers to a phenomenon that an increase in plate thickness decreases the fatigue strength. In the CSR(Common Structural Rules), thickness effect on fatigue is reflected as coefficient of thickness effect. Recently, HCSR(Harmonized Common Structural Rules) was revised to reduce the thickness effect of fatigue by adopting the IIW recommendation and related papers. This means that basic theory for thickness effect of fatigue is not established firmly by now.
In this study, all steps relevant to investigating the thickness effect on fatigue were carried out. Fatigue tests for butt weld joints including thickness range of 25mm, 50mm and 75mm were conducted. Coefficient of thickness effect was studied from nominal stress method, hot spot stress method and notch stress method. The influence of confidence level and slope of SN curve was investigated.

1. Introduction

Thickness effect on fatigue means a phenomenon that fatigue strength decreases with increasing thickness of steel plate. Gurney at 1979 found that the thickness of steel plate influences the fatigue strength and investigated thickness effect for the tube joint up to the thickness of 50mm by using the nominal stress method. In 1984, he proposed the correction factor for thickness effect on the design code of offshore. IIW recommends a correction factor for thickness effect proportional to 0.1 to 0.3 power of the thickness for various weld joints.
Thickness effect on fatigue is reflected as coefficient of thickness effect in the CSR. Recently, calculation procedure for coefficient of thickness effect in HCSR is modified by adopting the IIW recommendation and results of papers relevant to analytical and empirical investigation on thickness effect. This shows that the existing rules and codes for fatigue do not reflect the thickness effect well. Also, it shows the necessity to investigate the thickness effect on fatigue further.
In this study, all procedure concerned with investigating the thickness effect on fatigue were carried out. Fatigue tests were conducted by using the test specimens manufactured by three shipyards. For meaningful results, range of plate thickness was to include 25mm, 50mm and 75mm.
Three stress as nominal stress, hot spot stress and notch stress were considered for evaluation of thickness effect. In order to calculate stress concentration factor for hot spot stress and notch stress, analysis model was developed based on guideline from IIW recommendation.
The coefficient of thickness effect was calculated and analyzed. Influence of confidence level of 50% and 97.5% and slope variation of SN curves on thickness effect was investigated.

2. Fatigue Experiments

2.1 Preparation of butt weld

The fatigue tests of butt weld joints were carried out for 3 different thickness(25mm, 50mm, 75mm). They are necessary for meaningful derivation of the thickness effect coefficient. In order to cover real welding conditions in shipyard, three participating shipyards delivered 7 specimens per thickness. The same welding process of FCAW was used for all specimens. General welding procedure for butt weld is shown in Figure 1.
Figure 2 and 3 shows fatigue test specimens. Shape of specimens was adjusted to the special requirement of the testing machines. The specimen edge were ground in the weld area with radius of 1mm for t = 25mm and of 3mm for t=50mm and 75mm to prevent corner cracks.

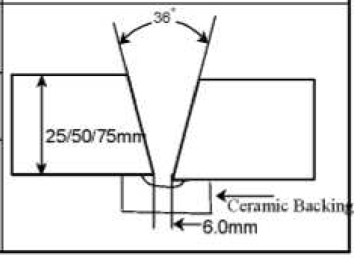
Welding process	Consumable	Weldng position	Base material – thickness	Joint detail
FCAW	E81T-K2	Flat (1G)	EH47-75t	
			EH47-50t	
			EH47-25t	

Fig.1 General welding procedure for EH47 butt welds

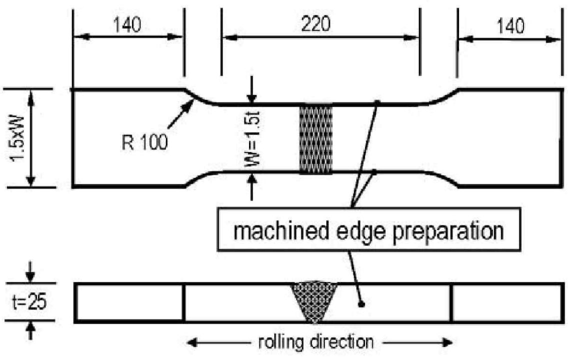


Fig 2. Butt weld specimen(25mm)

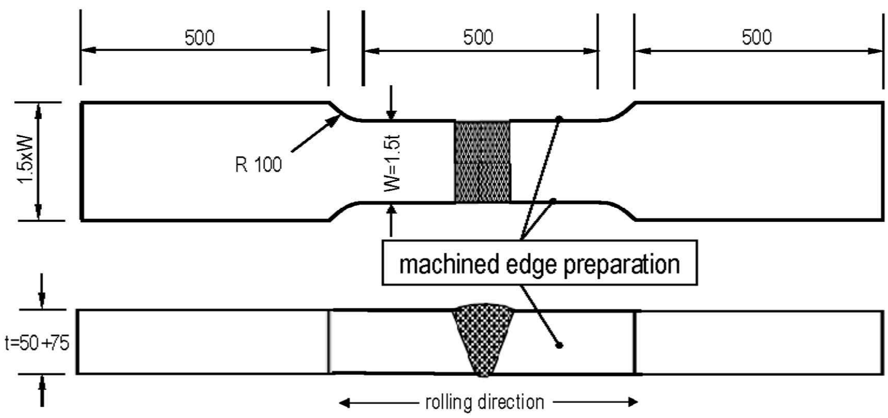


Fig 3. Butt weld specimens(50mm, 75mm)

2.2 Distortion measurement of butt weld

In welding metal, distortion cannot be avoidable. For butt welding, misalignment and angular distortion can easily occur. These induce bending stress influencing the fatigue strength in fatigue test of butt weld joints.
For precise evaluation, they were measured for all specimens and Table 1 shows values. Misalignment and angular distortion varies separately depending on shipyard's welding conditions. It was found that the misalignment and angular distortion decrease with the increase of plate thickness irrespective of shipyard difference.

Table 1 Misalignment and angular distortion

Plate thickness(mm)	Type	Misalignment(mm)	Angular distortion(˚)
25	A	0.5	1.02
	B	1.475	6.04
	C	0.5	5.03
50	A	0.2	0.45
	B	1.1	1.81
	C	0.6	1.58
75	A	0.45	0.49
	B	0.375	0.24
	C	0.525	0.74

2.3 Performing and evaluating fatigue experiments

The fatigue tests were carried out on resonance testing machines. The test frequency was approximately 30Hz. All tests were carried out under axial load with a stress ratio, R of 0.1. Complete fracture of the specimens was employed as the failure criterion.
The fatigue test results were evaluated in two ways e.g. with a fixed slope and with the slope directly calculated by the tests. According to IIW recommendation, other Rules and Guidelines, the slope of the SN curve is fixed to m=3.0 for all welded joints. In fatigue tests of smooth notched welded joints such as butt welds, larger slope of SN curves can be observed. Therefore there will be a significant influence whether a fixed slope m=3.0 or the slope obtained directly by the tests will be employed for fatigue test evaluation.
Even though specimens for butt weld joints were prepared by three shipyards, evaluation procedure treats all sub-series as one statistical basis. The results of fatigue tests were evaluated by typical statistical procedure. Using this method, the characteristic values of the SN curves were determined.

3. 3D Analysis

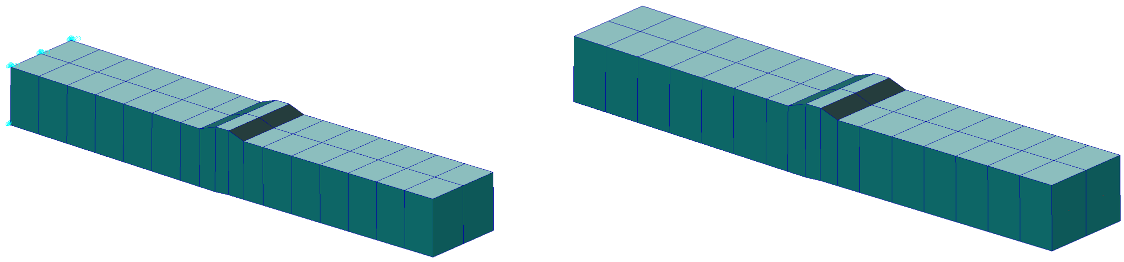
In order to consider hot spot stress and notch stress in evaluation of fatigue test, linear FEM(finite element method) analysis of 3D were carried out. Through this, stress concentration factor were calculated and used as multiplication factor for nominal stress to get hot spot stress and notch stress.
MSC Patran/Nastran was used as pre/post processor and solver. Basic material properties of steel including young's modulus of E=206GPa and poisson's ratio of ν=0.3 were used.

3.1 Hot spot stress method

A full model for butt weld joints was used in order to calculate the stress concentration factor. Basic model design for hot spot stress follows the clause 2.2.3.4 "calculation of Structural Hot spot stress" of IIW recommendation. Relatively fine models with element size of 0.4t*t and extrapolation points of 0.4t and 1.0t in Table 2.2.2 in IIW recommendation were chosen. In this case, hot spot stress is calculated as Equation (1).

$$\sigma_{hs} = 1.67 \cdot \sigma_{0.4t} - 0.67 \cdot \sigma_{1.0t} \quad (1)$$

Two boundary conditions were applied as shown in Figure 4. One end of solid model was fixed end and the other end was applied by tension of 1MPa.



(a) Fixed condition (b) Tension condition

Fig. 4 Boundary conditions in hot spot stress model

By reading nodal principal maximum stress at 0.4t and 1.0t, hot spot stress was calculated based on equation (1) and shown in Table 2.
By multiplying nominal stress with stress concentration factor, hot spot stress was calculated.

Table 2 Evaluated stress concentration factor

Plate thickness(mm)	Type	Misalignment(mm)	Angular distortion(°)	Stress Concentration Factor
25	A	0.5	1.02	1.070
	B	1.475	6.04	1.005
	C	0.5	5.03	0.830
50	A	0.2	0.45	1.006
	B	1.1	1.81	1.053
	C	0.6	1.58	1.003
75	A	0.45	0.49	1.014
	B	0.375	0.24	1.020
	C	0.525	0.74	1.008

3.2 Notch stress method

When calculating stress concentration factor for notch stress method, a half model was used for reduction of calculation time.
The modeling of flank angle and toe radius is important because flank angle and toe radius is dominant in determining stress concentration factor. However it is difficult to measure these precisely along weld toe line of specimens. Also, modeling these in analysis model is time consuming due to the variation of flank angle and toe radius along toe line.
In this study, basic design for flank angle and toe radius was accordance with IIW recommendation. Clause 2.2.4.1 of IIW recommendation suggests to use toe radius of 1mm for structural steel and aluminum alloys and flank angle of 30° for butt weld joints.
An element size was determined based on clause 2.2.4.2 of IIW recommendation. For the determination of effective notch stress by FEA, element size of not more that 1/6 of the radius are recommended in case

of linear elements, and 1/4 of the radius in case of higher order elements. These sizes have to be observed in the curved parts as well as in the beginning of the straight part of the notch surfaces in both directions, tangential and normal to the surface. The bead height for all specimens was assumed in accordance with the ASW D1.1. Figure 5 shows one example of detail at the weld toe.

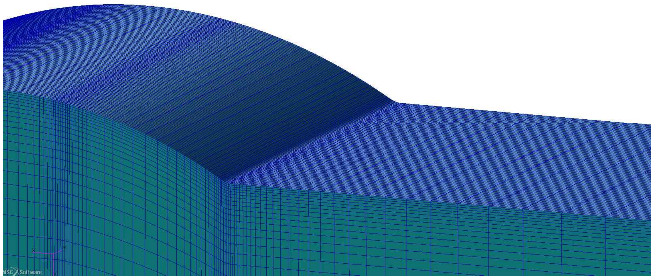
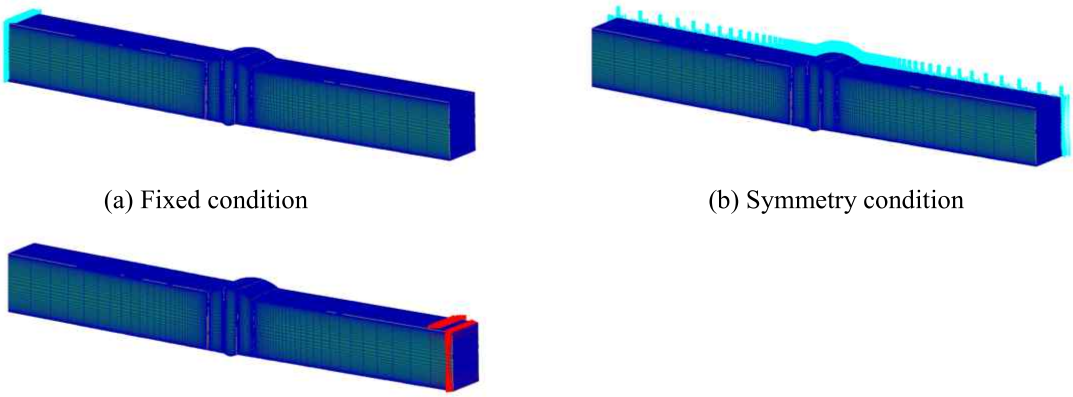


Fig. 5 Detail at the weld toe

Three boundary conditions were used. By fixing one end of solid model in three degree of freedom, it was used to prevent rigid body motion. Symmetric condition was applied to middle section along longitudinal direction one side as shown in Figure 6. Tension was applied at the other end with pressure of 1MPa.



(a) Fixed condition

(b) Symmetry condition

(c) Tension condition

Fig. 6 Boundary conditions

Typical principal stress distribution is shown in Figure 7. It shows the principal maximum stress occurs along the toe line, which means that crack initiate along weld toe. It is consistent with general fatigue phenomenon.

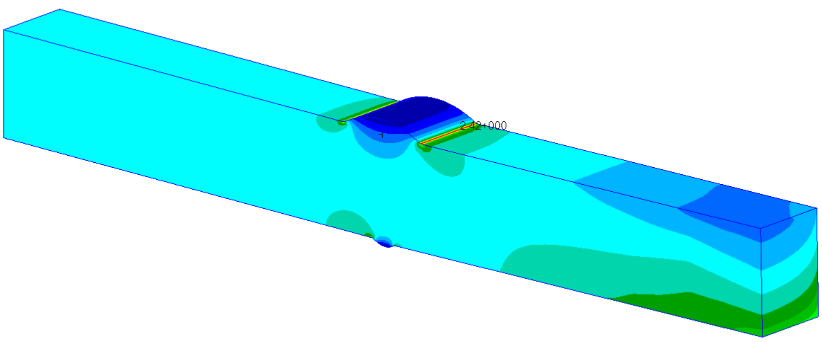


Fig. 7 Sample of Principal stress distribution

By reading the principal maximum stress in analysis results, stress concentration factors were determined and shown in Table 3. All values are about 2.2~ 2.6, similar to those of related papers on thickness effect in fatigue test.
By multiplying nominal stress with stress concentration factor, notch stress calculated.

Table 3 Evaluated stress concentration factor

Plate thickness(mm)	Type	Misalignment(mm)	Angular distortion(°)	Toe radius(mm)	Stress Concentration Factor
25	A	0.5	1.02	1	2.42
	B	1.475	6.04	1	2.56
	C	0.5	5.03	1	2.25
50	A	0.2	0.45	1	2.35
	B	1.1	1.81	1	2.57
	C	0.6	1.58	1	2.42
75	A	0.45	0.49	1	2.38
	B	0.375	0.24	1	2.38
	C	0.525	0.74	1	2.39

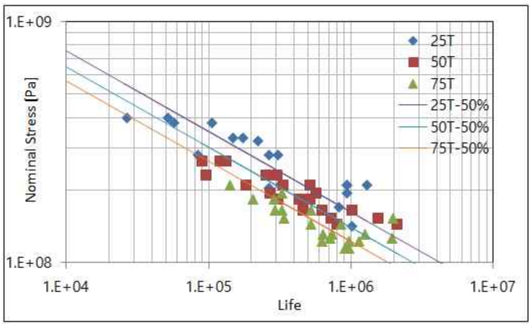
4. Results

4.1 Nominal stress method

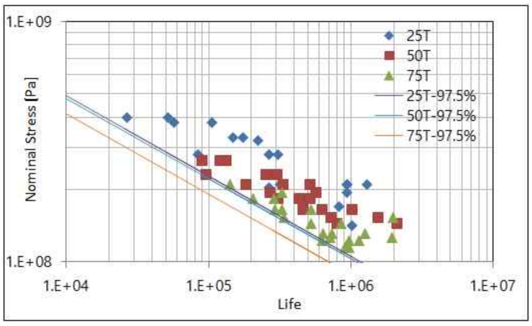
Figure 8 shows the results of fatigue tests from the viewpoint of nominal stress. S-N relationship ($N = \log C \cdot \Delta S^{-m}$) was calculated by using these fatigue test results in accordance with IIW recommendation describing the statistical procedure. Table 4 and 5 shows the results. The slope of the SN curve was considered with two cases of m=3.0 and m calculated by fatigue test. Two confidence levels of 50% and 97.5% were taken into consideration in order to investigate the influence of confidence level on thickness effect of fatigue.

The thickness effect on fatigue is evident in case of m=3 and confidence level of 50%. Thickness effect in the case of m=3 and confidence level of 97.5% is a little low. This is due to the dense fatigue results of 50mm which make standard deviation smaller and its SN curve is close to the SN curve of 25mm as shown in figure 8(b).

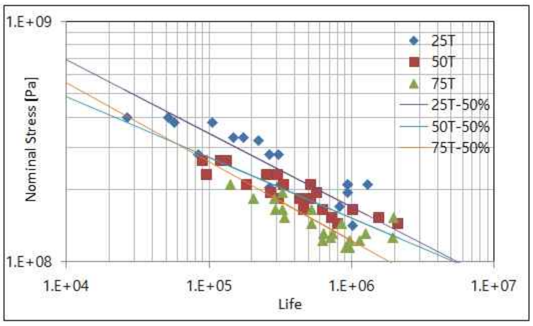
When slope of SN curves is calculated based on the fatigue tests, the thickness effect is not clear. The value, m of SN curve of 50mm is relatively larger than the other cases as shown in Table 5. It causes the SN curve of 50mm crosses those of 25mm and 75mm, which makes the thickness effect vague.



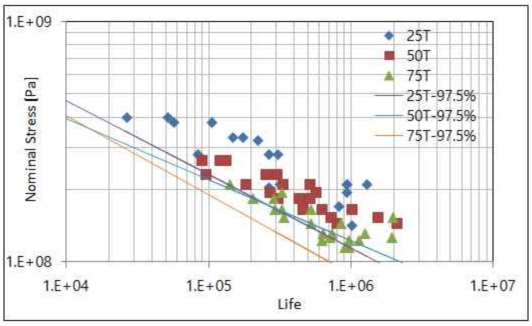
(a) m=3, confidence level of 50%



(b) m=3, confidence level of 97.5%



(c) m calculated, confidence level of 50%



(d) m calculated, confidence level of 97.5%

Fig. 8 Nominal stress S-N curve

Table 4 S-N relationship with slope of 3

Plate thickness(mm)	Factor	Values
25	m	3
	$\log C$	30.63
50	m	3
	$\log C$	30.44
75	m	3
	$\log C$	30.26

Table 5 S-N relationship of slope calculated

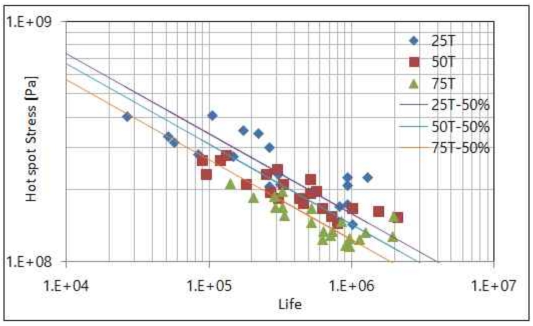
Plate thickness(mm)	Factor	Values
25	m	3.27
	$\log C$	32.90
50	m	3.95
	$\log C$	38.35
75	m	3.05
	$\log C$	30.65

4.2 Hot spot stress method

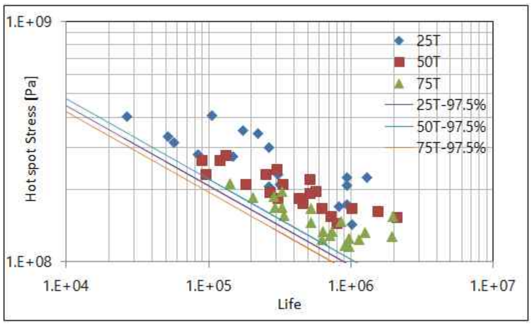
Figure 9 shows SN curves based on hot spot stress calculated by multiplying nominal stress with stress concentration factor. Similar to section 4.1 of nominal stress method, two SN curve slope and two confidence levels were considered. S-N relationship was calculated and the results are shown in table 6 and 7.

The thickness influence on fatigue is dominant in the case of m=3 and confidence level of 50%. The compact distribution of fatigue test results of 50mm makes its SN curve above that of 25mm in the case of 97.5%.

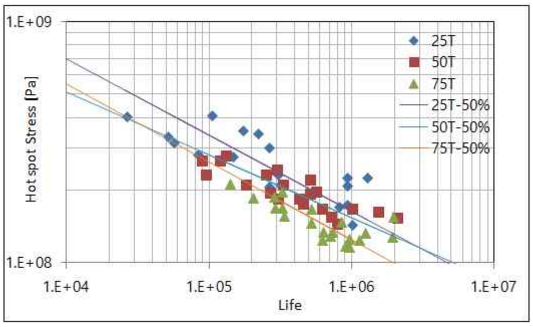
When slope of SN curve was determined by fatigue tests, thickness effect of 50% and 97.5% is vague due to that the SN curve of 50mm crosses those of 25mm and 75mm.



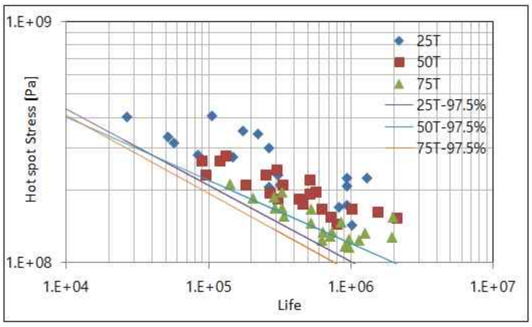
(a) m=3, confidence level of 50%



(b) m=3, confidence level of 97.5%



(c) m calculated, confidence level of 50%



(d) m calculated, confidence level of 97.5%

Fig. 9 Hot spot stress S-N curve

Table 6 S-N relationship with slope of 3

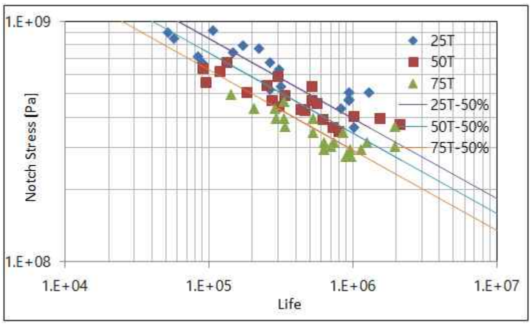
Plate thickness(mm)	Factor	Values
25	m	3
	$\log C$	30.60
50	m	3
	$\log C$	30.47
75	m	3
	$\log C$	30.28

Table 7 S-N relationship of slope calculated

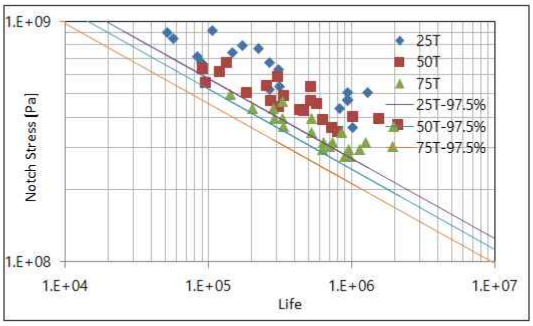
Plate thickness(mm)	Factor	Values
25	m	3.16
	$\log C$	31.94
50	m	3.82
	$\log C$	37.25
75	m	3.09
	$\log C$	30.99

4.3 Notch stress method

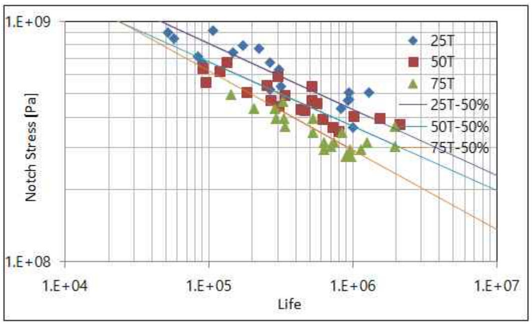
Figure 10 shows the result of fatigue tests with notch stress. Notch stress was calculated by multiplying the nominal stress by stress concentration factor evaluated by FEM. Similar to the analysis of nominal stress method, two slopes of SN curves and two confidence level were considered. S-N curve was calculated and the results are shown in table 8 and 9.
The thickness effect on fatigue is clear in the case of m=3, irrespective of the confidence level. As shown in figure 10(b), the SN curve of 50mm exists in the middle of those of 25mm and 75mm, which is different from notch stress method and hot spot stress method.
In cases of the slope of SN curve estimated by fatigue tests, thickness effect seems to be ambiguous due to the steeper SN curve of 75mm.



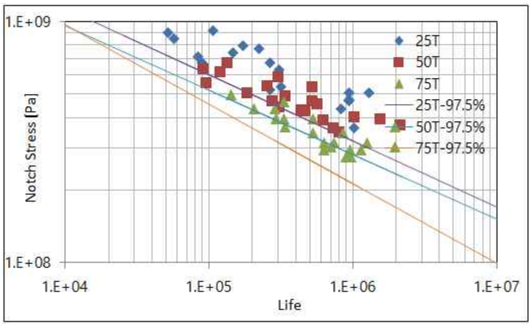
(a) m=3, confidence level of 50%



(b) m=3, confidence level of 97.5%



(c) m calculated, confidence level of 50%



(d) m calculated, confidence level of 97.5%

Fig. 10 Notch stress S-N curve

Table 8 S-N relationship with slope of 3

Plate thickness(mm)	Factor	Values
25	m	3
	$\log C$	31.79
50	m	3
	$\log C$	31.61
75	m	3
	$\log C$	31.39

Table 9 S-N relationship of slope calculated

Plate thickness(mm)	Factor	Values
25	m	3.64
	$\log C$	37.42
50	m	3.74
	$\log C$	38.04
75	m	3.03
	$\log C$	31.65

5. Calculation of thickness effect coefficient

Thickness effect on fatigue is usually considered by using a coefficient according to equation (2)

(2) $$f_t = \left(\frac{t_{ref}}{t_{eff}}\right)^n$$

t_{ref}: reference plate thickness
t_{eff}: effective plate thickness
n : coefficient of the thickness effect

Reference thickness, t_{ref} is 25mm in accordance with IIW recommendation. Effective plate thickness, t_{eff} is dependent on the structural detail to be investigated. For butt weld joints, t_{eff} is equal to the plate thickness. The thickness effect coefficient, n depends on the particular welded detail as well, e.g. n =0.2 for transverse butt welds and n = 0.3 for longitudinal stiffeners in IIW recommendation.
In this study, thickness effect coefficient was calculated with fatigue strength at cycle of $N=2 \cdot 10^6$. Cycle of $2 \cdot 10^6$ comes from the IIW recommendation in that fatigue class(FAT) is identified by the characteristic

fatigue strength of the detail in MPa at 2 million cycles. Through least square method, the coefficient of thickness effect was calculated and shown in Table 10 and figure 11.

Coefficient of thickness effect in the case of confidence level of 50% is larger than that in the case of confidence level of 97.5% except the case of notch stress method and slope of SN curve calculated by fatigue tests.

The distribution of each thickness is different and has various standard deviations. Dispersion of fatigue test in thickness of 50mm has narrow band compared to those of 25mm and 75mm. It causes the SN curves of confidence level of 97.5%, 50mm and m of 3 is similar to that of thickness of 25mm and m of 3 in nominal stress method and above that of thickness of 25mm and m of 3 in hot spot stress method.

The calculated fatigue strength of confidence level of 97.5%, 50mm and m of 3 is almost close to that in thickness of 25mm and m of 3 in nominal stress method and larger than that in thickness of 25mm and m of 3 in hot spot stress method. It causes the coefficient of thickness effect reduced compared to that for the cased of confidence level of 50% and m of 3 in nominal stress method and close to zero in for cases of confidence level of 50% and m of 3in the hot spot stress method.

When slope of SN curve is calculated by fatigue tests, the steeper slope of SN curve of 50mm is another factor for the reduction of coefficient of thickness effect in case of confidence level of 97.5% compared to those of the confidence level of 50%.

This show how the distribution of fatigue tests influence coefficient of thickness effect. Also, it explains the importance of whether slope of SN curve is 3 based on the previous studies or calculated by fatigue tests in determining the coefficient of thickness effect.

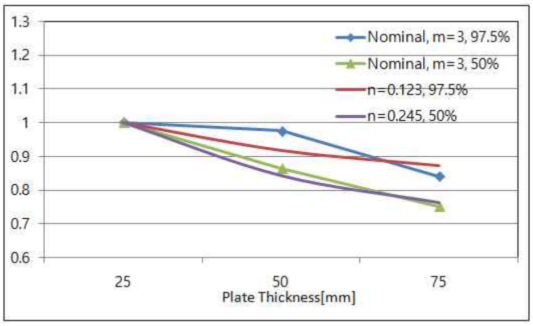
Even though there seems to be no thickness effect judging from slope of SN curve such as shown in figure 8(c), (d) and figure 9(c), (d), the coefficient of thickness effect was calculated to have some values. It is because the coefficient of thickness effect is determined by the fatigue strength at cycle of $2 \cdot 10^6$.

Notch stress method has largest values for coefficient of thickness effect among three methods. The stress concentration factor for thickness of 50mm is relatively larger than those for thickness of 25mm and 75mm. It causes the distribution of fatigue tests for thickness of 50mm dispersed and results in increasing the standard deviation and slope of SN curve similar to those of 25mm and 75mm as shown in Table 9. These factors makes coefficient of thickness effect larger in notch stress method.

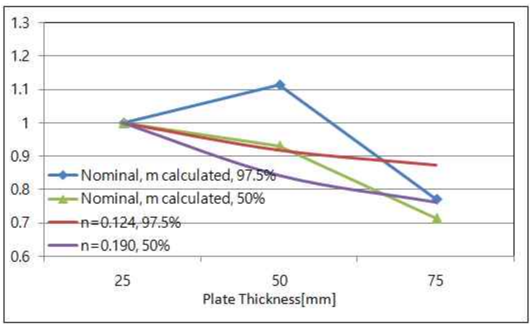
This shows how the stress concentration factor influences the coefficient of thickness effect.

Table 10 Calculated coefficient of thickness effect

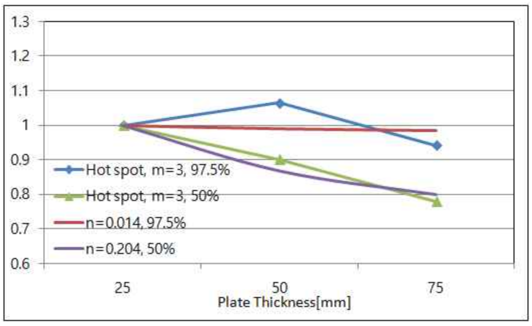
	Slope of m	Confidence level of 50%	Confidence level of 97.5%
Nominal Stress Method	3	0.245	0.123
	Calculated	0.248	0.124
Hot Spot Stress Method	3	0.204	0.014
	Calculated	0.186	-0.018
Notch Stress Method	3	0.253	0.196
	Calculated	0.337	0.338



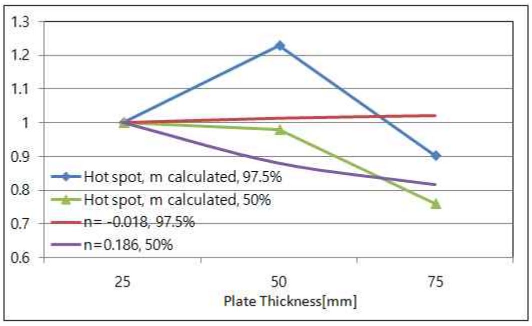
(a) Nominal stress, m=3



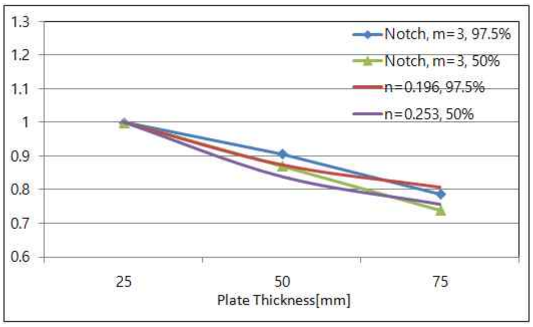
(b) Nominal stress, m calculated



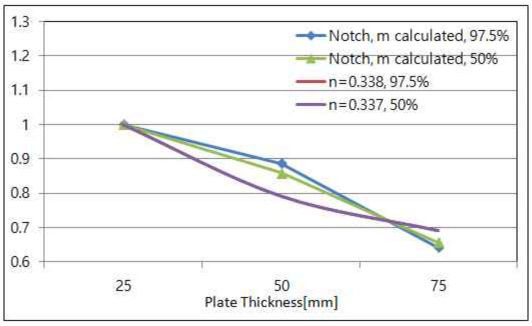
(c) Hot spot, m=3



(d) Hot spot, m calculated



(e) Notch stress, m=3



(f) Notch stress, m calculated

Fig. 11 Calculated coefficient of thickness effect

6. Conclusions

Design guideline for model of notch stress is accordance with IIW recommendation. The flange angle and toe radius along toe line in butt weld joints are assumed as 30° and 1mm, respectively. The bead height is based on AWS D1.1.

The coefficient of thickness effect is dependent on the confidence level. If the distribution of fatigue tests among different thickness varies, the standard deviation is calculated to have different values. It causes the ratio of fatigue strength at cycle of $2 \cdot 10^6$, resulting in variation of coefficient of thickness effect.

Whether slope of SN curve is fixed as 3 or calculated by fatigue tests changes the coefficient of thickness effect. In the cases of slope of 3 for SN curve, thickness effect can be easily seen compared to the cases when slope of SN curve is calculated.

Stress concentration factor calculated from finite element model changes the hot spot stress and notch stress in different level for each thickness. It causes the distribution of fatigue tests vary from raw fatigue test, resulting in the change of coefficient of thickness effect.