# Japanese Joint Research Project on the Thickness Effect to Fatigue Strength

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## Abstract

In recent years, fatigue strength issue on tanker structures has been one of the greatest concerns among the industries, and more and more consistent and direct analytical fatigue strength assessment method has been introduced to the international rules, such as the Common Structural Rules for Double Hull Oil Tankers (CSR-O/T). However, as compared with the rigorous analytical approach, the effect of plate thickness has been left alone with simple and conventional application of thickness exponent of $n$=1/4.

In this regard, the Shipbuilders' Association of Japan (SAJ) has had a great concern, and organized a joint research project with steel makers, classification societies and universities in 2010. Since then, we have carried out many experiments and associated analyses, including series of fundamental mother plate experiments, fundamental joint experiments and structure experiments.

This paper outlines the results of the project in combination with some considerations on how the harmonized CSR can incorporate the results of the project, and enhance the quality of structural design and safety of oil tankers.

## 1 Introduction

In recent years, fatigue strength issue on tanker structures has been one of the greatest concerns among the industries, and more and more consistent and direct analytical fatigue strength assessment method has been introduced to the international rules, such as the Common Structural Rules for Double Hull Oil Tankers (CSR-O/T) [1]. Such new rules take account of various parameters which affect fatigue strength, one of which is plate thickness. It is commonly known as thickness effect that increase in plate thickness causes a decrease in fatigue strength. Although some design standards [1, 2, 3] had taken account of this thickness effect, as compared with the rigorous analytical approach for other factors, the effect of plate thickness has been considered with simple application of thickness exponent of n=1/4, for example in CSR-O/T, based on the work by Gurney [4].

In this regard, it has been shown through some studies that this thickness effect can be relaxed by allowing for geometry of each specific joint, and some analytical or experimental studies were carried out accordingly. Yagi et al. [5, 6] carried out parametric experiments with thickness range between 10mm and 80mm, and revealed that the as-welded joints with constant-sized attachments have much milder thickness effect of an exponent of 1/10, while as-welded joints under bending stress have severer thickness effect of an exponent of 1/3. Nakamura et al. [7] conducted analytical research on stress concentrations in the welded joints between longitudinal stiffeners and web stiffeners, and concluded that the thickness effect is negligible. Polezhayeva et al. [8] studied the thickness effect for base material and butt welded joints of the thicknesses between 22mm and 66mm, and proposed a thickness exponent of 1/10 for base material and 1/5 for butt welds. Fukuoka et al. [9] carried out several fatigue tests and stress analyses, and pointed out that the thickness effect for weld joints on I-section beams is much smaller than that of established rules and standards, and proposed new correction exponents.

In this circumstance, the authors considered that more comprehensive study is necessary to establish more reasonable and reliable method to evaluate thickness effect applicable to variations of details of actual ship structures, to avoid prohibiting rational usage of thick plates to hull structures and to promote enhanced quality of structural design and safety of oil tankers. The Shipbuilders' Association of Japan (SAJ) has also had a great concern to this, and organized a joint research project with steel makers, classification societies and universities in 2010. Since then, we have carried out many experiments and associated analyses, including the following three types of experimental study:

(1) Fundamental experiment to reveal the difference of stress concentration and stress gradient to the thickness direction around the weld toe depending on the thickness difference. Small specimens which imitate the shape of fillet weld joint section of a series of different thicknesses were cut out from the steel plate, and were prepared to fatigue strength experiment.
(2) Basic welded joint experiment to confirm the outcome from the fundamental experiments. In this experiment, the effect of weld residual stress in the cruciform joint was also evaluated.
(3) Structural model experiment to reveal thickness effect in the actual ship structural details depending on the load transfer mechanism.

This paper outlines the results of the project in combination with some considerations on how the harmonized CSR [10] can incorporate the results of the project, and enhance the quality of structural design and safety of oil tankers.

## 2 Fatigue Tests

### 2.1 Fundamental experiment

To restrict the discussion to the effect of plate thickness to the stress concentration and stress gradient around the weld toe, excluding the possible effect of welding bead profile and residual stress, test specimens which imitate the shape of welded–joint section were made by cutting out from a steel plate of 20mm thickness (KA32) as schematically illustrated in Fig. 1.

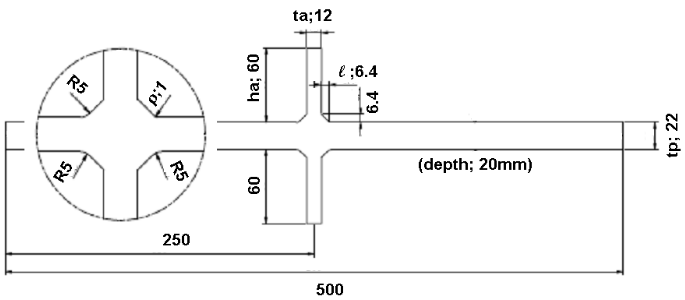



Fig. 1 Example of test specimen in fundamental experiment

Test patterns in the fundamental experiments are "A" change in main plate thickness, "B" change in attached plate thickness, "C" change in both thicknesses with same ratio and "D" change in toe radius. Table 1 summarizes the combinations of plate thicknesses.

### 2.2 Basic welded joint experiment

To comprehend the effect of weld residual stress on thickness effect, fatigue tests of cruciform fillet welded joint of as-welded specimen and of PWHT (post weld heat treatment) specimen were carried out. And, to comprehend the thickness effect on welded joint, fatigue tests of out-of-plane gusset welded joint were carried out. Test specimens were made of TMCP steel of YP32.

Table 3 summarizes the combinations of plate thicknesses. Fig. 2 shows the illustrations of test specimen. As shown in Fig. 2, length between the points clamped by test machine of cruciform fillet welded joint specimen and out-of-plane gusset welded joint specimen is about 500mm and 600mm respectively. Width of gusset plate is 120mm.

### 2.3 Fatigue test

Fatigue tests were carried out under load-controlled axial loading with pulsating constant amplitude (stress ratio; R=0.05) at room temperature in air. Test loads were determined so that the fatigue lives from $10^5$ to $10^6$ could be obtained effectively. Fatigue tests were stopped by the load cycles of approximately $5\text{x}10^6$ unless a fatigue crack was initiated.

In this study, failure life, Nf, is defined as the number of load cycles until the specimen is totally failed. Crack initiation life, Nc, in fundamental experiment is defined as the number of load cycles when the crack depth becomes 1mm. Crack depth was monitored by the strain measurements by using the analytically obtained relationship between crack depth and strain reduction. And, crack initiation life, Nc, in basic welded joint experiment is defined as the number of load cycles when the strain amplitude drops to 95%. In both experiments, strain was measured by the strain gauge which was installed at the point 5mm from the weld toe.

Simultaneously, fatigue tests of base material were carried out to obtain S-N relation of the material used in the fundamental experiment. Based on the fatigue tests, S-N relation of base material is obtained as follows. Fatigue strength at $2\text{x}10^6$ fatigue life is estimated as 393.32MPa.

$$N = 9.3 \times 10^{113} \cdot \Delta S^{-41.5} \tag{1}$$

Table 1 Combinations of plate thicknesses in fundamental experiment (unit: mm)

| Test pattern | Test No. | main plate thickness; tp | attached plate | | weld length; ℓ | toe radius; ρ |
|---|---|---|---|---|---|---|
| | | | thickness; ta | height; ha | | |
| A | 1 | 12 | 12 | 60 | 6.4 | 1 |
| | 2 | 22 | | | | |
| | 3 | 40 | | | | |
| | 4 | 80 | | | | |
| B | 3 | 40 | 12 | 60 | 6.4 | 1 |
| | 5 | | 22 | 60 | 8.4 | |
| | 6 | | 40 | 80 | 12 | |
| | 7 | | 80 | 160 | 20 | |
| C | 1 | 12 | 12 | 60 | 6.4 | 1 |
| | 8 | 22 | 22 | 60 | 8.4 | |
| | 6 | 40 | 40 | 80 | 12 | |
| | 9 | 80 | 80 | 160 | 20 | |
| D | 10 | 22 | 12 | 60 | 6.4 | 0.5 |
| | 2 | | | | | 1 |
| | 11 | | | | | 3 |
| | 12 | 40 | 22 | 60 | 8.4 | 0.5 |
| | 5 | | | | | 1 |
| | 13 | | | | | 3 |

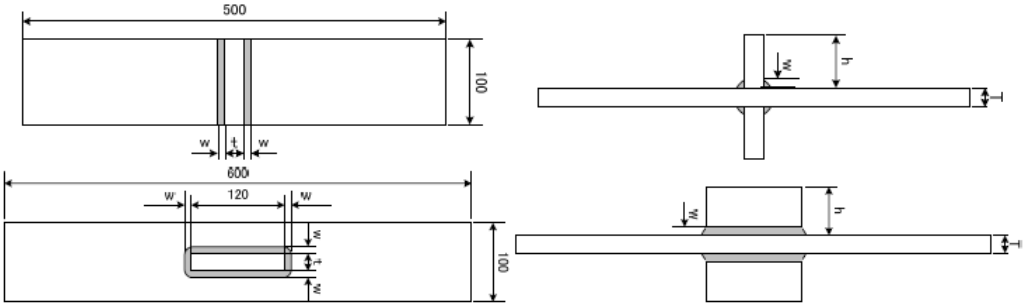



Fig. 2 Test Specimen in basic welded joint experiments

Table 3 Combinations of plate thicknesses in basic welded joint experiment (unit: mm)

| joint type | Test No. | main plate thickness | attached plate | | Target weld length | Target toe radius |
|---|---|---|---|---|---|---|
| | | | thickness | height | | |
| cruciform fillet welded joint | 2-AW | 40 | 22 | 60 | 8.4 | 1 |
| | 2-SR | 40 | 22 | 60 | 8.4 | 1 |
| | 3-AW | 40 | 80 | 160 | 12 | 1 |
| | 3-SR | 40 | 80 | 160 | 12 | 1 |
| out-of-plane gusset welded joint | 5-AW | 12 | 12 | 60 | 6.4 | 1 |
| | 6-AW | 22 | 12 | 60 | 6.4 | 1 |
| | 7-AW | 40 | 12 | 60 | 6.4 | 1 |
| | 8-AW | 80 | 12 | 60 | 6.4 | 1 |
| | 9-AW | 40 | 24 | 60 | 8.4 | 1 |

AW ; as welded, SR ; stress relieved by PWHT

## 3 Finite Element Analysis

### 3.1 Analysis model

Finite element elastic analyses using MSC/Nastran were carried out. Plane strain element FE model (1/2 model) was used for specimen of fundamental experiments, and solid element FE model (1/8 model) was used for specimen of basic welded joints experiments. For plane strain FE analysis, corrected Young's modulus of $E' = E/\left(1-\nu^2\right)$ was applied, where $E$=206GPa and $\nu$=0.3.

Identical element size of minimum 0.05mm was applied at the weld toe of all the specimens of fundamental experiments in order to eliminate the difference due to element size. Lengths of each side of the elements were made identical as far as practicable to keep accuracy of the analysis. Dummy rod elements were attached on the surface along the weld toe contour shape to obtain the boundary stresses along the weld toe surface.

Weld toe of specimens of basic welded joint experiments was modeled based on its toe radius. 10 elements were arranged along the curvature. Root face between main plate and attached plate was modeled by the slit of 0.4mm. In order to evaluate nodal load on the surface of main plate, membrane elements of $10^{-3}$ mm thickness were attached on the surface around the weld toe.

As illustrated in Fig. 3, principal stress direction $\phi$ was calculated in the surface element where the highest stress is exerted, and the stresses in this direction were obtained in the elements along the radial direction to the weld toe contour (i.e. along the through-thickness direction). Stress distribution down to the 1mm depth from the surface was calculated by fitting the stresses in each element to 6th order polynomial.

### 3.2 Results of the analysis

Fig. 4(a) shows the relationship between plate thickness and stress concentration factor and Fig. 4(b) shows the relationship between plate thickness and stress gradient. According to the results, changes in stress concentration factor and also stress gradient are remarkable when both main plate thickness and attached plate thickness are changing (series C). In the case that the attached plate thickness is not changing in spite of the change in main plate thickness (series A), changes in stress concentration factor and also stress gradient become stable when the main plate thickness becomes thicker than 22mm. Same tendency can be observed in the case of gusset welded joint when the main plate thickness becomes thicker than 40mm. In general, both stress concentration factor and stress gradient depend on the attached plate thickness than main plate thickness.

Figure 5 shows the relationship between stress concentration factor and stress gradient. As shown in this figure, stress concentration factor and stress gradient shows linear relationship. From the observation of the results of series D, this relationship seems to be dependent on the weld toe radius.

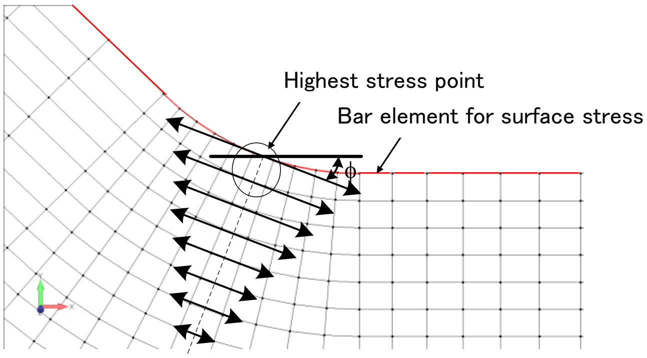
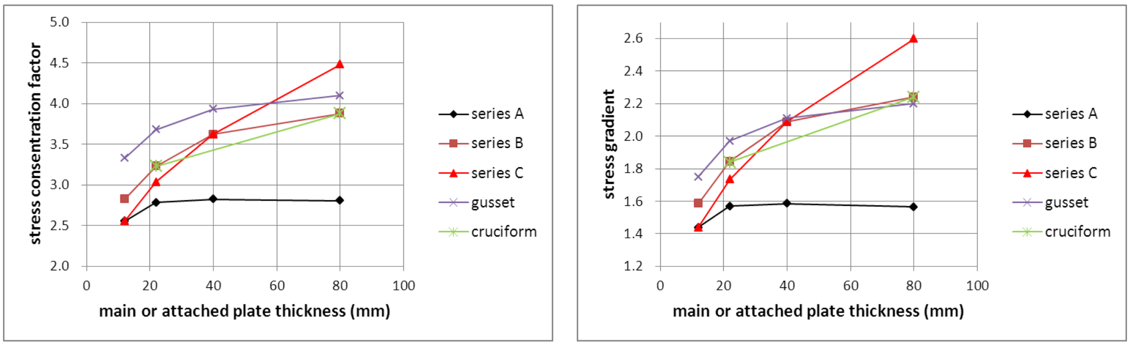



Fig. 3 Detail of FEA




(a) stress concentration factor (b) stress gradient

Fig.4 Dependency on the change in plate thickness

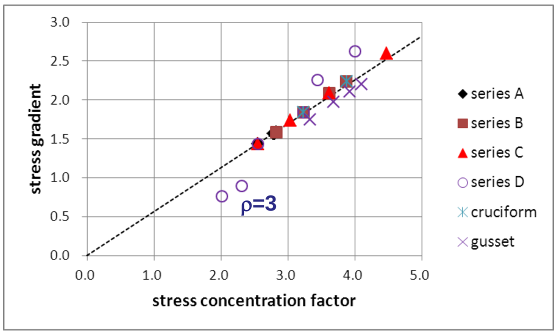


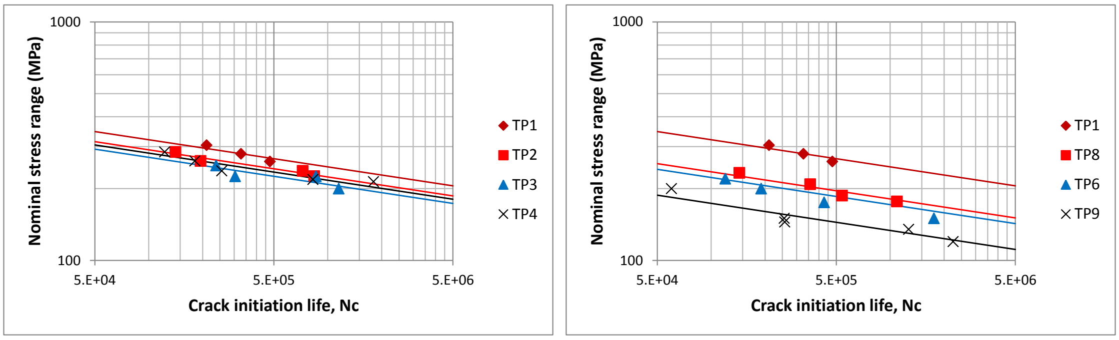

Fig. 5 Relation between stress concentration factor and stress gradient.

# 4 Fatigue Test Results

## 4.1 Fundamental experiments

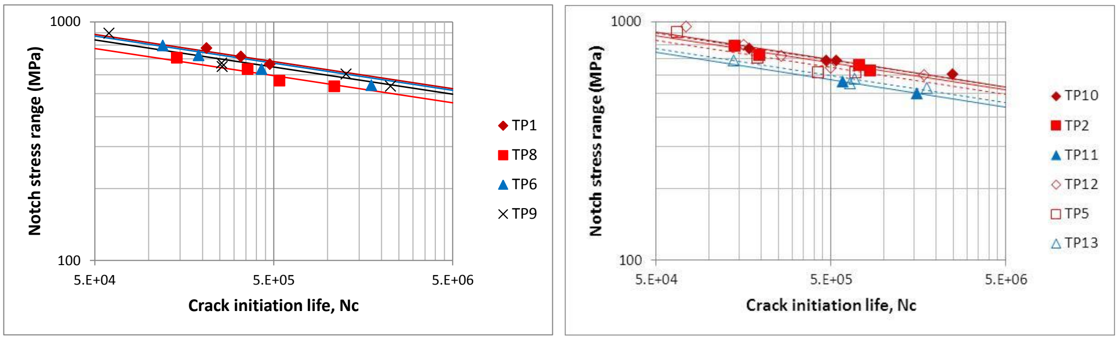
Fig. 6 and Fig.7 show some examples of the results of fundamental experiments. Fig. 6 shows the relation between nominal stress range and crack initiation life of series A and series C. As for series A where the thickness of attached plate does not change and only the thickness of main plate changes, no significant thickness effect was observed. On the other hand, as for series C where both the thicknesses of main plate and attached plate change simultaneously, the effect of plate thickness on fatigue strength was clearly observed.

Fig. 7 shows the relation between notch stress range and crack initiation life of series C and series D. Even for series C where significant thickness effect was observed when plotted with nominal stress range, this dependency on thickness disappears when plotted with notch stress range. On the other hand, from the observation of series D, lager toe radius gives smaller fatigue strength when plotted with notch stress range. This may be attributed to the fact that larger toe radius tends to give smaller stress gradient to the plate thickness direction, causing weakened fatigue strength when the notch stress is equivalent. This will be discussed in 5.2 of this paper.




(a) series A (b) series C

Fig.6 Relation between nominal stress and crack initiation life (series A & C)




(a) series C (b) series D

Fig.7 Relation between notch stress and crack initiation life (series C & D)

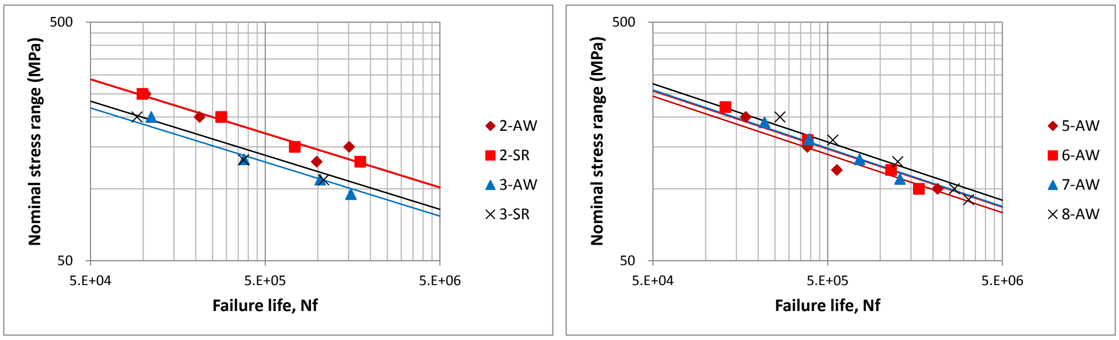
### 4.2 Basic weld joint experiments

Fig. 8 and Fig. 9 show some examples of the results of basic weld joint experiments. Fig. 8 is the results plotted with nominal stress range, and Fig. 9 is the results with notch stress range.

From Fig. 8, we can observe that thickness effect is observed in case of cruciform joint with the thickness variation of attached plate, whereas no thickness effect is observed in case of gusset welded joint with the thickness variation of main plate.

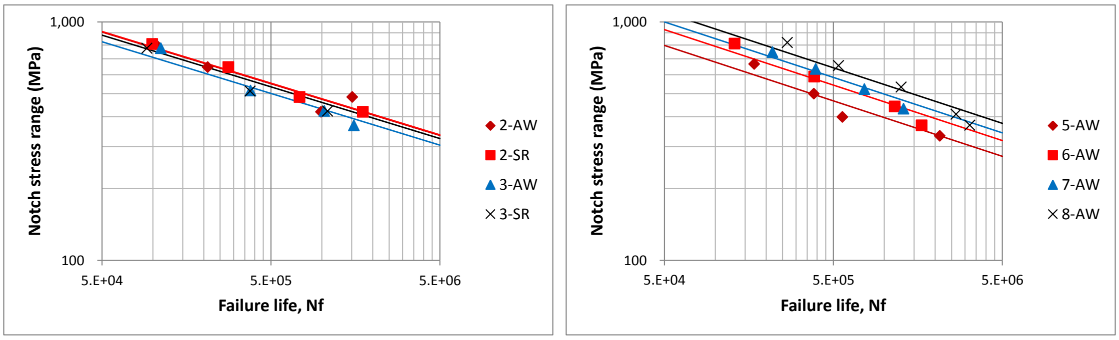
From Fig. 9, it is observed that increased plate thickness gives stronger fatigue strength in case of gusset welded joint plotted with notch stress range. This may be attributed to the longer crack propagation life in accordance with the increase in plate thickness of small welded specimen.

From the comparison between 2-AW/3-AW and 2-SR/3-SR, we can observe that no significant difference was caused by residual stress. Definite conclusion should be avoided because of the limited number of actually tested specimens, but at least it was confirmed that the main cause of the thickness effect is the stress concentration and stress gradient, rather than residual stress.




(a) cruciform welded joints (b) out of plane gusset welded joints

Fig.8 Relation between nominal stress and failure life




(a) cruciform welded joints (b) out of plane gusset welded joints

Fig. 9 Relation between notch stress and failure life

## 5 Thickness Effect

### 5.1 Thickness effect according to the results of fatigue tests

Thickness effect to fatigue strength is included in rules and standards [1, 2, 3], and is considered, for example, with the following formulae.

IACS CSR; $$\frac{1}{f_{thick}} = \left(\frac{t_{ref}}{t}\right)^n \quad t_{ref} = 22mm, \quad n = 0.25 \tag{2}$$

IIW; $$f(t) = \left(\frac{t_{ref}}{t_{eff}(t, L)}\right)^n \quad t_{ref} = 25mm, \quad n = 0.3 \tag{3}$$

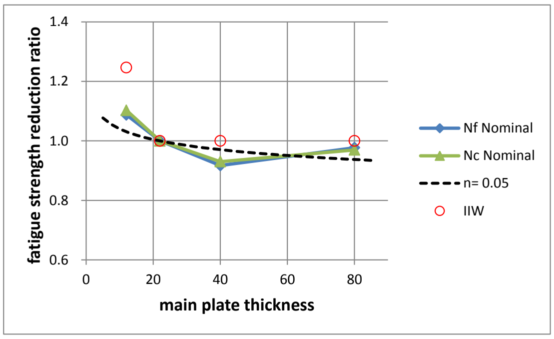
$$t_{eff}(t, L) = \begin{cases} 0.5L & ; \quad L/t \le 2 \\ t & ; \quad L/t > 2 \end{cases}$$

where $L$ is the length between weld toes of the attached plate

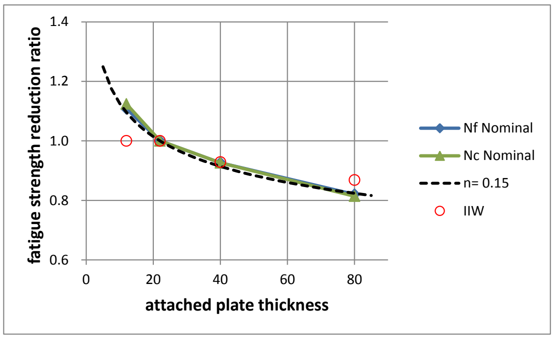
In equation (3), when the length between weld toes of the attached plate is smaller than twice the main plate thickness, half of this length will be used instead of the actual thickness of the main plate. Therefore, we can say that IIW formula is so stipulated that fatigue strength does not decrease in accordance with plate thickness increase when the thickness of main plate is relatively large in comparison with the thickness of attached plate.

Fig. 10 shows the ratio of fatigue strength against the fatigue strength of reference thickness for series A, B and C of fundamental experiments and gusset welded joint. In each figure, broken lines show the fitted curve to the equation (2) with the exponent $n$ adjusted to fit the results of the experiments. Fatigue strength reduction ratio obtained from equation (3) is plotted with red circle.

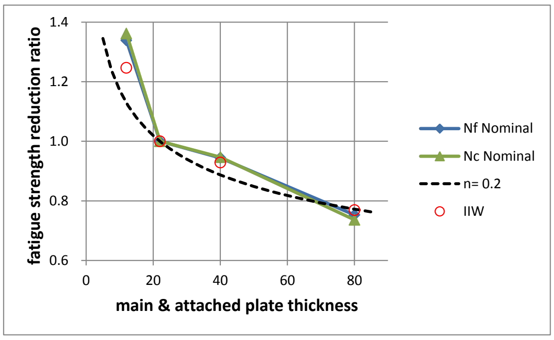
It is observed that the thickness effect depends strongly on the relation between the thicknesses of main plate and attached plate, resulting in $n$=0.05 for series A and $n$=0.2 for series C. At the same time, as to the cruciform joint, IIW formula gives good agreement to the experiments. Although the number of data is not sufficient, the results of the gusset welded joint show that thickness effect is not significant.



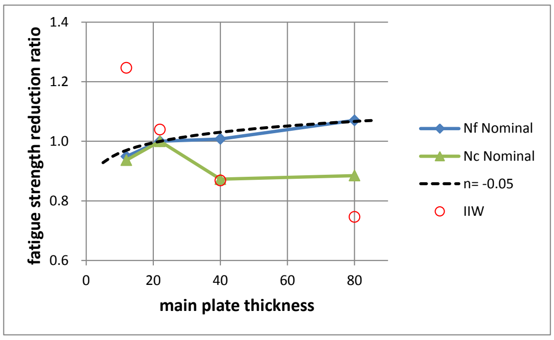

(a) series A




(b) series B




(c) series C




(d) gusset welded joint

Fig.10 Fatigue strength reduction due to thickness effect

### 5.2 Effect of stress concentration and stress gradient on fatigue strength

According to the results shown in Fig.4 and Fig.10, it is considered that the thickness effect on fatigue strength is closely related with stress concentration and stress gradient at weld toe. Regarding this matter, Siebel [11] showed the correlation between the stress gradient ( $\chi$ ) and the ratio of stress concentration factor to fatigue strength reduction factor ( $\alpha/\beta$ ) for various mechanically notched materials. Based on the Siebel's diagram of the steels whose yield stresses are 196MPa and 392MPa, correlation between $\chi$ and $\alpha/\beta$ for the material used in the fundamental experiments whose yield stress is 350MPa can be derived as shown in Fig.11.

Fatigue strength of fundamental experiments can be numerically estimated based on the Siebel's diagram shown in Fig.11 if the stress concentration factor and the stress gradient are obtained from FE analysis. Figure 12 indicates the relationship between the fatigue strength estimated by the Siebel's diagram and the fatigue strength calculated by the S-N curve, which is derived from the fatigue tests.

Although the estimation tends to make under-estimation of about 10% when compared with the experimental results, scatter in estimation is quite small. According to these results, it is considered that the fatigue strength is dominated by not only the stress concentration factor but also the stress gradient at weld toe that would change according to the form of joint. As the observation of the results of series D experiments, we pointed out that larger toe radius gives smaller fatigue strength when plotted with notch stress range. Because even these results fit well when plotted in Fig. 12, it is confirmed that the effect is attributed to the fact that larger toe radius tends to give smaller stress gradient to the plate thickness direction, causing weakened fatigue strength when the notch stress is equivalent.

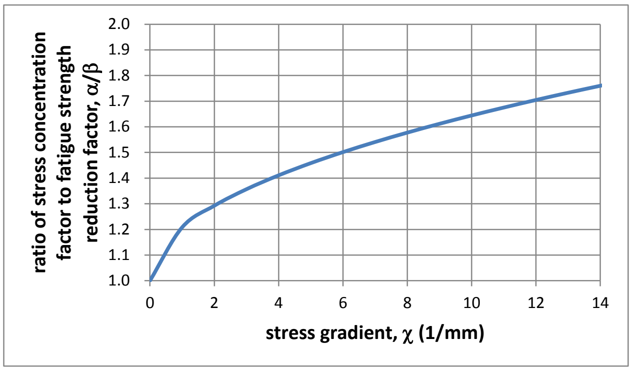



Fig.11 Correlation between the stress gradient ($\chi$) and the ratio of stress concentration factor to fatigue strength reduction factor ($\alpha/\beta$) for the material used in the fundamental experiments derived from Siebel's diagram

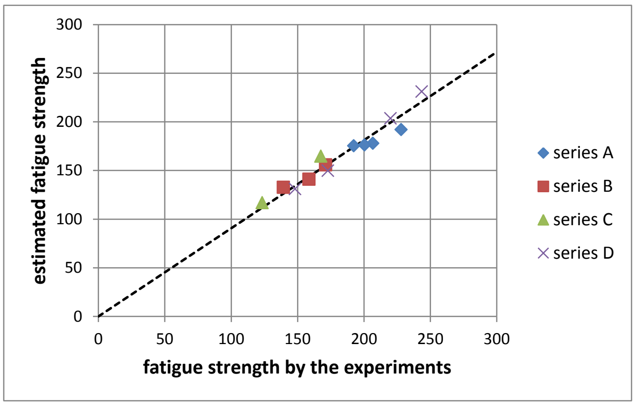



Fig.12 Relationship between the fatigue strength estimated by the Siebel's diagram and the fatigue strength calculated by the S-N curve derived from the fatigue tests

### 5.3 Review of draft harmonized CSR and feedbacks from this project

International Association of Classification Societies published second draft of the harmonized CSR [10] for external review in April this year. The authors reviewed this draft based on the results of this research project.

As a whole the authors appreciate that the IACS has introduced more rational treatment of thickness effect for each specific joint category based on recent research publications including the authors' previous publications which are part of this paper as well as Fukuoka et al. [9]. Especially, the authors appreciate that the draft harmonized CSR has already incorporated the IIW formula to the evaluation of cruciform joints, which is the main finding of this study.

Other findings of this study are that:

- With regard to gusset welded joints, no clear thickness effect was observed in the experiments. This coincides with the finite element analysis results that the stress concentration factor and stress gradient does not increase significantly according to the main plate thickness, as similar to the cruciform joints with constant-sized attachment.
- The main cause of the thickness effect is the stress concentration and stress gradient rather than residual stress and other factors. Fatigue strength can be estimated using Siebel's diagram when stress concentration and stress gradient can be calculated for different plate thickness and structural configurations.

Based on these findings, the authors further recommend that:

- There are still rooms to rationalize thickness effect exponent for gusset welded joints, butt joints and also large scale actual welded structures such as bilge hopper connections and lower stool connections.
- Thickness effect for such applications can be verified using calculated stress concentration factors and stress gradients. The thickness effect exponents given in the draft harmonized CSR should be verified based on this approach, or the Rules should include description to allow application of this approach to establish thickness effect for each specific application.

## 6 Conclusion

The main remarks obtained by the present study are as follows.

(1) According to the fundamental experiments, thickness effect on fatigue strength depends on the change in attached plate thickness rather than the change in main plate thickness.

(2) The reason of above mentioned tendency is considered to be that the fatigue strength is dominated by the stress concentration and the stress gradient at weld toe, that depend on the weld size. And, in the case of ship structural design, weld size is usually determined based on the attached plate thickness.

(3) According to the fatigue test results of out-of-plane gusset welded joint and the previously reported fatigue test results of cruciform welded joint [5] that the attached plate thickness were not changing, thickness effect was quite small. The reason of these facts is considered to be that the stress concentration and the stress gradient are not so sensitive to the increase in main plate thickness.

(4) With regard to the cruciform joint, the correction method of IIW is effective, taking account of the relation between the thicknesses of main plate and attached plate

(5) The authors reviewed the draft harmonized CSR, and confirmed that important part of the findings of this study have already been incorporated. In addition, the authors recommend that more rational approach to thickness effect using stress concentration factor and stress gradient should be applied to other welded joints, such as gusset welded joints, butt joints and large scale actual welded structures such as bilge hopper connections and lower stool connections.

These obtained results have been fed back to IACS to improve the quality of the forthcoming harmonized CSR, thus to enhance the safety level by applying reasonable considerations of the thickness effect to the fatigue strength.

Results of one of the Japanese joint research projects were introduced in this paper. SAJ will continue to devote its power to various research activities to give relevant feedbacks to rule making process, and contribute to the maritime safety.

## Acknowledgement

The authors would like to thank all the committee members of the Joint Research Project, who conducted the various experiments, analyses and discussions

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