Japanese Joint Research Project on the Thickness Effect to Fatigue Strength

- from Viewpoint of Feedback to Harmonized CSR -

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(Japan Marine United Corporation)

THE SHIPBUILDERS' ASSOCIATION OF JAPAN

Recent Joint Research Projects in Japan regarding Structural Design

- ☐ Research Project on "Thickness Effect to Fatigue Strength"
- ☐ Research Project on "Safety-related Issue of Extremely Thick Steel Plate Applied to Large Container Ships" (2^{nd} phase)

Thickness effect to fatigue strength

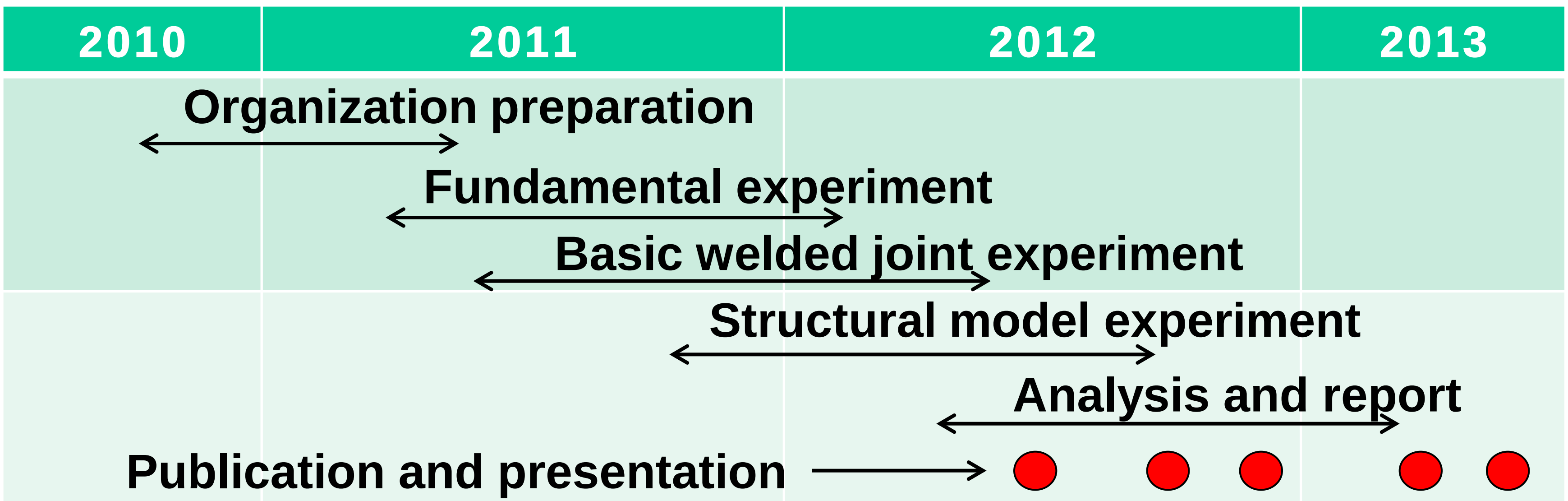
- It is commonly known as thickness effect that increase in plate thickness decreases fatigue strength.
- Current CSR accounts for this effect by 0.25 power index law as follows:

$$\log(N) = \log(K_2) - m\log\left(\frac{S_{Ri}}{(22/t_{net50})^{0.25}}\right)$$

- Recent worldwide research activities is revealing that this assumption is too conservative.

Thickness effect to fatigue strength

- To establish more reasonable and reliable method to evaluate thickness effect applicable to actual ship structural details, SAJ has organized a joint research project with steel makers, classification societies and universities.



ISOPE2012, IIW2012, JASNAOE 2012, IIW2013, TSCF2013

THE SHIPBUILDERS' ASSOCIATION OF JAPAN

Project Organization

- **Chairman**

Prof. Yoichi Sumi, Yokohama National Univ.

- **10 Shipbuilding Companies (SAJ)**

IHI, Oshima Shipbuilding, Kawasaki Heavy Industries, Sasebo Heavy Industries, Sanoyas Shipbuilding, Japan Marine United, Sumitomo Heavy Industries Marine & Engineering, Namura Shipbuilding, Mitsui Engineering & Shipbuilding, Mitsubishi Heavy Industries

- **3 Steel Makers**

Kobe Steel, JFE Steel, Nippon Steel & Sumitomo Metal

- **Expert Professors**

Prof. Takeshi Mori, Hosei University

Prof. Naoki Osawa, Osaka University

Prof. Koji, Goto, Kyushu University

National Maritime Research Institute

- **ClassNK**

Experiments carried out

In this project, three types of experimental study is planned:

- **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, its sole effect to fatigue strength getting rid of other factors such as weld residual stresses.

- **Basic welded joint experiment**

To reveal the effect of weld residual stress in the actual cruciform and gusset weld.

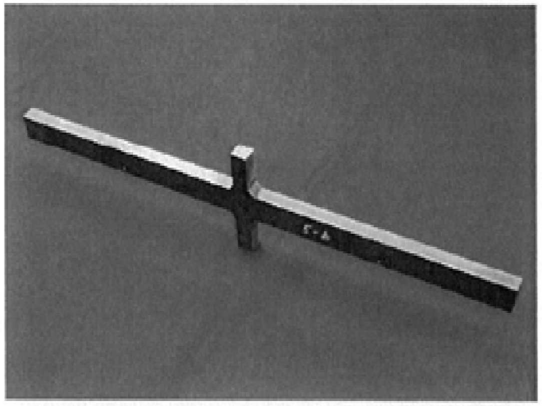
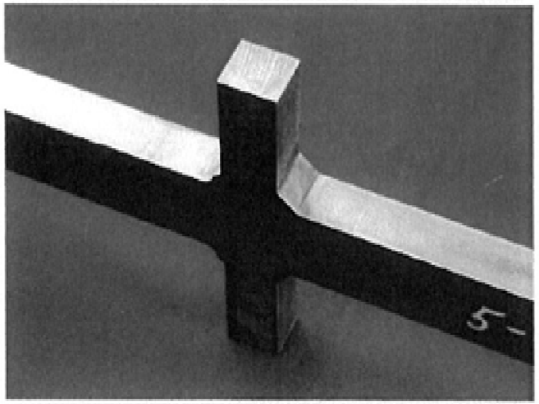
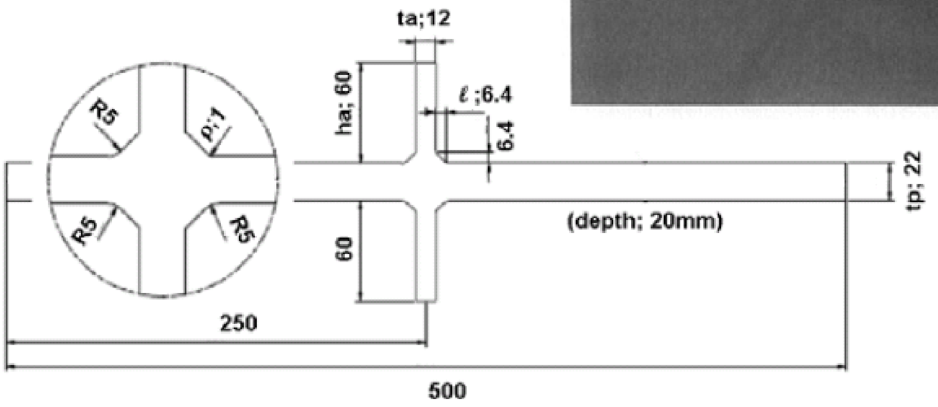
- **Structure experiment**

To reveal thickness effect in the actual ship structural details.

Thickness effect to fatigue strength: Fundamental experiment

First phase was focused on the Fundamental experiment.

To get rid of the factors other than the difference of stress distribution, test specimens were cut out from a steel plate of 20mm thickness, imitating the shape of welded cruciform joint section.

Thickness effect to fatigue strength: Fundamental experiment

Many combinations of plate thicknesses and proportions were fatigue-tested.

(unit: mm, width of specimen=20mm))

<table>
<tr><th colspan="2">TP No</th><th>main plate thick-ness; tp</th><th>attach-ed plate thick-ness; ta</th><th>attach-ed plate height ; ha</th><th>weld length; ℓ</th><th>toe radius; ρ</th></tr>
<tr><td rowspan="4">A</td><td>1</td><td>12</td><td rowspan="4">12</td><td rowspan="4">60</td><td rowspan="4">6.4</td><td rowspan="4">1</td></tr>
<tr><td>2</td><td>22</td></tr>
<tr><td>3</td><td>40</td></tr>
<tr><td>4</td><td>80</td></tr>
<tr><td rowspan="4">B</td><td>3</td><td rowspan="4">40</td><td>12</td><td>60</td><td>6.4</td><td rowspan="4">1</td></tr>
<tr><td>5</td><td>22</td><td>60</td><td>8.4</td></tr>
<tr><td>6</td><td>40</td><td>80</td><td>12</td></tr>
<tr><td>7</td><td>80</td><td>160</td><td>20</td></tr>
<tr><td rowspan="4">C</td><td>1</td><td>12</td><td>12</td><td>60</td><td>6.4</td><td rowspan="4">1</td></tr>
<tr><td>8</td><td>22</td><td>22</td><td>60</td><td>8.4</td></tr>
<tr><td>6</td><td>40</td><td>40</td><td>80</td><td>12</td></tr>
<tr><td>9</td><td>80</td><td>80</td><td>160</td><td>20</td></tr>
<tr><td rowspan="6">D</td><td>10</td><td rowspan="3">22</td><td rowspan="3">12</td><td rowspan="3">60</td><td rowspan="3">6.4</td><td>0.5</td></tr>
<tr><td>2</td><td>1</td></tr>
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<tr><td>12</td><td rowspan="3">40</td><td rowspan="3">22</td><td rowspan="3">60</td><td rowspan="3">8.4</td><td>0.5</td></tr>
<tr><td>5</td><td>1</td></tr>
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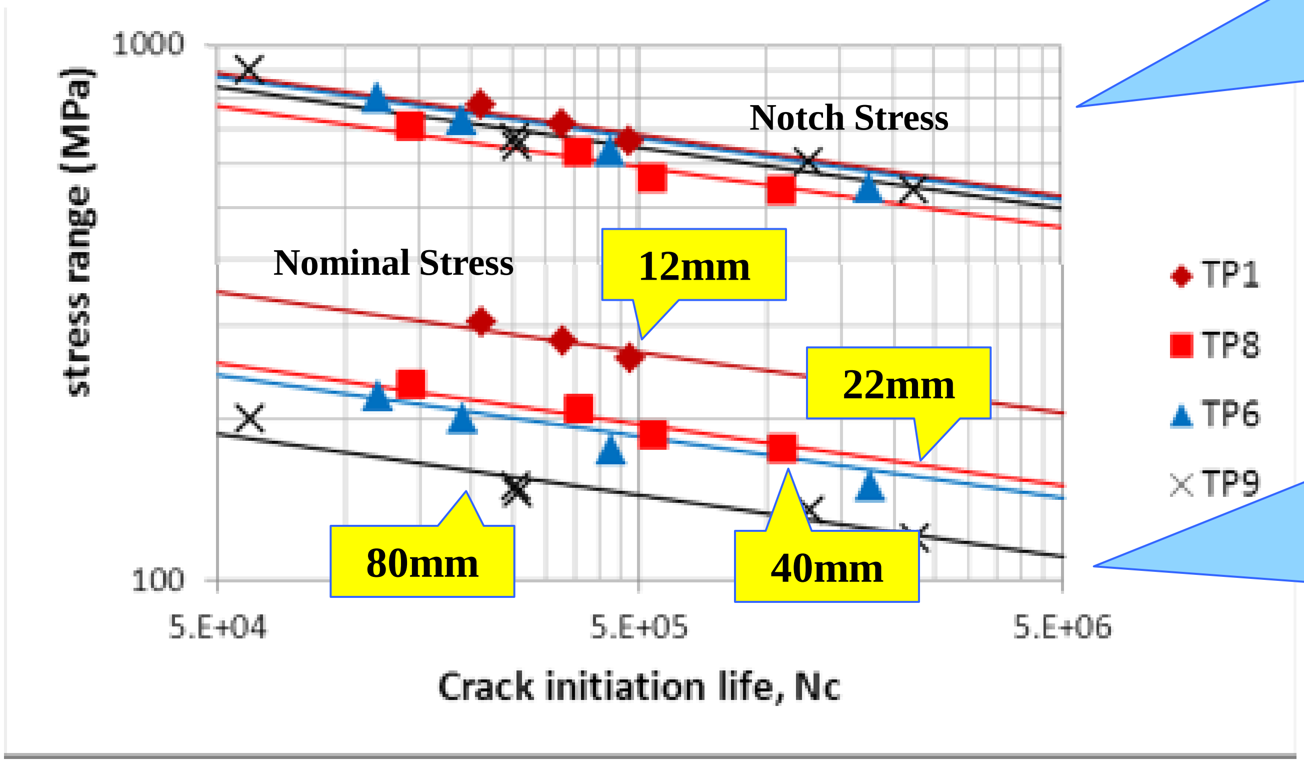
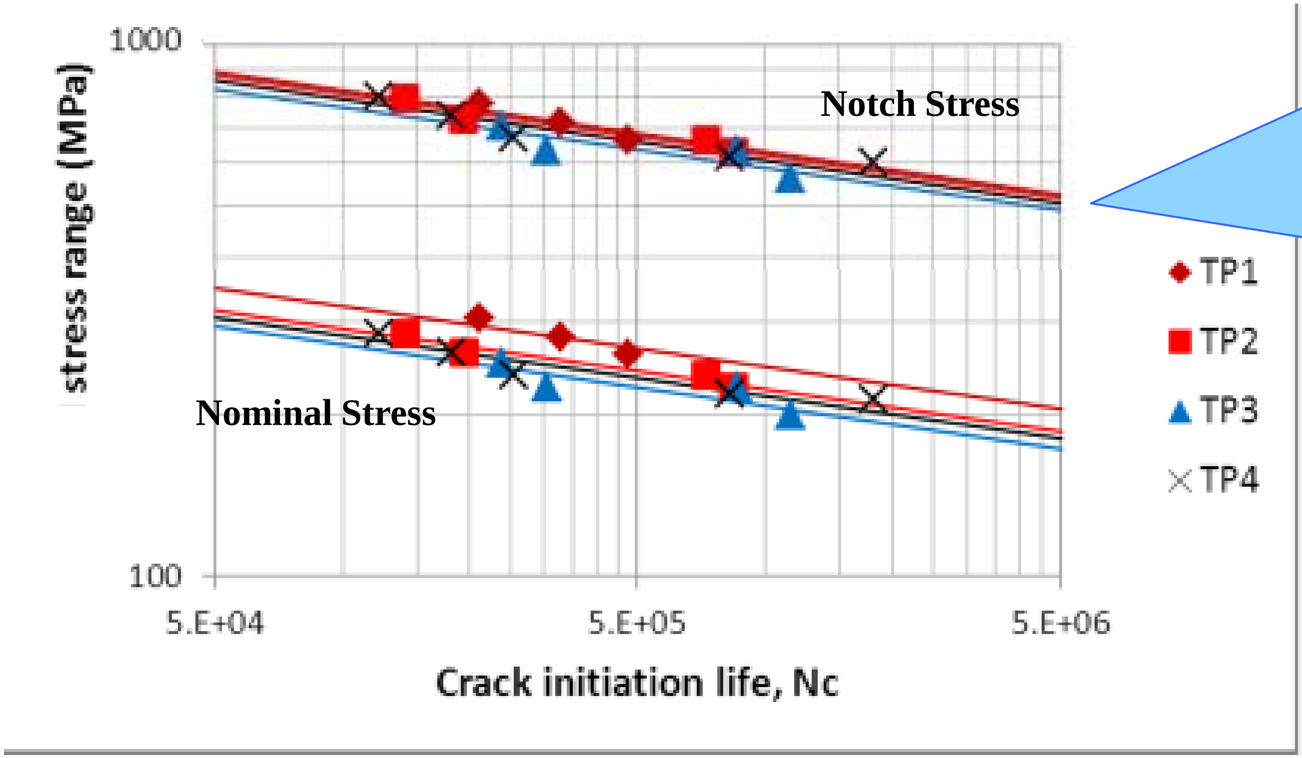
Series C: Thicknesses of both main plate and attached plate change



No significant thickness effect in case arranged by notch stress

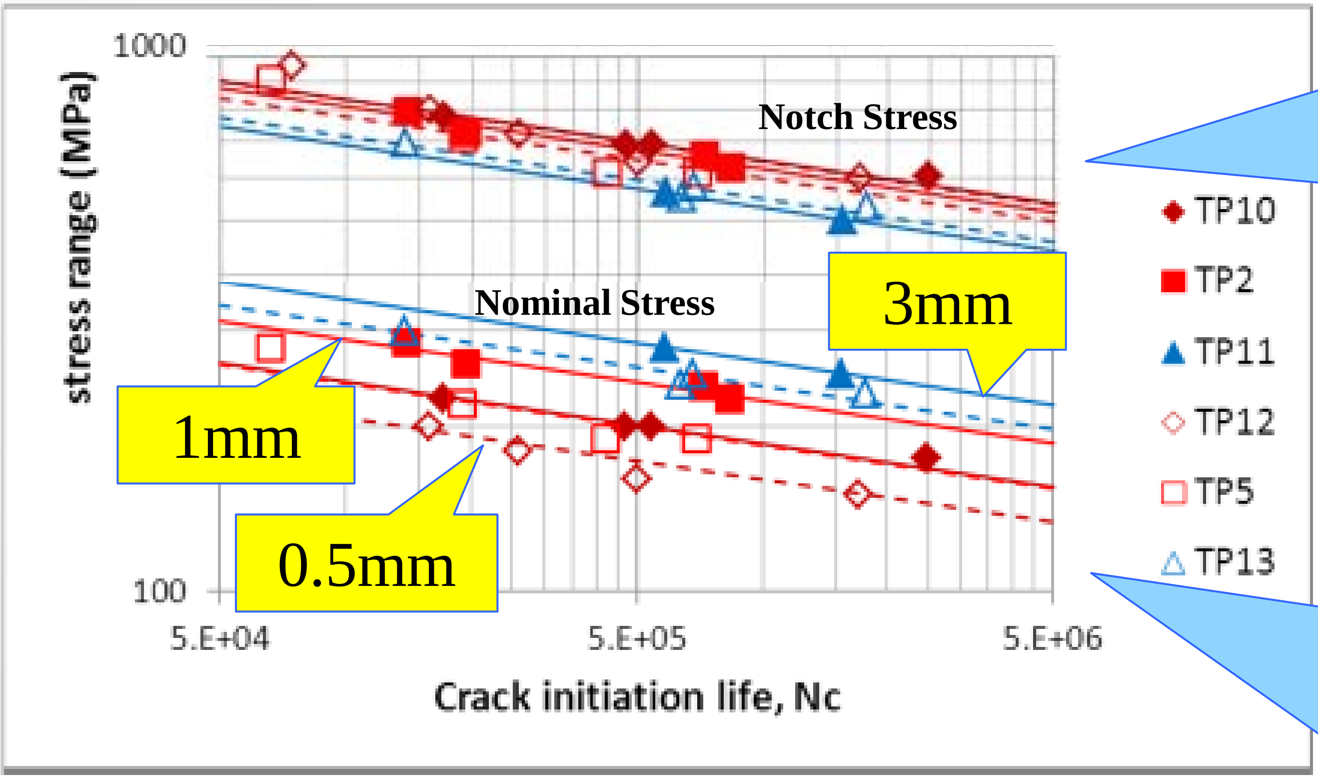
Apparent thickness effect in case arranged by nominal stress

Series A: Change in thicknesses of main plate only



No significant thickness effect in case arranged by both nominal stress and notch stress

Series D: Change in toe radius

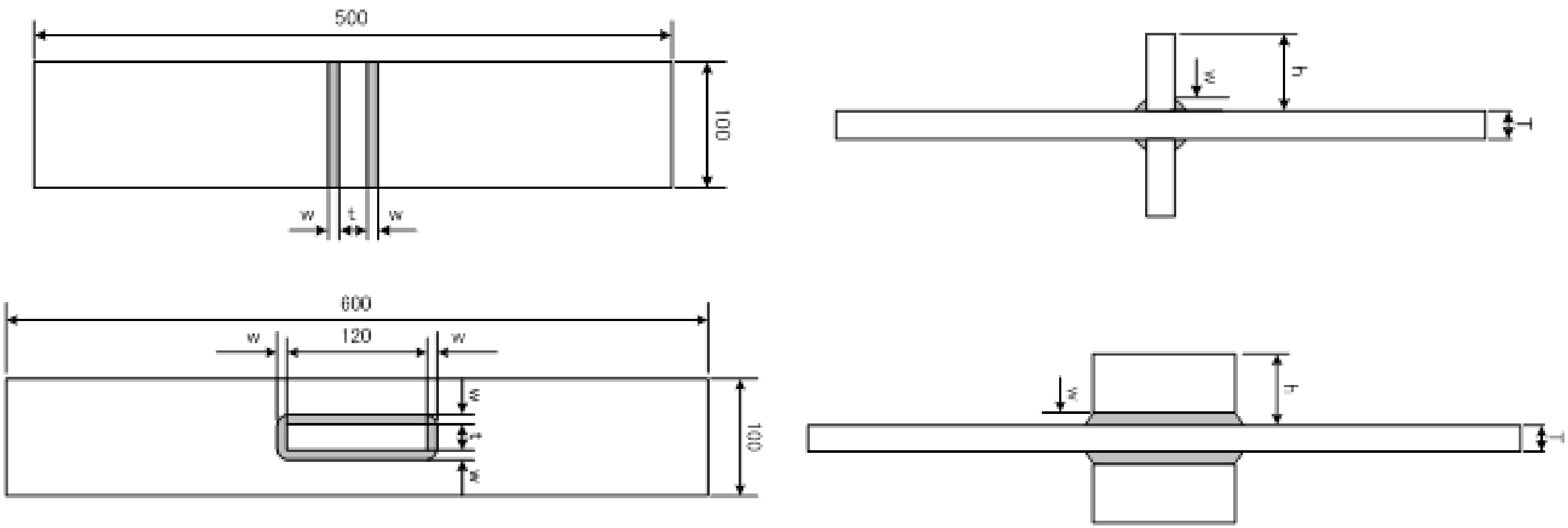


In case arranged in notch stress, larger radius is weaker

In case arranged in nominal stress, larger radius is stronger, of course

Thickness effect to fatigue strength:
Basic welded joint experiment

- To confirm thickness effect to basic welded joints
- To confirm the effect of residual stress in cruciform joints
    - PWHT (Post weld heat treatment) specimen and as-welded specimen



Thickness effect to fatigue strength: Fundamental joint experiment

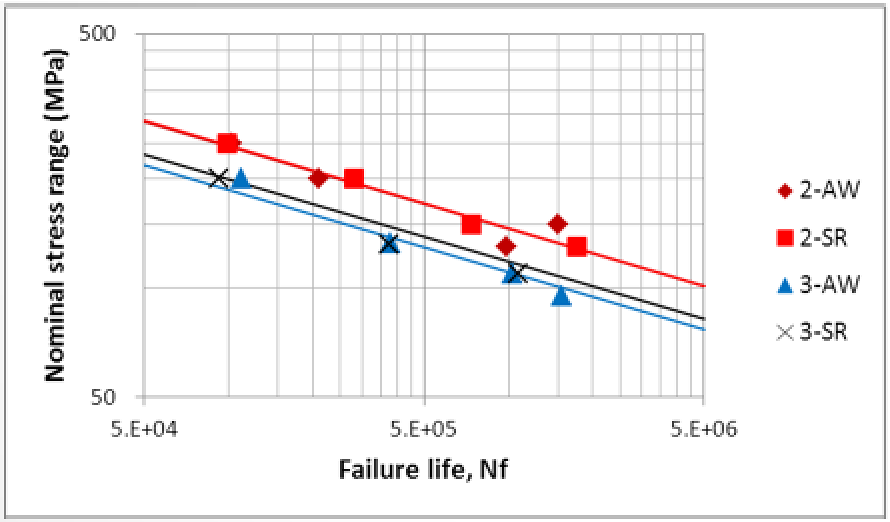
joint type	Test No.	main plate thickness	attached plate		Target weld length	Target toe radius
			thickness	height		
cruciform fillet welded joint	2-AW	40	22	60	8.4	1
	2-SR	40	22	60	8.4	1
	3-AW	40	80	160	12	1
	3-SR	40	80	160	12	1
out-of-plane gusset welded joint	5-AW	12	12	60	6.4	1
	6-AW	22	12	60	6.4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

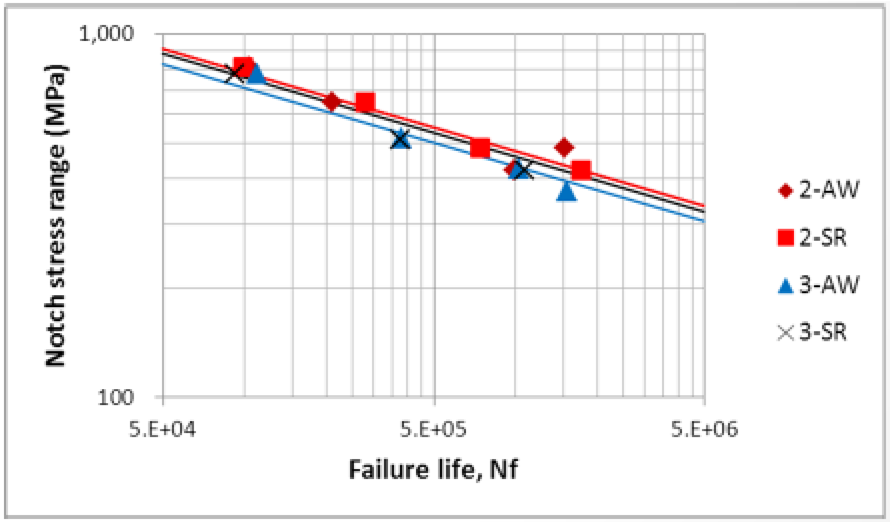
Weld length = 0.2 × thickness of attached plate + 4 mm

AW ; as−welded joint

SR ; PWHT joint

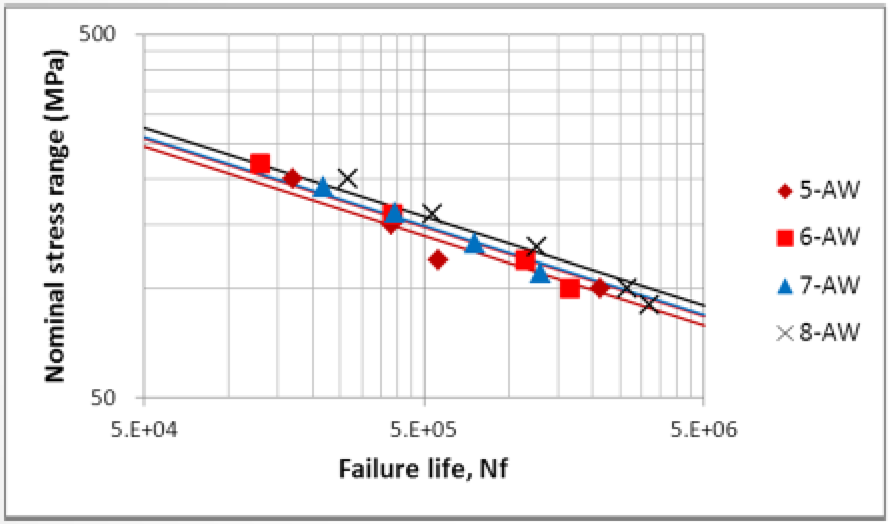
Cruciform Welded Joint

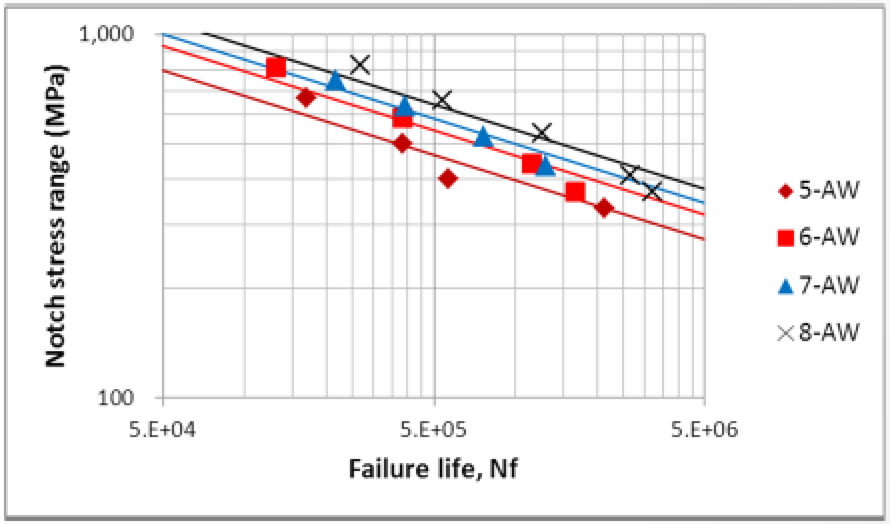




- When plotted with nominal stress range (left figure), effect of attached plate thickness on fatigue strength is observed.
- However, the effect of residual stress (difference between AW and SR) is not observed.
- When plotted with notch stress (right figure), effect of plate thickness disappears.

Gusset Welded Joint

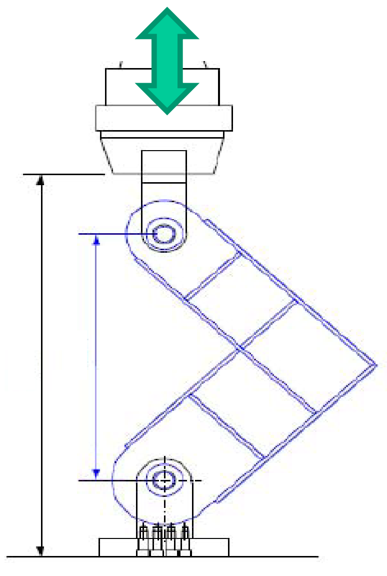


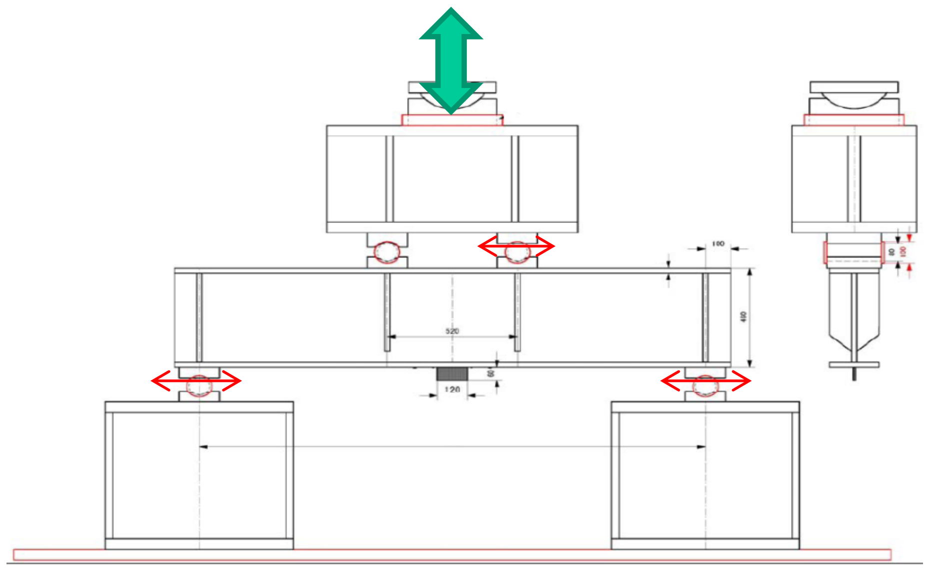


- No significant thickness effect is observed in case of gusset welded joint with the thickness variation of main plate.
- However, when plotted with notch stress range, thicker plate seems to have longer fatigue life. This may be attributed to the longer crack propagation life in accordance with the increase in plate thickness.

Thickness effect to fatigue strength: Structural model experiment

- To reveal thickness effect in the actual ship structural details depending on the load transfer mechanism
- To confirm the findings from fundamental experiments and basic welded joint experiments
- Structural model simulating general ship hull structure
  - L type model and I type model

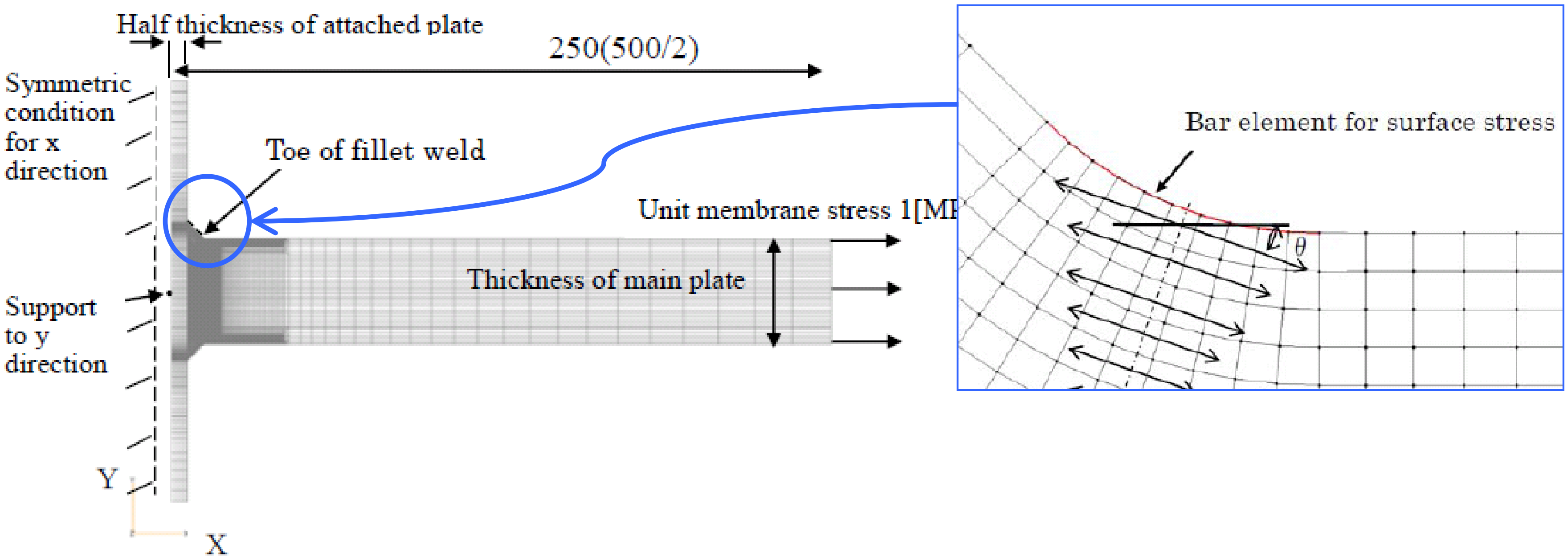




Thickness effect to fatigue strength: FEM correlated with experiment

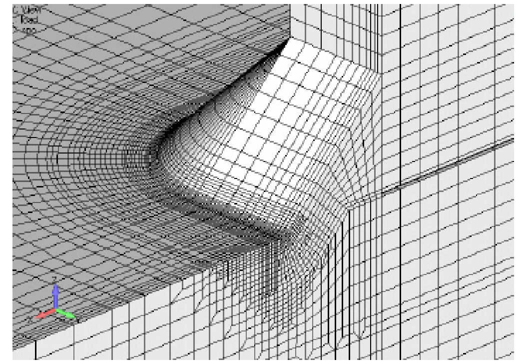
FEM was carried out to correlate with experiment.

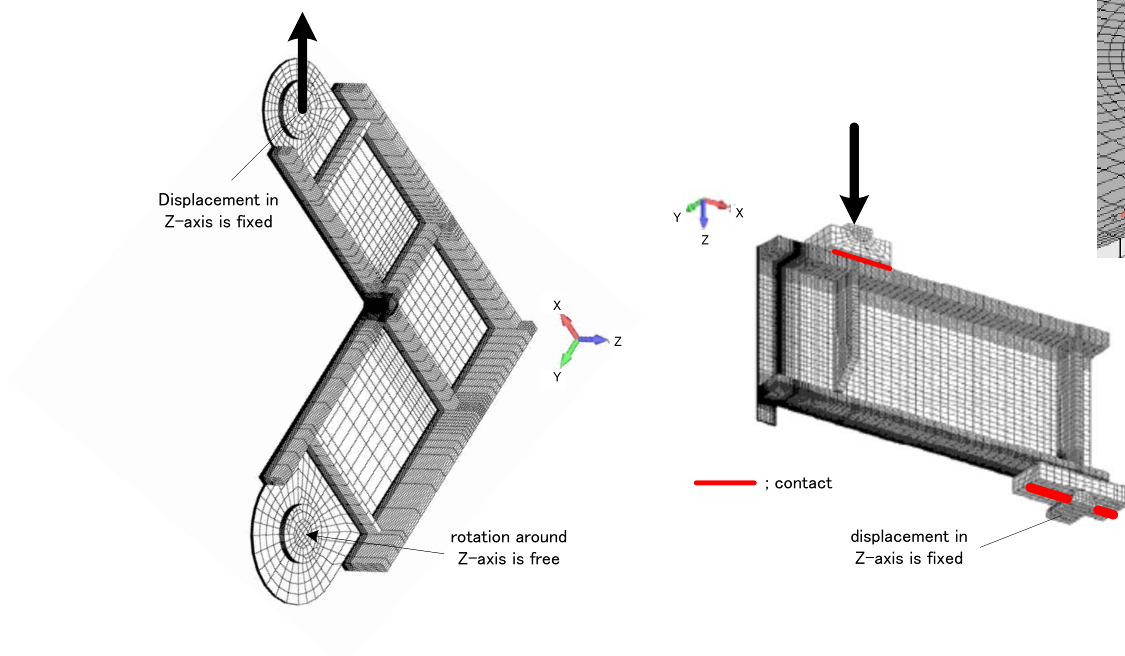
Stress concentration α and stress gradient χ were obtained from the analysis.



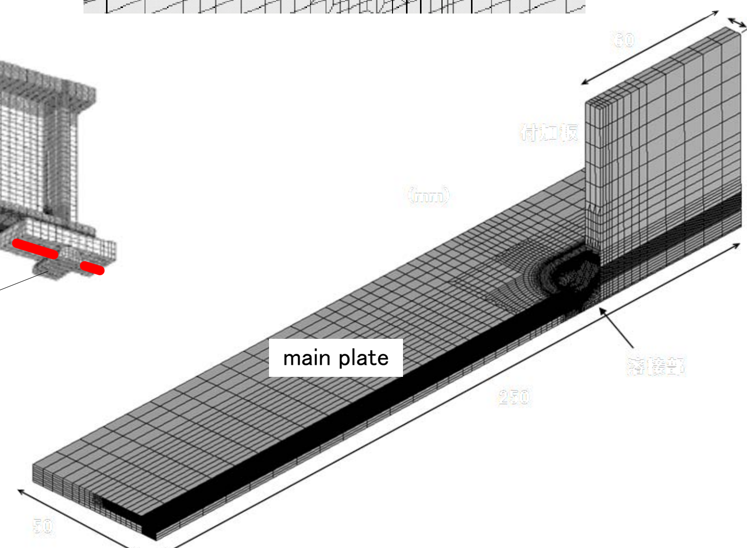
FEM models

Weld bead model detail



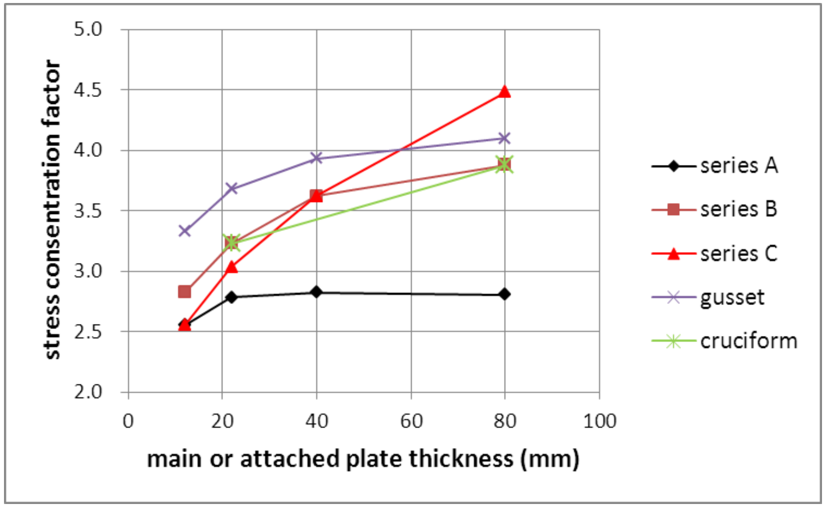


Structural model experiment

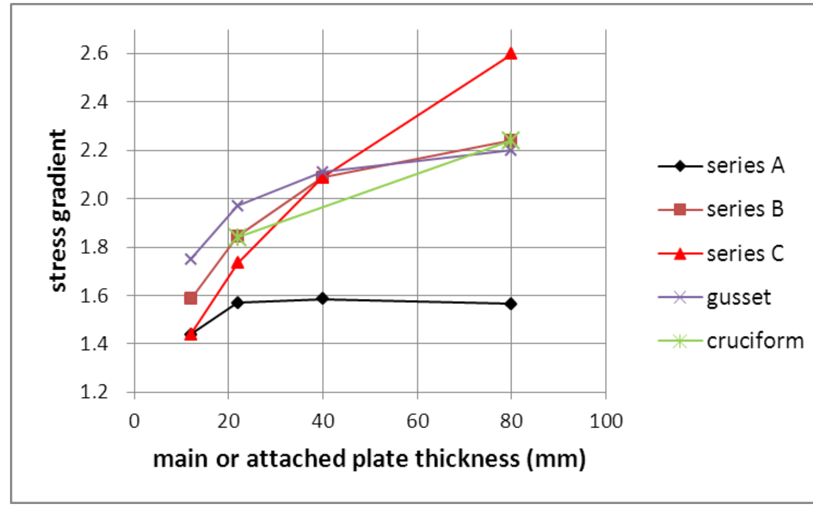


Basic welded joint experiment

Stress concentration factor and stress gradient



Stress concentration factor

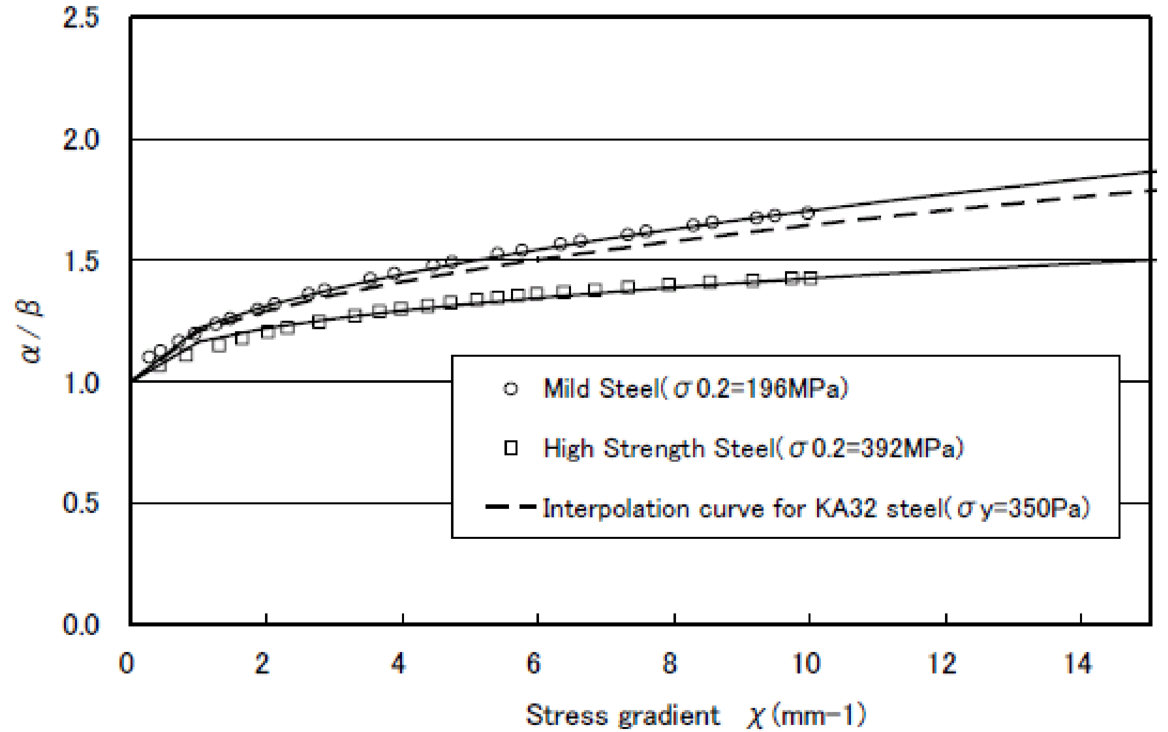


Stress gradient

- When the attached plate thickness is constant, changes in SCF and stress gradient become stable.
- When the attached plate thickness changes, both the SCF and stress gradient increase remarkably in accordance with thickness increase.
- Thickness effect is negligible in case of gusset welded joint.

Thickness effect to fatigue strength: FEM correlated with experiment

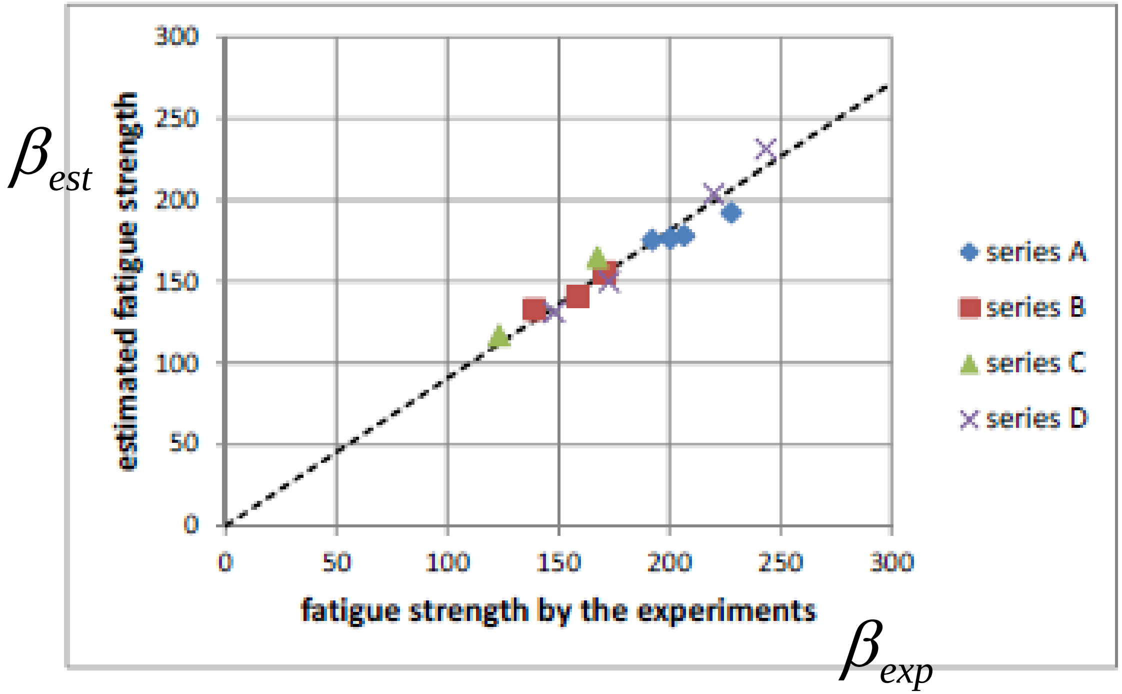
Then, applying Siebel's diagram, fatigue strength reduction factor β_{est} was identified, using the mechanical properties of the tested material.



Thickness effect to fatigue strength: FEM correlated with Fundamental experiment

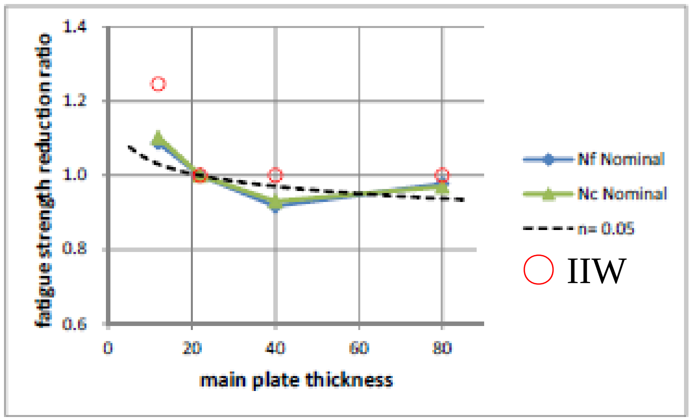
Then, β_{est} was compared with β_{exp} which was obtained from the experiments. They are in good agreement. It was confirmed that fatigue strength reduction can be predicted using calculated stress concentration and stress gradient.

Thickness effect can be estimated using stress concentration factor and stress gradient.

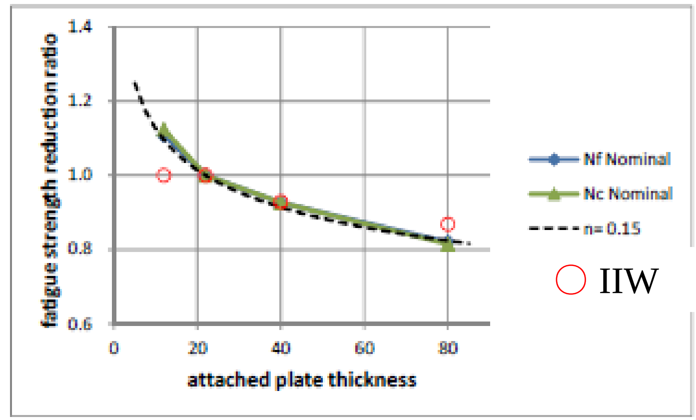


Evaluation of thickness effect

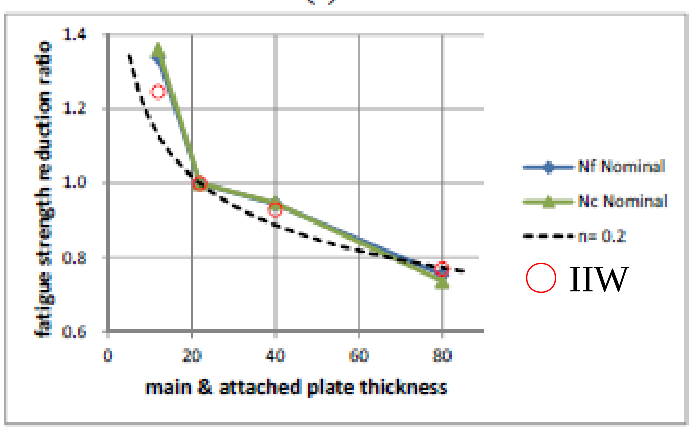
IIW Formula better fits the test results in case of cruciform joints.



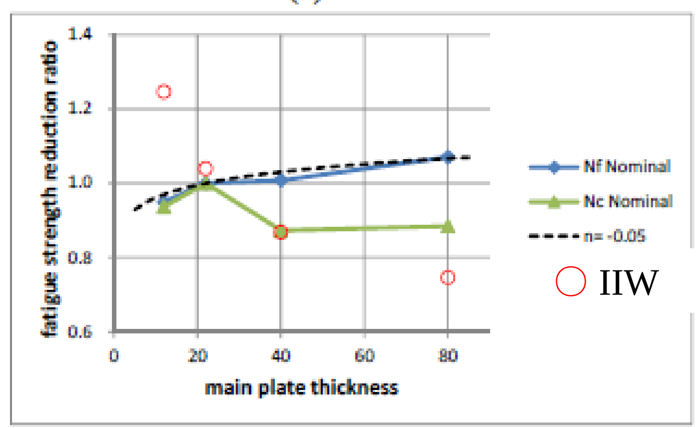
(a) series A



(b) series B



(c) series C



(d) gusset welded joint

Findings

1. 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 basic welded joint experiments where the attached plate thickness were not changing, thickness effect was quite small. The reason 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, IIW formula gives better fit to test results, because it accounts for the effect of constant attachment thickness.

Feedback to Harmonized CSR

As a whole, newly published draft of the H-CSR has introduced more rational treatment of thickness effect for each specific joint category, e.g.:

①Introduction of the effect of constant attachment thickness (similar to IIW formula) to the 90° attachment:

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

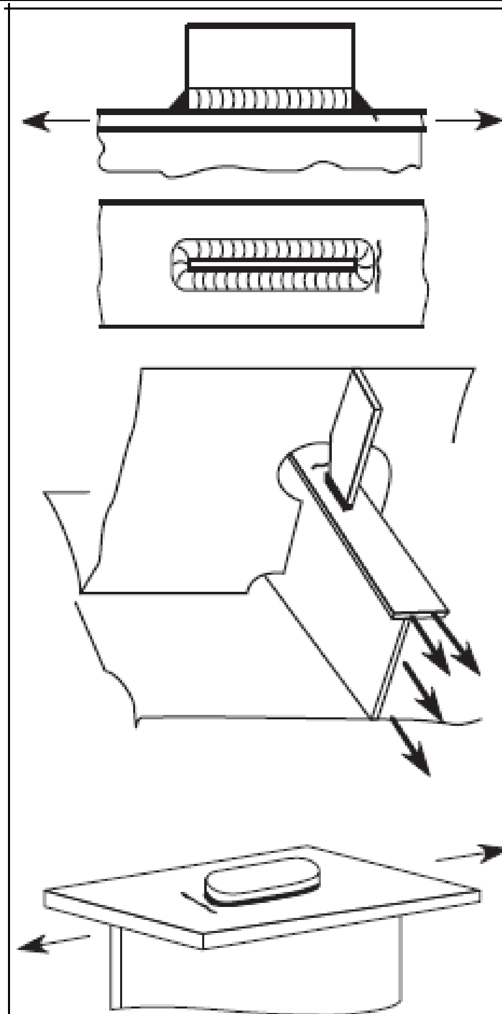
IIW; $f(t) = \left(\frac{t_{ref}}{t_{eff}(t, L)}\right)^n \quad t_{ref} = 25mm, \quad n = 0.3$

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

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

Feedback to Harmonized CSR

② Introduction of more rational thickness exponent based on past publications (e.g. right figures)

	As-welded	0.1
	Weld toe treated by post-weld improvement method (1)	0

Feedback to Harmonized CSR

Other findings of this study are that:

1.Regarding gusset welded joints, no clear thickness effect was observed in the experiments. This coincides with the FE analysis results that the stress concentration factor and stress gradient do not increase according to the main plate thickness, as similar to the cruciform joints with constant-sized attachment.

2.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.

Feedback to Harmonized CSR

Based on these findings, the authors further recommend that:

1.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.

2.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.

Thank you for your attention!

谢谢您的关注！