Enhanced safety of a VLCC by employing Fatigue Crack Arrester steel

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Abstract

MITSUBIHI HEAVY INDUSTRIES, Ltd. (MHI) achieved enhanced safety of a VLCC which complied with Common Structural Rules for Oil Tankers (CSR-OT) by applying Fatigue Crack Arrester (FCA-W) steel for her Bottom and Inner Bottom longitudinal stiffeners. The FCA-W steel, which had been developed by NIPPON STEEL and SUMITOMO METAL CORPORATION (NSSMC) can extend fatigue crack initiation life of welding joints by optimizing metallographic structure, which can bring improvement in the S-N curve. MHI investigated characteristics of the FCA-W steel thoroughly, and acquired approval of the application of FCA-W steel to the VLCC from NIPPON KAIJI KYOKAI (ClassNK). This report presents the results of the evaluation for the establishment of the design S-N curve of FCA-W steel, and the effect of the application to the VLCC. Similar effect is expected by applying FCA-W steel to hull structure of various ships including Bulk Carriers and Oil Tankers complying with harmonized Common Structural Rules...

1 Introduction

The CSRs are formulated by unifying and enhancing individual classification rules and require the fatigue strength assessment for longitudinal stiffeners such as Bottom and Side longitudinal stiffeners.

Then, it is possible that reinforcements for fatigue strength are required for longitudinal stiffeners of VLCC according to CSR. Especially, for Bottom longitudinal stiffeners, fatigue strength is dominated by hull girder longitudinal stress, local stress concentration, and fatigue characteristics of welding joint.

Local stress concentration may be reduced by improvement of local structural design, but its effect is limited. Hull girder longitudinal stress is able to be reduced by increasing hull girder section modulus by newly design, but hull steel weight should increase a lot in this case. In contrast, it can be one of the solutions if the fatigue strength is able to be increased by adopting high performance steel to longitudinal stiffeners.

From this viewpoint, MHI had investigated the applicability of FCA-W steel for hull structures, and employed them to bottom longitudinal stiffeners of CSR VLCC.

2. CSR-VLCC under application of FCA-W steel

MHI developed the VLCC which satisfied to CSR by adopting the FCA-W steel to Bottom and Inner Bottom longitudinal stiffeners.

The size of developed CSR-VLCC is shown in Table 1. Fig. 1 shows over view of developed CSR-VLCC, and Fig. 2 shows the general arrangement.

Table 1 Size of the new CSR-VLCC

Loa	(m)	333
B (mld.)	(m)	60
D (mld.)	(m)	29.1
Design draft (mld.)	(m)	20.50
DW	(t)	Approx. 298,500
Speed	(kt)	Approx. 15.5
Main propulsion plant		MITSUBISHI-UE (7UEC85LSII)

Fig.1 CSR-VLCC

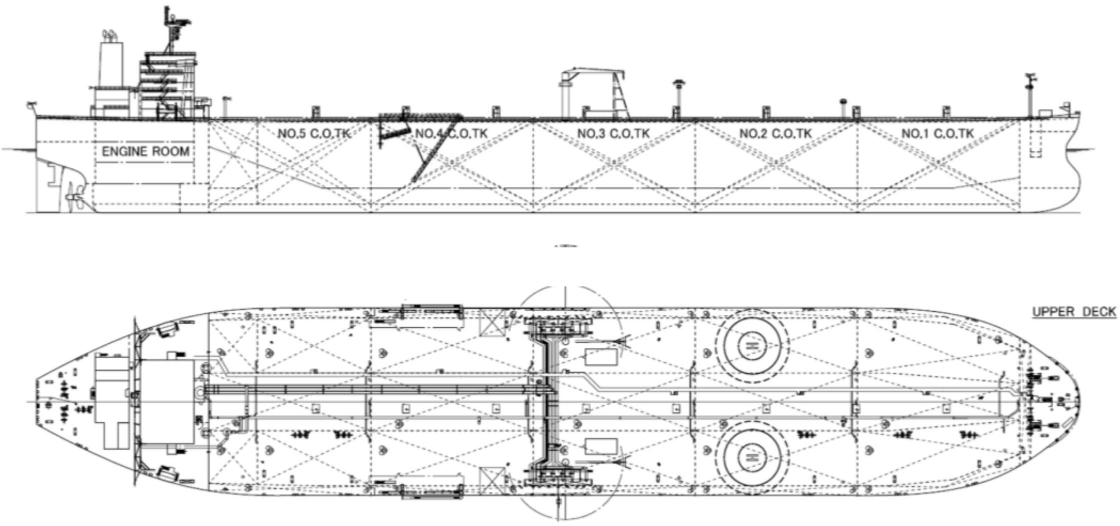


Fig.2 General Arrangement

3. Evaluation of applicability of FCA-W steel for hull structure

It is necessary to quantify the influence of the environmental factors to fatigue strength properties of the FCA-W steel in order to reflect the fatigue strength improvement effect of the FCA-W steel on structural design. On this point of view, fatigue strength of FCA-W steel and influence of environmental factors (as shown in Table 2) are investigated.

In this study, aiming to reflect the achievement of FCA-W steel for hull design, the design S-N curve for FCA-W steel was derived following conventional S-N curve.

Table 2 Investigation items for environmental factor

Influence factor	Investigation methods
Excessive loading	Fatigue tests after pre-loading
Fluctuation of welding condition	Fatigue tests using the specimen processed under various conditions. (Including repair welding)
Welding toe shape	Comparison of toe shape confirmation results

Konda evaluated the characteristic of FCA-W steel and derived the design S-N curve for FCA-W steel in present study [3]. However, aiming to reflect the achievement of FCA-W steel for hull design, the design S-N curve was derived following conventional S-N curve, in this study.

3.1. Development of design S-N curve for FCA-W steel

Fig. 3 shows boxing joint specimen used for fatigue tests. For securing of reliability of data, specimen processing and fatigue tests had been executed by both MHI and NSSMC as shown in Fig. 4.

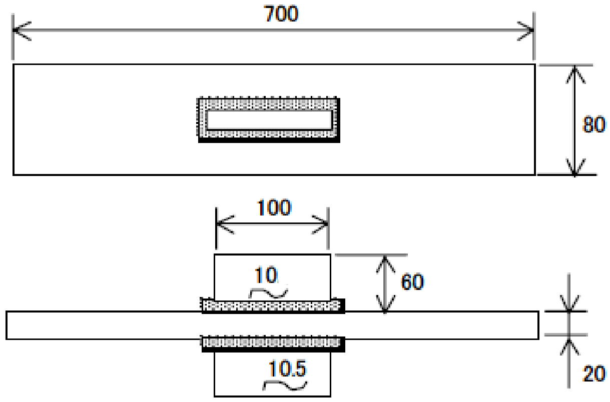


Fig. 3 Boxing joint fatigue specimen

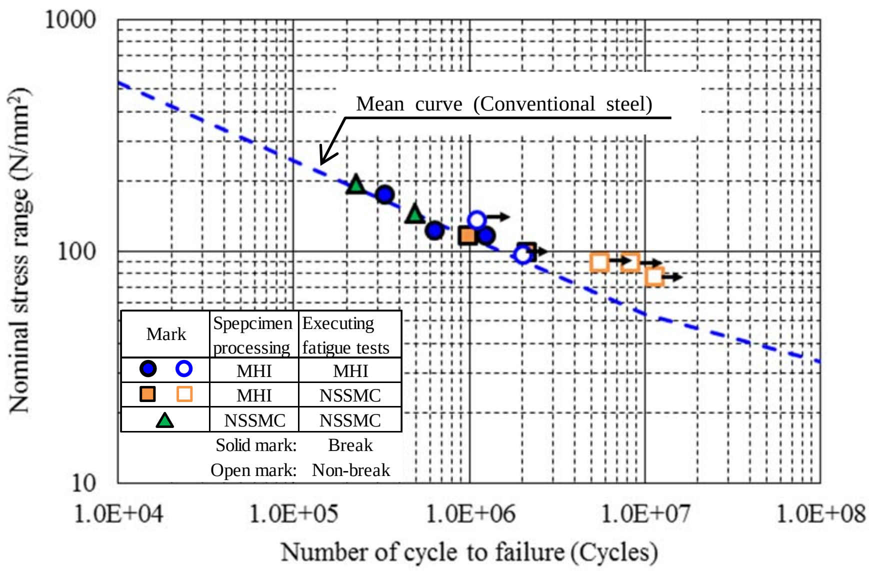


Fig.4 Fatigue test results

The fatigue strength of FCA-W steel shows similar relation to conventional steel at high stress region ($N < 10^6$), and FCA-W steel represents high fatigue strength at low stress region from Fig. 4.
The design S-N curve for FCA-W steel had been developed by the following procedure.

(1) The mean S-N curve had been estimated by least square approximation from fatigue test results.
(2) Estimation of the intersection point between mean curve of FCA-W steel and mean curve of 'F' grade (F-mean) defined in CSR
(3) Adjusting the high stress side from intersection point to F-mean curve
(4) The conversion from a mean curve to a design curve by applying standard deviation (0.2183) for 'F' grade curve of CSR.

The derived mean S-N curve for F grade of FCA-W steel shows good agreement with experimental results as shown in Fig. 5.

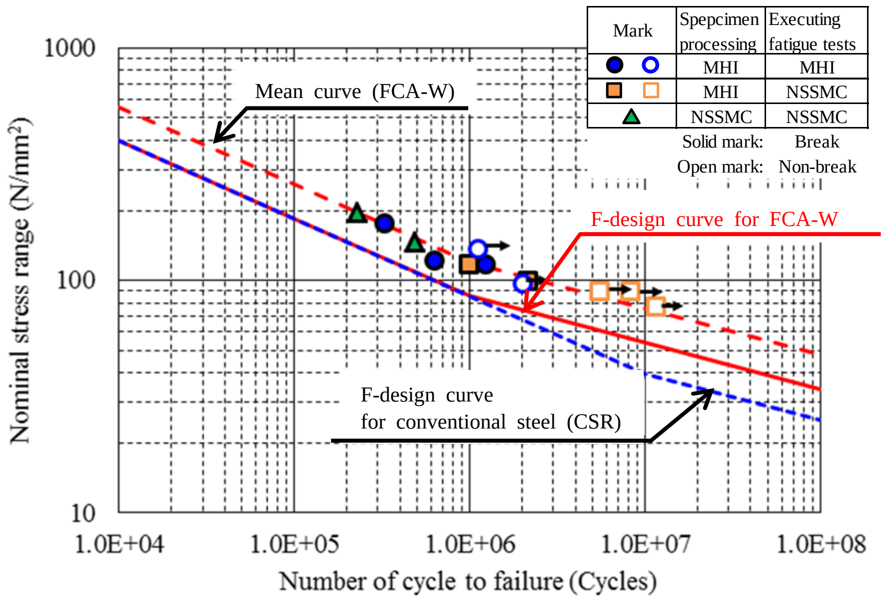


Fig. 5 Comparison of fatigue strength curve

Comparison of the design S-N curve of FCA-W steel and conventional steel which was shown in Fig.5 shows that the knuckle point of design curve can be shifted to the higher stress side by adopting FCA-W steel. The design diagram of FCA-W steel corresponding to F2 grade had been derived by shifting the knuckle point of the design diagram of F2 grade of conventional steel to the high stress side.
Table 3 shows parameters in expression (1) for each design S-N curve.

$$log_{10}(\mathrm{N}) = \begin{cases} log_{10}(K_2) - 3 \times log_{10}(\Delta\sigma) \ \ (For\ N \leq N_k) \\ log_{10}(K_2') - 5 \times log_{10}(\Delta\sigma) \ \ (For\ N > N_k) \end{cases} \tag{1}$$

Table 3 Parameters in expression (1) for each design S-N curve

Parameters	F grade		F2 grade	
	FCA-W steel	Conventional steel	FCA-W steel	Conventional steel
K_2	6.30×10^{11}	6.30×10^{11}	4.30×10^{11}	4.30×10^{11}
K_2'	4.63×10^{15}	9.97×10^{14}	2.45×10^{15}	5.28×10^{14}
N_k Number of cycle at knuckle point	1.0×10^{6}	1.0×10^{7}	1.0×10^{6}	1.0×10^{7}

3.2. Evaluation of excessive load effect

The influence of excessive load on fatigue strength of FCA-W steel had been evaluated by executing fatigue tests after applying pre-load. Fig. 6 shows the comparison between fatigue test result after pre-loading and derived S-N curve for FCA-W steel. The pre-loaded specimen show higher fatigue strength compare to mean curve of FCA-W steel from Fig. 6.
It means that the influence of excessive load to fatigue strength of FCA-W is not significant, and fatigue strength would not be reduced by excessive load.

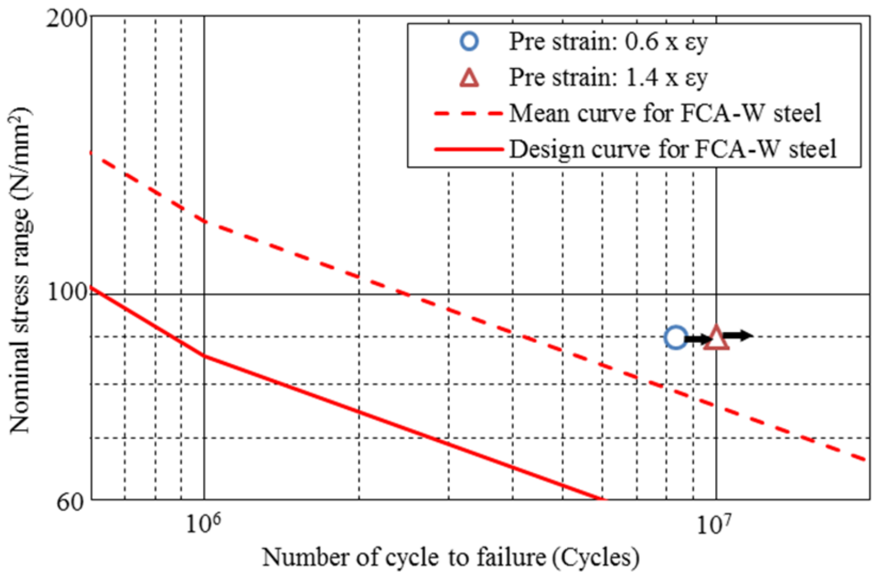


Fig. 6 Fatigue test result of pre-load condition

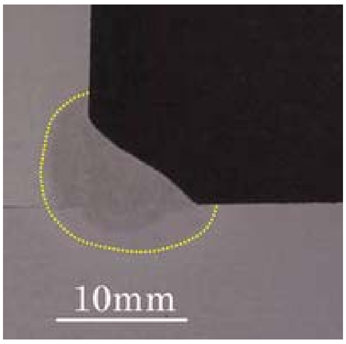
3.3. Influence of heat input

The influence of heat input had been evaluated by executing fatigue tests for welding joints constructed under various welding condition as shown in Table 4.

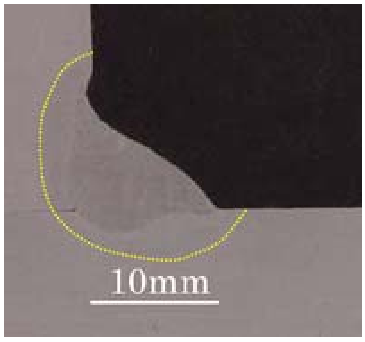
Table 4 Welding conditions to evaluate influence of heat input

Condition	Joint type	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)
Low heat input	Cruciform joint	300	31.0	46	12
High heat input	Cruciform joint	300	31.5	33	17
Repair welding	Boxing joint	260	32.0	42	12
Standard	Cruciform joint	250	26	26	15
	Boxing joint	260	32	40	12

High heat input condition demonstrate the maximum heat input of standard construction condition, and low heat input case is the minimum. Cruciform joint type specimen had been used for high heat input and low heat input specimens to secure the uniformity of heat input. To establish the multiple heating condition, repair welding bead had been processed after removing corner weld, for repair welding specimens. Fig. 7 shows macro samples and Table 5 shows hardness measurement results.

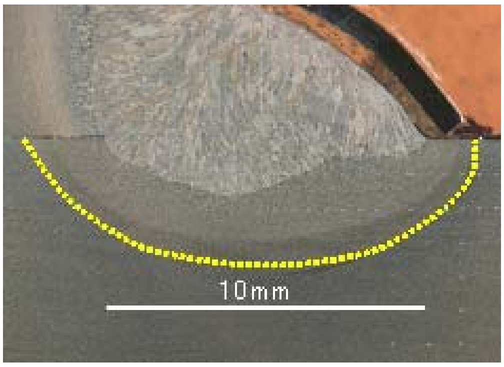


(a) Low heat input condition



(b) High heat input condition

(c) Repair welding



(d) Normal condition

Fig. 7 Macro samples for each welding condition (2/2)

Table 5 Hardness distribution around welding toe

	Measuring position (See Fig. 8)	Boxing joint		Cruciform joint		
		Standard (As-weld)	Repair	Low heat input 12 (kJ/cm)	Standard 15 (kJ/cm)	High heat input 17 (kJ/cm)
Hardness Hv (1kg)	A	180	239	225	220	194
	B	180	206	201	206	175
	C	198	182	222	195	181
	D	197	185	209	192	176

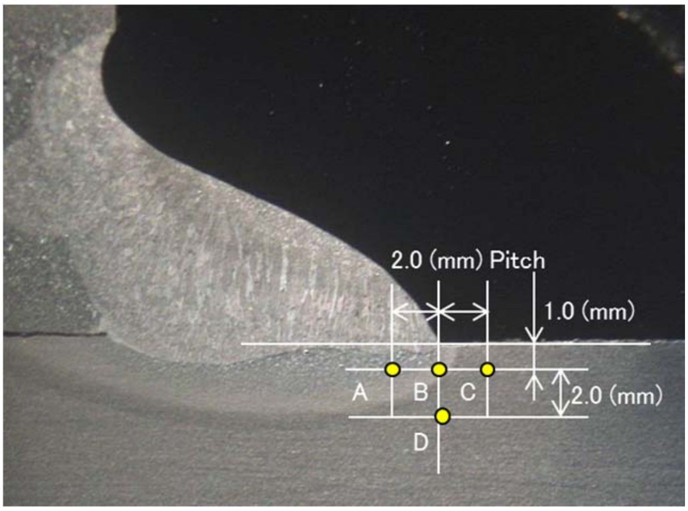


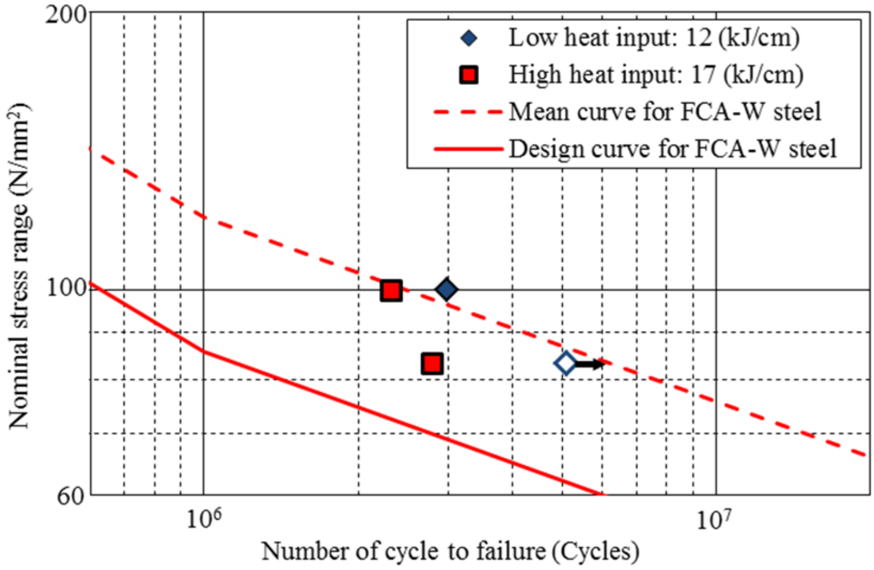
Fig. 8 Arrangement of measuring position

Such tendency is observed that when the heat input was reduced, the hardness increased and leg length decreased from Fig. 7 and Table 4.
To investigate the influence of this tendency to fatigue strength, fatigue tests had been executed by using each specimen. Aiming unified evaluation, nominal stress on cruciform joint ($\Delta\sigma_{Cru}^{Nom}$) had been modified to nominal stress on boxing joint ($\Delta\sigma_{Box}^{Nom}$) adopting stress concentration factor for each joint.

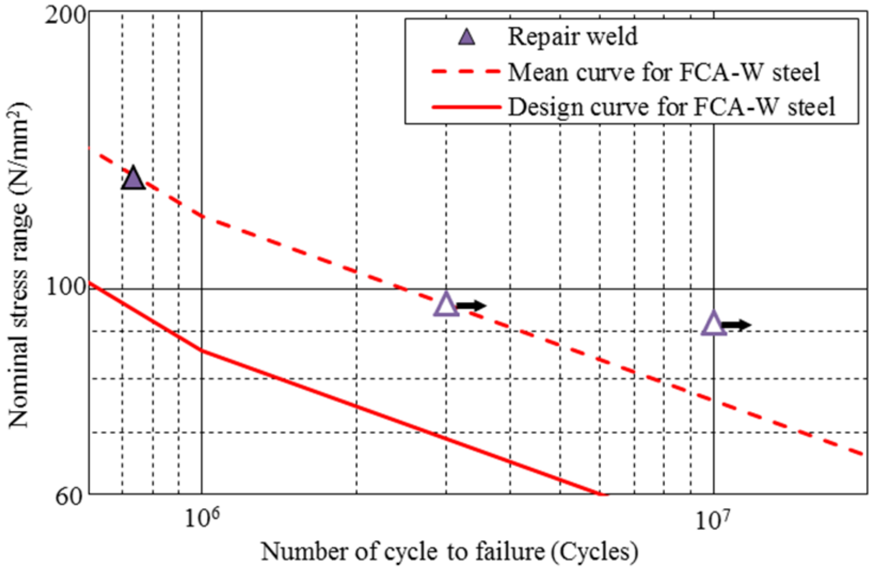
$$\Delta\sigma_{Box}^{Nom} = \Delta\sigma_{Cru}^{Nom} \times K_{Cru}/K_{Box} \qquad (2)$$

Here, K_{Cru}: Stress concentration factor of Hot Spot stress for Cruciform joint.($K_{Cru} = \Delta\sigma_{HS}/\Delta\sigma_{Cru}^{Nom} = 1.21$)
K_{Box}: Stress concentration factor of Hot Spot stress for Boxing joint ($K_{Box} = \Delta\sigma_{HS}/\Delta\sigma_{Box}^{Nom} = 1.01$)

Fig. 9 shows fatigue test result.



(a) Fatigue test results for low heat input and high heat input condition
Fig. 9 Comparison of fatigue test results for various welding condition

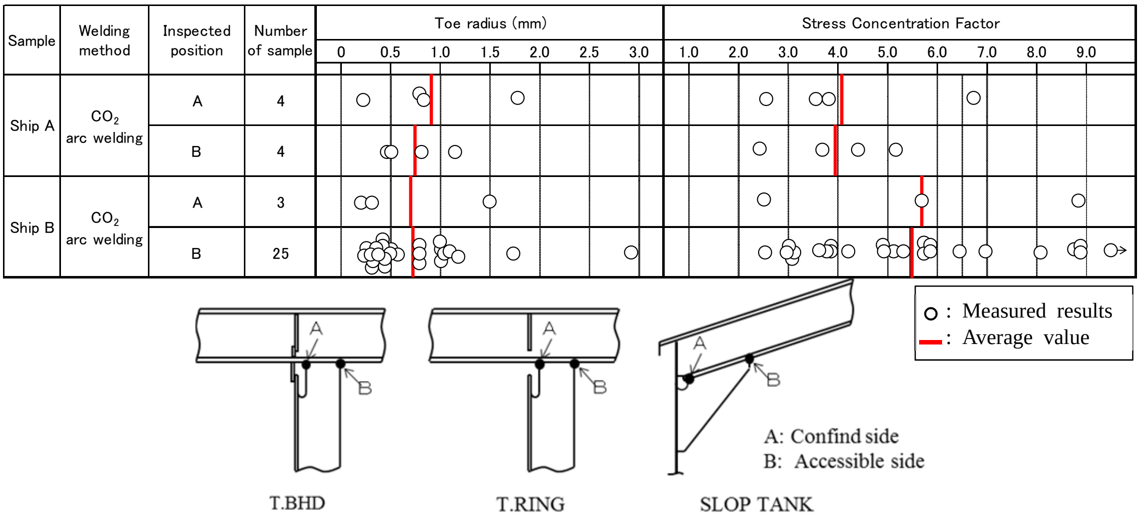


(b) Fatigue tests results for repair welding condition
Fig. 9 Comparison of fatigue test results for various welding condition

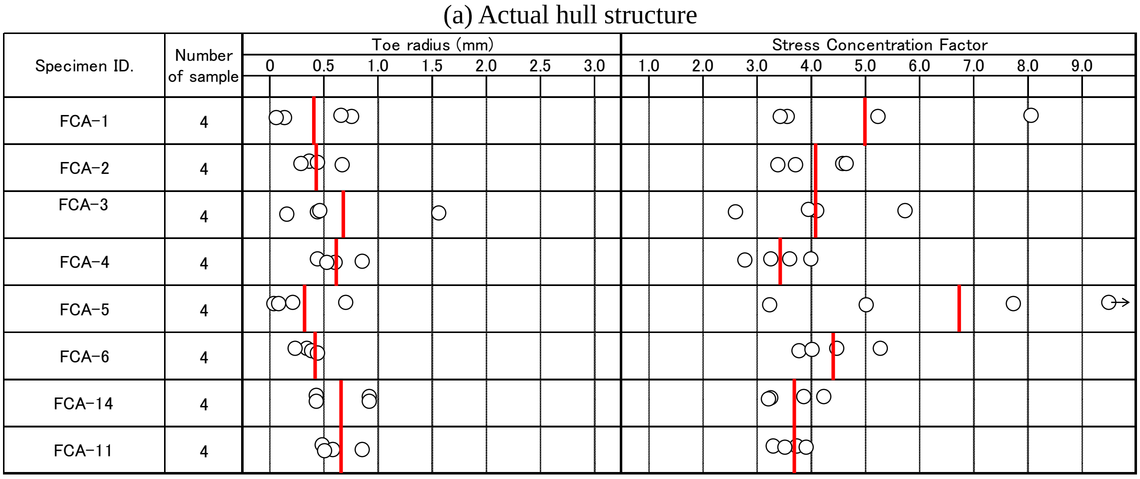
According to Fig. 9, test results exist within the scatter band and it can be judged that the fatigue strength of FCA-W is not affected by heat input as far as the heat input range is settled in standard construction condition. Therefore, it can be concluded that the special management of the heat input for FCA-W steel at construction stage is not necessary.

3.4. Welding toe shape effect

Welding toe shape of the actual hull structure has been measured to inspect whether fatigue strength of the specimen represented the fatigue strength of actual hull structure. Fig. 10 shows the inspected results of welding toe shape of the actual hull structure and fatigue specimen.



(a) Actual hull structure



○ : Measured results
: Average value

(b) Fatigue specimen
Fig. 10 Measured results Welding toe shape

It can be observed that the range of welding toe shape of fatigue specimens is similar to the range of welding toe shape of the actual hull structure from Fig. 10.

It can be judged that the fatigue specimen had represented the welding condition of the actual hull structure. Therefore, fatigue strength of hull structure can be estimated by using fatigue strength curve derived from fatigue test results.

4. Application of FCA-W steel to hull structure

CSR requires fatigue strength assessment for longitudinal stiffeners sample of which is shown in Fig. 11. The critical points of fatigue strength are the welding joints of 'floor stiffeners' with 'Bottom longitudinal stiffeners' and 'Inner Bottom longitudinal stiffeners'.

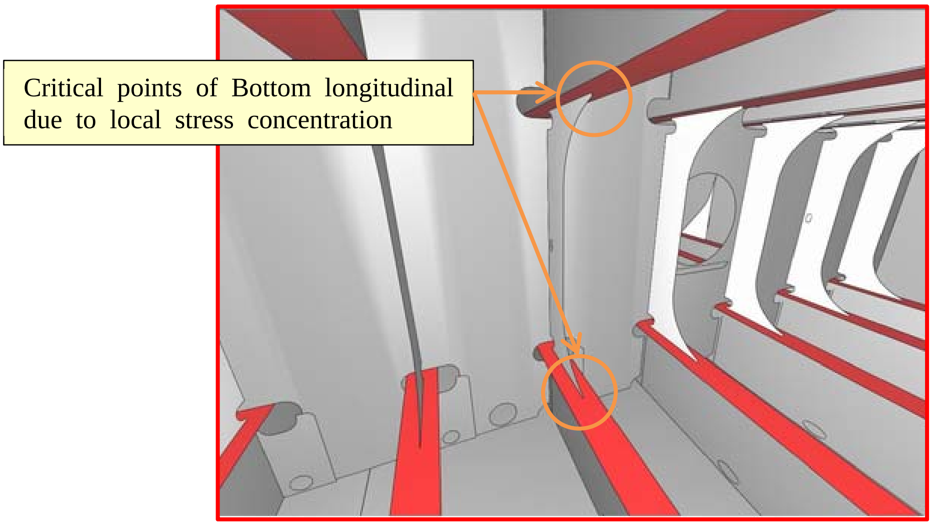


Fig. 11 Structural arrangement around Double Bottom part

The local stress concentration occurs at the welding toe on face plates, and fatigue crack will initiate at the welding toe and propagate in the face plate of those longitudinal stiffeners.
Therefore, fatigue strength of those points can be improved by adopting FCA-W to face plates of 'Bottom longitudinal stiffeners' and 'Inner Bottom longitudinal stiffeners' as highlighted in Fig. 11.
The efficiency of FCA-W steel application had evaluated by comparing damage factors with original design as shown in Fig. 12. The reduction ratio of damage factor is calculated by expression (3).

$$R = (C_w{}^{Conv} - C_w{}^{FCA-W})/C_w{}^{Orig} \tag{3}$$

Here, $C_w{}^{Conv}$: Damage factor for original design (applying conventional steel)
$C_w{}^{FCA-W}$: Damage factor applying FCA-W steel

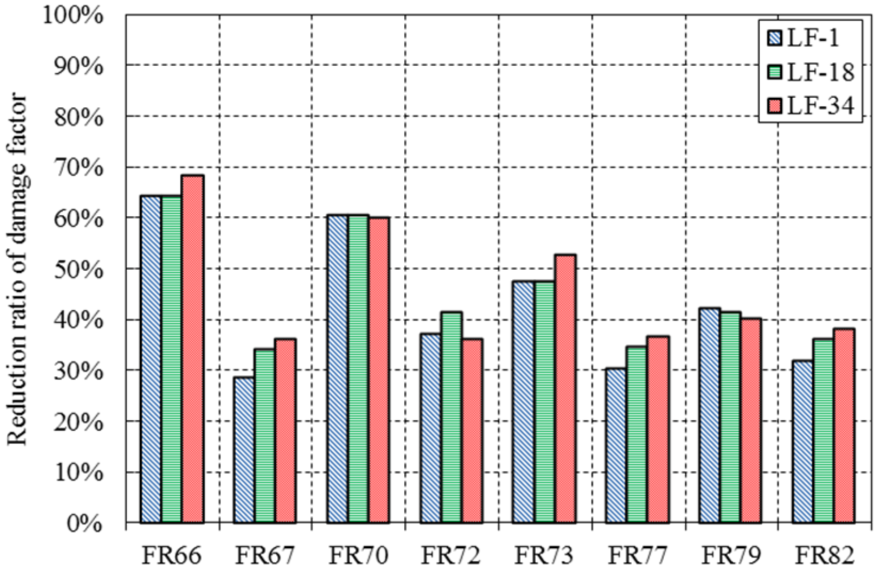


Fig. 12 Distribution of reduction ratio of damage factor on bottom longitudinal stiffeners

According to Fig. 12, it is clarified that the damage factor can be reduced more than 20% by adopting FCA-W to face plate of Bottom longitudinal stiffeners. The 20% reduction of damage factor is equal to the 4% reduction of hull girder longitudinal stress. Therefore, the application of FCA-W contributes the reduction of hull weight while being based on CSR.

5 Conclusions

In this paper, fatigue strength of FCA-W steel and the influence of external factors exists in construction condition had been evaluated. Also the effectiveness of FCA-W steel for CSR-VLCC had been evaluated.

These evaluation results were concluded as follows.

- Fatigue strength curve for FCA-W steel had been derived as denoted in expression (1).
- The influence of external factors (such as fluctuation of heat input and excessive loading) on fatigue strength of FCA-W is not significant. And the fatigue strength of FCA-W on actual hull structure can be estimated by using fatigue strength curve derived in this paper.
- According to fatigue strength evaluation for CSR-VLCC, applying FCA-W steel achieves an equal effect to reduce section modulus by 4% which contributes the reduction of hull weight.

In addition, similar effect will be provided by applying FCA-W steel to hull structure of HCSR-VLCC.

Reference

(1) Rules and Guidance for the Survey and Construction of Steel Ships (Part CSR-T Common Structural Rules for Double Hull Oil Tankers) by Nippon Kaiji Kyokai (ClassNK)

(2) Rules and Guidance for the Survey and Construction of Steel Ships (Part CSR-B&T Common Structural Rules for Bulk Carriers and Oil Tankers) by Nippon Kaiji Kyokai (ClassNK)

(3) Konda, N., Arimochi, K., Inami, A., Takaoka, Y., Yoshida, T., Lotsberg, I.,:Development of Structural Steel with High Resistance to Fatigue Crack Initiation and Growth PART 4, Proceedings of OMAE’11, 30th International Conference on Ocean, Offshore and Arctic Engineering, June 19-24, 2011, Rotterdam, The Netherlands