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Assessment of Fatigue Crack Propagation Considering the Redistribution of Residual Stress due to Overload

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Abstract

For the assessment of the retardation of fatigue crack propagation behavior due to overload, new FE analysis algorithms considering compressive residual stress redistribution near crack tip was proposed in this paper. The size of plastic zone near crack tip was obtained by elasto-plastic analysis and it was compared with Irwin's equation. The amount of residual stress redistribution was assessed by subsequent elasto-plastic analysis, and the difference of residual stress distributions between constant amplitude load and overload was obtained. In the analysis of fatigue crack propagation, the applied SIF range was evaluated by ASTM E647, and the effect of residual stresses on crack propagation was considered using the effective SIF concept. The test results of crack propagations were compared with the predicted data obtained by the analysis.
Keywords: overload, residual stress, elasto-plastic analysis, redistribution of residual stress, retardation of fatigue crack propagation, effective SIF

1 Introduction

Because of ship and ocean structure becoming huge, light and speedy, load effect in stress concentration region such as welding region is getting bigger. For applying one of fatigue design techniques, Damage-Tolerance Design, Crack growth length generated on structure must be predicting and the crack must be evaluating for influence on ship structure during design life of ship. Ship and ocean structure also go through fluctuation load of various conditions except on constant amplitude load. Therefore, fatigue crack growth for fluctuation load need to evaluate.

For assessment of fatigue crack growth by fluctuation, many research has been performed as follow. Elber(1971) defined crack closing phenomenon by compressive residual stress in face of fatigue crack, and applied to crack growth retardation analysis by overload with concept of effective stress intensity factor. Wheeler(1972) persisted that plastic zone grow big in crack face by overload, and suggested crack growth retardation model for plastic zone size by constant amplitude load and overload. Kim(2003) measured plastic zone size of crack face by ESPI(Electronic Speckle Interferometry) system, and suggested crack growth retardation model related crack growth length and plastic zone size. But these researches have limitations that plastic zone must be confirmed in crack face and the coefficient of suggested crack growth retardation model must be decided by experiment.

Song(2004) and Jang et al.(2002) performed analytical research for fatigue crack growth in constant amplitude load considering residual stress redistribution. They also developed redistribution simulation techniques of residual stress field for fatigue crack growth and verified analytical technique of fatigue crack growth in tensile residual stress zone and compressive residual stress zone considering residual stress redistribution for special quality of residual stress relaxation and crack growth by external load through experiment. But these researches do not consider plastic zone in crack face by overload and constant amplitude load, because fatigue crack movement was analyzed in residual stress field only by local heat like welding.

So, we performed two cases of experiment with using CT (Compact Tension) specimen of ASTM E647. 1^{st} case is fatigue crack growth experiment for just constant amplitude loading. 2^{nd} case is fatigue crack growth experiment for after overloading, and constant amplitude loading. And then, we compared fatigue crack growth rate for 2 cases and confirmed retardation of fatigue crack growth by overload. Also, we calculated compressive residual stress in crack face by constant amplitude load and overload through finite element analysis. And we performed residual stress redistribution simulation for fatigue crack growth and fatigue crack growth retardation analysis, and compared with results of experiment.

2 Fatigue crack growth experiment

For comparison and assessment of fatigue crack growth retardation due to overload, fatigue crack growth experiment was performed with CT specimens of Figure1. Material of specimen is SS400 and has properties as shown in Table 1. Experiment equipment is INSTRON 5582, fatigue experiment equipment. Measuring equipment is digital optical microscope of 10^{-6}m unit. (Figure 2)

Experiment procedure is ASTM E647. In case of constant amplitude load condition, applying load is maximum load P_{max}=1800kg and definition of load ratio is to be indicated in R=0($R=P_{min}/P_{max}$). In case of overload condition, at first 2100kg loading and then constant amplitude loading of 1800kg.

Table 1: Material properties

Material	SS400
Yield stress	250 MPa
Tensile strength	435 MPa
Young's modulus	210 GPa
Elongation	38%

Figure 3 is result of experiment for fatigue crack growth. The result shows fatigue crack growth rate for crack length of each other loading condition. Fatigue crack growth rate is retarded in applying overload and then crack growth rate is retrieved in near crack length of 10mm.

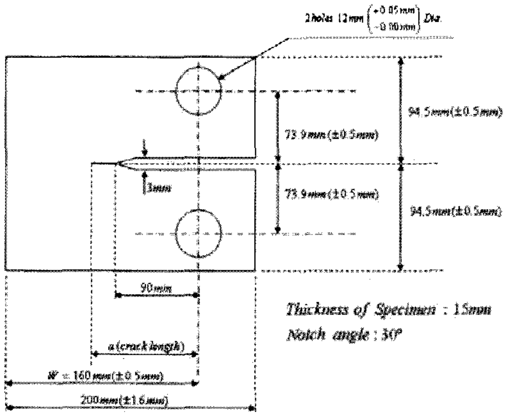

Figure 1: Dimensions of compact tension specimen

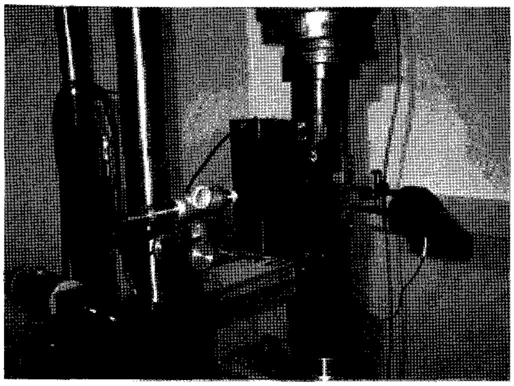

Figure 2: Fatigue crack propagation test setting

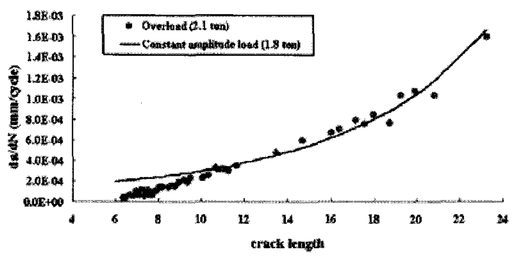

Figure 3: Result of fatigue crack propagation test

3 Analysis for plastic zone size & residual stress redistribution.

Plastic zone and compressive residual stress for constant amplitude load and overload in crack face was evaluated by finite element analysis. Analysis model is symmetric model like Figure 4 and element is two dimensional element of 8 nodes.

Irwin introduced concept of stress intensity factor K_I and described elastic stress field near crack face. And then Irwin suggested radius of plastic zone like equation (1) and Figure 5 in plane strain condition.

$$r_Y = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_Y}\right)^2 \quad (1)$$

Where, r_Y is radius of plastic zone, K_I is stress intensity factor, σ_Y is yield stress.

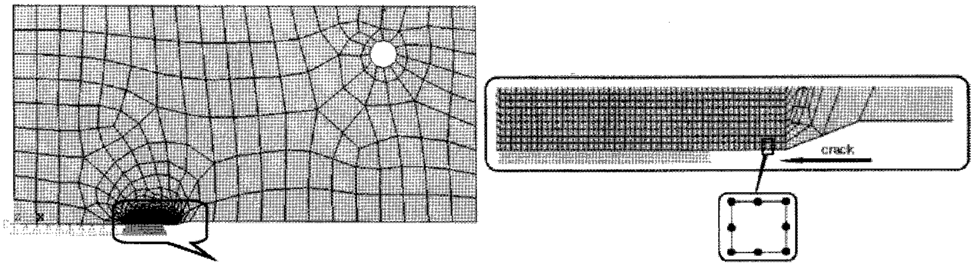

Figure 4: Finite element analysis model

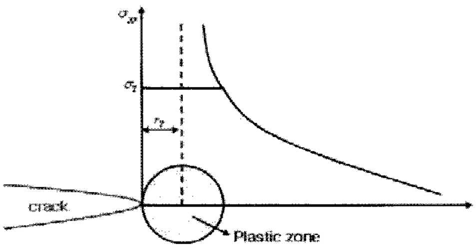

Figure 5: Plastic zone of Irwin

Figure 6 is plastic zone size for constant amplitude load(1.8ton) in crack face. Figure7 is plastic zone size for overload(2.1ton) in crack face. Table 2 is comparison between finite element analysis and Irwin's equation by constant amplitude load and overload in crack face.

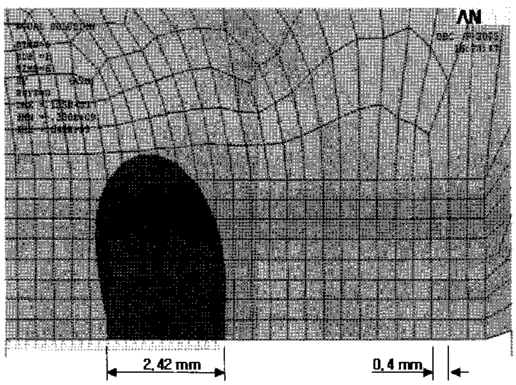

Figure 6: Plastic zone size by FE analysis(Constant Amplitude Load = 1.8 ton)

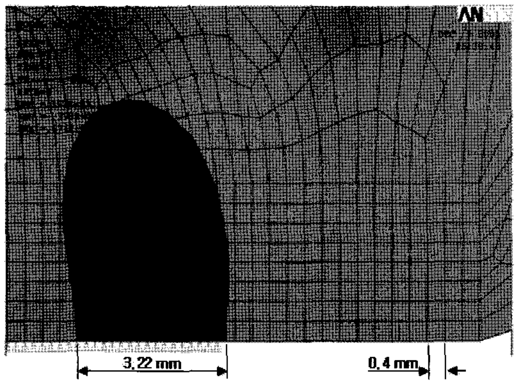

Figure 7: Plastic zone size by FE analysis(Overload = 2.1 ton)

Table 2: Comparison of plastic zone size

	Constant Amplitude load	Overload
Irwin	2.3 mm	3.1 mm
Analysis	2.4 mm	3.2 mm

Simulation analysis of residual stress redistribution for each load condition was performed in crack face. Figure 8 is result of residual stress redistribution in constant amplitude load condition. Figure 9 is result of residual stress redistribution in overload and then constant amplitude loading condition.

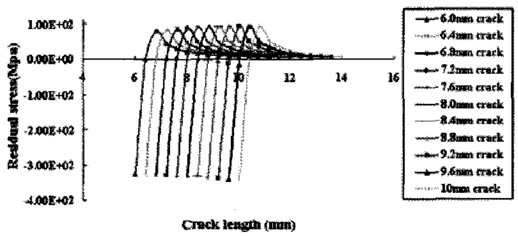

Figure 8: Residual stress redistribution due to crack propagation (Constant Amplitude Load = 1.8 ton)

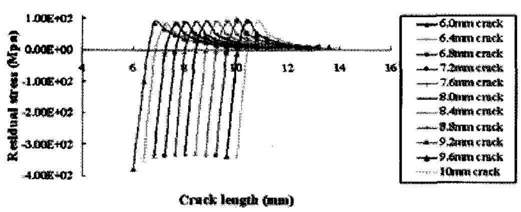

Figure 9: Residual stress redistribution due to crack propagation (overload = 2.1ton)

As remarked above results, compressive residual stresses for overload and constant amplitude load have a gap in about 6mm crack length. After 6mm crack, crack grows and gap of residual stress decreases. And gap of residual stress make no odds near 10mm crack length. Figure 10 is gap of compressive residual stress for constant amplitude load and overload in crack length of 6mm to 10mm.

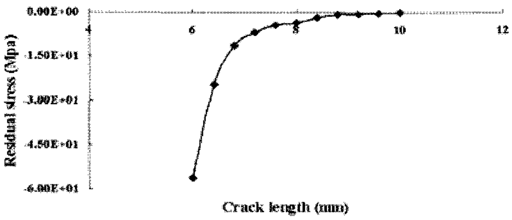

Figure 10: Difference of residual stress between constant amplitude load (CAL) and overload

4 Analysis of fatigue crack growth for considered residual stress redistribution

For stable growth of fatigue crack in Paris's rule, Analysis of fatigue crack growth is performed by stress intensity factor range, concept of *K*. Equation (2) is relation of fatigue crack growth rate *da/dN* and stress intensity factor ΔK for Paris's rule. C and m are crack growth parameters. They are computed by fatigue crack propagation experiment. In case of SS400, $C=3.561\times10^{-11}$, $m=4.321$.

Equation (3) is effective stress intensity factor K_{eff} for superposition of residual stress effect in residual stress field.

$$\frac{da}{dN} = C(\Delta K)^m \tag{2}$$

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^m \tag{3}$$

In compressive residual stress field of crack face by overload, external load induces crack close phenomenon. Therefore, effective stress intensity factor K_{eff} is computed by concept of Elber, " Just stresses of crack opening part contribute to crack propagation speed." Equation (4) is the definition by Elber.(Jang et al. 2002).

$$\Delta K_{eff} = \Delta K_{app} - \Delta K_{op} \tag{4}$$

Where, ΔK_{app} is stress intensity factor by external load and ΔK_{op} is stress intensity factor by crack opening load. Each other computation process for stress intensity factor is as follows.

First, K_{app} is calculated by stress intensity factor equation for CT specimen of ASTM E647.

Equation (5) is stress intensity factor of CT specimen.

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (5)$$

Where, $\alpha = a/W$, a is crack length, B is thickness of specimen, W is width of specimen.

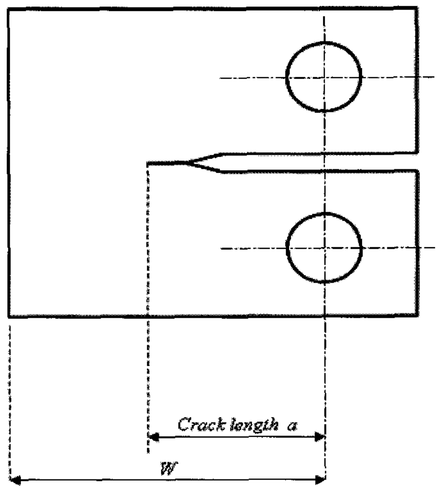

Figure 11: Notations for estimation of stress intensity factor

Second, K_{op} is calculated by crack opening load, P_{op}.

After residual stress analysis by initial external load and welding residual stress redistribution analysis by crack growth, difference between residual stress distribution by constant amplitude load and residual stress distribution by overload is crack closing zone on crack face. When this zone is superposed by external load effect and crack face is opened, minimum load is P_{op} and the P_{op} substituted in equation (5). And then K_{op} is calculated. Figure 12 is result for fatigue crack growth analysis considering residual stress redistribution and experiment.

According to comparison with experiment and analysis result, fatigue crack retardation speed by initial overload does almost correspond. Although there is difference for recovering value of fatigue crack growth rate between analysis value and experiment value, tendency of crack growth does correspond in near 10mm crack length.

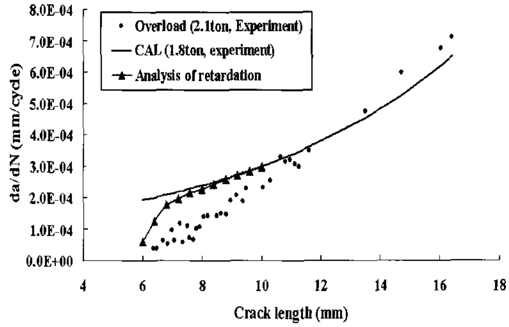

Figure 12: Comparison of crack propagation results (analysis vs. experiment)

5 Conclusion

Conclusion for fatigue crack growth analysis considering residual stress by overload is as follows.

1) To recognize the retardation of crack propagation due to overload, experiment for fatigue crack propagation is performed.

2) To verify the analysis method, plastic zone sizes are evaluated by finite element analysis and Irwin's equation. The size for finite element analysis is similar to that by Irwin's equation.

3) Analysis for residual stress redistribution is performed.

4) The analysis of crack propagation based on the concept of the effective stress intensity factor was performed. The analysis results have been compared with experimental ones and showed good agreement.

5) Residual stress redistribution for overload and constant amplitude load was realized. And we confirmed that a cause of crack growth retardation is big compressive residual stress in overload.

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