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Numerical simulation of fatigue crack propagation under variable amplitude loading with different frequency components

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Abstract

Fatigue crack propagation behaviour under variable amplitude loading with different frequency components is highlighted. Numerical simulation of the fatigue crack propagation based on an advanced fracture mechanics approach with the RPG (Re-tensile Plastic zone Generating) load criterion is is improved to extract the effective loading sequence for the fatigue crack growth.

The critical value of plastic work, which corresponds to the plastic hysteresis of stress versus strain relation consuming in the vicinity of a crack tip, is defined as the control parameter to extract the effective loading sequences for the crack propagation. Comparison of fatigue crack growth curves obtained from the numerical simulations with the measurements under the constant amplitude loadings superimposing small constant amplitude components with high frequency and the damping amplitude loadings superimposing small damping amplitude components with high frequency are performed. These comparisons conduct the validity of proposed treatment of extracting the effective loading sequences for the fatigue crack propagation from random loading sequences.

Keyword: Fatigue, RPG load, Numerical simulation of fatigue crack growth, Effective loading history for fatigue

1. INTRODUCTION

It is well known that ships vibrate for different reasons. Such vibrations categories into two main components; transient vibrations caused by wave impacts or slamming referred to as the whipping and resonance vibrations caused by oscillating loadings along the hull or locally referred to as the springing. The magnitude and consequence of the vibration depends on the ship geometries, speeds, heading to wave, encountered sea state and so on. Recently, the influence of such wave induced vibrations on the structural integrities cannot be ignored because of the huge dimensions which reduce the natural frequency of hull structures and increasing of the average voyage speed which excites the frequencies of loading to hull structures.

In this research, fatigue crack propagation behaviour under variable amplitude loading with different frequency components is highlighted, because the fatigue crack growth behaviour is strongly affected by the loading sequence. Numerical simulation of the fatigue crack propagation based on advanced fracture mechanics approach, which the RPG (Re-tensile Plastic zone Generating) load criterion proposed by Toyosada et al. [1] is applied as the fatigue crack propagation law, is improved to extract the effective loading sequence from applied random loading sequences for the fatigue crack growth.

The critical value of plastic work, which corresponds to the plastic hysteresis of stress versus strain curve consuming in the vicinity of a crack tip, is defined as the control parameter to extract the effective loading sequences. This control parameter is implemented into the numerical simulation method of the fatigue crack propagation considering the fatigue crack opening / closing behaviour with the RPG load criterion. Comparison of fatigue crack growth curves obtained from the numerical simulations with the measurements under the constant amplitude loadings superimposing small constant amplitude components with high frequency and the damping amplitude loadings superimposing small damping amplitude components with high frequency are performed.

2. OVERVIEW OF FATIGUE CRACK PROPAGATION TEST

Fatigue crack propagation tests under the constant amplitude loadings superimposing small constant amplitude components with high frequency and the damping amplitude loadings superimposing small damping amplitude components with high frequency were performed by the joint industries project organized by the Japan Ship Technology Research Association (JSTRA) [2]. Fatigue crack growth curves measured by this JIP are applied as reference data in this research. Overview of the experiments is introduced in this section briefly.

Specimen configurations and material used

Specimen configurations are shown in Fig.1. Centre cracked tensile (CCT) specimens were used. Steel for hull structures classified as KA36 in ClassNK is applied as a material of specimens. Chemical composition and mechanical properties are shown in Tables 1 and 2 respectively.

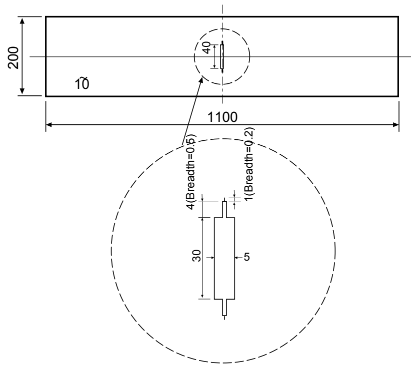


Fig.1 *Specimen configuration used*

Table 2. *Mechanical propaties*

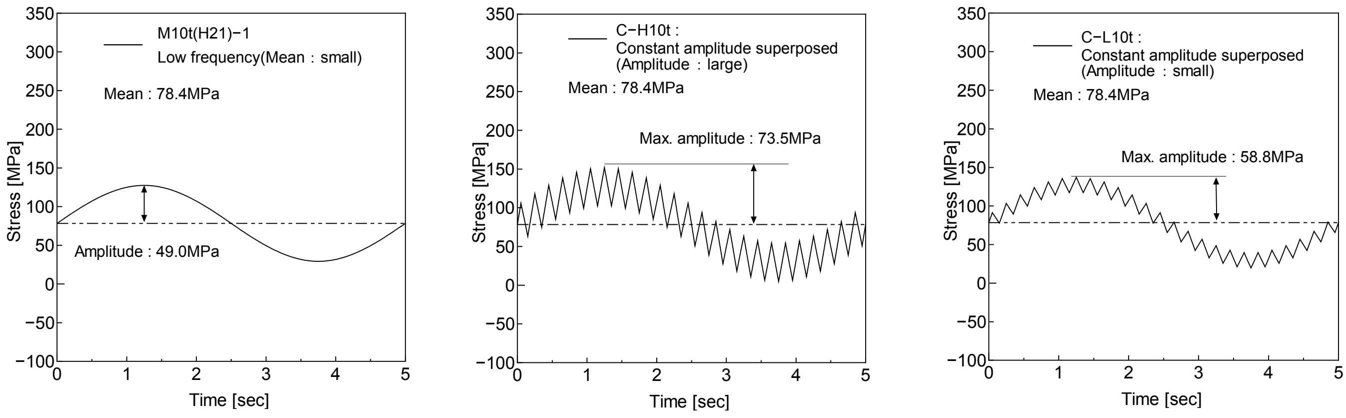
Yield stress [MPa]	Tensile strength [MPa]	Elongation [%]
457	577	20

Table 1. *Chemical composition*

		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Ceq
Material used		0.15	0.27	1.17	0.014	0.006	0.01	0.01	0.03	0.003	0	0	0.35
Standard	Max.	0.18	0.5	1.6	0.035	0.035	0.35	0.4	0.2	0.08	0.05	0.1	-
KA36	Min.	-	-	0.9	-	-	-	-	-	-	0.02	0.05	-

Applied loading conditions

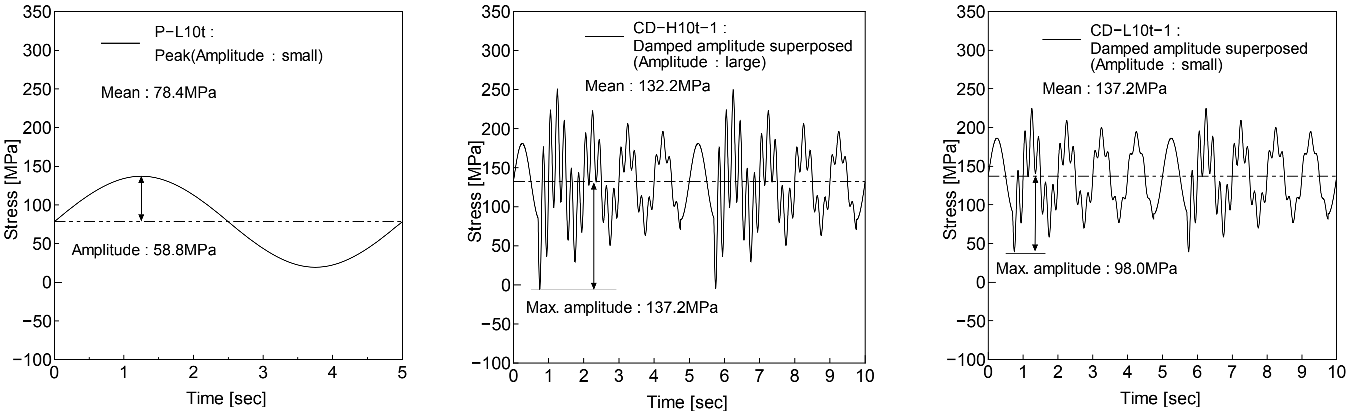
Applied loading patterns are shown in Fig.2.



(a)M10t(H21)_1:
Low frequency only
(Mean: small)

(b) C-H10t:
Constant amplitude superimposed
(Amplitude: large)

(c)C_L10t:
Constant amplitude superimposed
(Amplitude: small)



(d)P_L10t:
Low frequency only
(Envelope curve of C_L10t)

(e)CD_H10t_1:
Damped amplitude superimposed
(Amplitude: large)

(f)CD_L10t_1:
Damped amplitude superimposed
(Amplitude: small)

***Fig.2** Applied loading sequences*

Fatigue test resuls

Measured fatigue crack growth curves ara shown in Fig.3. As shown in Fig.3, the following trends listed below are confirmed.

1. Fatigue crack growth behaviour of Specimens P_L10t and C_L10t are almost same.
2. Fatigue crack growth behaviour of Specimen C_H10t is faster than Specimen C_L10t.
3. Fatigue crack growth behaviour of Specimen CD_H10t_1 is faster than Specimen CD_L10t_1.

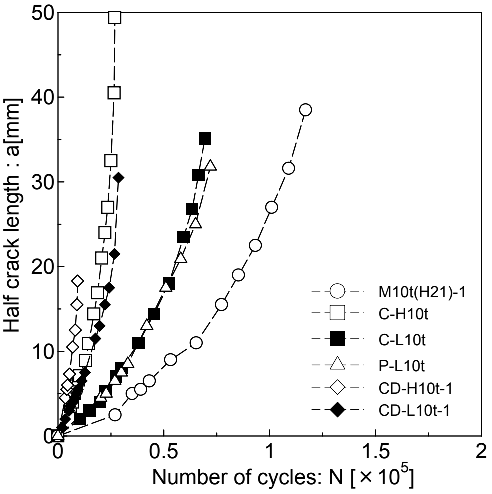


***Fig.3** Measured fatigue crack growth curves under various loading conditons*

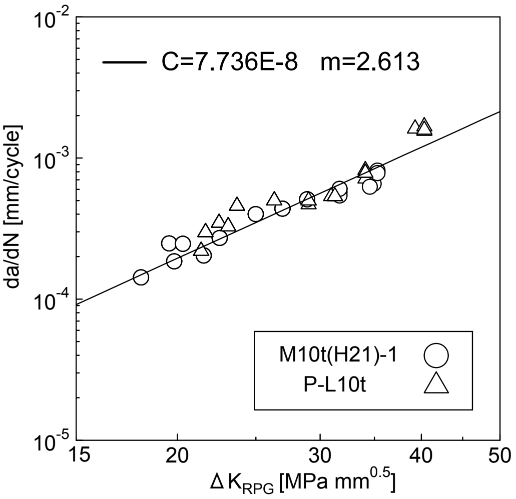


***Fig.4** Relationship between the crack propagation rate and the effective stress intensity factor range based on the RPG load*

Fatigue crack growth simulation is perfomed based on the the Paris' law type fatigue crack propagation law shown in Equation (1)

$$\frac{da}{dN} = C\left(\Delta K_{RPG}\right)^{m} , \qquad (1)$$

where a is the crack length, N is the loading cycles, ΔK_{RPG} is the effective stress intensity factor range based on the RPG load criterion, C and m is material constants respectively.

In order to estimate material constants C and m in Equation (1), the RPG load must be measured during the fatigue crack propagation test. However, the RPG loads had not measured during the experiments. Material constants C and m is identified by the approximative treatment mentioned as follows.

Relationship between the crack length and the RPG load is obtaind from numerical simulation results of the fatigue crack growth. This relationship is obtained from constant loading amplitude test shown in Fig.2 (a) and (d), because we have no knowledge of the RPG load behaviour under superimposed loading sequence like Fig.2 (b), (c), (e) and (f) until now. Numerical simulation code applied in this research is esatblished according to the algorithm proposed by Toyosada et al.[1]. ΔK_{RPG} as a function of crack length is obtained by applying estimated RPG load as a function of crack length. Fig. 4 is the estimated relation between the ΔK_{RPG} and the crack propagation rate da/dN . Material constants C and m are obtained from the slope and the intercept of Fig.4. Obtained values are shown in Fig.4.

3. EXTRACTION OF THE EFFECTIVE LOADING SEQUENCE FOR FATIGUE CRACK GROWTH

We focused on the alternating plastic region, which corresponds to the overlapped region of tensile and compressive plastic zone during one cyclic loading, because it is considered that the plastic hysteresis consumig near a crack tip provides the fatigue crack driving force. Then, we consider that it is necessary for the fatigue crack propagation to provide a certain amount of plastic work to generate the crack driving force during one loading cycle and the small loading amplitude which cannot provide sufficient crack driving force should be ignored for the numerical simulation of fatigue crack propagation. The plastic work consuming in reversed tensile and compressive plastic zone is represented by Equation (2)

$$\xi = \int_{CL}^{PZ} \sigma_Y \varepsilon_p \left(x \right) dx \ , \tag{2}$$

where σ_Y is the yield strength of material, ε_p is the plastic strain near a crack tip, other characters is illustrated in Fig.5.

Physical crack tip location is changing during the cyclic loading because of the fatigue crack opening/closing phenomenon. Schematic illustration of this phenomenon is introduced in Fig.6. The value of ξ must exceed a certain critical value in both unloading and reloading process in one cycle for the fatigue crack growth. The loading cycle, which the value of ξ is less than the critical value ξ_{limit} , should be ignored to extract the effective loading sequences for the fatigue crack propagation. This concept of extracting the effective loading cycle for the fatigue crack propagation is introduced in Fig.7.

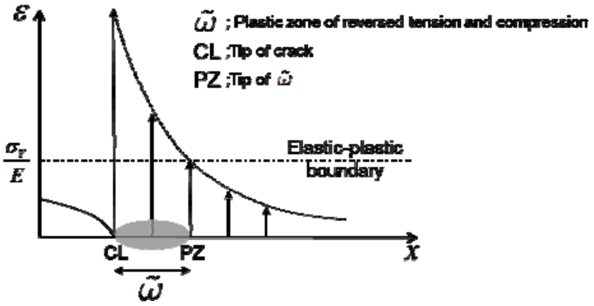


Fig.5 *Schematics illustration of the alternating plastic region*

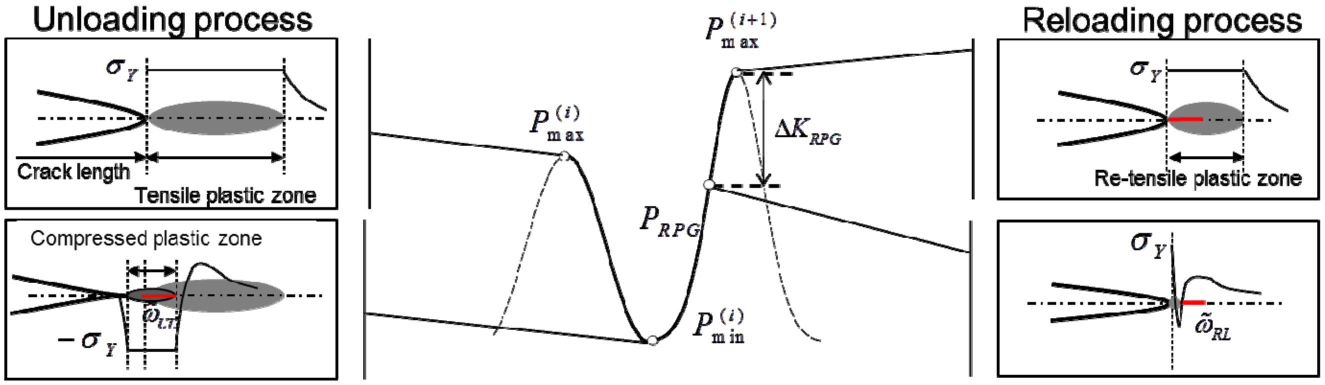


Fig.6 *Schematic illustration of the plastic zone formation during the cyclic loading*

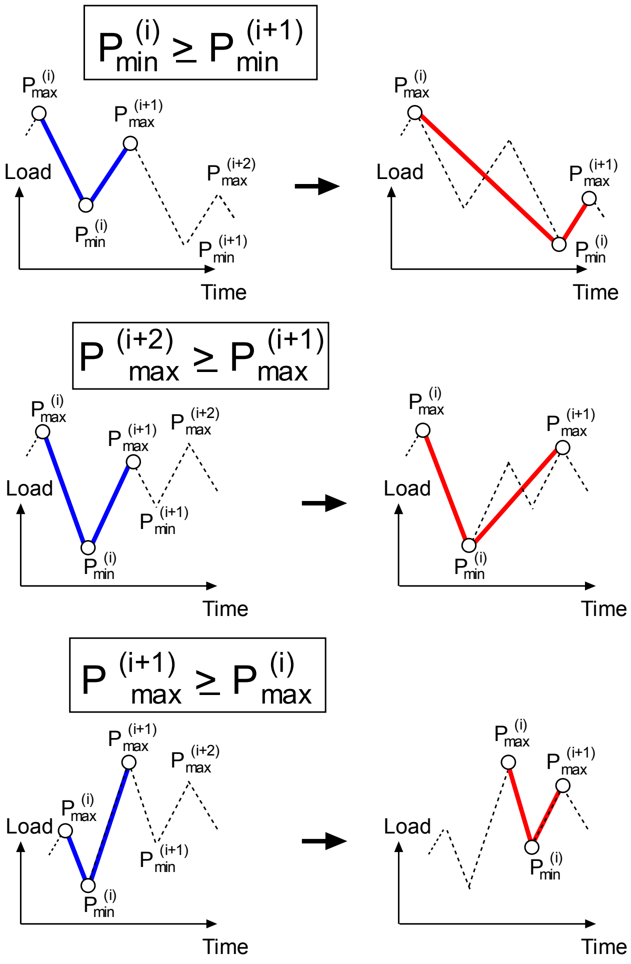
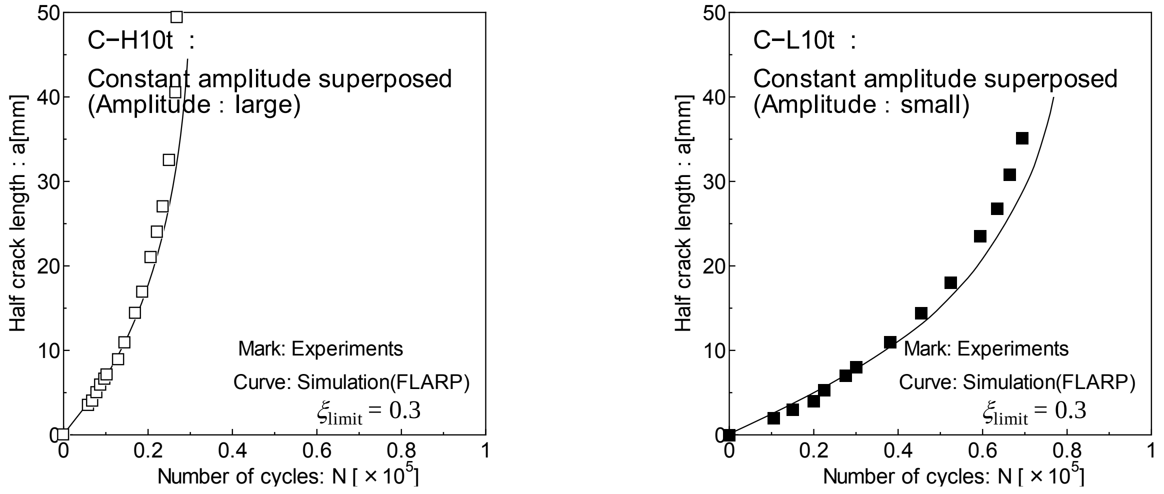


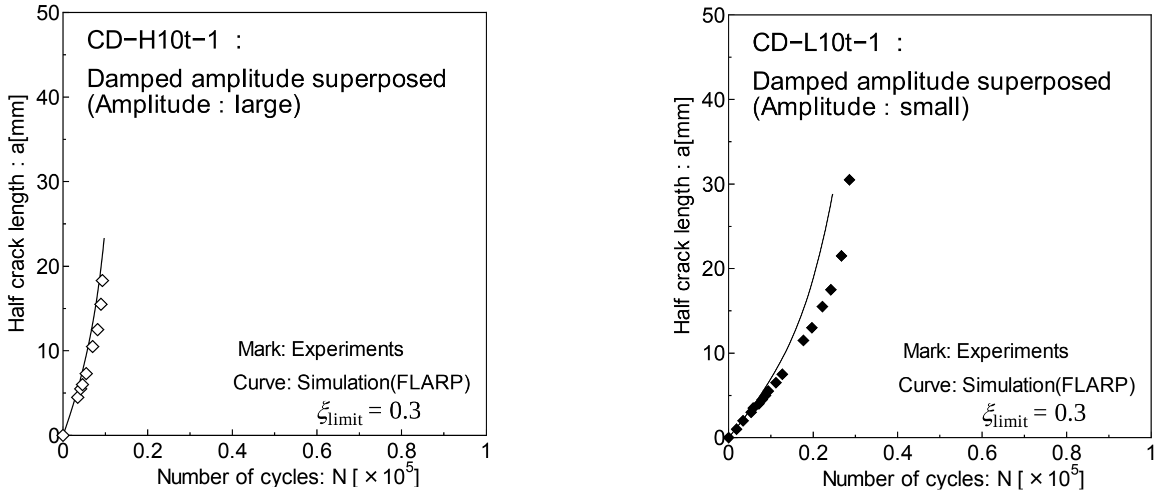
Fig.7 *Extraction procedure of the effective loading sequence during the random loading.*

Comarison of the fatigue crack growth curves under variable loading sequences obtained by measurements with numerical simulation results are performed. Critical value of the plastic work ξ_{limit} defined by Equation (2) set to 0.3 [MPa.mm] as a result of trial and error to obtain good estimation result of numerical simulations. These results are shown in Fig.8. Marks and curves in these figures mean the measurements and estimated by the numerical simulation, respectively.



(a) C-H10t:
Constant amplitude superimposed
(Amplitude: large)

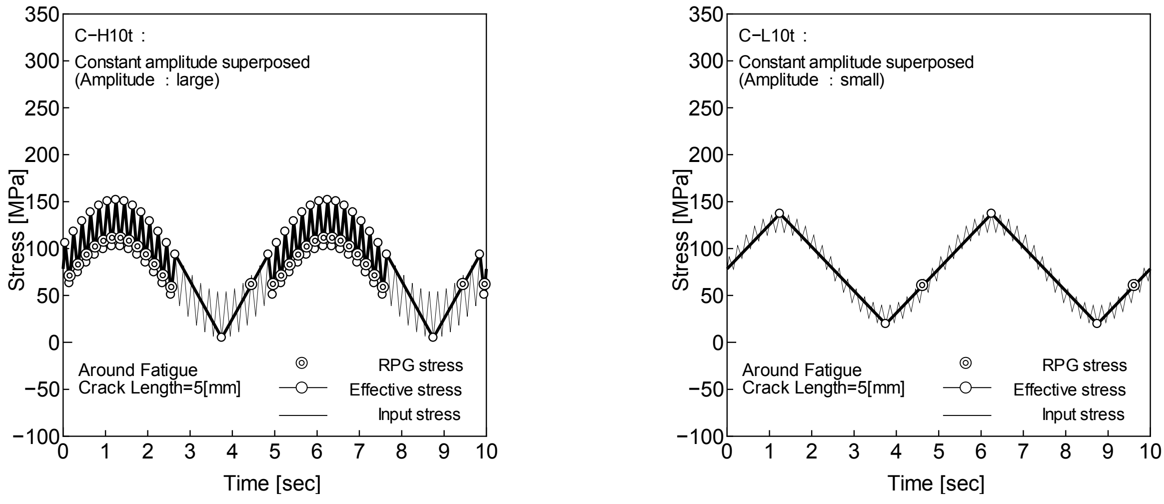
(b) C-L10t:
Constant amplitude superimposed
(Amplitude: small)



(c) CD-H10t_1:
Damped amplitude superimposed
(Amplitude: large)

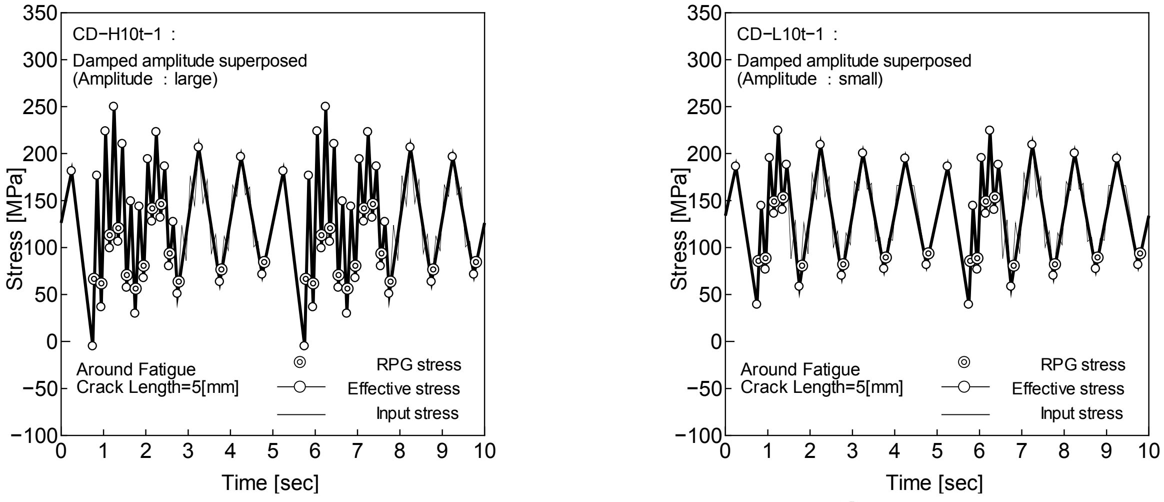
(d) CD-H10t_1:
Damped amplitude superimposed
(Amplitude: small)

Fig.8 *Comparison of measured crack growth curves with estimated ones under variable loading sequences*



(a) C-H10t

(b) C-L10t



(c) CD-H10t-1

(d) CD-L10t-1

Fig.9 *Examples of the extracted effective loading sequences under variable loadings*

The validity of proposed extraction procedure of the effective loading sequences can be confirmed by referring Fig.8. Fig.9 shows examples of the extracted effective loading sequences for each tests when the crack length reaches about 5mm. It makes clear from Fig.9 that the small applied loading amplitude, which cannot generate a critical value of the plastic work during one cycle, is ignored. For example, it is confirmed from Fig.9 that the extacted effective loading cycles of specimen C-L10t is equal to the applied loading cycle of specimen P-L10t. Meanwhile, measured fatigue crack growth curves of specimens C-L10t and P-L10t shown in Fig.3 is almost same. This observed result supports the validity of extraction algorhitm of the effective loading sequence proposed in this research.

On the other hand, it is expected that the fatigue crack growth under whipping or slamming vibration can be estimated if the envelope of working loading sequence is applied for the numerical simulation with the extracting alogrithm of the effective loading cycle, see Figs.8 (c), (d) and Figs.9 (c) and (d).

4. CONCLUSIONS

The extraction alogorithm of the effective loading sequences for the fatigue crack propagation under variable amplitude loading is proposed in this research. Proposed algorithm is implemented into the numerical simulation of fatigue crack propagation based on the RPG load criterion. The critical value of plastic work is defined as the control parameter to extract the effective loading sequences. Comparison of fatigue crack growth curves obtained from the numerical simulations with the measurements under the constant amplitude loadings superimposing small constant amplitude components with high frequency and the damping amplitude loadings superimposing small damping amplitude components with high frequency are performed. As a result, the validity of proposed alogorithm is confrimed.

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