**Simulation-based fatigue crack management of ship structural details
applied to longitudinal and transverse connections**

by

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Abstract

It is of continuing importance for ship structural design to establish a system to compute the growth behavior of fatigue cracks propagating in structural details. In the present paper, a simulation program is developed for multiple fatigue cracks propagating in a three-dimensional stiffened panel structure, where it can predict fatigue crack lives and paths by taking into account of the interaction of multiple cracks, load shedding during crack propagation and welding residual stress. Various fatigue crack propagations in longitudinal stiffeners of ship structures are investigated by both the present simulation method and experiments. From these results, it is found that the crack propagation may considerably change, depending on the loading conditions, structural details and residual stress distributions. This means that one could possibly manage to avoid fatal damage of the skin-plate by properly designing the structural details. Furthermore, these results may imply a possibility to realize a rational fatigue crack management if one can estimate the fatigue crack-propagation behavior during the ship lifecycle. The present simulation program may offer a useful numerical tool for this purpose.

Key Words: *Fatigue crack, Ship structures, Simulation, Fatigue crack management, FEM, Fatigue test*

Introduction

There exists an urgent need to establish a system to simulate fatigue crack propagation in ship structures during their lifecycles. In a typical double hull tanker, fatigue cracks may initiate at the stress concentrating points such as the connection between a face-plate of a longitudinal stiffener and a web-stiffener attached to a transverse girder (see Fig.1). These cracks may propagate in web-plate of the longitudinal stiffeners and penetrate into the inner or outer skin-plate, whose failures may lead to the loss of oil and/or water tightness of critical compartment boundaries. In order for cracks to be detected by inspections so as to ensure the functional requirement of structures, we need accurate information regarding the fatigue crack propagation.

Fatigue crack propagation in the longitudinal stiffener can be categorized into the following three stages:

1. a surface crack propagating at a weld toe (Fig.2 (a));
2. a "through-the-thickness" crack propagating in the face-plate and the web-plate, which has three crack tips (Fig.2 (b));
3. a "through-the-thickness" crack propagating in the web-plate (Fig.2 (c)).

In order to predict the fatigue crack growth, practical methods are needed to estimate the stress intensity factors considering the several influencing factors [1]. In the first stage, although the surface crack is usually approximated by a semi-elliptical surface crack and can be analyzed by a finite element model using three-dimensional solid elements, it is a quite time-consuming and laborious work, because a manual procedure is, at present, the only way to make the model. Alternatively, several simple methods could be used for surface crack problems [2,3]. After the surface crack penetrates

through the thickness of the face-plate, it becomes a "through-the-thickness" crack, which can be modeled by shell finite elements. This is the second stage, where the crack has three crack tips, two in the face-plate and one in the web-plate, propagating simultaneously with the effect of multiple crack interactions. Having the face-plate been broken off, the crack has only one crack tip in the web-plate, where its path begins to play an important role, because it may govern whether or not the crack leads to a serious hazard to a ship structure [4,5]. If the crack propagates straight to the normally intersecting skin-plate, it may result in its unacceptable penetration into the skin-plate, while, in some cases, it may propagate in a curved fashion so as to avoid the penetration into the skin-plate. The crack growth behavior may be changed, depending on the stress biaxiality and/or the structural interaction effects with the adjacent members. Besides the crack growth may be retarded due to the compressive residual stress distributed in the middle part of the web-plate and the load shedding effect.

Usually, fatigue cracks in ship structures are detected by surveyor's visual inspection. Although fatigue cracks are preferred to be detected at an earlier stage, small cracks such as those illustrated in Fig.2 (a) may sometimes be overlooked because of the poor accessibility and visibility in ship structures. In contrast, the long fatigue cracks such as those in Figs.2 (b) and (c) may be easily detected by visual inspection, but their remaining lives generally make up just a few percent of the total lives. If one can utilize the several favorable effects to retard the propagation rate and also to avoid hazardous crack propagation mentioned above, a rational fatigue crack management as illustrated in Fig.3 could be applied, where the fatigue crack propagation behavior should be predicted accurately so as to manage the periodical inspections of fatigue cracks of

visible size at least once or twice during the service life [6,7].

In our previous studies, Sumi and his associates have developed a simulation program, "CP-System," for fatigue crack propagating in a welded plate structure, which can predict fatigue crack lives and paths [3-8]. In the simulation program, "through-the-thickness" crack propagation is formulated as a two-dimensional in-plane problem, and the crack propagation behavior is simulated by step-by-step finite element analyses. In order to simulate the realistic fatigue crack propagation in large-scale structures, the super-element technique is utilized, and the influencing factors such as geometry of structural details, load shedding during crack propagation, and welding residual stress are taken into consideration. In the previous works [6,7], it has been confirmed that the simulation program can reasonably estimate the fatigue crack propagation lives in welded plate structures, however, several issues still exist to be solved;

- the problem of multiple cracks simultaneously propagating in a three-dimensional stiffened panel structure (i.e. the crack propagation in Fig.2 (b)),
- reduction of computation time.

In the present paper, the program is improved regarding the above two issues. It is then applied to the fatigue crack propagation at the connection of longitudinal stiffeners and transverse girders. In the numerical simulations, various aspects are considered such as the loading conditions, the sizes of a structure to be modeled, the structural details of longitudinal and transverse connections, and the welding residual stress. Finally, the numerical results are compared with full-scale fatigue tests.

An analysis of multiple cracks simultaneously propagating in a three-dimensional stiffened panel structure

A definition of a boundary value problem of a three-dimensional stiffened panel structure with multiple growing cracks

Let us consider a thin plate structure as shown in Fig.4, which consists of thin plates containing multiple cracks. The structure is divided into M subdomains, Ω_l ($l=1,\dots,M$), in which there exists no more than one crack tip. An orthogonal coordinate system is defined in each subdomain. Body force, f_i^l , is prescribed in the subdomain Ω_l . Surface traction, t_i^l , is prescribed on the outer boundary, S_l^l , and on the crack surfaces, $S_C^{l\pm}$. Surface displacement, v_i^l , is prescribed on the outer boundary S_u^l . The boundary of the subdomain Ω_l is denoted by Γ_l and the interface between the subdomain Ω_l and its neighboring subdomain Ω_n is denoted by $\Gamma_l \cap \Gamma_n$. The external unit normal vector on the boundary surface of the subdomain Ω_l is denoted by n_j^l ($j=1,2$). The quantities, β_{km}^{lg} and β_{km}^{ng} ($k,m=1,2,3$), are respectively the direction cosines of the coordinate system in the subdomains Ω_l and Ω_n with respect to the global coordinate system. The corresponding boundary-value problem prior to the crack growth is defined by

$$\begin{aligned}
 \sigma_{ij,j}^l + f_i^l &= 0 && \text{in } \sum_l \Omega_l, \\
 \sigma_{ij}^l n_j^l &= t_i^l && \text{on } \sum_l S_l^l \text{ and } \sum_l S_C^{l\pm}, \\
 u_i^l &= v_i^l && \text{on } \sum_l S_u^l, \\
 \beta_{km}^{lg} u_m^l - \beta_{km}^{ng} u_m^n &= 0 && \text{on } \sum_n (\Gamma_l \cap \Gamma_n) \text{ for } l=1,\dots,M, \\
 \beta_{ki}^{lg} \sigma_{ij}^l n_j^l + \sum_n \beta_{ki}^{ng} \sigma_{ij}^n n_j^n &= 0 && \text{on } \sum_n (\Gamma_l \cap \Gamma_n) \text{ for } l=1,\dots,M, \\
 &&& (i,j=1,2,k,m=1,2,3)
 \end{aligned} \tag{1}$$

where σ_{ij}^l and u_i^l are the stress tensor and the displacement vector in the subdomain Ω_l , respectively. The forth and fifth conditions of Eq.(1) are the compatibility condition for displacement and the equilibrium condition for stress, along the interfaces of subdomains, respectively. In the developed finite element program, the forth and fifth conditions of Eq.(1) are satisfied by connecting each neighboring subdomain using rigid bar elements with zero-length. With regard to the finite element modeling, the membrane element is employed because the effect of the local out-of-plane bending component is sufficiently small in the problem treated in this study.

Crack path prediction

As shown in Fig.5, an orthogonal coordinate system is defined in such a way that its origin is located at the l -th pre-existing crack tip and the x_1^{IC} -axis directs along with the tangent at the pre-existing crack tip. Each crack is assumed to propagate in a slightly curved fashion. The deviation of the crack path from the x_1^{IC} -axis is approximated by

$$\lambda_l(h_l) = \alpha^l h_l + \beta^l (h_l)^{3/2} + \gamma^l (h_l)^2 \quad (2)$$

where α^l , β^l and γ^l are the shape parameters of the crack profile, and h_l is the projected crack length on the x_1^{IC} -axis [9]. In order to solve the crack growth problem along the path represented by Eq.(2), we shall define the following boundary value problem ;

$$\begin{aligned}
\sigma_{ij,j}^l + f_i^l &= 0 && \text{in } \sum_l \Omega_l, \\
\sigma_{ij}^l n_j^l &= 0 && \text{on } \sum_l S_t^l \text{ and } \sum_l S_C^{l\pm}, \\
\sigma_{ij}^l n_j^l &= T_i^l && \text{on } \sum_l S_b^{l\pm} \\
u_i^l &= 0 && \text{on } \sum_l S_u^l, \\
\beta_{km}^{lg} u_m^l - \beta_{km}^{ng} u_m^n &= 0 && \text{on } \sum_n (\Gamma_l \cap \Gamma_n) \text{ for } l = 1, \dots, M, \\
\beta_{ki}^{lg} \sigma_{ij}^l n_j^l + \sum_n \beta_{ki}^{ng} \sigma_{ij}^n n_j^n &= 0 && \text{on } \sum_n (\Gamma_l \cap \Gamma_n) \text{ for } l = 1, \dots, M, \\
&&& (i, j = 1, 2, k, m = 1, 2, 3)
\end{aligned} \tag{3}$$

where T_i^l is the distributed force-couple applied along the predicted crack path $S_b^{l\pm}$ so as to cancel out the internal forces due to the solution of Eq.(1). Adding the solutions of Eqs.(1) and (3), one can obtain the solution of the extended crack, where the stress intensity factors at the extended crack tips are calculated from Eq.(3) because the solution of Eq.(1) does not contribute the stress singularity there. By applying the local symmetry criterion [10], the shape parameters are determined as

$$\begin{aligned}
\alpha^l &= -2 \frac{k_{II}^l}{k_I^l}, \\
\beta^l &= \frac{8}{3} \sqrt{\frac{2}{\pi}} \frac{T^l}{k_I^l} \alpha^l, \\
\gamma^l &= \left\{ \frac{3\sqrt{2\pi}}{4} \beta^l T^l - \frac{1}{2} b_{II}^l + \frac{1}{4} \alpha^l b_I^l - \sum_{n=1}^M \left[(k_I^n - \alpha^n k_{II}^n) \bar{k}_{21}^{ln} \right. \right. \\
&\quad \left. \left. + (k_{II}^n - \alpha^n k_I^n) \bar{k}_{22}^{ln} - \frac{1}{2} \alpha^n (k_I^n \bar{k}_{11}^{ln} + k_{II}^n \bar{k}_{12}^{ln}) \right] \frac{h_n}{h_l} \right\} / k_I^l.
\end{aligned} \tag{4}$$

where k_I^l, k_{II}^l are the stress intensity factors, and T^l, b_I^l, b_{II}^l are the T-stress and the higher order stress field coefficients, which are calculated by solving the boundary-value

problem (1). The coefficients, $\bar{k}_{ij}^{ln}$ ($i,j=1,2$), represent the interaction effect of l -th and n -th crack propagation [8].

Crack growth calculation and determination of extensional lengths of multiple cracks

For crack growth calculation, we shall use the following crack growth law [11];

$$da / dN = C \{ (U \cdot \Delta K)^m - (\Delta K_{\text{eff}})_{\text{th}}^m \}, \quad (5)$$

where ΔK is the stress intensity factor range, C , m and $(\Delta K_{\text{eff}})_{\text{th}}$ are the material properties and U is the effective stress range ratio, which is given by

$$U = \begin{cases} 1/(1.5 - R) & (-\infty \leq R \leq 0.5) \\ 1 & (0.5 \leq R \leq 1), \end{cases} \quad (6)$$

where R is the stress ratio. In order to simulate simultaneous propagation of multiple fatigue cracks in a structure, extensional crack length in each subdomain, h_l ($l=1, \dots, M$), should be determined based on Eq.(5). If the incremental number of cycles is assumed as ΔN , the extensional length of the l -th crack, h_l , is determined as

$$h_l = \Delta N \cdot C^l \{ (U^l \cdot \Delta K^l)^m - (\Delta K_{\text{eff}}^l)_{\text{th}}^m \}, \quad (7)$$

where, ΔK^l , C^l , m^l and $(\Delta K_{\text{eff}})_{\text{th}}^l$ and U^l are the parameters corresponding to the l -th crack.

Simulation system for fatigue crack propagation

Procedure of simulation

By introducing the aforementioned method, the simulation program was improved in order to deal with multiple cracks propagating in a three-dimensional structure. The main procedure of the simulation is summarized as follows (see Fig.6);

1. finite element mesh is automatically generated by an advanced paving method [12] in each crack-propagating domain, while a super-element is generated to model the surrounding structure,
2. stress field parameters near an each crack tip are calculated by the method of superposition of analytical and finite element solutions [13],
3. extensional lengths of cracks are calculated by Eq.(7),
4. all cracks are extended along the crack paths calculated by Eqs.(2) and (4), and
5. go back to step1 to continue the simulation.

An example of analysis

As an example, crack propagation in a three-dimensional angled panel structure subjected to uniaxial tension was calculated. This structure has two crack tips simultaneously propagating in the different plates (see Fig.7). Figure 8 shows an example of the finite element mesh in the crack-propagating domains while the surrounding structure is treated as a super-element, which is connected to the boundary of these crack-propagating domains.

The calculated stress intensity ranges are plotted against the corresponding crack length as shown in Fig.9, where the corresponding solutions obtained by the general purpose

program 'MSC.Nastran' are also plotted. The latter is modeled by the two-dimensional crack tip elements, and the shell elements. It shows that the stress intensity ranges obtained by the developed program agree reasonably well with the results by 'MSC.Nastran'.

The solution time primarily consists of the finite element analysis, more precisely the Gaussian elimination process, because the bandwidth of the stiffness matrix becomes considerably large in case of connecting super-elements to the interface of the crack-propagating domain. The computation speed can be improved by applying the skyline method [14] to solve the simultaneous linear equations instead of the band matrix method. The total computation time of the example problem is plotted in Fig.10. This computation was carried out in a Dell Workstation (Precision 530; Intel (R) Xeon 2.7GHz). It shows that the total computation time of the skyline method is less than 10 percent of that of the band matrix method. The detailed computation time at 20th step of the both methods is compared in Fig.11, where the finite element model of the crack propagating domains has 4,298 degrees of freedom and bandwidth 4,087. It is evident that the reduction of the total computation time results from the reduction of solution time for simultaneous linear equations.

A simulation of fatigue crack propagation in a longitudinal stiffener of a ship structure

In order to examine the fatigue crack propagation behavior at the intersection between longitudinal stiffeners and a transverse girder, numerical simulations of fatigue crack propagation were carried out by using the developed simulation program. In the present

study, the characteristics of fatigue crack propagation are discussed focusing attention on the effects of the loading conditions, the structural details and the residual stress distribution. The effects of the different boundary conditions of the problem are also discussed with regard to load *versus* displacement boundary condition, and the extent of a structural model.

On the effects of the loading conditions and the structural details

An analysis model is illustrated in Fig.12, where it extends to 2 transverse spacing and 1.5 longitudinal spacing. In order to model the periodicity of the longitudinal stiffeners, symmetric conditions are prescribed along the both sides of the analysis model. The longitudinal stiffeners are connected to the transverse girder by a flat bar stiffener or a variety of brackets as illustrated in Fig.13 (a)-(d). We assumed either the water pressure loading condition or the axial loading condition separately as shown in Fig.14. In the case of the water pressure loading, uniform lateral pressure loading of constant amplitude is applied on the skin-plate, and the lateral displacement is restrained at the positions of the transverse girder. The longitudinal displacement is also restricted at the both ends. In the case of the axial loading condition, an axial force of constant amplitude is applied at the both ends of the model, and the lateral displacement is restrained at the positions of the transverse girder. The material properties of the analysis model are summarized in Table 1, where we used the parameters for the crack growth law listed in Ref.[15].

Figure 15 shows the finite element models. In the present simulation, it is assumed that the crack initiation point is fixed at the intersection of the face-plate and the end of the

web-stiffener. The initial crack is configured such that it has 40mm width in the face-plate and 10mm depth in the web plate, however, it should be noted that the plate thickness of the face-plate cannot precisely be taken into consideration within the framework of analysis by using shell elements. In the beginning of the simulation, crack-propagation domains are defined in the both parts of the face-plate and the web-plate. Having a crack reached the edge of the face-plate, the face-plate is treated as completely broken off, and the simulation continues by re-defining a single crack (see Fig.15).

The simulated crack paths in the web-plate are illustrated in Fig.16, where the origins of coordinates are set at the intersections of the face-plate and the end of the web-stiffener. Under the water pressure loading, the cracks initiated from the end of web-stiffeners propagate toward the transverses girders. In the case of the structural details (b), (c) and (d), the cracks gradually curve and tend to avoid the penetration into the skin-plate of a ship structure. On the other hand, in the case of the structural detail (a), the crack tends to propagate towards the skin-plate, which may result in the failure of a compartment boundary. Under the axial loading, the cracks tend to propagate towards the skin-plate regardless of the structural details. As illustrated in Fig. 17, the cracks in the face-plate propagate along the same path regardless of the structural details and the loading conditions, and these crack paths are perpendicular to the free edges.

In Figs.18 and 19, the variations of stress intensity ranges in the web-plate and in the face-plate are respectively illustrated under the water pressure loading. In Fig.20, the corresponding crack growth curves are illustrated. It is found that the stress intensity

ranges and the crack propagation lives are significantly affected by the structural details under the water pressure loading. The difference of the crack propagation lives mainly occurs before the complete break-off of the face-plate. This difference of the crack propagation lives is caused by the difference of the nominal stress and/or the stress concentration at the initial crack of each model. In Figs.21 and 22, the variations of stress intensity ranges in the web-plate and in the face-plate are respectively illustrated under the axial loading. The corresponding crack growth curves are illustrated in Fig.23. Under the axial loading, the effect of the structural details is relatively small with regard to the stress intensity range, the crack propagation live as well as the crack path.

On the effect of the residual stress distribution

It is well known that the behavior of fatigue crack propagation in welded structures is significantly affected by the welding residual stress [16]. Since welding residual stress is not a fluctuating stress, we assume that it simply changes the stress ratio, R , and the effective stress ranges ratio, U , which is calculated based on Eq.(6). In the developed simulation program, the stress intensity factor contributed by the residual stress is calculated by applying the tractions, which cancel out the internal forces acting on the virtual crack faces in an intact body. The actual stress intensity factor is calculated by the superposition of the stress intensity factors due to the applied load and the residual stress.

In order to investigate the effect of the residual stress against the fatigue crack propagation in the stiffened panel structures, a residual stress distribution is measured by using the test specimen, whose details are described in the following section (see

Fig.30). The measured residual stress distribution is illustrated in Figs.24 and 25. Very high tensile residual stress appears along the fillet welds, and its counterbalancing compressive residual stress appears near the edges of the face-plate and in the middle part of the web-plate. The simulated crack propagation lives with and without residual stress are illustrated in Fig.26 for the structural detail (b). It is found that the crack propagation live before the break of the face-plate is considerably reduced by the effect of tensile residual stress. However, the fatigue crack is gradually retarded due to the effect of the compressive residual stress in the middle part of the web-plate, and it is almost arrested near the skin plate, which may be caused by the combined effects of the compressive residual stress and the structural redundancy.

Effects of the applications of boundary conditions and the extents of structural models

When one analyzes fatigue crack growth in ship structures, the load application and the finite element modeling should be properly configured with regard to the load shedding effect due to crack propagation. Although the axial loading was applied as nodal forces in the previous section, it can be applied as prescribed nodal displacements. In the case of prescribed displacement, the acting stress in the cracked stiffener is much more reduced with the crack growth in comparison with that in the case of prescribed force. Simulated fatigue crack propagation lives under the two kinds of axial boundary conditions are compared in Fig.27. The model of the structural detail (b) is used, and the residual stress is not taken into consideration for this simulation. Although the fatigue crack lives agree with each other for short cracks, difference gradually increases with the crack growth. Eventually, the fatigue crack life by the prescribed displacement is about 7% longer than that by the prescribed force.

In a real ship structure, stresses are transmitted to the cracked stiffener through the surrounding structures, so that the boundary condition of a real ship structure is in the intermediate condition between the prescribed force and the prescribed displacement. In order to obtain a reliable result, the finite element modeling should be conducted for adequately large area of a ship structure. To investigate the appropriate modeling size, fatigue crack simulations are carried out by the three varieties of structural models as illustrated in Fig.28. Symmetric boundary conditions are prescribed along the both sides of each model as well as those illustrated in Fig.12. The fatigue crack propagation lives after the break of the face-plate are simulated and shown in Fig.29. It is obvious in the model (C) that the crack propagation lives of the two boundary conditions are completely different, so that this model is not adequate for simulations. However, the crack growth curves of the two boundary conditions approach closer each other with increasing the model size. Even though it may be preferable to use the model (A), the model (B) could be used for the simulations of the present problem.

Fatigue tests

From the results of the simulation, a fatigue crack in a longitudinal stiffener may exhibit rather different crack growth behavior under the water pressure loading. If a flat bar stiffener is used, a fatigue crack may penetrate into a skin-plate. On the contrary, if a large bracket is used, a fatigue crack may curve and tend to avoid the penetration into the skin-plate. In order to verify the result of the simulation, fatigue tests were carried out by using full-scale stiffened panel specimens.

General outline of the fatigue tests

Figure 30 is a schematic illustration of the fatigue tests. The material used is SM490A specified in JIS standard, whose material properties are shown in Table 2. The specimens are designed so that the applied stress, residual stress, and structural redundancy are equivalent to those attained in real ships. The specimens consist of three longitudinal stiffeners and a transverse girder at the middle span. The center longitudinal stiffener is connected to the transverse girder with a large bracket (the same dimensions as illustrated in Fig.13 (c)) or a flat bar stiffener (the same dimensions as illustrated in Fig.13 (a)), where these specimens will be called as the bracket-type specimen and the stiffener-type specimen, respectively. A fatigue crack initiation is expected only at the intersection of the center longitudinal stiffener and the end of the web-stiffener. Then, in order to prevent fatigue crack initiations from unexpected points, the remaining longitudinal stiffeners are connected by round end stiffeners. The loading condition is the three-point bending, and the applied hotspot stress range is set to 120MPa at the critical point. The repetition frequency of fatigue loading is set to 3~4Hz with the stress ratio, 0.05. In advance of the fatigue tests, it had been confirmed by using the developed simulation program that the fatigue cracks in the designed specimens present almost the same behavior as those in real ships.

Results of the fatigue tests

The fatigue cracks in the bracket-type specimen exhibited the following behavior (see Fig.31 (a));

- (1) a fatigue crack initiates at the end of the bracket, and propagates into the face-plate,
- (2) other cracks initiate from the weld root, and propagate to coalesce with the first

crack,

(3) the first crack is arrested in the face-plate, and

(4) the secondary cracks propagate into the face-plate.

The experiment was stopped just after the step (4). From the observed crack growth behavior, it is inferred that the cracks may repeat the above process (2)-(4), so that they may result in the separation of the web-stiffener from the face-plate. This crack growth behavior is quite different from the previous numerical simulation, but from the viewpoint of the ship structural safety, this sort of cracks may be favorable rather than those penetrating into the web-plate. Figure 31 (b) shows the fracture surface of this specimen, where multiple fatigue cracks are initiated from the weld root, and their crack surfaces show some inclined angles. This may be due to the high out-of-plane shear stress with respect to the plane of the lack-of-penetration zone.

In the stiffener-type specimen, a fatigue crack was initiated at the weld toe of the face-plate, and propagated into the web-plate as expected in the numerical simulation. In Figs.32 (a) and (b), the crack paths and the crack growth curves are illustrated, respectively, where they are compared with the numerical results. It can be seen that the fatigue crack in the experiment is slightly curved and propagates toward the shell plate, which is in good agreement with the simulated crack path. From Fig.32 (b), it can be seen that the fatigue cracks propagating in the face-plate exhibit asymmetric behavior with respect to the center line. The reason may be explained by the complex residual stress distribution and/or the asymmetric loading caused by the welding deformation. On the experimental crack growth curve in the web-plate, the fatigue crack growth rate is rapidly increased at two points, $N=2.5 \times 10^6$ and $N=3.5 \times 10^6$, respectively, which

correspond to the breaks of the each edge of the face-plate. The simulated crack growth curve also exhibits the similar phenomena except for the asymmetric crack growth behavior in the face-plate.

Conclusions

A simulation program has been developed for multiple cracks propagating in a three-dimensional stiffened panel structure. The characteristics of fatigue crack propagation in ship structures have been investigated by using the developed numerical simulation program and experiments. The conclusions of this study are summarized as follows;

- It has been confirmed that the developed program can reasonably predict fatigue crack propagation behavior in a three-dimensional stiffened panel structure within a practical calculation time.
- From the numerical results, it has been found that the fatigue cracks from the intersection of the face-plate and the end of the web-stiffener may change their propagation behavior depending on the loading conditions and the structural details. In the case of the structural details (b)-(d) under the water pressure loading, the fatigue cracks show curved paths so as to avoid the penetration into the skin-plates. It has been also shown that, in certain cases, the fatigue cracks may be arrested in the web-plate because of the effect of the compressive residual stress.
- In the experiment of the bracket-type specimen, the fatigue crack separated the web-stiffener from the face-plate. This sort of cracks may be favorable for the ship structural safety rather than those penetrating into the web-plate.
- In the experiment of the stiffener type specimen, the fatigue crack propagation is in

good agreement with the simulation so that the applicability of the present simulation program has been verified.

- From the results of the present simulations and the experiments, it is shown that the fatigue cracks in a longitudinal stiffener may avoid fatal damage of the skin-plate in certain cases. This may imply a possibility to realize a rational fatigue crack management based on numerical simulations. The present simulation program may offer a useful tool for this purpose.

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Table and Figure Captions

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Table 2: Material properties of the specimen.

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Figure 2: Fatigue crack propagation in a longitudinal stiffener; (a) surface crack at the weld toe, (b) through-the-thickness crack in the face-plate and the web-plate, (c) through-the-thickness crack in the web-plate.

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