Computational Crack Path Prediction for Ship Structural Details

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ABSTRACT. *The characteristics of fatigue crack propagation and the remaining life assessment of ship structures are investigated focusing attention on a curved crack path due to the effects of weld, complicated stress distributions at three-dimensional structural joints, and structural redundancy. An advanced numerical simulation method is demonstrated for the remaining life assessment of curved crack propagation. The simulation method is based on a step-by-step finite element analysis. The crack path is predicted by the perturbation method with the local symmetry criterion, which gives a higher order approximation of the crack path, while the finite element re-zoning is carried out by an improved paving method. Fatigue crack paths in the welded structural details of the transverse girder of a ship structure are investigated so that one can find the detailed design, which prevents the break of the plates forming a compartment boundary. It is found that the present method may offer an efficient simulation-based tool for the design of critical details.*

INTRODUCTION

The fitness for serviceability of structural members of ships is of great interest for the prevention of instantaneous failures as well as the loss of serviceability such as oil and/or water tightness of critical compartments [1]. The characteristics of fatigue crack propagation and the remaining life assessment of ship structures have been investigated focusing attention on a curved crack path due to the effects of weld, complicated stress distributions at three-dimensional structural joints, and structural redundancy [2, 3, 4] .

In the present paper, an advanced numerical simulation system is proposed for the remaining life assessment of curved crack propagation. The simulation method is based on a step-by-step finite element analysis. Crack paths are predicted by the perturbation method applying the local symmetry criterion, which gives a higher order (curved) approximation of an each incremental crack extension. The finite element re-zoning is carried out by an improved paving method, which provides a very robust mesh generation by quadrilateral finite elements during the entire crack growth process without user intervention.

Fatigue crack paths are investigated for welded structural details of a transverse girder of a ship structure, and their crack propagation lives are estimated to prevent the break of the shell plate during the ship operation. The influencing factors such as geometry of structural details, welding residual stress, structural redundancy, as well as crack paths are taken into consideration in the simulation, so that realistic phenomena of fatigue crack propagation can be obtained. It is found that the present method may offer an efficient simulation-based tool for the design of critical details where retarded cracks can be visually detected by the regular inspection.

AN ADVANCED SIMULATION SYSTEM FOR THE ASSESSEMENT OF REMAINING LIVES AND PATHS OF FATIGUE CRACKS

Simulation System

In this section discussions are made for a simulation system, which may give an accurate assessment of both the crack propagation life and the final failure mode of a welded ship structure. A step-by step finite element approach, which was originally developed for brittle crack paths, has been extended to fatigue crack path prediction [2, 3, 4], in which an accurate stress intensity analysis, a proper crack path criterion, an accurate growth rate equation, and an automatic mesh generation algorithm are required. A fatigue crack is modeled as a two-dimensional crack in a plate, and the simulation consists of the following steps;

1. Prepocessing: finite element mesh is automatically generated by an advanced paving method [5,6], and the super-element is also defined for structural elements outside the crack propagating zone,
2. Crack analysis: stress field parameters near a crack tip are calculated by the method of superposition of analytical and finite element solutions [7,8],
3. Crack path prediction: curved crack extension is predicted by the first order perturbation method with the use of local symmetry criterion [9,10,11],
4. Crack growth calculation: crack growth is calculated by the Paris' law ,
5. Back to step 1 to continue simulation.

In each step a cracked domain is subdivided into new finite element mesh by an advanced paving method, which is specially developed for the refined smooth mesh gradation for crack analysis in the present work. The stress field parameters of the Irwin-Williams' expansion are determined by the method of superposition of analytical and finite element solutions [7,8], where not only the stress intensity factors but also the T-stress and higher order coefficients are determined for an accurate prediction of a curved crack path. The crack tip is then moved to a certain point on the predicted path, which is obtained analytically by the first order perturbation method [9,10] with the local symmetry criterion [11]. The crack growth life is evaluated by the stress intensity range along the curved crack path, and the procedure will be repeated until the final stage of the crack propagation is reached. A GUI-system has been developed so that user-friendly environment is established for the input and output phases of the simulation.

In the present paper, the above step-by-step approach is extended to include the super-element technique, which exactly represents the stiffness and loading transmitted between the crack propagating zone and complicated three-dimensional welded structures surrounding the zone. The effects of welding residual stress are taken into account for the stress analysis by considering the stress re-distribution, and the crack growth rate so obtained reflects the effect of weld in terms of mean stress.

Super-Element Technique for Three-Dimensional Structures

In order to analyze fatigue crack propagation in three-dimensional ship structures, a super-element technique has been introduced so that the re-distribution of load effects in highly redundant welded structures are properly taken into considerations. The analyzed domain is first decomposed into the two distinct domains; i.e. the two-dimensional crack propagating domain and the surounding three-dimensional structures. The latter will be modeled as a super-element by the static condensation algorithm so that the degree of freedom is reduced to those corresponding to the interface boundary between the two domains.

A general purpose structural analysis code "MSC-NASTRAN" is used to model the three-dimensional surrounding structures. The stiffness coefficients and nodal forces of the super-element are automatically formed and stored in an output file by using the super-element option. Having added these stiffness coefficients and nodal forces to the degrees of freedom along the interface boundary in the crack propagating domain, fatigue crack propagation is simulated. In the present approach, the nodal arrangement along the interface boundary must be the same for the both domains, and the resultant stiffness matrix may be full in the case when the super-element completely surrounds the crack-propagating zone, which may slightly slow down the solution, but may not be an essential problem.

Treatment of Welding Residual Stress

Since welding residual stress is not a fluctuating stress, we assume that it simply changes the stress level, which may change the stress ratio, R, and effective ranges of stress intensity factors. For a given cracked geometry we can calculate the stress intensity factor contributed purely from the residual stress by applying the tractions, which cancel out the tractions due to welding residual stress acting in an intact body. This procedure is incorporated in the structural analysis procedure using the same finite element modeling. Let us denote the opening mode of stress intensity factors due to the applied load and the residual stress by K_{I} and K_{IR}, respectively. In the following analysis, we assume that the ranges of the stress field parameters at the crack tip are accounted for as far as the condition, $K_{\mathrm{I}} + K_{\mathrm{IR}} > 0$, holds during a load cycle. The range of stress intensity factor and the stress ratio, R, so defined are used for the crack growth calculation. It should be noted that the stress intensity factors, K_{IR}, could be negative due to compressive residual stresses so that the reduction of ranges of stress intensity factors may be expected under these circumstances. For crack propagation calculation, we shall use the standard equation for ship structural steel [12], which is given by:

$$\mathrm{d}a/\mathrm{d}N=1.80\mathrm{x}10^{-11}[(\mathrm{U}\ \Delta K_{\mathrm{I}})^{\mathrm{m}}-\Delta K_{\mathrm{th0}}{}^{\mathrm{m}}], \quad (1)$$

where m=2.932 and the threshold range of the stress intensity factor, ΔK_{th0} at R=0 is 2.45MPa m $^{1/2}$. The effective crack opening ratio, U, is calculated by

$$U= 1/(1.5\text{-}R) \ \text{ for } \ 0<R<0.5, \qquad \text{and} \qquad 1.0 \ \text{ for } \ R>0.5. \quad (2)$$

A SIMULATION-BASED FATIGUE DESIGN FOR SHIP STRUCTURAL DETAILS

Critical Structural Details

Typical critical locations of fatigue failure of a double-hull crude oil carrier are shown in Fig. 1. Ships consist of inner and outer skin plate such as longitudinal bulkheads, side shell plates, deck plates, and inner and outer bottom plates which are supported by internal longitudinal stiffeners and transverse girders as illustrated in the figure. Plate thicknesses of normal members are 10mm to 30mm, while ship length is 200m to 350m. Moreover, the ship structure has many structural discontinuities causing stress concentrations, most of which are the three-dimensional intersection of structural members connected by welding.

Fatigue cracks rarely initiate at skin plates. They generally initiate at the intersection of internal supporting members, more specifically at weld toes of wrap-around weld and fillet weld, where stress concentrations due to structural discontinuity and weld geometry could be superimposed [13, 14]. In Fig. 1 typical examples of fatigue cracks at the end of transverse girder is illustrated, where fatigue cracks of certain types must be prevented because they may lead to the leakage of cargo oil. Large numbers of cracks initiated at these internal structural members may be detected by in-service inspections, so that they could be repaired before they become hazardous.

Simulation-Based Design

Once fatigue cracks are found in ship structures, appropriate countermeasures such as the repair and the design improvement of structural details should be scheduled. In the example of fatigue cracks in Fig. 1, cracks of the type b must be avoided because it may lead to the potentially hazardous situations. In this case it is essential for the fatigue cracks to be of the type a, which can visually be detected by periodic inspection.

In order for cracks to be of the type, their growth behavior may possibly be retarded due to certain mechanisms such as compressive welding residual stress and structural redundancy, where their paths may play an essential role. In Fig. 2, such a fracture control concept is described; a fatigue crack at weld toe initially grows to a certain detectable size, and then its growth behavior is retarded for a certain period of time, during which periodic inspections may be expected at least once. This concept may require a simulation-based fracture control for the remaining life assessment of ship structures, in which various factors in relation to fatigue crack growth must be taken into consideration i.e.; welding residual stress in the crack propagating zone, stress concentration and stress biaxiality at the structural discontinuities of three-dimensional intersections, and structural redundancy, whose combined effects may affect the non-collinear crack paths and their retarded growth behavior. The present advanced simulation system may provide a useful tool to perform the detailed fatigue design based on this concept.

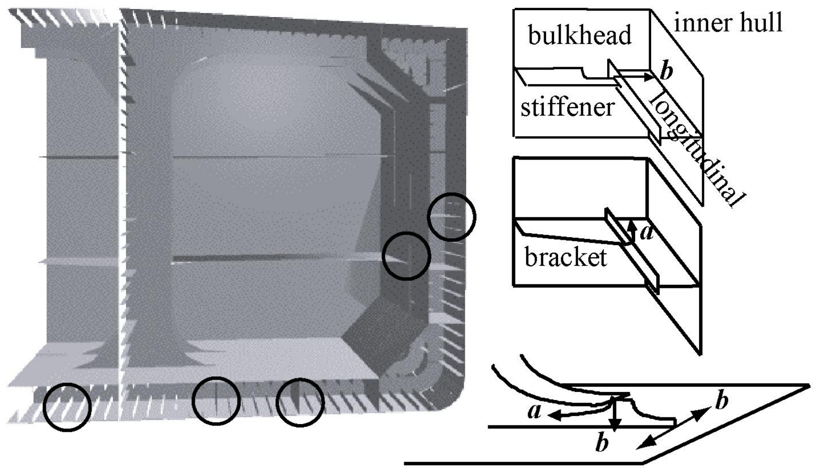


Figure 1. Typical fatigue cracks in ship structures, where cracks of type (b) should be prevented.

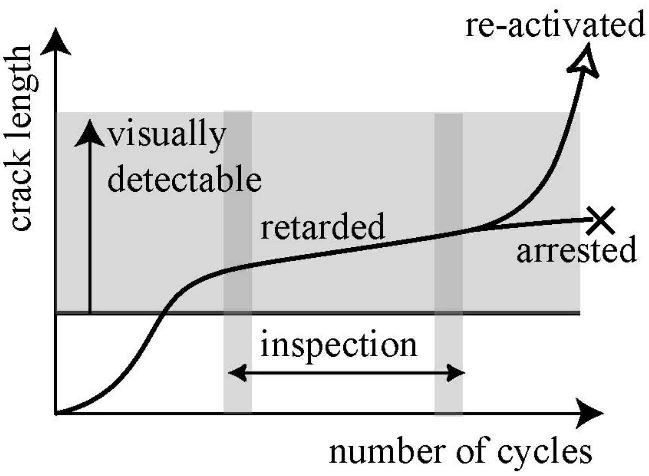


Figure 2. Concept of fatigue control of a ship structure.

ILLUSTRATIVE EXAMPLES - FATIGUE CRACKS IN A DOUBLE-HULL TANKER -

Figure 3 shows an example of a FE-model of a structural module of a double hull tanker. In Fig.4(a) the structural detail at the end of a horizontal girder is zoomed up as one of the potentially critical zone of fatigue damage. A fatigue crack may initiate at the end of the face-plate, and the possible crack propagation in the web is simulated by the present system, where typical FE-mesh used in the crack propagating domain is illustrated in Fig.4(b). The whole structural module of a tanker and the corresponding wave loads acting on the hull are modelled by the super-element technique, and the corresponding stiffness and the load vectors are applied to the boundary of the crack-propagating domain. The load applied to the hull module is derived from the fatigue design load defined by Class NK [15].

The crack path so obtained is also illustrated in Fig.4(b), which shows a slightly curved path. The corresponding fatigue crack growth is shown in Fig.5(a). The crack initially grows to the size of order 20-30mm and then it is retarded considerably due to the compressive residual stress. Finally, it increases its growth rate with increasing its length. This behavior is essentially governed by the welding residual stress, which is assumed to be nearly equal to 300MPa near the fillet weld along the face plate and the inner hull, while it is compressive and close to –200MPa in between the welds in the web. The corresponding change of the stress intensity range is also illustrated in Fig.5(b), where one can see the effect of residual stress.

This result indicates that the fracture control concept described in the previous section is actually applicabe to the fatigue cracks of this kind. It may initially grow to a certain detectable size, and then retarded for a certain period of time during which periodical inspections could be expected.

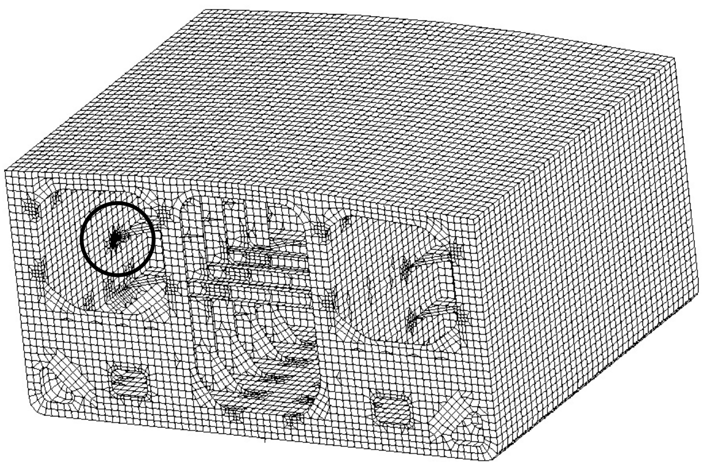
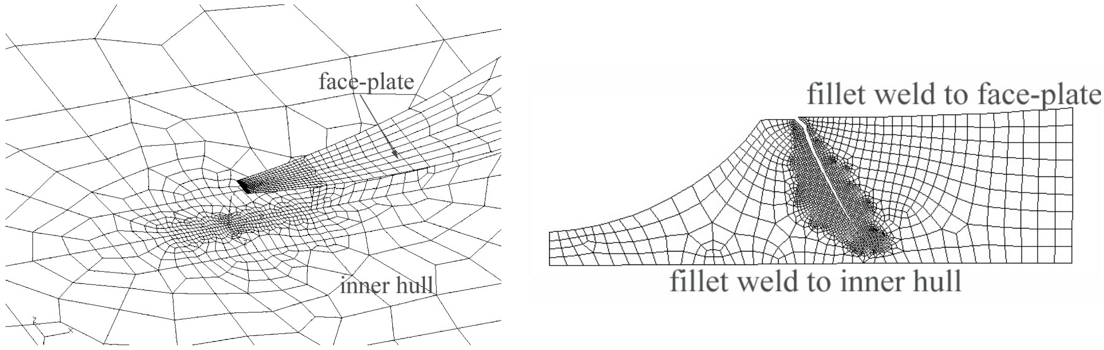
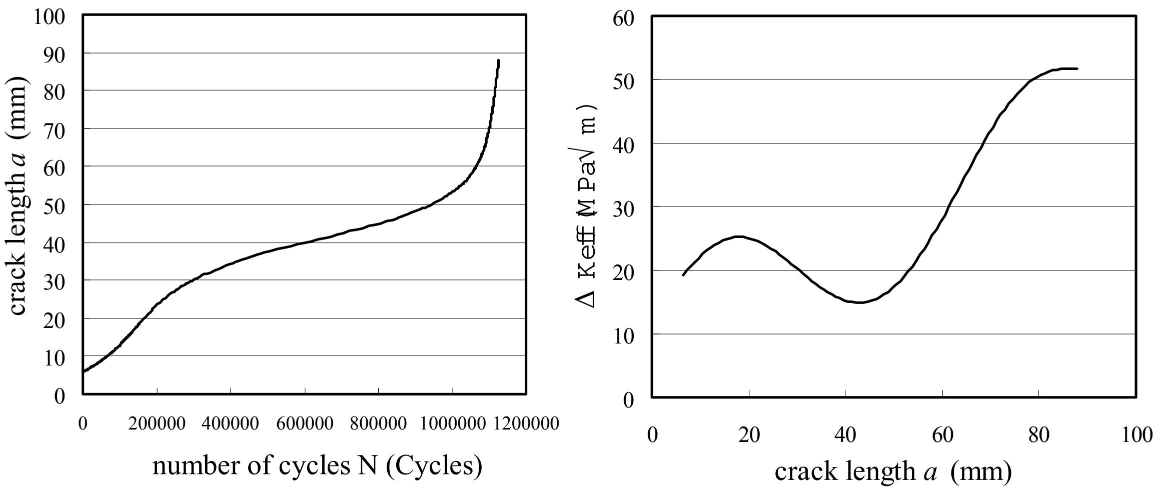


Figure 3. Critical location of fatigue damage of a double hull tanker: FE-model of a unit hull module.



(a) Structural detail (b) Crack-propagation domain

Figure 4. Critical detail at the end of a horizontal girder: (a) a super-element surrounding the crack-propagating domain, (b) an automatically generated FE-model of the crack-propagating domain.



(a) a – N curve (b) $\Delta K_{\mathrm{eff}} - a$ relation

Figure 5. Simulated fatigue crack growth and the corresponding stress intensity range.

CONCLUSIONS

An advanced simulation system is proposed for the remaining life assessment of curved crack propagation. The simulation method is based on a step-by-step finite element analysis. Fatigue crack paths are investigated for welded structural details of a transverse girder of a ship structure, and their crack propagation lives can be estimated for the prevention of the break of a compartment during ship operation. The influencing factors such as geometry of structural details, welding residual stress, structural redundancy, and crack paths can be taken into account in the simulation, so that realistic phenomena of fatigue crack propagation may be obtained. It is found that the present method may offer an efficient simulation-based tool for the design of critical details where retarded cracks can be visually detected by a periodical inspection.

ACKNOWLEDGEMENT

This work has been supported by the Program for Promoting Fundamental Transport Technology Research (Project No.2001-03) from Corporation for Advanced Transport and Technology (CATT), and by the fund from Japan Ship Classification Society (Class NK). The author is grateful for their support.

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