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Numerical Study of Fatigue Crack Growth at a Web Stiffener of Ship Structural Details

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Abstract**—**It is necessary to manage the fatigue crack growth (FCG) once those cracks are detected during in-service inspections. In this paper, a simulation program (FCG-System) is developed utilizing the commercial software ABAQUS with its object-oriented programming interface to simulate the fatigue crack path and to compute the corresponding fatigue life. In order to apply FCG-System in large-scale marine structures, the substructure modeling technique is integrated in the system under the consideration of structural details and load shedding during crack growth. Based on the nodal forces and nodal displacements obtained from finite element analysis, a formula for shell elements to compute stress intensity factors is proposed in the view of virtual crack closure technique. The cracks initiating from the intersection of flange and the end of the web-stiffener are investigated for fatigue crack paths and growth lives under water pressure loading and axial force loading, separately. It is found that the FCG-System developed by authors could be an efficient tool to perform fatigue crack growth analysis on marine structures.

Keywords**—**Crack path, Fatigue crack, Fatigue live, FCG-System, Virtual crack closure technique.

I. INTRODUCTION

IT is well known that ship and offshore structures may be exposed to fatigue failure due to dynamic loads induced by waves and slowly varying loads due to loading and unloading operations. If fatigue crack growth is not well managed, it may finally either cause the loss of oil/water tightness of critical compartments to degrade serviceability, or lead to catastrophic crack size to break down the structures. To avoid those events, it is necessary to establish the inspection process and inspection planning in frame of fatigue crack growth with the economic and safety targets [1]-[4]. Therefore, analysis on fatigue crack growth in maritime structures has attracted much more attentions recently.

In this paper, a fatigue crack growth analysis system, named after FCG-System, is established through ABAQUS Scripting Interface (ASI), which is an objected-oriented programming (OOP) using Python language. It can simulate fatigue crack growth with arbitrary path in space under mix-mode loading. Under the idea of virtual crack closure technique (VCCT), a formula is proposed to compute stress intensity factors (SIFs) for shell elements based on nodal forces and nodal displacements. Several illustrative examples, both with a single crack and multiple cracks, have shown that the developed system is accurate and robust to simulate fatigue crack growth [5]. To our experiences, the developed FCG-System is relatively easy to practice, insensitive to mesh size and computationally efficient which makes the system is particularly powerful to handle problems of multiple cracks growing in a simultaneous but uneven manner. Therefore, it is a promising tool for naval engineers to perform fatigue crack growth analysis on marine structures.

II. FCG-SYSTEM FOR CRACK SIMULATION

A. Framework of FCG-System

The framework of implementation of FCG-System has been explained in [5]. The main procedure of the simulation is summarized as follows (see Fig. 1):

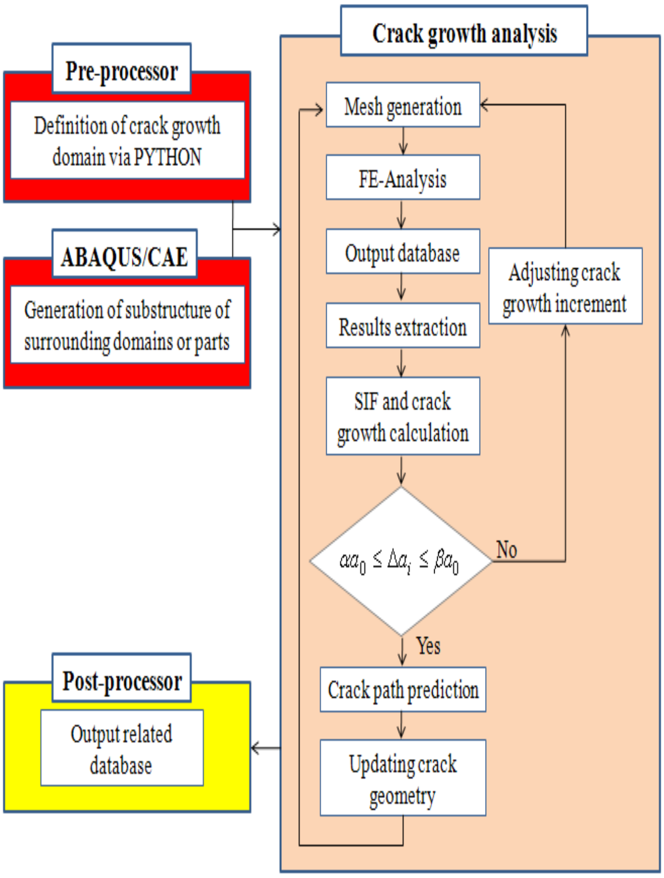

Fig. 1 Flow chart of numerical procedure of FCG-System

1) Pre-processing: finite element mesh is generated by free-mesh algorithm built-in ABAQUS, which can achieve

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fine mesh in very complex region. In order to simulate the practical fatigue crack growth in large-scale marine structures, the substructure technique can be applied to the structure surrounding the crack growth domain.

2) FEM analysis: The created model is then submitted to ABAQUS solver as a job. The obtained results are saved to external files so as to be ready for next analysis.
3) SIFs calculation: nodal forces at the crack-tip and displacement openings behind crack-tip can be extracted from .odb file, and the stress intensity factors can be calculated by VCCT.
4) Crack path prediction: crack growth direction is predicted by the maximum circumferential stress criterion.
5) Crack growth calculation: fatigue crack growth is calculated by the crack growth law.
6) Next simulation: go back to step1 to continue simulation until a desired crack length or a prescribed fatigue cycle is reached.
7) Post-processing: output some data to external files and plot charts if necessary.

The system consists of four sub-systems which are implemented by ABAQUS Scripting Interface using Python language [6]-[8]. In numerical procedure, each sub-system is iteratively executed until a desired crack length or a prescribed fatigue cycle is reached. In each step, the ABAQUS solver only deals with small amount of output database files to avoid the management of the large output files [6]. In this way, the FCG-System can run efficiently.

B. Calculation of Stress Intensity Factors

With VCCT, strain energy release rates can be expressed in terms of nodal forces at the crack tip and nodal displacements behind the crack tip [9]-[12]. However, the formula for the through thickness crack with shell elements has not been developed. In this paper, we apply the formula proposed by us to treat the three-dimensional plate structures using shell elements. For general mixed-mode loading, the strain energy release rates G_{I}, G_{II} and G_{III} can be expressed with the corresponding nodal forces and displacement vector components in the local coordinate system $(\overline{\mathrm{X}},\overline{\mathrm{Y}},\overline{\mathrm{Z}})$, the strain energy release rates can be calculated by

$$\begin{cases} G_{\mathrm{I}} = \frac{1}{2BL}\left(\overline{F}_y\overline{\Delta u}_{y3,4} + \overline{M}_Z\overline{\Delta\theta}_{Z3,4}\right) \\ G_{\mathrm{II}} = \frac{1}{2BL}\left(\overline{F}_x\overline{\Delta u}_{x3,4}\right) \\ G_{\mathrm{III}} = \frac{1}{2BL}\left(\overline{F}_z\overline{\Delta u}_{z3,4} + \overline{M}_x\overline{\Delta\theta}_{x3,4} + \overline{M}_y\overline{\Delta\theta}_{y3,4}\right) \end{cases} \tag{1}$$

where B is the width of the cracked body, L is the rosette size (see Fig. 2). Then the stress intensity factors can be computed from the following relations:

$$\begin{cases} K_{\mathrm{I}} = \sqrt{\overline{E}G_{\mathrm{I}}} \\ K_{\mathrm{II}} = \mathrm{sign}\left(\overline{F}_x\right)\sqrt{\overline{E}G_{\mathrm{II}}} \\ K_{\mathrm{III}} = \sqrt{2\mu G_{\mathrm{III}}} \end{cases} \tag{2}$$

where $\overline{E} = E\,/(1-v^2)$ for plane-strain condition. E is the modulus of elasticity, and v is Poisson's ratio; μ is shear modulus of elasticity. The sign of K_{II} can be determined by the sign of $\overline{F}_x$.

Under mixed mode condition it is necessary to introduce an equivalent stress intensity factor, K_{eff}, considering Mode-I, -II and –III simultaneously.

$$K_{eff} = \sqrt{K_{\mathrm{I}}^2 + K_{\mathrm{II}}^2 + (1+v)K_{\mathrm{III}}^2} \tag{3}$$

Once the direction of crack growth is determined, the next issue is to calculate the crack growth rate based on the crack growth law. In this paper, the following crack growth law [4] is used,

$$\frac{\mathrm{d}_a}{\mathrm{d}_N} = C\left\{\left(U\Delta K_{eff}\right)^m - \left(\Delta K_{eff}\right)_{th}^m\right\} \tag{4}$$

where ΔK_{eff} is equivalent stress intensity factor range; C and m are material constants to be found experimentally, and $\left(\Delta K_{eff}\right)_{th}$ is the threshold range of stress intensity factor, and U is the effective stress range ratio, which is given by

$$U = \begin{cases} 1/(1.5-R) & (-\infty \le R \le 0.5) \\ 1 & (0.5 \le R \le 1) \end{cases} \tag{5}$$

where R is the stress ratio. If the fatigue cycle increment is assumed as ΔN, the crack growth increment Δa_i of the crack tip node i,

$$\Delta a_i = \Delta N\left\{(U\Delta K)^m - \left(\Delta K_{eff}\right)_{th}^m\right\} \tag{6}$$

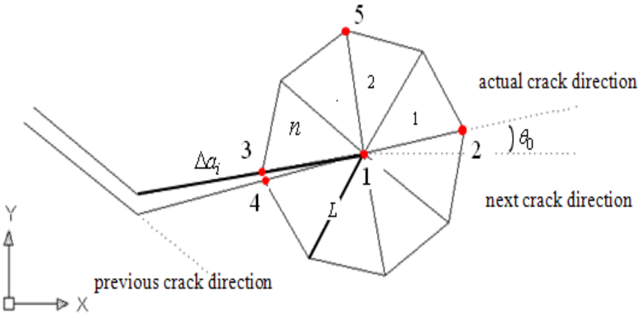

Fig. 2 Crack growth direction and rosette meshes at the crack tip

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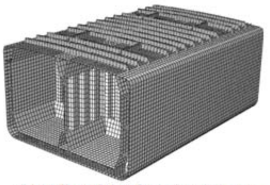
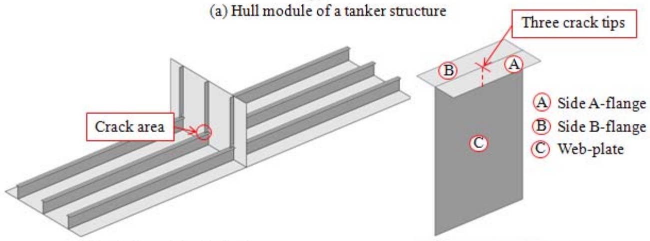
III. FATIGUE CRACK GROWTH IN SHIP STRUCTURE DETAILS



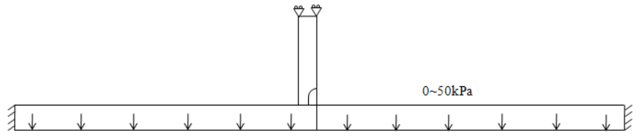
(a) Hull module of a tanker structure



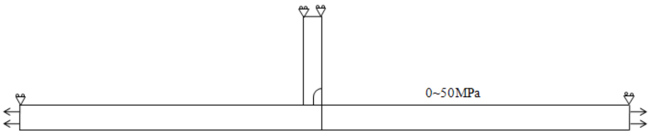
(b) Shell model with flat bars (c) Crack growth domain

Fig. 3 Analysis model of the investigated ship. (a) global FE model of hull module; (b) shell model with flat bars attached to web frame and longitudinal stiffeners; (c) crack growth domain with three crack tips.

This section focuses on the application of the established FCG-System to a real tanker vessel as shown in Fig. 3. The global FE model of hull module is built up. Fig. 3 (b) shows the local shell model for the FE analysis at the critical position on the inner plate with flat bar attached to longitudinal stiffener and transverse girder. Crack growth domain in the local shell model is defined in Fig. 3 (c). Water pressure or axial force is applied to this local model as loading conditions of constant amplitude, separately (see Fig. 4).



Water pressure



Axial force

Fig. 4 Loading condition

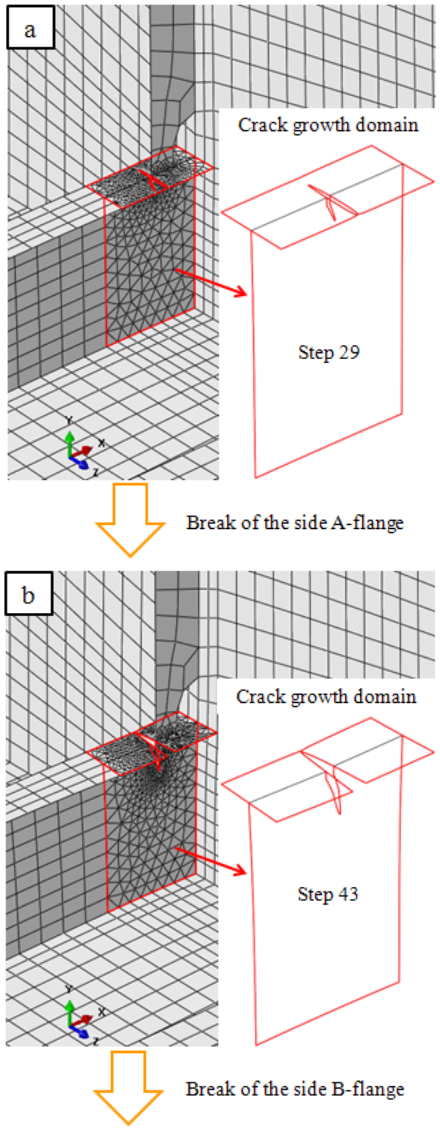
A. Structure Details Description

Fatigue cracks that initiate from the intersection of flange and the end of the web-stiffener, are considered to grow and propagate until a leakage occurs at the bottom plate or side shell plate. In the process of fatigue crack growth, the crack is considered to be “through-the-thickness” one. The initial cracks are assumed that they have 20mm width in the side A-flange and 10mm width in the side B-flange, and 10mm depth in the web-plate. With this respect, fatigue crack growth in the longitudinal stiffener can be categorized into the following three stages:

1) In the beginning, cracks grow in the flange and the web-plate with three crack tips (see Fig. 5 (a));
2) After the break of side A-flange, cracks grow in the other side of flange and web-plate continuously with two crack tips (see Fig. 5 (b));
3) After the break of side B-flange, a crack grows in the web-plate continuously with only one crack tip (see Fig. 5 (c)).

B. Predicted Results and Analysis

Fig. 5 shows the finite element model at three stages of crack growth which is modeled by shell elements. In the process of complete crack growth, once there is a plate broken, the remaining crack tips have to be re-defined while surrounding domain needs not to be remodeled.



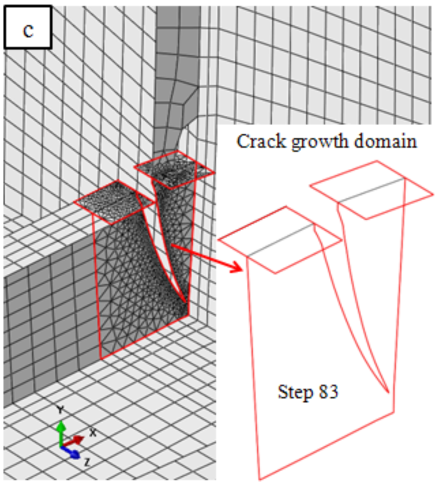


Fig. 5 Illustration of finite element model and crack geometry in the longitudinal stiffener

The simulated crack paths in the web-plate are presented in Fig. 6. Under water pressure loading, the crack tends to grow towards the transverse frame, which may result in the failure of a compartment boundary. Under axial force loading, the crack tends to bottom plate. The cracks in the flange grow nearly in a straight line, which are perpendicular to the free edge as shown in Figs. 7 and 8.

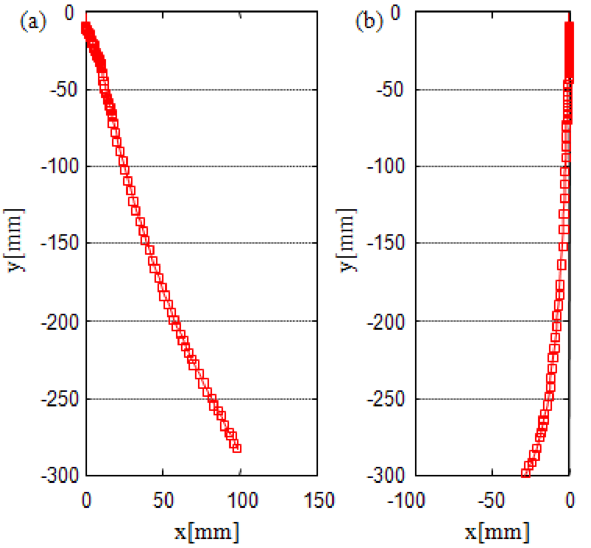


Fig. 6 Crack paths of the web plate; (a) water pressure loading, (b) axial force loading

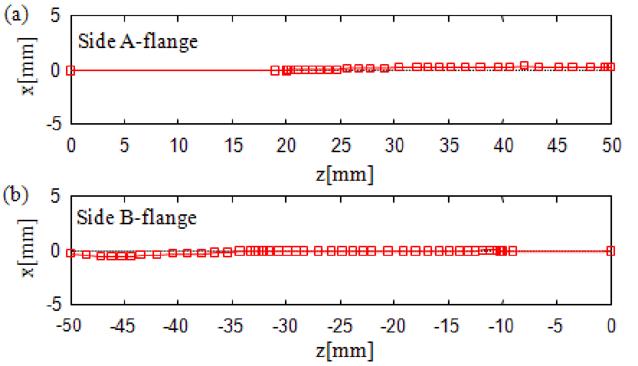


Fig. 7 Crack paths of the flange under water pressure loading; (a) Side A-flange, (b) Side B-flange

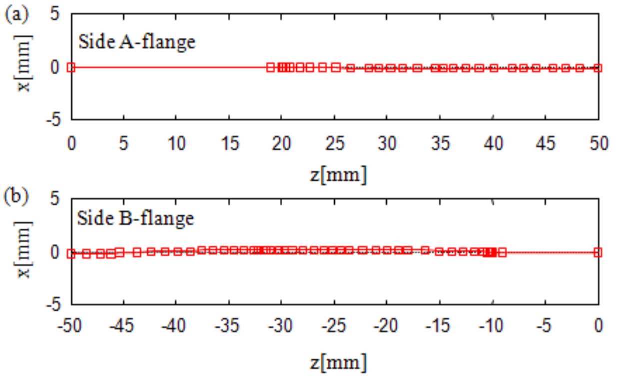


Fig. 8 Crack paths of the flange under axial force loading; (a) Side A-flange, (b) Side A-flange

The simulated corresponding crack growth lives are presented in Figs. 9 and 10. Once the flange fractures, sudden changes will occur for the crack growth rates in the remaining plates, especially the change in web-plate after the complete fracture of side A-flange. It can be found that fatigue cracks can promptly grow and propagate until a leakage occurs at the bottom plate or side shell plate after the complete fracture of flange.

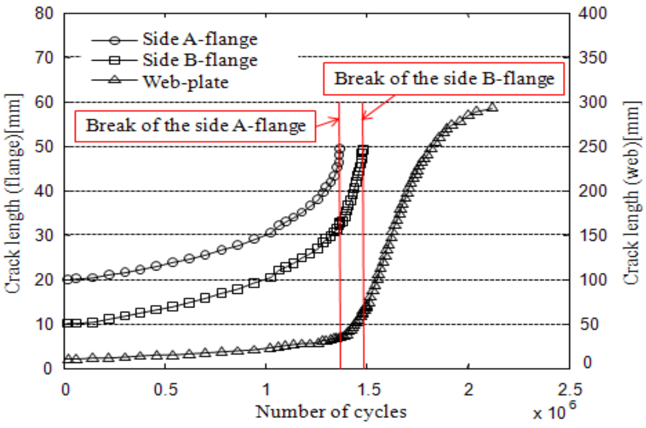


Fig. 9 Simulated crack growth lives in the flange and the web-plate under water pressure loading

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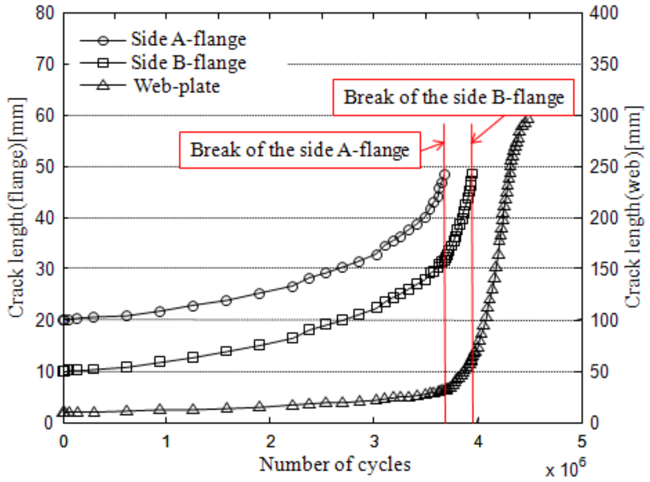

Fig. 10 Simulated crack growth lives in the flange and the web-plate under axial force loading

IV. CONCLUSION

In this paper, a simulation program (FCG-System) is developed utilizing the commercial software ABAQUS with its object-oriented programming interface to simulate the fatigue crack path and to compute the corresponding fatigue life. Fatigue cracks initiating from the intersection of flange and the end of the web-stiffener are investigated for fatigue crack paths and growth lives under water pressure loading and axial force loading, separately. The present method may offer an efficient simulation-based tool for the design of critical details, which prevents the failure of the plates forming a compartment boundary.

Therefore, the FCG-System developed by authors could be a useful tool to perform fatigue crack growth analysis on marine structures.

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