Fatigue life estimation for a long through thickness cracks in large-scale specimen in imitation of hull skin plate

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ABSTRACT

Fatigue crack growth curves for long through thickness cracks in large-scale specimens in imitation of ship hull skin plates are performed by applying fatigue crack growth simulation code FLARP (Fatigue Life Assessment by Re-tensile Plastic zone generated load) developed by authors. Histories of stress range during the crack extension for each specimen and residual stress distributions of as welded and of stress-relieved specimens are taken into consideration by applying FLARP. Estimated fatigue crack growth curves by FLARP are good in agreement with measured crack growth curves. It is confirmed that FLARP enables to estimate the fatigue crack growth curves of long cracks in ship hulls.

KEY WORDS: Fatigue; Fatigue crack growth curves; Numerical simulation of fatigue crack growth; FLARP; Structural integrity

INTRODUCTION

Many fatigue damages cannot be eliminated perfectly in ship and offshore structures even though high grade TMCP steels with excellent weldability are applied to these structures. The reason is considered to be due to the application of higher allowable stress to structures in the design stages due to the higher strength under static loading conditions. Then, it is important to estimate fatigue life of these structures with good accuracy.

Many fatigue damages in VLCCs with high grade steels were reported in the 1990s (SR216, 1993). In these damages, fatigue cracks initiate in the welded connections between side longitudinal stiffeners and transverse frames and bulkheads of ships. It is also reported that some of these cracks grow and penetrate through the hull skin plate. Cracks in hull skin plates lead to the fatal damage of ships. It is considered that the wave loads introduce significant dynamic stresses in the side shell below the mean water level. It is now considered that this type of cracks is eliminated by the research project (SR216, 1993) and improvements of structural design.

Unpredictable fatigue cracks will, however, occur in structural members and some of them will grow and reach hull skin plates because of the change of structural design for the application of the new or improved materials for the structural members. Besides, insufficient maintenances are preformed in some aging ships and cause the serious fatigue damages in hull skin plates of aging ships shown in Fig.1 by an example.

Fig.1 Cracked deck in the tanker Castor (IMO, 2006)

On the other hand, floating production storage and offloading units (FPSOs) are widely operating in the offshore fields for energy resources development. Generally, FPSOs are placed on the same location for a rather long lifetime without scheduling of any shutdown for maintenance and repair comparing with ships. This implies that stricter considerations to a reliable fatigue design are required in FPSOs than in general merchant ships. Besides, the consequence cost of a repair may be significant for FPSOs as compared with tankers when cost of lost production is considered during the repair of fatigue cracks (Lotsberg et al., 1998).

One of the conventional fatigue life estimation methods in the design stages of welded built-up structures is the combination of S-N curves and cumulative damage rules, e.g. Miner's rule. In case that fatigue cracks occurred in stress concentration regions caused by structural arrangements, the hot spot stress methodology, which is the combination of hot spot stress obtained by finite element analysis and cumulative damage rules, is applied (Fricke, 2002). This is commonly applied and the assessments for many types of structural elements are reported (Kim and Lotsberg, 2004) (Lotsberg and Landet, 2005).

The conventional fatigue life estimation method based on S-N curves contains some serious weaknesses as follows.
1. S-N curve method cannot give the fatigue crack growth history.
2. The transferability of fatigue life obtained by S-N curves to in-service structures has not established yet. That is, the relation between fatigue crack length found in in-service structures and fatigue life obtained by S-N curves is not defined clearly.

On the other hand, many attempts based on fracture mechanics for the improvement of fatigue life prediction are performed in order to overcome the weaknesses of the conventional S-N curve approaches. However, most of fatigue life assessments based on fracture mechanics also contain insufficient points as follows.
1. Estimated fatigue crack growth curve is strongly affected by the setup of initial crack geometries.
2. Insufficient evaluation of fatigue crack opening/closing behavior, which directly affects the fatigue crack growth, under variable loading.

Authors proposed the simulation algorithm of fatigue crack growth from sound (zero initial defect) or cracked stress concentration sites for welded built-up steel structures considering loading histories and residual stress caused by welding (Toyosada et al., 2004a and 2004b) and developed the numerical simulation code ``FLARP'' implemented into the algorithm mentioned above. Extended strip yield model is applied in order to perform the numerical simulations of fatigue crack opening / closing.

In this study, fatigue crack growth simulations by FLARP are performed for large-scale experiments in imitation of hull skin plate (Bjørheim, 2006) and the possibility of high accuracy fatigue crack growth estimation is investigated.

SUMMARY OF LARGE-SCALE EXPERIMENTS

Bjørheim performed large-scale fatigue crack propagation tests in imitation of hull skin plate (Bjørheim, 2006). In these experiments, fatigue crack growth curves were measured. Outline of specimen configurations are listed below.

Table 1. Outline of specimens used.

Types of specimen	Base material, butt weld joint with as-welded condition and butt weld joint with stress relieved treatments.
Size	Height: 2,000mm, Width: 4,000mm, Plate thickness: 20mm Butt weld with K-shape groove were performed both as-welded and stress relieve treatment specimens.
Base material	NVD 36 Steel, Yield strength: 386~391 MPa Tensile strength: 532~533 MPa
Initial crack length	100mm, setup in the center of specimens.

Fabrication process of specimens with butt weld joint is similar to the restraint specimen with slit for cracking test in order to generate high residual stress fields. That is, the first welding process is both 1,000mm from side edges and slit (length 2,000mm) in the center of specimens is remained. The following welding process joins the remained slit. Light tapering 1.5mm per 20mm vertical direction is introduced along upper toe of butt weld bead in order to keep straight crack propagation.

Residual stresses were measured at 1,500mm from right edge of specimen. The hole-drilling strain gauge method according to ASTM E837-01 is applied in order to measure the residual stresses. Measurement points are three different points perpendicular distances to the weld (5mm, 25mm and 50mm from upper weld toe). Schematic illustration of butt weld joint and measured points of residual stresses are shown in Fig.2

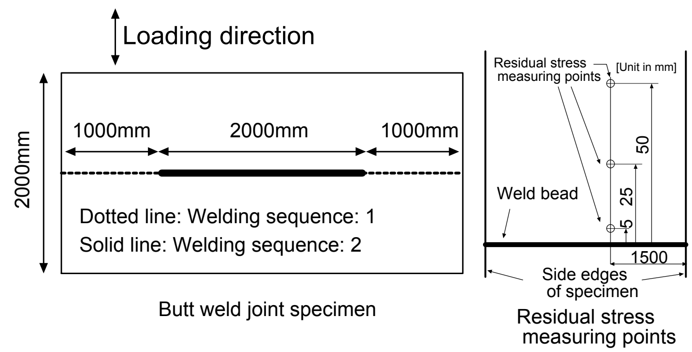

Fig.2 Specimen configuration and residual stress measuring points

The purpose of this large-scale testing was to simulate fatigue crack growth in a hull skin plate. Ship structures being exposed to waves will always experience the same load regardless of the length of the crack, or the response of the structure. In other words, a reduction in net section will make the structure increase its displacement, but the nominal stress in the remaining net section remains the same. By considering the type of loading for ships mentioned above, fatigue tests were performed in order to keep the constant net stress range whose setting value is about 120 MPa. That is, the maximum load was decreasing and the minimum load was increasing according to crack extension. Fatigue tests were terminated when crack length reached about 2,000mm.

No out-of-plane bending was occurred during the stable fatigue crack growth by monitoring strain gauge outputs put on both specimen surfaces. Photo of test rig are shown in Photo 1. Detailed experimental procedures are introduced in the reference (Bjørheim, 2006)

Photo 1 Overview of large-scale test-rig and specimen (Bjørheim, 2006)

OUTLINE OF FATIGUE LIFE ESTIMATION

Most of proposed fatigue crack growth estimation methods based on fracture mechanics neglect the role of the cyclic plasticity around a crack tip. Behaviour of cyclic plasticity near a crack tip affects the fatigue crack growth for the following reasons:

1. The alternating cyclic plastic works generated ahead of a crack tip supplies the driving force for fatigue crack.
2. The fatigue crack propagates in the plastic zone generated ahead of a crack tip. The plastic region is taken over the crack surfaces as the crack wake and the wake has an important contribution to the fatigue crack opening/closing, which dominates the fatigue crack growth.

An improved effective stress intensity factor range (ΔK_{RPG}) for use in the fatigue crack propagation law has been defined in order to represent the effect of cyclic plasticity behaviour ahead of a crack tip (Toyosada et al., 2004a). ΔK_{RPG} is formulated by replacing the crack opening load with the Re-tensile Plastic zone Generating load (RPG load) which was derived by considering the cyclic plastic behaviour ahead of a fatigue crack tip.

The fatigue crack growth simulation code FLARP, which enables the quantitative simulation of the fatigue crack opening/closing, has been developed (Toyosada et al., 2004a and 2004b). The main characteristics of FLARP are as follows.

1. Extended strip yield model is applied in order to describe the crack opening / closing by considering the role of crack wake on crack surfaces near a crack tip.
2. ΔK_{RPG} is adopted as the parameter for the fatigue life estimation. The definition of ΔK_{RPG} is

$$\Delta K_{RPG} = \left(S_{\max} - S_{RPG}\right)\sqrt{\pi a}\, f \quad (1)$$

   where $S_{\max}$ and $S_{\min}$ are the maximum and RPG stress, see Figs.3, 4, 6 and 7, a is crack length and f is the magnification factor. Fatigue crack propagation law based on RPG load is

$$da/dN = C\left(\Delta K_{RPG}\right)^{m} \quad (2),$$

   where $C = 4.5 \times 10^{-11}, m = 2.7$ unit in ΔK_{RPG} corresponds to MPa $m^{1/2}$. These material constatns can be applied to the rolled steels supplied for general welded built-up steel structures (Toyosada et al., 2004a).
3. Fatigue crack growth can be simulated in sound welded joints. The beahvior, whcich the tip of cyclic plasticity region is fixed during the fatigue crack initiates and propagates in the first grain, is considered in order to establish the scheme for the estimation of the fatigue crack initiation life. Detailed algorithm is described in the references (Toyosada et al., 2004b).
4. The effect of loading histories applied to structures can be taken into consideration quantitatively for the fatigue crack growth estimation.
5. The effect of the pre-existing residual stresses and the dead load (mean stresses) for the fatigue life can be considered.
6. The fatigue crack growth curve as a function of the number of cycles can be calculated.

Material constants and other coefficients are less than in other numerical simulation codes of fatigue crack growth. All the constants and coefficients in FLARP have physical meaning. Detailed explanation about each parameter's physical meaning is described in the references (Toyosada et al., 2004a).

FATIGUE CRACK GROWTH ANALYSIS

Numerical fatigue crack growth analysis code FLARP mentioned above section is applied in order to estimate fatigue crack growth curves for the experiments. The same material constants are applied to these calculations because the constants were obtained from specimens made of a similar grade steels and welded joints.

Specimens with base material

Twice experiments (Specimen BM1 and Specimen BM2) were performed for specimens made of base materials. Applied loading histories for both specimens are shown in Figs.3 and 4.

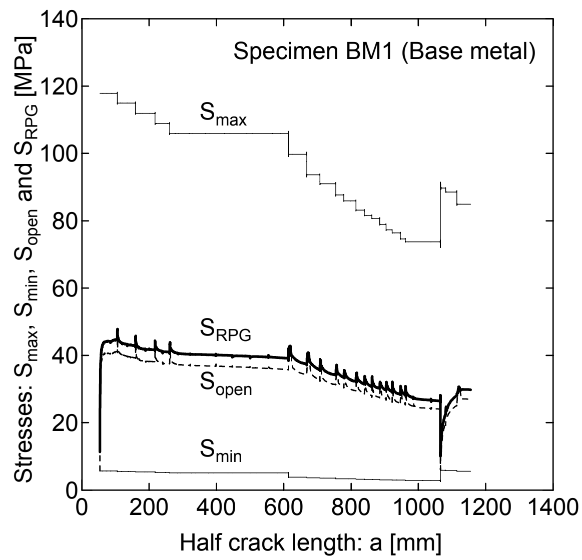

Fig.3 Histories of stresses for half crack length (Base metal, Specimen BM1)

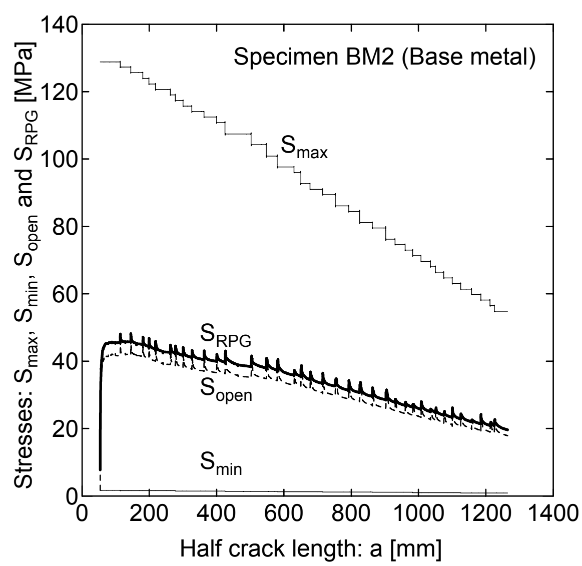

Fig.4 Histories of stresses for half crack length (Base metal, Specimen BM2)

The maximum (S_{max}) and minimum stresses (S_{min}) shown in Figs.3 and 4 are the nominal stresses measured and the maximum stress are decreasing and the minimum stress are increasing in order to keep constant net stress of specimen according to the crack extension. Experiment with Specimen BM1 was performed at the beginning. In this experiment, applied stress range seems to a constant during the crack length is from 200mm to 600mm. It is considered that this reason is insufficient load control in the experiment. In addition, both maximum and minimum stresses are increasing rapidly after crack length reach 1000mm. It is estimated by the observation during the experiment that the crack closure occurred at crack surfaces except in the vicinity of a crack tip. Then, crack wake except near a crack tip (about 100mm) was eliminated by gas cutting at adequate time intervals in order to prevent crack surface contact except near a crack tip in the following experiments.

RPG (Re-tensile Plastic zone Generating) and crack opening stresses obtained from numerical simulation code FLARP are also shown in Figs.3 and 4. RPG stresses (S_{RPG}) are drawn by bold curves and crack opening stresses (S_{open}) are drawn by dotted curves in each figure. Both RPG and crack opening stresses increase just after decreasing applied maximum stresses and have local maxima. Following by local maxima, both stresses approach certain constant values. This is so because the crack closure region at the minimum load extends due to decrement of the thickness of the residual tensile layer in the crack increment region and decrease of COD just after the maximum load. Consequently, the crack closure region extends over the crack surfaces at the minimum load and both RPG and crack opening stresses increases. Both stresses approach a stationary condition under current constant stress range according to fatigue crack propagation.

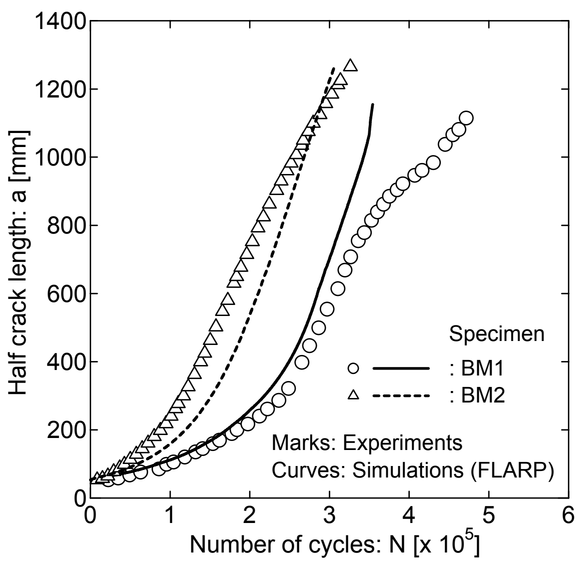

Fig.5 Crack propagation curves for base metal (Specimen BM1 and BM2)

Fatigue crack growth curves obtained from numerical simulations and measured results are shown in Fig.5. In Specimen BM1, calculated results do not show the retardation after half crack length reaches 800mm. The reasons are estimated as follows.

1. The effect of crack closure occurred after half crack length reaches 1000mm mentioned above. Measured fatigue crack growth curve in Specimen BM1 shows two retardation points, which half crack length is equal to 800mm and 1,000mm, respectively.
2. Applied stress ranges of half crack length between 960 mm to 1065mm is constant in the numerical simulation, see Fig.3. On the contrary, the retardation of crack extension is observed. Then, it is postulated that stress ranges were decreasing in order to keep constant net stress ranges during this period. The reason of discrepancy seems to be insufficient measurement of stresses during the experiment.

Considering the situation, which detailed information about the experiments cannot be obtained from the reference, it is confirmed that calculated results show a good agreement with measured ones.

Specimens with butt weld join of as-welded and of stress relieve treatments

Histories of each stress (S_{max}, S_{min}, S_{RPG} and S_{open}) for as-welded specimen (Specimen PL1) and stress relieved specimen (Specimen PL2) are shown in Figs.6 and 7 respectively. Behaviors of S_{RPG} and S_{open} after changing stress ranges are similar to the ones observed in base material specimens (Specimen BM1 and BM2) shown in Figs.3 and 4.

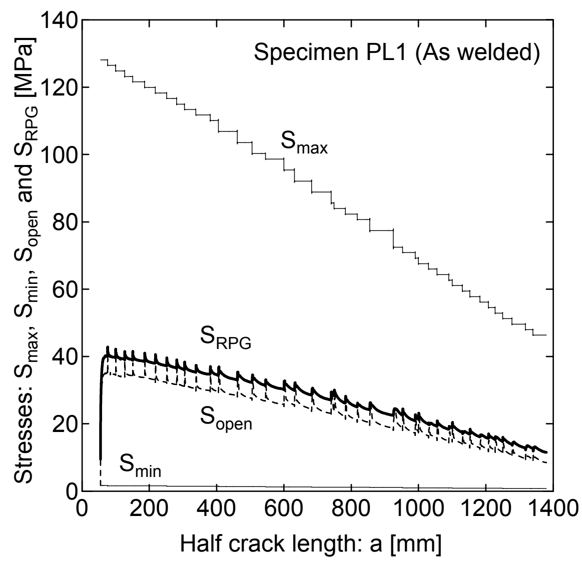

Fig.6 Histories of stresses for half crack length (As-welded, Specimen PL1)

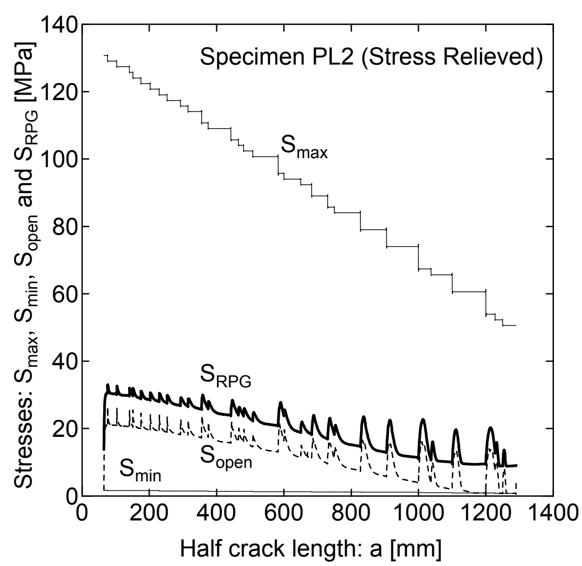

Fig.7 Histories of stresses for half crack length (Stress relieved, Specimen PL2)

Fig.8 is the comparison of fatigue crack growth curves between calculated results and measured ones. Residual stress distributions in each specimen are considered in the numerical simulations. Because residual stress distributions along a crack path (in this case, crack path corresponds to upper side weld toe) were not measured, these distributions are estimated by the following procedure.

1. Measured residual stresses at 1,500mm right edge of specimen are interpolated as a quadratic function and residual stress at weld toe is estimated as an extrapolation value. Extrapolation value of as-welded specimen is 20.4MPa and of stress relieved specimen is 71.4 MPa.
2. Referring to the general tendency of residual stress distribution of the restrained butt weld joint specimen with slit (Fujimoto, 1997), it can be seen that the residual stress distribution in the center of specimen keeps constant value. Because fatigue crack propagation region in these specimens corresponds to these constant residual stress regions, it is postulated that the residual stress distributions along a crack path keep the constant values obtained from the extrapolations.

It is considered that numerical fatigue crack growth simulations based on the strip yield model give valid results because the fictitious crack tip calculated in each simulations stays on the slit weld region where residual stresses set up the constant value.

It is confirmed that estimated fatigue crack growth curves have a good agreement with measured ones, although residual stress distributions are estimated from poor information.

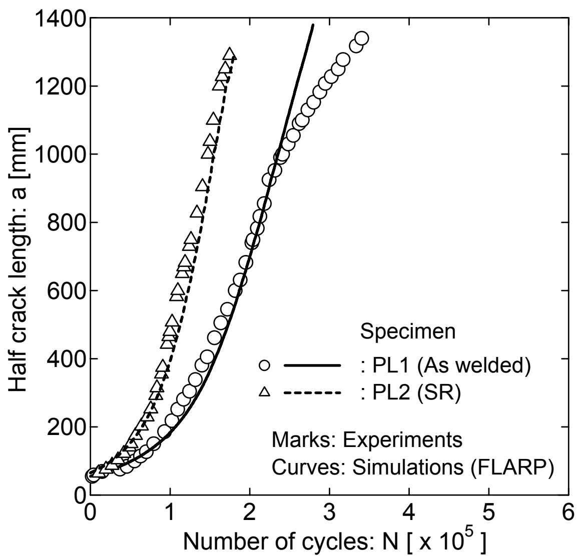

Fig.8 Crack propagation curves for as welded and stress relieved Specimens (Specimen PL1 and PL2)

CONCLUSIONS

Fatigue crack growth simulation for long through thickness cracks in large-scale specimens in imitation of ship hull skin plates are performed by applying fatigue crack growth estimation code FLARP developed by authors. Histories of stress range during the crack extension for each specimen and residual stress distributions for as welded and for stress-relieved specimens are taken into consideration by applying FLARP. Estimated fatigue crack growth curves by FLARP are good in agreement with measured crack growth curves. It is confirmed that FLARP enables to estimate the fatigue crack growth curves of long cracks in ship hulls.

In order to develop the fatigue life estimation based on proposal method, it is necessary for more complex and larger structures to validate the availability.

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