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ABSTRACT

The steel water gate, which received variable water pressure due to gap of water level between sea and balancing reservoir, damaged in its gate lip by fatigue crack. In order to find the cause of this damage, various investigate programs, including observation with microscope and measurement of stress and water level, were performed. By the comprehensive analysis of the results of these investigation programs, it was concluded that this damage was caused by the cyclic loading on the gate lip from the ground surface, and found out the relation between sea water level and stress occur at damaged point. After then, the damaged part was replaced with new reinforced element. In addition, for checking the effect of this measure, the crack growth estimation was executed with FLARP, the numerical simulation code which was developed by the authors. As the result of the numerical simulation, the crack growth curve became visible quantitatively, and it was confirmed that the possibility of the reoccurrence of the fatigue crack was removed by the measures which we took, under the assumed loading condition.

INTRODUCTION

The shell structural roller gate gives higher performance of water closing than other structural types, especially has higher structural stiffness than the girder type. It is the reason why this type is applied to large-scale closing gates that need a long span. Against the water pressure due to the difference of water level between front and back of the gate, in this type, side rollers perform mainly, and the frictional resistance due to contact between the bottom of the gate lip and the ground surface works at the same time. Thus, this cyclic loading due to the variation of water level could damage gate lip, especially the gate is put in bay for reclamation.

In general fatigue design works of the water gate, we only judge “brake or safe” using S-N curves (Wöhler curves) base on the results of fatigue tests with small test specimens under constant amplitude loading. This is the fatigue limit design. Thus, we neglect the effect of the history of variable amplitude loading on crack growth in real structural systems. If we run a simulation base on the crack opening/closing phenomena, as represented by the modified Paris-Elber’s law, we can carry out a fatigue life prediction considering the effect of the history of variable amplitude loading, in theory. But, even in that case, it is impossible that we consider the variation of threshold value of the effective stress intensity factor range based upon the crack closing load (ΔK_{eff}), and we have to presuppose an initial crack without considering the crack initiation period. Consequently, it is not exactly that we estimate the fatigue life quantitatively.

In sound structure, fatigue cracks are generated as small surface cracks along the line of stress concentration point, for example, welding toe of fillet weld. These cracks join together interfering with each other, and integrate together. And then, the surface crack grow to a through thickness crack. In order to estimate the fatigue life quantitatively, the authors developed a numerical simulation code “FLARP”[1],[2].

In the former part of this study, we investigated the damage condition of the gate leaf. Then we investigated that it was fatigue damage and assumed how the crack appeared in service period. In the latter part, we carried out numerical simulations of fatigue crack propagation with FLARP. In the result, we

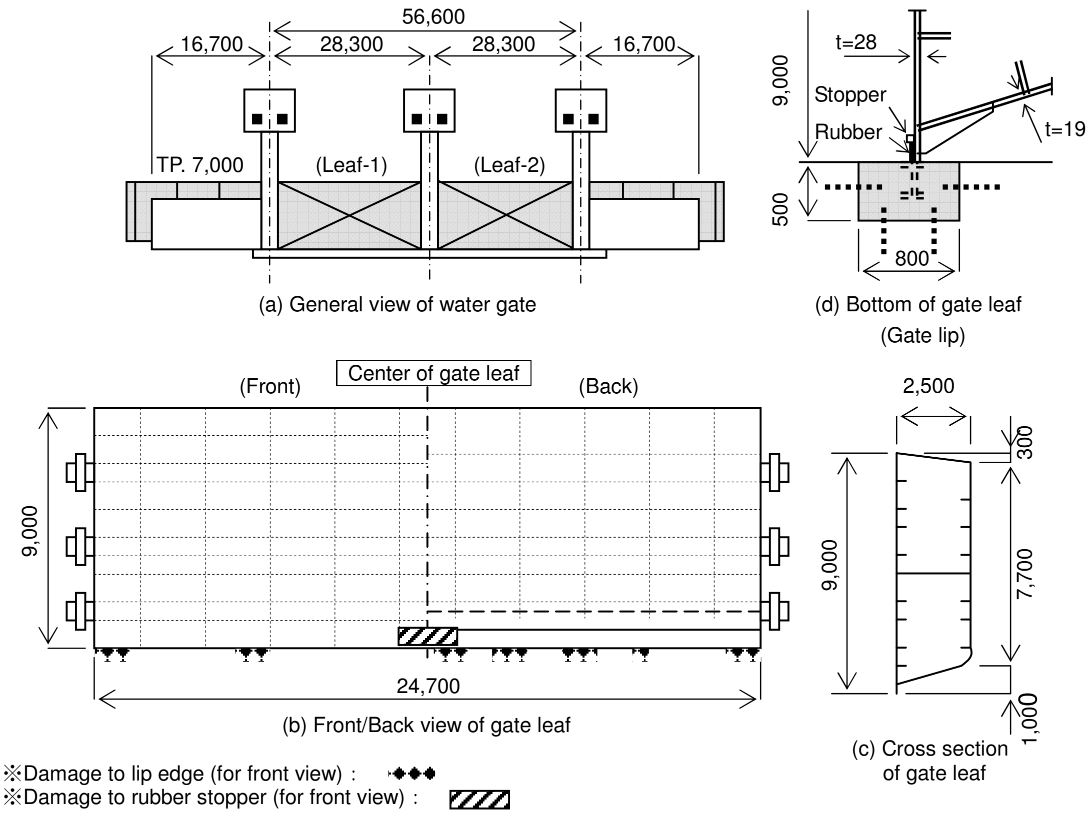


Fig.1 Steel water gate leaf [mm]

Table 1 Structural profile

Type	Steel roller gate
Size	width:25.0(m)×hight:9.0(m)
Weight	2589(kN)

Table 2 Structural material

Member	Material
Gate lip	SM490B
Reinforcing rib	SM490A
Rubber stopper	SS400

investigated the damage mechanism and verified quantitatively the effect of the reinforcement measures.

SUMMARY OF THE GATE LEAF

The object of this study is a steel water gate leaf which was put between sea and balancing reservoir, as a part of the dike surrounding reclaimed land. The summary of this structure is shown in Fig. 1 ,Table 1 and Table 2.

The object is categorized as the shell structural roller gate. This type has some guide rollers on each side faces of main steel box and a gate lip under the bottom. Compared within same type, the object has relatively tall gate lip, because it was designed for both direction overflows from front/back of the gate. Therefore, in order to improve the bending strength of the gate lip, reinforcing ribs are welded on the back surface of the gate lip. At the bottom of the gate lip, watertight rubber is attached with steel stopper.

INVESTIGATIONS AND MEASURES

3 years and 10 months after the starting of using of the gate, a thickness through crack was found out in the central part of gate span. It was a horizontal crack along the line of the root of the gate lip. In response to this inspection report, on-site investigation and laboratory tests, including material tests and fractographic studies were carried out. Based on the result of these reports, we assumed how these damages appeared and decided the reinforcement measure.

1. Results of the on-site investigations

a) By the magnetic-particle test, it was confirmed that the crack had grown along the welding line between gate lip and back plate and had a length of 1958[mm] (Fig.2, Fig.3).

b) Paint coating on the bottom surface of the gate lip was damaged by friction between the gate and ground surface. As shown in Fig.1, these damages were distributed throughout the gate span, but the most serious damage occurred in the central part, as the crack. By the level measurement of the gate and the ground, accuracy of dimension of these structures met design standards. But, even if within the permissible value, small error of level can contribute to the unbalanced friction between these members. In this case, it was guessed that the gate lip was received cyclic loading at the center of span of the gate by friction due to gap of water level between sea and balancing reservoir.

c) In the central part of the gate span, it was the most damaged area, some reinforcing lib were peeled from the welding seam.

2. Material tests

In order to verify the material quality, after the on-site investigation, the damaged part was cut off and a few material tests were carried out based on JIS3106. Collection positions of specimens are shown in Fig.3.

The result of tensile test is shown in Table 3, charpy impact test is in Table 4, chemical analysis is in Table 5. As the result of these tests, it was confirmed that material steel conformed to this standard.

3. Fractographic studies

In order to find out the cause of the crack initiation, fractographic studies were carried out with optical microscope and scanning electron microscope. Collection positions of specimens are shown in Fig.3. As shown in this figure, specimen A was took from the center of the gate leaf, specimen B was from the center of rib attached span, specimen C and D were from the sections at where typical fracture surfaces were seen. As the result of these studies, circular beach marks and striations were observed on the surface of A and C (Fig.4). In consequence, it could be presumed that the thickness through crack was due to fatigue.

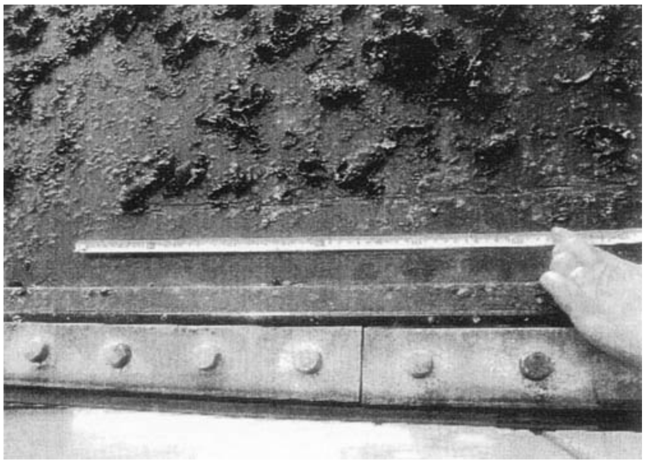


Fig.2 Horizontal through thickness crack at the root of gate lip (front view)

4. Reinforcing measurement

In response to the result of these investigations, it was presumed that the crack was a fatigue crack which was caused by cyclic loading to the bottom of the gate lip. By our supposition, because there were very small level gap between the bottom of the lip and the ground surface and they contacted each other in the central part of the gate span, friction between them were concentrated there. And by the change of the difference of water level between front and back of the gate, variable friction force was exerted to it. Consequently, as a measure, we attached a new gate lip, and increased the bending stiffness of the lip by addition of the reinforcing ribs.

Normally, the measures for fatigue damage should be taken after identifying the characteristics of cyclic loading and confirming the validity of the measures. But in this case, because there is an urgent need to repair and put the gate again to the original position, we decided to verify it after.

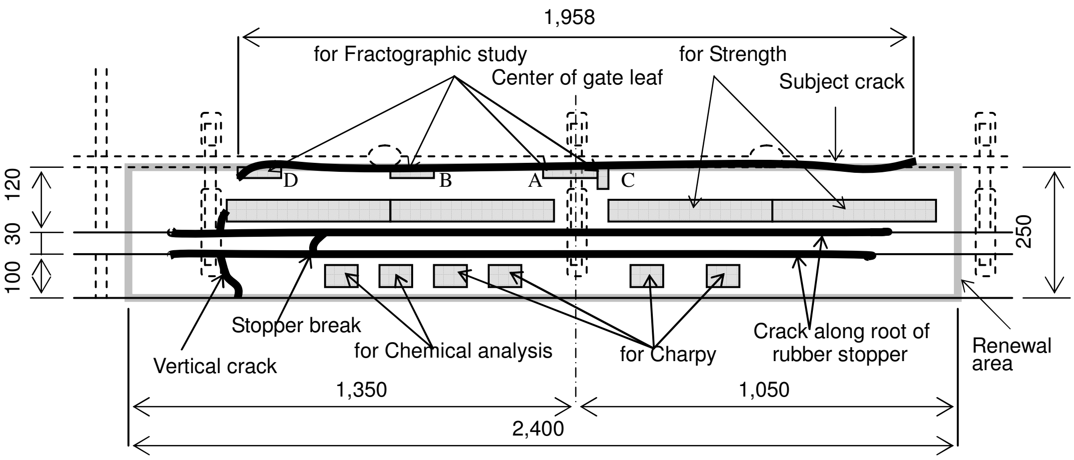


Fig.3 Collecting position of test pieces (front view) [mm]

Table 3 Results of Strength tests

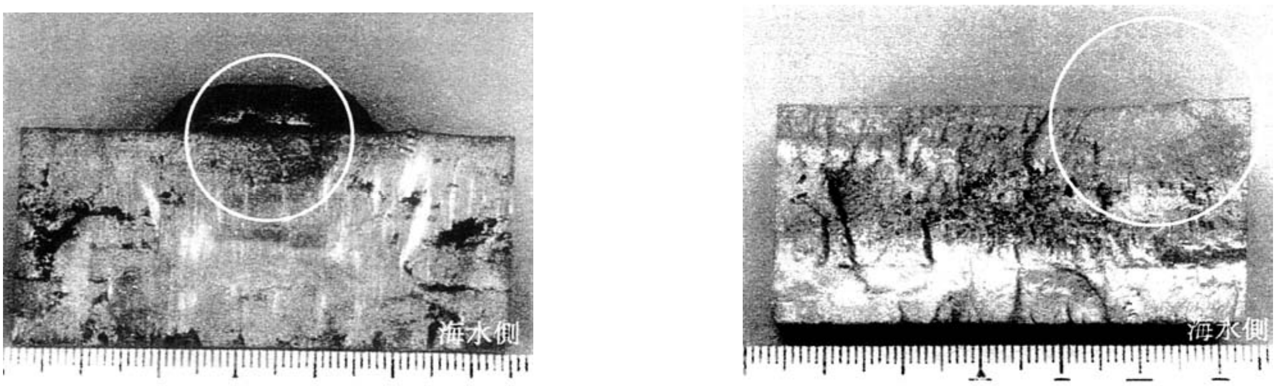
	Yield point or 0.2% proof stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Yield ratio (%)
Specimen	340	535	30	64
	323	537	28	60
JIS	over 315	490～610	over 21	－

Table 4 Results of Charpy tests

	direction	Temperature (℃)	Absorbed energy (J)		Brittle fracture surface(%)	
			measured	average	measured	average
Specimen	L	0	165	177	40	35
			181		35	
			185		35	
	C	0	84	87	75	75
			93		70	
			85		75	
JIS	－	0	－	over 27	－	－

Table 5 Result of Chemical analysis

	Chemical component (mass%)				
	C	Si	Mn	P	S
Specimen	0.17	0.38	1.46	0.015	0.005
JIS	under 0.18	under 0.55	under 1.60	under 0.035	under 0.035



(a) Specimen A (b) Specimen C

Fig.4 Fracture surface of the thickness through crack

WATER LEVEL AND STRESS MEASUREMENT FOR CRALIFICATION OF FATIGUE DAMAGE

In order to understand the relation between water level and stress in the lip, which was thought to attribute the fatigue damage, measurement of water level and stress were carried out. Based on the results of these measurements, we considered the behavior of the gate and determined what led to the through thickness crack.

1. Measuring method

By the stress measurement, stresses on the back surface of the lip were measured in vertical (height of the gate) and horizontal (width of the gate) direction. For the measuring, some biaxial gauges were put in the central area of the gate, as in Fig.5.

The measuring was constantly carried out for 21 days, from 11th April to 1st May of one year, without short period for collecting the measured data each night. Because 13th April was with new moon and 27th April was with full moon, it can be

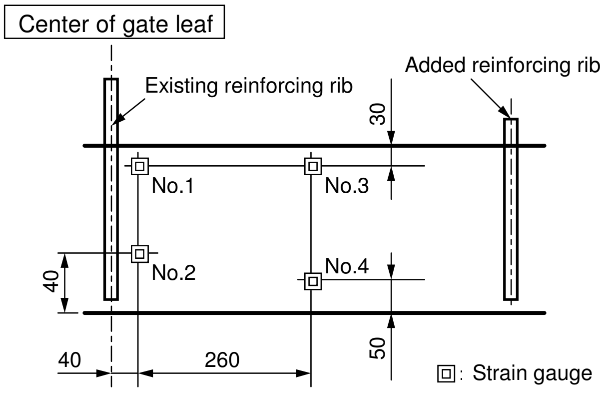


Fig.5 Location of strain gauge (back view) [mm]

said that the measuring period covered 1/2 synodic period. During the period, the gate was opened at high tide for charge of seawater to the balancing reservoir and at low tide for discharge the pool water. That means the gate lip was free from the friction force about twice a day.

2. Result of measurement

Fig.6 shows the time history of measured vertical stress with No. 3 gauge, which was the most dominant factor for initiation and propagation of the crack, with tide level and pool water level. Fig.7 showed the relation between measured stress and the relative water level, which was gap between tide level and pool water level, for some terms, which were separated from the measuring period as shown in Fig.6. And the local maximum values and the local minimum values were plot based on the relative water level in Fig.8.

1) TERM-1 (Fig.7(a)) and TERM-6 (Fig.7(d)) correspond to the period of spring tide. As shown in these figures, the hysteresis curves draw large trajectory, it can be said consequently that there is strong nonlinearity in the relation between them. And as shown in Fig.8, measured stress are distributed within ±50[N/mm^2], we can see the upper/lower limits which are independent of the relative water level. Thus, for these terms we can say as below. For small relative water level, there was no slippage between the lip and the ground surface, and the lip received large friction force at the bottom. But for large relative water level, the lip slipped on the ground surface, and the friction force decreased.
2) TERM-3 (Fig.7(b)) corresponds to the period of neap tide. In the figure, we can not see the nonlinearity in the relation between them, but we can see that measured stress depend on the relative water level. Thus, in this term, we can say that there was no slippage between the lip and the ground surface, and the lip repeated to transform in response to changes of the water levels around the gate.
3) TERM-5 (Fig.7(c)) corresponds to the period of spring tide, too. As shown in the figure, we can see the nonlinearity between them as well as in TERM-1 and TERM-6. But as shown in Fig. 8, in this term, measured stress are distributed within ±100[N/mm^2] unlike TERM-1 and TERM-6. For this difference, it might be caused by the condition of contact.
4) TERM-2 and TERM-4 correspond to the transition period between these characteristic periods, and did not show any regularity on the relation between measured stress and the relative water level.

3. How the crack damage occurred ?

Based on the result of the investigations and the measurement, we determined how the crack damage occurred as below.

The gate was put in the bay which has large variation of tide, as the maximum tide variation was measured 4.5[m] in the measuring period. Compared with normal situation, it was a hard situation which the gate receive large variable water pressure. When the gate receives water pressure due to the difference of water level between front and back of the gate, side rollers perform mainly the and the body deform elastically.

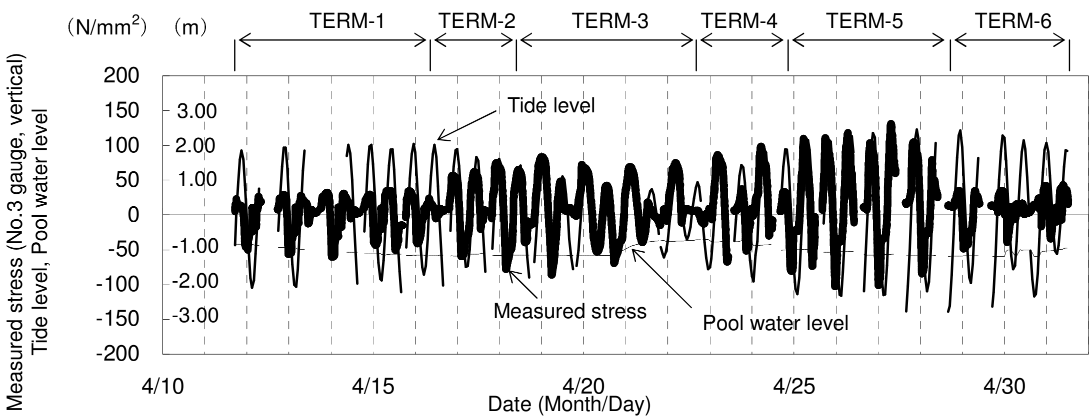


Fig.6 Result of the field measurement

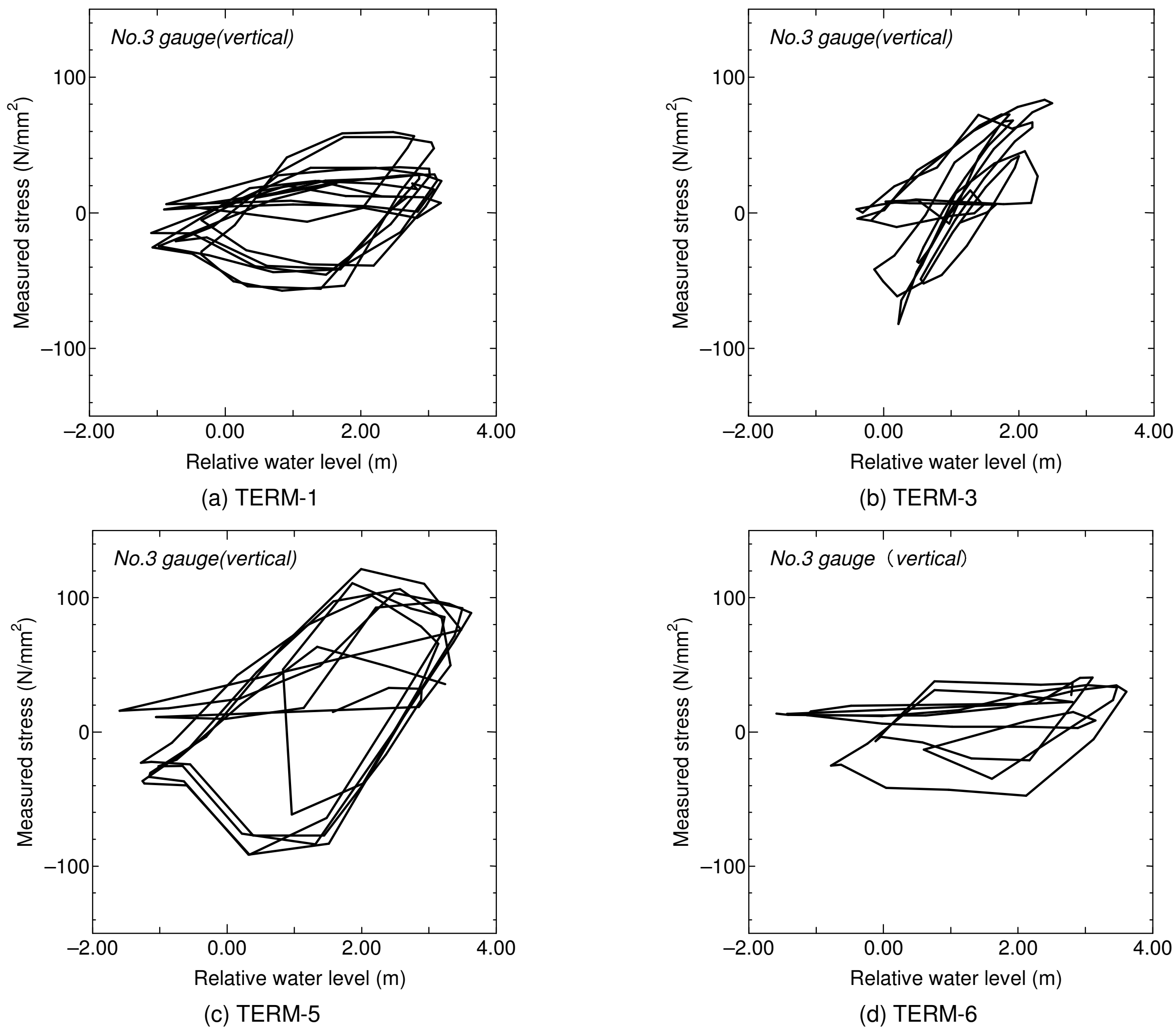


Fig.7 Relation between relative water level and measured stress

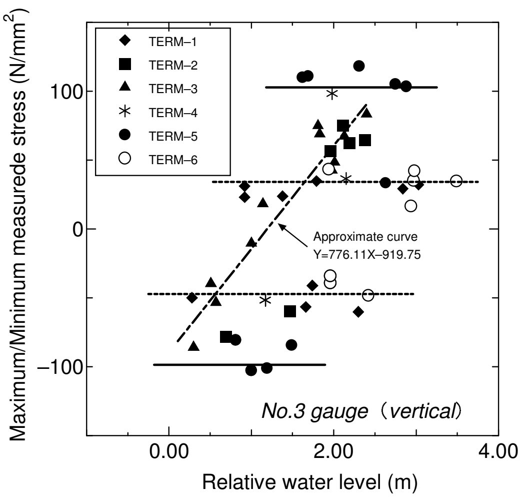


Fig.8 Relation between relative water level and Max./Min. measured stress

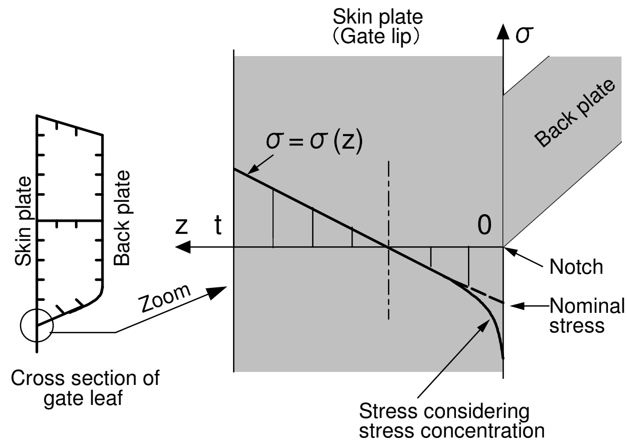


Fig.9 Stress distribution in skin plate

At the same time, the bottom of the lip receives the friction force, while slipping or stopping on the surface of ground. The friction force is not distributed on the bottom of the lip equally, but variable depending on the situation of contact between the lip and the ground.

In the case of this gate, the contact surface of them was arranged at the center of the span. Therefore, root of the lip was received large cyclic bending moment due to the concentrated frictional loading to the bottom of the lip. And in the perpendicular direction to the weld line between the lip and the back skin plate, stress was amplified by the notch effect. In the result, fatigue crack initiated from the root of notch and grew to the thickness thorough crack.

NUMERICAL FATIGUE LIFE PREDICTION BASED ON CRACK OPENING/CLOSING PHENOMENA

Numerical simulations of fatigue crack propagation were carried out with FLARP, which was developed by authors et al.. In these studies, we set a target period of simulation from the start of service to the moment when the crack grow to plate thickness, based on the opinion that passing through the thickness of the plate member is the most specific situation to define the hazardous fracture for the structures. And we set the crack pass as a thickness direction strait line from the notch root of the weld toe, based on the opinion that fatigue crack make progress nearly in the vertical direction to the plate surface under condition that the bending moment is distinguished[3] like this case.

1. Stress distribution in the lip plate

a) Stress concentration by notch

In the lip plate, as shown in Fig.9, stress is distributed under influence of notch effect. Distribution of conventional stress was calculated by elastic FEM analysis with a half gate leaf model, which was constructed with shell elements, as structural engineers did generally in their design work.

The stress concentrate factor was obtained as Eq.(1.a) and Eq. (1.b)[4].

$$K_t = 1 + \left\{0.629 + 0.058 \cdot \ln\left(\frac{S}{t}\right)\right\} \cdot \left(\frac{\rho}{t}\right) \cdot \tanh\left(\frac{6h}{t}\right) \cdot f_\theta \quad (1.a)$$

$$f_\theta = \frac{1 - \exp\left\{-090\sqrt{\dfrac{t+L}{2h}} \cdot \theta\right\}}{1 - \exp\left\{-090\sqrt{\dfrac{t+L}{2h}} \cdot \dfrac{\pi}{2}\right\}} \quad (1.b)$$

where S is a size of the appendage ($S = t + 2L$ in case of T shape joint), t is the thickness of the lip plate, ρ is radius of the notch, h is height of the welding leg, f_θ is the influence function of flank angle θ. In this case, because the shape of welding point had not been measured in detail, we assumed the radius of the notch as 1.0[mm], which was a general value in the large structures like bridges and ships, the height of the welding leg as 19[mm], which was thickness of the back plate, and the flank angle as $\pi/4$ [rad.], which was from ideal welded shape. Consequently, the stress concentrate factor K_t was 2.87.

Based on the stress concentrate factor, stress distribution influenced by notch effect was calculated with Eq.(2)[5].

$$\sigma(z) = K_t \sqrt{\frac{\rho}{\rho + 4z}}\,\sigma_0(z) \qquad \left(0 \le z \le \sqrt{\rho/2}\right) \quad (2)$$

where $\sigma_0(z)$ is the nominal stress without the influence of notch effect.

b) Weld residual stress

In these studies, because there was not enough information for calculating the weld residual stress, referring WES2809[6], residual tensile stress was assumed as the of the 1/3 yield point of the material of the lip, as Eq.(3).

$$\sigma_R = \sigma_Y / 3 \quad (3)$$

where σ_R is the weld residual stress, σ_Y is the yield point of SM490B.

2. Variable relative water level model

In the objected gate leaf, constant stress by the self load, constant weld residual stress and variable stress by relative water level occurred. About the variable stress, in case of that the linear relation between the relative water level and occurring stress is figured out, like TERM-3, if the distribution of stress by the unit relative water level was known, we can obtain the distribution of variable stress in the lip by multiplying the relative water level to this distribution.

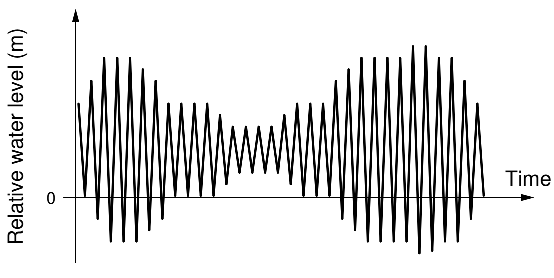
a) Effect of tide

In order to make input relative water level data for the long period of fatigue life assessment, from the measuring period of 21 days, the measuring result for 15 days, which is corresponding to 1/2 synodic period, were extracted and aligned it repeatedly (Fig.10(a)).

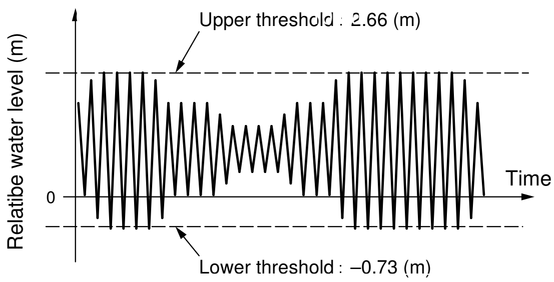
Note that in case that the nonlinearity in the relation between the relative water level and measured stress and the upper/lower limits of stress are found, like TERM-1, 5 and 6, input relative water level data is used with setting thresholds, which are corresponding to the upper/lower limits of measured stress, as shown Fig.10(b).

b) Effect of wave

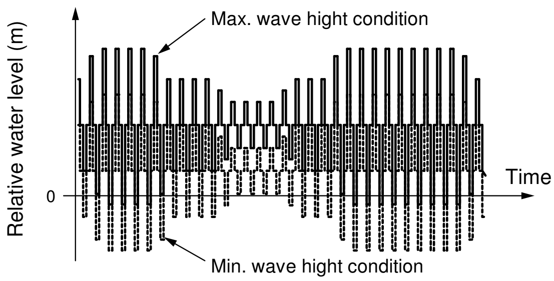
It is difficult to measure the variation of level by ocean wave, because it varied widely and the wave cycle is too short to measure. Thus, considering that the gate was put in a comparatively quiet bay, we assumed the wave height as 1.0[m][7] and wave frequency as 10^8[wave/20-years][8].



(a) Measured value



(b) Modified with thresholds



(c) Considering wave effect

Fig.10 Relative water level model

In contrast, because the variation of pool water level was smaller than ocean and has difference wave cycle from bay's, we saw no need to consider it and assume that it was constant

c) Input relative water level model

Input variable relative water level data was obtained by superimposing the wave effect on the time history of relative water level. In doing so, measured time history of relative water level was used after simplified with maximum, minimum and average value as shown. (Fig.10(c))

3. Crack initiation life and crack propagation life[1],[2]

a) Crack initiation life

Under normal service condition, fatigue crack comes into existence as some slip lines in the crystal grain (The first crystal grain), which is at stress concentrate point like notch root of the fillet welded joint. Then these lines change into shear crack

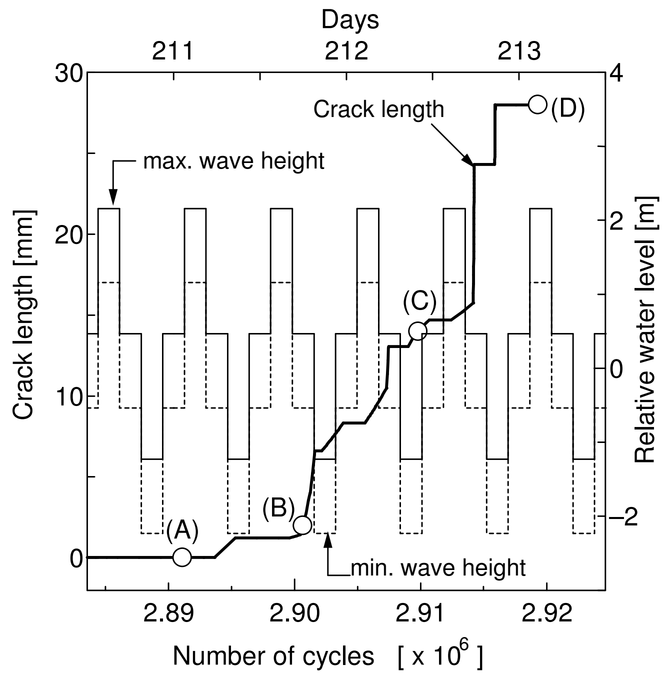


Fig.11 Result of simulation: Crack growth curve (before reinforcement)

(mode II), and the shear crack grow to the first grain boundary. When the shear crack reach the boundary, the crack make the act of opening/closing phenomena (mode I), because the direction of the slip band is deferent between grains laying side-by-side. In this simulation, we assumed the scale of the first crystal grain as 0.03[mm], which is normal scale of steel for these structures, and defined the crack initiation life as the period from start of the service to the moment when crack grow to the first grain boundary.

b) Crack propagation life

After initiation period, opening type surface cracks appear in the welding line. These surface cracks grow combining into one and became a thickness through crack. In this simulation, for the surface crack, we presumed these surface cracks as a semiellipse and obtained the relation between the depth of the surface crack, which was the reference crack length, and stress intensity factor (a-K relation). The simulation was carried out on the reference crack length with this a-K relation.

RESULT OF THE NUMERICAL SIMULATION

1. Result for before reinforcing

Fig.11 shows the crack growth curve for before reinforcing and the input relative water level, but only maximum wave height and minimum wave height. In this figure, (A) means the moment when the crack reach the first grain boundary, (B) means the moment when the crack length grows to 2[mm], which can be checked with eyes, (C) means the moment when the crack length reach 14[mm], which is 1/2 depth of the lip plate and (D) means the point when the crack reach the depth of the lip plate. From this result, it was supposed that the crack grew to the plate thickness 213 days, about 7 months, after start of the service.

The object crack was found as a thickness through crack about 3 years and 10 months after start of the service. By this simulation, it was supposed that the crack took 213 days for growing to the plate depth, and after then, grew to the length of 1958[mm].

2. Result for after reinforcing

The crack could not initiate under the presumed loading condition, which was reduced by the reinforcement measurement. It means that the measurement prevent the initiation of fatigue crack, except when the thickness of the lip is reduced by corrosion, etc., under the presumed loading condition.

CONCLUSIONS

1. The cause of the fatigue damage

In case that the water gate is put in the place at where the large variation of water level exists, for example, as a part of the dyke surrounding reclaimed land and at the mouth of a liver, it is possible that the gate receives variable cyclic loading due to the difference of water pressure between front and back of it. As the result, the supporting points of the gate, for example, gate lip, could suffer from fatigue and friction.

In case of this study, addition of reinforcing ribs was effective in reducing the stress induce the fatigue damage at the weak point, the root of the gate lip.

2. Results of the fatigue life assessment

As the result of the numerical fatigue life assessment for before reinforcing, under presumed loading condition, it was supposed that the crack grew to the plate thickness 213 days, about 7 months, after start of the service. And as the result for after reinforcing, it was confirmed that the reinforce measurements could prevent the fatigue damage which we subjected.

3. Applicability of FLARP on the real structures

It was confirmed that by the use of FLARP, we could study the fatigue crack initiation and propagation in the real structures continuously and quantitatively, and obtain the fatigue the crack growth curve. In consequence, this simulation code may have applicability to design of not only new structures but also repairing and reinforcing.

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