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Prediction of Fatigue Crack Propagation of Double Surface Cracks by "SCAN"

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ABSTRACT

The authors have proposed an influence function method by which stress intensity factor, K, of surface cracks can be calculated easily for arbitrarily distributed surface stresses. They have developed the database of influence coefficients, Kij, for various types of surface cracks through a series of finite element analyses [1]. And they also have developed a software system “SCAN”, based upon the above developed database, by which K-values of surface cracks can be evaluated promptly, and further, fatigue crack propagation can be simulated easily by a personal computer.

In this paper the authors have studied how they can apply the SCAN system to the problem of the double coplanar surface cracks. They have developed ″ SCAN-Double Crack Version″ ,where SCAN is improved by following the scenario described in ASME Code Section XI [2].They have found that the database of a surface crack in a flat plate already installed in the SCAN system can be applied to this problem with satisfactory accuracy, which means the K-values of this problem can be evaluated promptly by the SCAN system and the fatigue crack propagation of double cracks can be simulated easily with “SCAN-Double Crack Version”.

KEY WORDS: stress intensity factor, surface crack, influence function method, double coplanar surface crack, fatigue crack propagation, Paris’ law, ASME Code Section XI, SCAN.

INTRODUCTION

There are many investigations about the simulation of fatigue crack propagation for a single surface crack existing in a structural component. But there are many cases where plural surface cracks initiate and propagate, and then they coalesce into a single large crack. Such cases quite often happens when cracks initiate at the stress concentrated parts such as along a welding line or at the notch root. In this case the simulation of fatigue crack propagation is rather difficult because we have to think of the effect of interference of the two neighbouring cracks. In this paper the authors have proposed a simple approximation model to simulate the fatigue crack propagation for arbitrary combination of double coplanar surface cracks against arbitrarily distributed surface tractions.

The authors have proposed an influence function method by which the stress intensity factors of the surface cracked components can be calculated easily against arbitrarily distributed surface stresses on the cracked surface. And they have developed the database of influence coefficients, Kij, for various types of surface cracks. These are semi-elliptical surface crack and quarter elliptical corner crack in a rectangular plate, respectively, part-elliptical surface crack in a round bar, and longitudinal and circumferential surface crack on the inner or outer surface of a pipe. Further, the authors have developed a software program, called "SCAN", that is, Surface Crack ANalysis program, by which they can calculate K-values and simulate the fatigue crack propagation easily on a personal computer for these surface cracks against arbitrarily distributed surface stress on the cracked surface.

However, at the moment, in the SCAN system, there exists no database for the double surface cracks. Since the double surface cracks have various parameters, enormous amount of FEM analysis are necessary to develop those databases. In the present study, the authors have proposed a simple model based upon the ASME Code Section XI, and they have applied the SCAN system to the problem of the double surface cracks. In this paper, they will describe how the database of double surface cracks have been approximated by those of a single surface crack in a flat plate already installed in the SCAN system, and how we can calculate K-values and simulate fatigue crack propagation easily by the SCAN system. Finally, they will show that the proposed approach is reasonable to predict the experimental results.

SOFTWARE SYSTEM “SCAN”

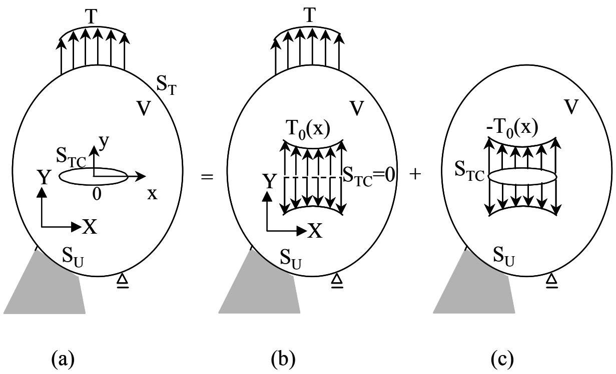
According to the procedure of the proposed influence function method, the value of K can be calculated by superposing the data of Kij and σ_j through the algorithm of Eq.(1) (See Fig.1 and Fig.2),

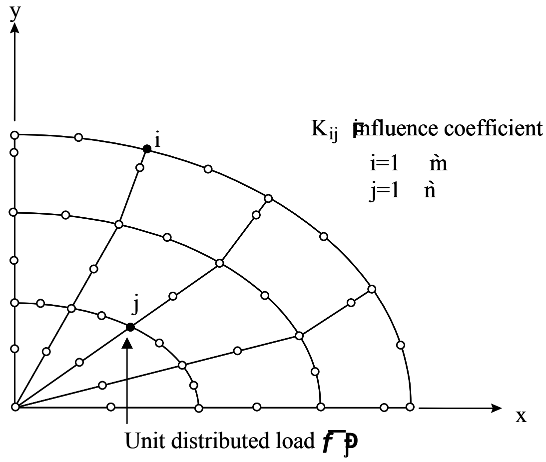
$$K_i = \sum_{j=1}^{n} K_{ij}\sigma_j \qquad (1)$$

where Kij is the influence coefficient of the stress intensity factor defined by K-value at the point i on the leading edge of the surface crack due to the unit distributed load $\overline{\sigma}_j$ applied at the point j on the cracked surface, σ_j is the value of arbitrarily distributed surface stress on the cracked surface at the point j, and Ki is the value of K at the point i due to the distributed stress described by σ_j.

Therefore, if the database of Kij is previously obtained, it is only the matter of obtaining σ_j, which is the surface traction on the virtual crack face, obtained through the stress analysis of uncracked body as shown in Fig.1(b). The uncracked body can be often approximated by the two-dimensional or axially symmetric problem, it is easy to carry out the stress analysis. Fig.3 shows the flow of the K-analysis based upon the proposed influence function method. In the previous paper[1], some examples were presented to show how the proposed method is effective to calculate K of the surface cracks in such complicated stress fields as thermal stress, residual stress, and the concentrated stress at the notch root.

It has been shown that the proposed influence function method is very effective and useful, but, at the moment, the analysis of K based on the method can be carried out only by authors since the database is owned only by them. It is much more useful to publish the database to the open domain for everyone to make use of it. But the database itself is composed of a great amount of numeral lists, and it is very difficult to make use of it directly for the general users other than authors. Therefore, it may be the best way to make a software system, where the database is installed, and by which the analysis of K and the following simulation of fatigue crack propagation can be carried out easily by a personal computer. The authors have developed such a software system and named it "SCAN", that is, surface crack analysis system. Details of the developed system are described in the reference [3].





K_{ij}

Fig.1 Principle of superposition applied to the crack problem • • • • • • Fig.2 Definition of the influence coefficient

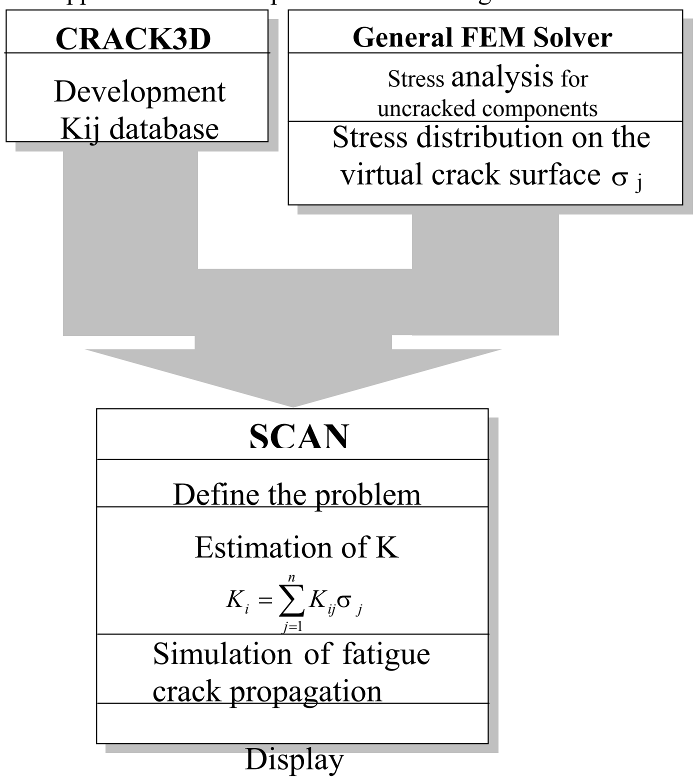


Fig.3 Flow of the K-analysis and fatigue crack propagation based upon the proposed influence function method

APPLICATION OF THE SCAN SYSTEM TO THE DOUBLE SOURFACE CRACKS

A simplified simulations model

Fig.4 shows a model of the double coplanar surface cracks existing in a flat plate, where a1, a2: depth of the cracks, c1, c2: half crack length, s: distance between the two cracks, t: thickness of the plate. When alternating stresses are applied perpendicular to the cracked surface, the two cracks will propagate gradually and coalesce into a single crack as illustrated in Fig.5. When the two cracks approach very close, the K-value at the nearest points are affected by the existence of the opposite crack. It increases remarkably as the distance, s, decreases and coalescence will occur rapidly. It is very difficult to simulate this process rigorously, since we have to calculate the change of K-value by accounting the interference effect at every step of the fatigue crack propagation. Therefore, we will neglect this interference effect and adopt a simple model proposed by ASME Code Section XI, where as shown in Fig.5 it is supposed that each crack propagate independently until the edge of the crack contact each other, i.e., the distance, s, becomes zero, at which these two cracks can be regarded as a single crack with the depth and width defined by $a\text{-}_{ASME}$ = Max(a1,a2), $c\text{-}_{ASME}$ = c1+c2. Through the above assumption we can make use of the Kij database for a single surface crack already installed in the SCAN system. By using the database we have developed a new version of SCAN system specified for the fatigue crack propagation of the double cracks. The algorithm of the fatigue crack propagation is the same as used in the SCAN system, that is, we use the most typical Paris' law.

$$\frac{da}{dN} = C(\Delta K_a)^m \qquad \frac{da}{dN} = C(\Delta K_c)^m$$

where •Ka and •Kc are the ranges of K against the applied stress range at the deepest and surface points of the crack, and C and m are the material constants describing the Paris' law.

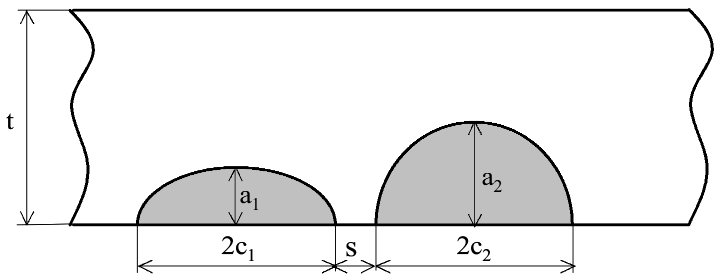
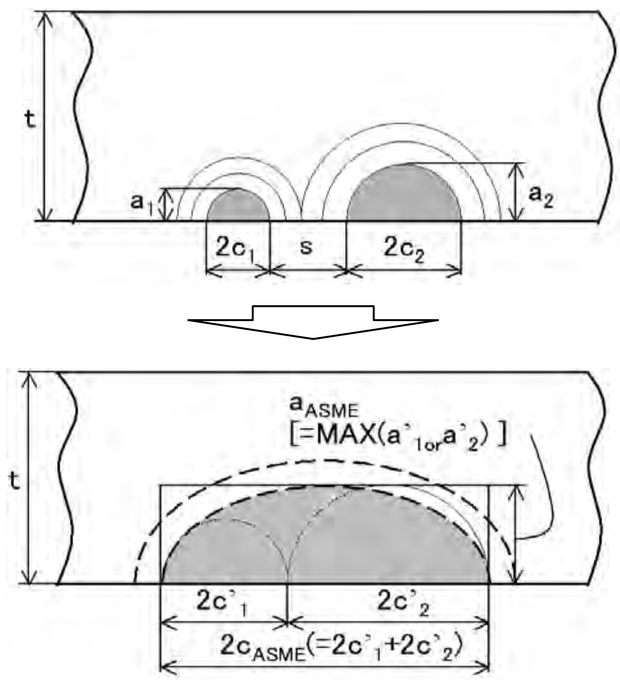
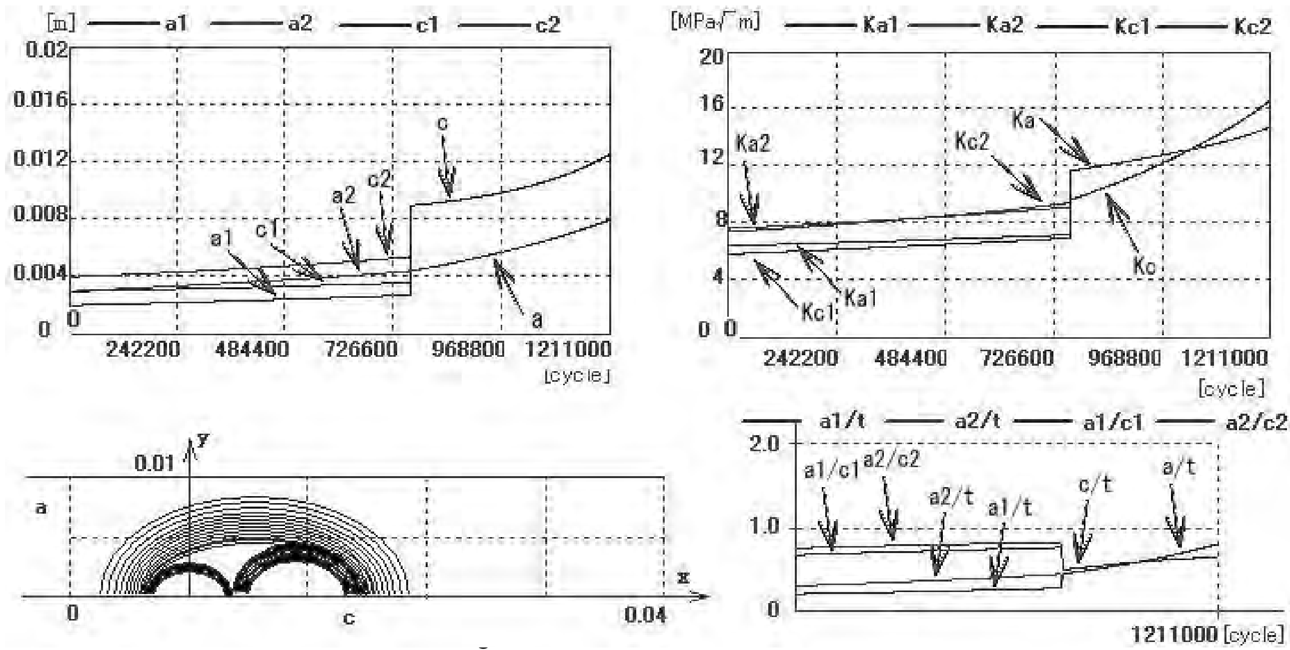


Fig.4 The double surface cracks model



Results of the simulation

Fig.6 shows an example of fatigue crack propagation by the proposed model for the case of the two initial cracks a1 = 2.0, c1 = 3.0 and a2 = 3.0, c2 = 4.0 with s = 2.0 and t = 10.0(mm), against the uniform pulsating stress. The two cracks propagate independently until about 730,000 cycles at which they coalesce together into one crack, then you can see the discontinuity of a, c, and K-values at this stage, respectively. After this stage the coalesced crack will propagate as a single crack.



EXPERIMENTS OF THE FATIGUE CRACK PROPAGATION WITH DOUBLE INITIAL CRACKS

In order to study how the proposed model can describe the behavior of fatigue crack propagation for double initial cracks, the authors have carried out a series of experiments. Fig.7 shows the specimen with two surface notches which are produced by the electro-dischange method. The material used for the test number 1,2,3, 6 and 7 is YP40 steel, a carbon steel for ship building, with $\bullet_u$ = 540MPa and$\bullet_y$ = 415MPa. In this case the material constants C and m characteriging the Paris'law is C = 4.23×10^{-12} , m = 3.0 in SI unit. But the material for the cases of the specimen 4 and 5 is a little different, that is, A533B-1 steel with the values of C = 2.07×10^{-12}, m = 3.17 [4]. A uniform pulsating stress with the stress ratio of 0.1 were applied to the specimen with a 10 ton fatigue machine at room temperature. The test speed was 10Hz for every case. Table1 shows the specifications of the specimens, applied stresses and the values of C and m.

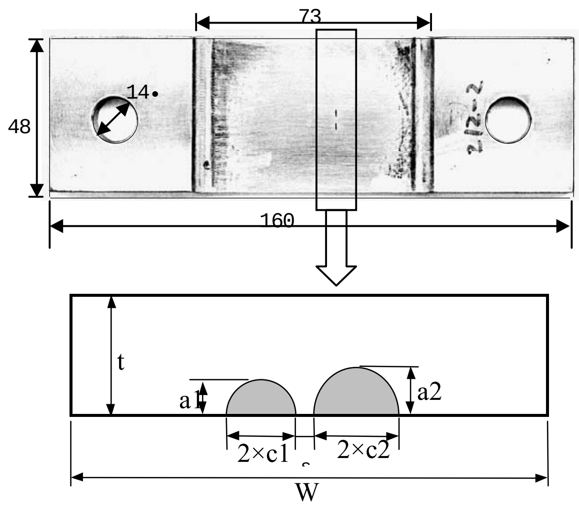


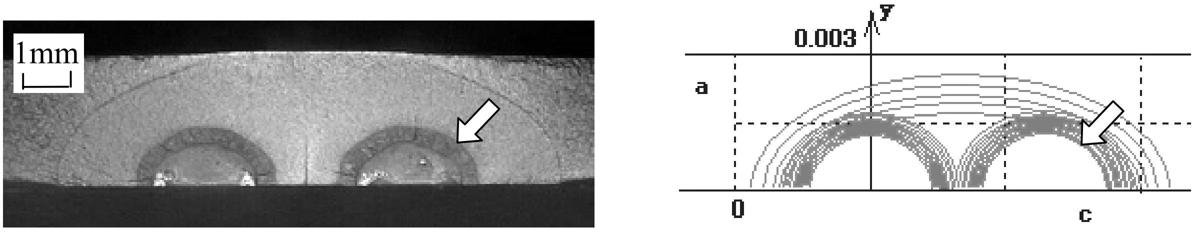
Fig.7 Notch part section

Table1 Specifications of specimens, applied forces and material constants

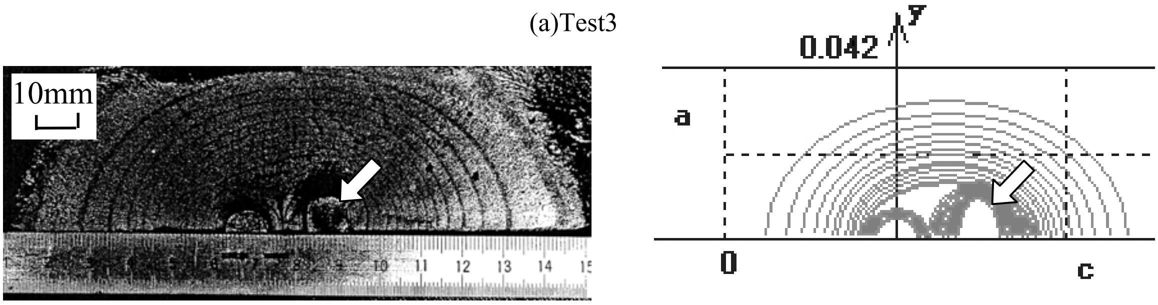
Test No.	1	2	3	4	5	6	7
a1(mm)	1.67	1.39	1.22	5.00	5.00	1.30	1.24
2c1(mm)	3.70	2.73	2.68	10.00	10.00	2.88	2.45
a2(mm)	1.75	1.26	1.24	10.00	10.00	1.20	1.20
2c2(mm)	3.61	2.67	2.71	10.00	10.00	2.72	2.50
s(mm)	0.26	1.27	1.15	10.00	30.00	1.11	1.54
t(mm)	5.00	5.00	3.00	42.00	40.60	4.00	4.00
W (mm)	48.00	48.00	48.00	180.00	180.00	40.00	40.00
ƒ max(Mpa)	332.00	332.00	333.00	218.00	218.00	332.00	332.00
ƒ min(Mpa)	32.00	32.00	33.00	22.00	22.00	32.00	32.00
C	4.23x10-12			2.07x10-12		4.23x10-12	
m	3.00			3.17		3.00	

SIMULATION OF EXPERIMENTS BY SCAN

Fig.8 shows the beach marks of fatigue crack propagation obtained through the experiment for the case of (a) test3 and (b) test4, respectively. These are compared with the simulated results by SCAN. You can see nearly the same pattern is obtained for each cases compared. Therefore, as far as the pattern of fatigue crack propagation of double cracks is concerned, the assumption based upon the ASME Code Section XI can be regarded as reasonable. Further, Table2 and Fig.9 show the comparison of the numbers of cycles at leakage between the experiment and the simulation by SCAN. In the SCAN system it is difficult to simulate the exact number of cycles at leakage because it is difficult to calculate K-values just before the leakage. Therefore, it is assumed in the SCAN system that the leakage will occur just after the value of a/t approaches to 0.8. Since the size of the crack is large enough for a/t •••0.8, the number of cycles of this crack to leakage is small enough to be neglected. Fig.9 shows that all results fall nearly on the solid line showing Nf = Nfs with the scatters within the two dotted lines showing Nf = 2Nfs and Nf = 1/2Nfs. Where Nf and Nfs are the numbers of cycles at the leakage obtained by the experiment and the simulation, respectively. This means that the experimental fatigue crack propagation lives at leakage can be well estimated through the simulation by SCAN as a first-order approximation within the scatter of so called " double or half" scatters.



(a)Test3



(b)Test4

Fig.8 Shape of fatigue crack propagation

Table2 Numbers of cycles at leakage

Test No.	1	2	3	4	5	6	7
SCAN•Nfs•	34200	63700	40700	182400	206400	51900	38200
Exp•Nf•	58494	89935	32910	144170	161830	40067	69162
Nf/Nfs	1.71	1.41	0.81	0.79	0.78	0.77	1.81

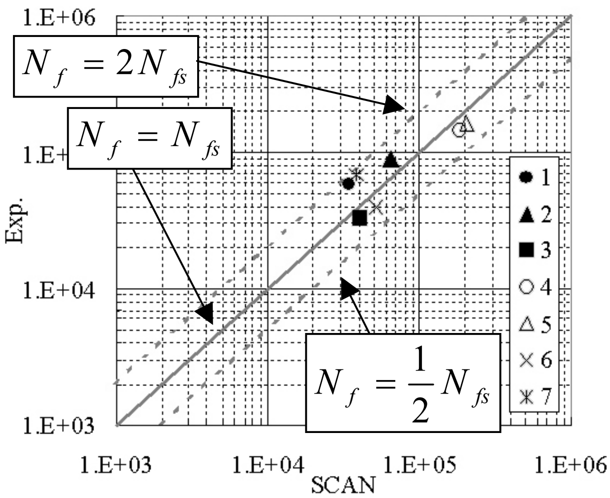


Fig.9 Comparison of numbers of cycles at leakage between the experiment and the simulation by SCAN

DISCUSSION ABOUT THE SAFETY MARGIN OF THE SIMULATION

As reviewed in the previous section, the proposed simulation approach by SCAN system combined with the ASME Code Section XI can give a good estimation for both of the patterns and leakage lives of the fatigue crack propagation initiated from double surface cracks. But there are scatters in fatigue lives at leakage as shown in Fig.9. Therefore, if we want to estimate the fatigue lives only through the simulation, it sometimes occurs that the estimated fatigue lives are longer than the experimental results. This means that the simulation sometimes results in dangerous estimation with negative safety margin. One approach to avoid this situation is to use the curve of Nfs = 2Nfs, that is, to give the safety margin of two to the simulated fatigue life, Nfs. This is a simple approach but it does not have a validity for the purpose of general application because it is validated only by the small number of experiments. Therefore, the authors would like to propose another approach where the intrinsic nature of the scatter can be considered statistically. In the previous simulation model, the material constants C and m have been assumed as $C = 2.07 \times 10^{-12}$ and m = 3.0 in SI unit for the case of YP40 steel. These values were determined through the least mean square method about many row data points on log da/dN vs. log•K diagram (see Fig.10). Therefore, the values of C and m described above are the mean values of the data with scatters. In order to describe the nature of the scatter more precisely, we assume that the value of m = 3.0 is fixed but that the value of C is a statistic parameter. Then the scatter of C can be defined by C-• where • is the expected value. Then from the data shown in Fig.10 we can obtain a probabilistic density distribution of logC as shown in Fig.11. This figure shows that C can be expressed by the logarithmic-normal distributions [5]. Based upon this distribution we can estimate the values of C against •+• and •+3•,respectively, where • is the standard deviation of this distribution (see Table3). By using these C values, it is easy to simulate fatigue crack propagation for double initial cracks. Again we can use the SCAN-double crack version. Finally we could obtain the result shown in Table4 and Fig.12. In this simulation we use the same scatter data of C about YP40 steel even for the A533B-1steel except for the mean values since we don't have the row data of log da/dN vs. log •K for the latter steel. You can see that the use of C(•+•) will result in the safe estimation for all the cases of the experimental data, but if you want further safety margin, the use of C(•+3•) is recommended because it results in the safety margin larger than 1.8 for all the cases of the experimental data as shown in Table4 (Nf/Nfs'').

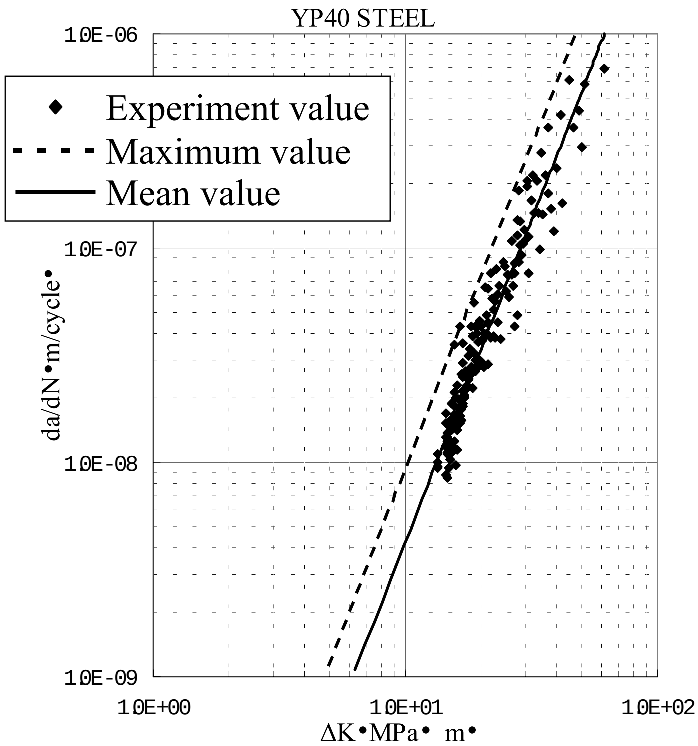


Fig.10 CT examination result of YP40 steel

Table3 The mean value and standard deviation in a CT examination result of YP40 steel

	LogC	C
Standard diviation (σ)	0.1214	
Mean Value (μ)	-11.3709	4.25734E-12
C (μ• σ)	-11.2495	5.63038E-12
C (μ• 3σ)	-11.0067	9.84777E-12

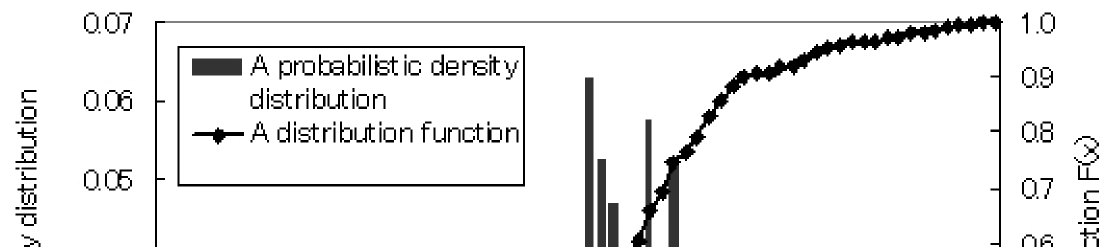


Fig.11 A probabilistic density distribution

Table4 Numbers of cycles by C of the security side

Test No.	1	2	3	4	5	6	7
SCAN(C(μ))Nfs	34200	63700	40700	182400	206400	51900	38200
SCAN(C(μ+σ))Nfs	25900	48200	30800	137900	156000	39400	29000
SCAN(C(μ+3σ))Nfs	14900	27600	17700	79000	89300	22500	16600
EXP Nfs	58494	89935	32910	144170	161830	40067	69162
Nf/Nfs	1.71	1.41	0.81	0.79	0.78	0.77	1.81
Nf/Nfs'	2.26	1.87	1.07	1.05	1.04	1.02	2.38
Nf/Nfs"	3.93	3.26	1.86	1.82	1.81	1.78	4.17

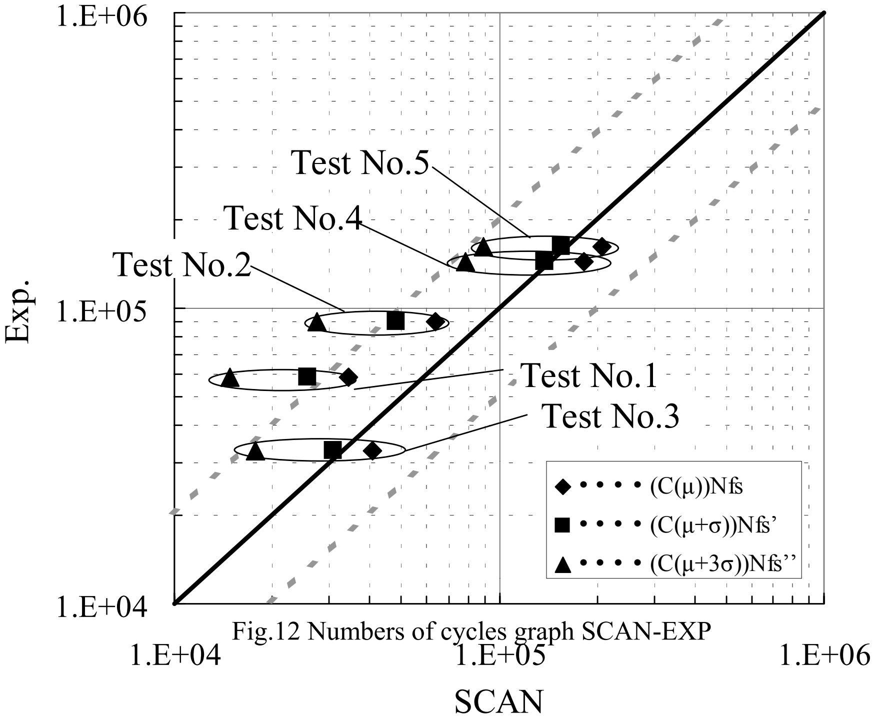


Fig.12 Numbers of cycles graph SCAN-EXP

CONCLUSIONS

The authors have proposed a simplified approach by which the fatigue crack propagation of the double initial surface cracks can be simulated promptly by a personal computer. The basic concept of the proposed approach is based upon the already proposed SCAN-system for a single surface crack combined with the assumption of ASME CodeSection XI for the crack coalescence, therefore, they call this system " SCAN-Double Crack Version" . They have done some experiments to examine the validity and accuracy of the proposed simulation approach. It has been found that the approach can give a good estimation as a first-order approximation but that it is important to look into the nature of scatter existing intrinsically in the parameter of C if we are more sensitive to the scatter of fatigue lives than the mean values.

NOMENCLATURE

a - depth of crack, mm;
c - half-length of crack, mm;
F - boundary-correction factor for corner crack at a hole in a plate under tension, -;
K - stress-intensity factor (mode I), MPa $m^{1/2}$;
t - thickness, mm;
s - distance between cracks, mm;
σ - stress, MPa.

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