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FRACTURE BEHAVIOR OF A CORRODED ANNULAR PLATE UNDER A MULTI-AXIAL STRESS STATE

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ABSTRACT

For the purpose of risk assessment of damaged structure, bend tests were carried out on a corroded annular plate prepared from the oil storage tank. Corrosive attack occurred extensively on the outer surface of the annular plate. Seriously developed cracking was noted in the high deflection region depending upon the degree of corrosion damage. From successive observation of crack growth behavior on the roughened corroded surface, it was clearly recognized that the multiple cracks, initiated around pits, grew rapidly not only by crack growth by itself, but also by coalescence with other neighboring cracks under the influence of plastic constraint derived from the welded joint. Then, it should be emphasized that the development of serious cracking, leading to a catastrophic failure, was expected to occur on a corroded component through the linking up of multiple cracks under a multi-axial stress state.

KEYWORDS

risk assessment, corrosion damage, annular plate, multiple cracks, crack coalescence, stress concentration, plastic constraint.

INTRODUCTION

Some of the existing structures degrade in service resulting from various types of deterioration. The reliability assessment of the damaged structure should be considered to minimize the risk of failures. Research activities are mainly concerned with degradation occurring in high temperature power plants, commonly known as creep damage and temper embrittlement .

However, corrosion of the structural component is the simplest and most common form of degradation, and occurs frequently under normal service condition. Besides, a generally uniform corrosion produces a rough surface on the component in some situations.

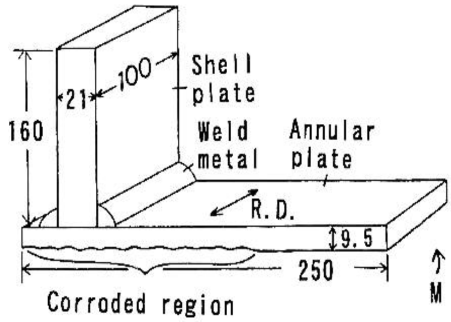
In such circumstances, a more serious problem should be supposed to occur under a multi-axial stress state around the welded joint. Hence, the reliability of the corroded component should be considered against various loading or stress state that would be envisaged to be applied in service.

In this study, the fracture behavior of a corroded annular plate, prepared from the oil storage tank, was investigated under bending load, to identify the significance of corrosion damage for risk assessment.

EXPERIMENTAL PROCEDURE

Material and Bend Specimen

L-shaped bend specimens were machined from the welded joint between the shell plate and the annular plate of the oil storage tank. The geometry and dimensions of the bend specimen is given in Fig.1. The general appearance of the corroded surface is a roughened one with a relatively uniform reduction in thickness. A large number of pits, which had developed to a visible size, are distributed randomly over the corroded surface. The annular plate is made of high strength steel with a tensile strength of 613MPa. It should be noted that the major axis of the bend specimen is transverse to the rolling direction.



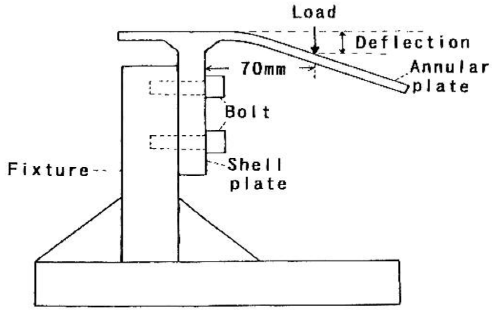


Fig.1. Geometry of L-shaped bend specimen. (dimensions in mm).

Fig.2. Schematic illustration of setup for bend test.

Fig.2 shows the schematic illustration of setup for the bend test. The axial load was applied on the corroded surface of the annular plate. It was envisaged to be applied in a case of huge earthquake followed by sinking of the foundation of the tank.

Quantitative Assessment of Corrosion Damage

Three specimens with varying degree of corrosion damage were prepared. Each specimen was labeled specimen A to specimen C. The pitting depth distribution over an extent of 10mm in length and 100mm in width adjacent to the welded joint was evaluated stochastically. In addition, the pit root radius and the depth of deepest bottom of the pit was measured for specimen A and C over an extent of 15mm in length and 100mm in width. The stress concentration factor K_t due to a pit is given approximately under bending load by

$$K_t=1+2(d/\rho)^{1/2} \qquad (1)$$

where d is the depth of deepest bottom of pit and ρ is the pit root radius[1].

Observation of Crack Growth Behavior

Crack growth behavior on the corroded surface was observed after attaining every increment of deflection of 5mm. The surface crack length was measured on the photographs, where its length was represented by the projected length in the direction perpendicular to the loading axis.

Notched Tensile Specimen

Notched tensile specimens with different notch acuity were prepared from the annular plate to investigate the effect of stress concentration on the fracture strain. The fracture strain in the minimum section is given by

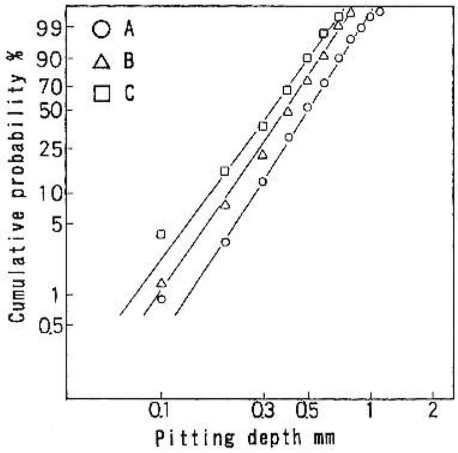
$$\varepsilon_f=2\ln(d_0/d) \qquad (2)$$

where d is the diameter of the minimum section at fracture and d_0 is the initial value of d.

RESULTS AND DISCUSSION

Distribution of Pitting Depth and Stress Concentration Factor

Fig. 3 shows the probability distributions of pitting depth on Weibull distribution paper.



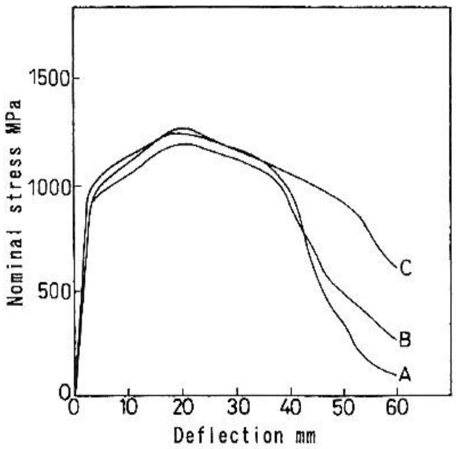


Fig.3. Weibull distributions of pitting depth for specimen A, B and C.

Fig.4. Nominal stress versus deflection curves for specimen A, B and C.

The distribution of pitting depth can be approximately described as a Weibull distribution. Three specimens were found to be corroded to a greater depth in order of specimen A, B and C. While, the probability distributions of stress concentration factors are fitted to log-normal distribution. The median values for specimens A and C were 2.1 and 1.9, respectively.

Nominal Stress-Deflection Curve of Bend Specimen

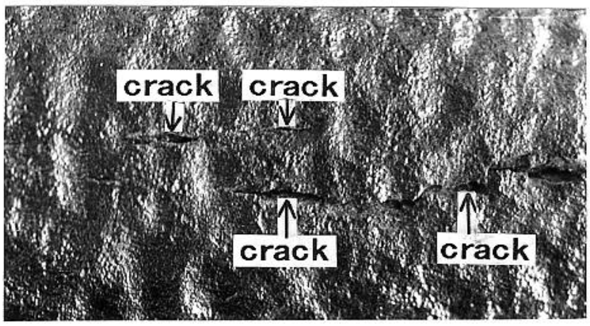
Fig.4 shows the results of bend tests. The nominal stress σ_n is given by

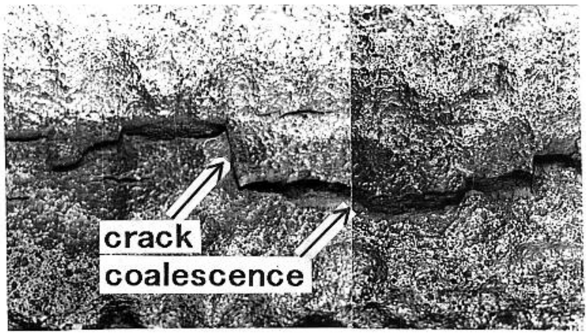
$$\sigma_n = 6PL/bh^2 \qquad (3)$$

where P is the applied load, L is the span length, b and h are the width and thickness of the bend specimen. The thickness of the specimen was defined here as the difference between the thickness of annular plate in the non-corroded region and the median value of pitting depth. At the early stages of deformation, the stress rises with increasing deflection. Then, the stress reaches a maximum value and thereafter starts to decrease after a deflection of about 20mm. A difference in the stress-deflection curves for three specimens is scarcely recognized at the early and the middle stage of deformation. In contrast, a different response was noted after attaining a deflection of about 35mm, associated with a varying degree of corrosion damage.

Crack Growth Behavior on the Corroded Surface

The reason of different shapes of the stress-deflection curves was successfully explained from successive observation of crack growth behavior on the corroded surface. Photographic evidence showed that the multiple cracks had initiated after a deflection of 35mm on the corroded surface of specimen A and B. Thereafter, rapid crack growth occurred through crack growth by itself and coalescence with other cracks. Typical examples of crack coalescence are shown in Fig.5. Several cracks, initiated around pits, grew rapidly into large crack by coalescence with neighboring cracks. Hence, it should be emphasized that the linking up of multiple cracks and the subsequent development of extensive cracking is considered to be a characteristic event of the roughened corroded component, and is expected to occur in the high deflection region depending upon the degree of corrosion damage. Plastic constraint, derived from the welded joint, produced a multi-axial stress state, and presumably accelerated crack growth among multiple cracks.





(a)Deflection 50mm. 5mm (b)Deflection 60mm.

Fig.5. Crack coalescence with increase of deflection for specimen B.

Well developed cracks at a deflection of 60mm for specimen A are demonstrated in Fig.6. In contrast, the development of cracks for specimen C is less extensive in concurrence with a lesser degree of corrosion damage. The increase in surface crack length for specimen A is shown in Fig.7. Several cracks had developed on the corroded surface at a deflection of 35mm. These cracks grew rapidly to join other cracks with increase of deflection. A coalescence of crack a and crack b in Fig.7 leads to larger crack c at a deflection of 50mm. As a result, an extensive crack①A and ②A with a length of 64 and 35mm had been formed for specimen A.

Similarly, multiple cracks, initiated on the corroded surface of specimen B, continued to grow and coalesce rapidly into large cracks. Consequently, an extensive crack with a length of 71 mm had been developed at a deflection of 60mm. Whilst, specimen C showed a much lower crack growth rate, and the largest crack①C in Fig.8 is 31 mm long.

The increase in surface crack length for specimen A, B and C were re-plotted in Fig.9 in terms of total crack length. The difference in fracture behavior of each specimen has been clarified in Fig.9. The deeper the pitting depth, the more rapidly the dimension of total crack length has increased. A high pit density and a higher stress concentration factor for

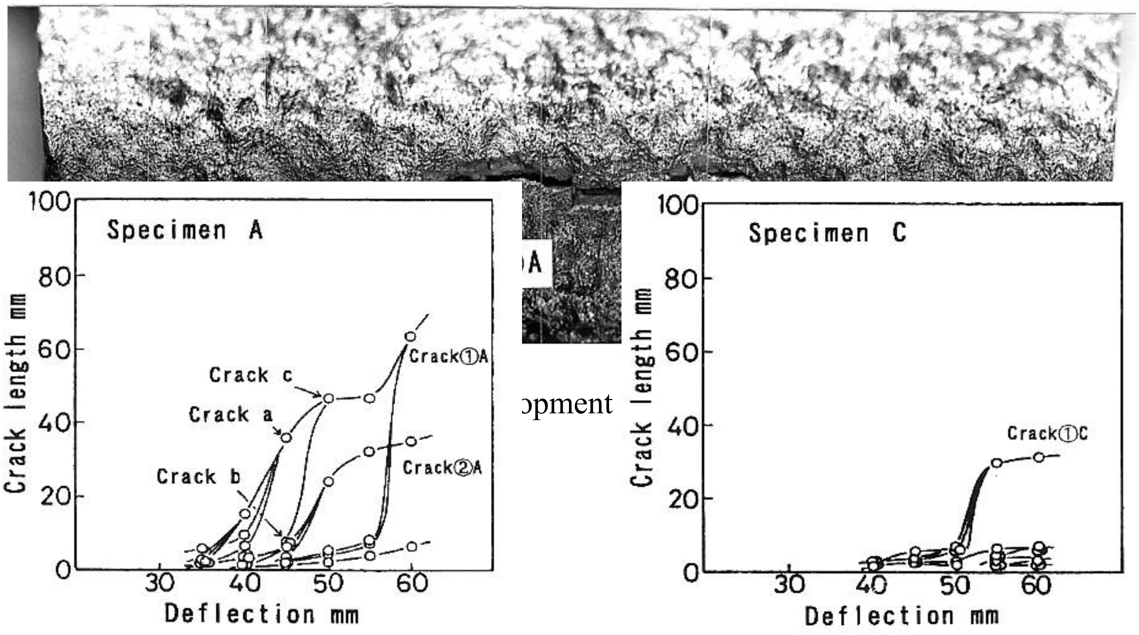


Fig.7. Relation between crack length and deflection for specimen A.

Fig.8. Relation between crack length and deflection for specimen C.

specimen A was also presumed to promote crack growth. The experimental results have led to the possibility that more serious crack growth might occur in a component subjected to a higher degree of corrosion damage. Hence, the fracture behavior of the corroded structure should be considered for the risk assessment to minimize the risk of catastrophic failure.

Ductility of the Annular Plate

Poor ductility of the annular plate in the transverse direction was assumed to promote crack growth. Fig.10 shows the relationship between the fracture strains and stress concentration factors of tensile specimens[2] for both the transverse and longitudinal directions. The fracture strain in the transverse direction was about a half of that in the longitudinal

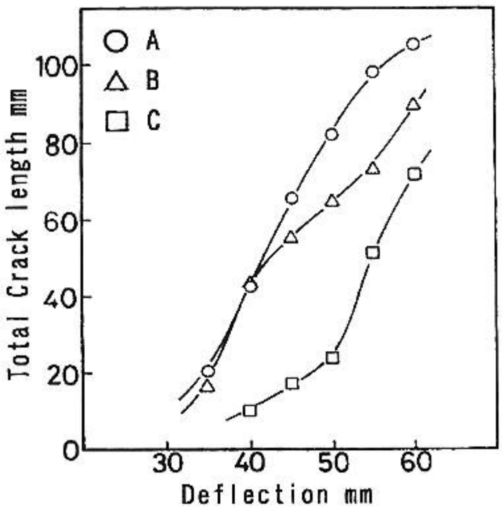


Fig. 9. Relation between total crack length and deflection.

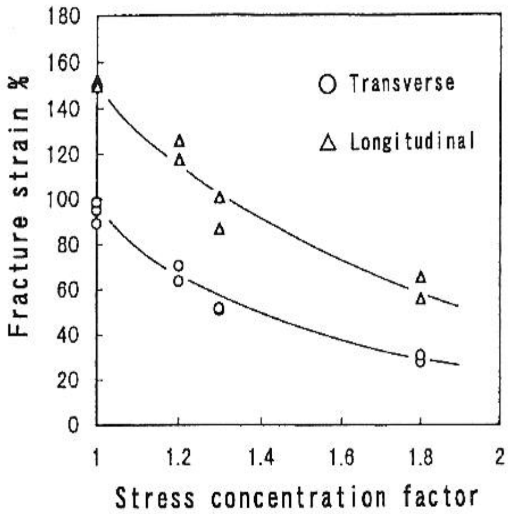
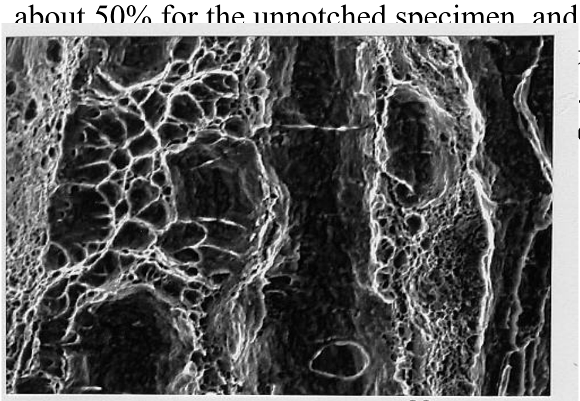
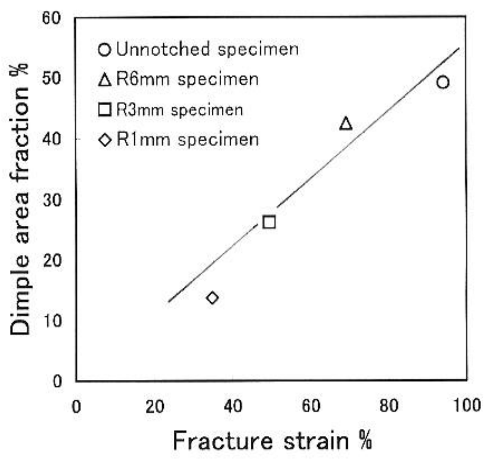


Fig.10. Relation between fracture strain and stress concentration factor.

direction, and was found to be a small value under a high stress concentration factor. Thus, the crack growth behavior was certainly accelerated by low ductility of the annular plate.
Also, poor ductility of the annular plate was well explained from a detailed fractographic examination. A typical fractograph of the annular plate is shown in Fig.11. The fracture surfaces are composed of equiaxed dimple area and featureless zone that is supposed to be caused by cracking and decohesion of non-metallic inclusion. The greater portion of the fracture surface is covered by featureless area. An average value of area fraction covered by dimple for 14 views was found to be a small value of 22% because of low ductility of the annular plate.
The relationship between dimple area fraction and ... n the transverse direction was developed in Fig.12. Dim... ne of about 50% for the unnotched specimen, and decrea... rain. ...ate de... men ... Using ... f the ... ely low ... ction





20 μ m

Fig.11. SEM fractograph of the annular plate. Fig.12. Relation between dimple area fraction and fracture strain.

CONCLUSION

In this study, the fracture behavior of a corroded annular plate was clarified for the reliability assessment of damaged structure. The main conclusions are as follows.

As a result of bend tests, well developed extensive cracking was noted in the high deflection region correlated with varying degree of corrosion damage. From successive observation of crack growth behavior on the corroded surface, it was clearly demonstrated that the multiple cracks, initiated around pits, grew rapidly into large cracks not only by crack growth by itself but also by coalescence with other neighboring cracks under the influence of plastic constraint. Then, it should be emphasized that the development of serious cracking through the coalescence of multiple cracks was considered to be a characteristic event of the corroded component, and was envisaged to occur under a multi-axial stress state depending upon the degree of corrosion damage.

REFERENCES

[1]. R. E. Peterson(1953), “Stress concentration design factors”, John Wiley & Sons, 136.

[2]. R. E. Peterson(1953), “Stress concentration design factors”, John Wiley & Sons, 35.