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# Stress Analysis of a Nuclear Power Plant LP Turbine Rotor Disc Using Finite Element Method

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## ABSTRACT

Fracture phenomenon have been reported on blades, rotors, connections and rotor discs of LP turbines of nuclear power plants, which are caused by fatigue, stress corrosion and erosion. In this study, as a tool of reliability evaluation, stress and fracture analysis are performed on the defected area under various operating conditions using finite element methods. Possible defects on key-way and rotor disc are assumed as two-dimensional cracks and centrifugal force, temperature distribution and shrink-fit effect are included as external loads. From stress analysis results, stress intensity factors are obtained and used to evaluate reliability and predict remaining lifetime of the turbine discs.

## 1. INTRODUCTION

As commercial running time of domestic nuclear power plants is getting longer, there is more possibility to find defects and cracks around key-way and rim of turbine rotor discs at periodical evaluation, which cause more frequent operation stops. Hence, it is getting more important to evaluate reliability and to predict remaining lifetime of the nuclear power plants.

According to the survey for the causes of operation stops in domestic nuclear power plants between 1985 and 1988, fifty cases were caused by defects in the system of turbine and generator out of 128 cases in total. Especially in turbine, it has been reported that the defects are mainly caused by fatigue, stress corrosion and erosion in blades, connections of blade and disc and rotor discs.

In this study, stress analysis of LP turbine rotor disc is carried out for Kori 1, 2 and Yungkwang 1 nuclear power plants. The stress analysis results are used to calculate stress intensity factors, SIF, for possible cracks with arbitrary sizes at arbitrary locations. Once the sizes and locations of cracks are found by nondestructive inspection, these resultant stress intensity factors will be applied and reliability evaluation, inspection period determination and remaining lifetime prediction will be performed. For this purpose, in this study, a GUI(Graphical User Interface) computer program was developed based on the experimental and computational results to help plant operators to apply them to each turbine rotor disc conveniently.

## 2. NUCLEAR POWER PLANT TURBINE

In domestic nuclear power plants, tandem compound type turbines were commonly adopted, where each axis of turbine is directly connected to a generator as shown in Fig. 1. And in a number of domestic major nuclear power plants, including Kori nuclear power plant 1 and 2, shrunk-on type turbine rotor discs were utilized. A shrunk-on type rotor disc is composed of key-way, bore, rim, and locking-pin which prevents disc on axis from sliding and blades are attached to a disc rim as shown in Fig. 2. This shrunk-on type rotor disc is designed to overcome centrifugal force and subject to general dynamic loads including temperature distribution, vibration, thrust and so on. LP turbine rotor discs are usually made of 3.5% NiCrMoV alloy which is strong in erosive environment.

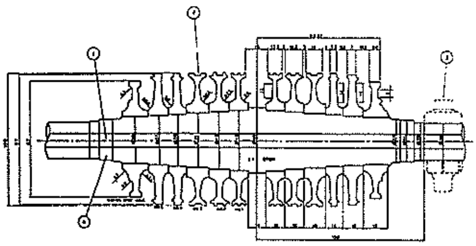

Fig. 1 Configuration of Yungkwang Power Plant LP Turbine

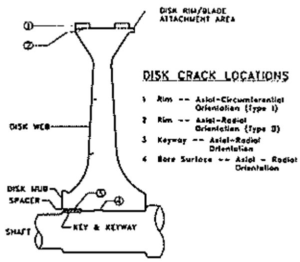


Fig. 2 Locations of Cracks on the LP Rotor Disc

## 3. LOADS IN TURBINE ROTOR DISC

A shrunk-on type rotor disc is assembled to an axis by shrink-fitting so that contact and friction force developed between rotor disc and axis transmit rotational force. In general, the amount of shrink-fitting is designed in such a way that the contact force is equal to centrifugal force due to rotation when rotational speed reaches 120%-130% of operating speed, so called lift-off speed. This contact force results in hoop stress of the rotor disc and compressive stress of the axis in circumferential direction. Moreover, rotor disc is subject to centrifugal force and temperature distribution loads at operation starts and stops. These external loads cause and develop defects and cracks at the corners of rim and rotor disc, where stress concentration occurs. Possible locations of frequent defects and cracks are illustrated Fig. 2.

In this paper, a finite element analysis is performed on shrunk-on type rotor disc considering contact and centrifugal force and temperature distribution. In Fig. 3 and 4, illustrated are calculated radial and circumferential stresses at the fifth disc due to these external loads along radial direction, among which the circumferential stress will be utilized as crack opening load. It should be noted that the tangential stress has a discontinuity on the shaft surface because of contact force caused by shrink-fitting and that the radial stress has discontinuity in slopes due to variance in thickness of shaft, bore and disc.

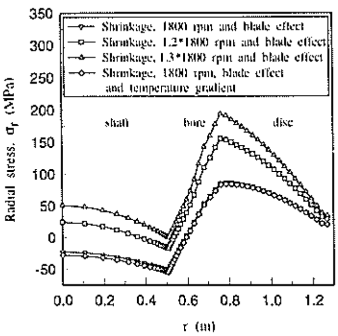


Fig. 3 Radial stress of the fifth disc (Kori)

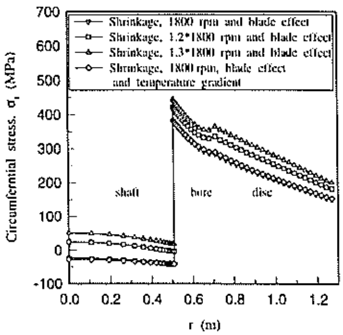


Fig. 4 Circumferential stress of the fifth disc (Kori)

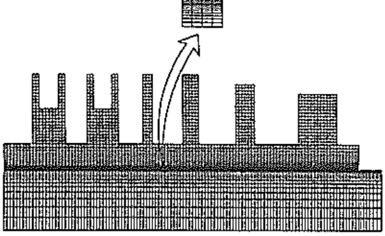

Fig. 5 Axisymmetric Modelling of the Rotor Disc of Kori

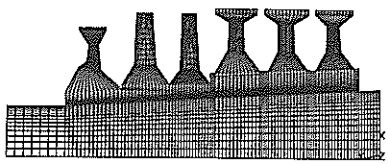

Fig. 6 Axisymmetric Modelling of the Rotor Disc of Yungkwang

4. FRACTURE ANALYSIS USING FINITE ELEMENT METHOD

Inevitably, defects or cracks happen during manufacturing process and operation. Stress intensity factor, $K$, is generally used as representing fracture parameter determining safety and remaining lifetime and has been obtained by many researchers for cracks with various geometry under general loads. As mentioned above, frequently defected areas are key-way, rim and bore, where general three dimensional cracks are found.

In this study, since fracture analysis should be performed for many possible locations and crack sizes, only two dimensional penetration cracks in axial direction are assumed to avoid complex and time consuming three dimensional analysis. This assumption is based on the following facts. First, cracks in axial direction is more apt to grow than those in circumferential direction. Secondly, analysis results from two dimensional penetration crack is more conservative than those of three dimensional crack.

In order to perform the two dimensional finite element analysis, method of superposition was used with two 2 dimensional models, which are shown in Fig. 5, 6 and 7. As in fig. 5 and 6, two dimensional axisymmetric model is composed of an axis and discs with $y-z$ symmetric plane. On this model, two dimensional axisymmetric analysis is performed and centrifugal force, shrink-fitting effect and temperature distribution are included as boundary conditions. Radial and tangential stress distributions are obtained as shown in Fig. 3 and 4. These resultant stress distributions are applied plane stress model shown in Fig. 5 which involves penetration crack with crack size a and fracture analysis is performed to calculate stress intensity factor $K_I$. This procedure is repeated according to various crack location and size and displacement extrapolation method is used at the crack tip to calculate $K_I$.

## 4.1 FINITE ELEMENT ANALYSIS OF KORI PLANT

The LP turbine of Kori nuclear power plant consists of six stages and first two stages have two sets of discs and blades. Material properties and axisymmetric model used in analysis are shown in Table 2 and Fig. 5 respectively. In axisymmetric analysis, 4983 nodes and 4669 rectangular elements are used and at the contact surface of bore node to node contact elements are used to simulate shrink-fitting effect. The amount of shrink-fitting is given 0.2% as designed. Temperature distribution is shown in Table 1 and applied to each stage. Centrifugal force is calculated considering mass of blades and rotating speed and applied to the end of disc where blades are attached.

In Fig. 8 and 9, resultant contact and tangential stress distributions are illustrated along axis, which shows that tangential stress increases and contact stress decreases as rotating speed increases. From figures, it can be also seen that contact stress vanishes almost everywhere except the fifth and sixth stages when rotating speed reaches 130% of operating speed. Also, centrifugal force turned out to be the most effective and temperature distribution does not have much contribution in resultant contact stress.

| | | |
|---|---|---|
| Young's modulus, | E (Pa) | $2.06 \times 10^{11}$ |
| Poisson's ratio, | ν | 0.3 |
| Coefficient of thermal expansion, | α (1/℃) | $12.00 \times 10^{-6}$ |
| Thermal conductivity, | κ (W/m K) | 54.0 |
| Density, | ρ (kg/ m$^3$) | $7.833 \times 10^3$ |

Table. 1 Material Properties of the Turbine Rotor Disc

| Bore No. | Disc stage No. | Outer temperature (℃) |
|---|---|---|
| 1 | 1 | 216 |
| | 2 | 162 |
| 2 | 3 | 128 |
| | 4 | 110 |
| 3 | 5 | 93 |
| 4 | 6 | 77 |
| 5 | 7 | 55 |
| 6 | 8 | 36 |

Table. 2 Temperature Distribution of the Turbine Rotor Disc of Kori

| Disc stage No. | Outer temperature (℃) |
|---|---|
| 1 | 260.00 |
| 2 | 223.84 |
| 3 | 187.66 |
| 4 | 151.49 |
| 5 | 115.32 |
| 6 | 79.15 |

Table. 3 Temperature Distribution of the Turbine Rotor Disc of Yungkwang $10^3$ m$^3$

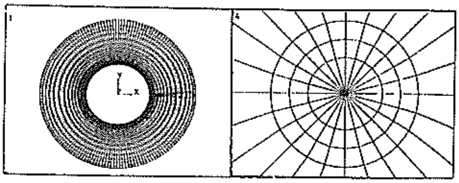

Fig. 7 Finite Element Model of a Crack on a Disc

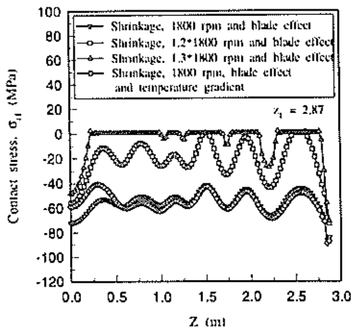


Fig. 8 Contact Stress Distribution along Shaft at the Interface of Shaft and Bore (Kori)

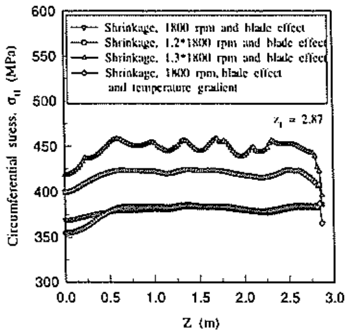


Fig. 9 Circumferential Stress Distribution along Shaft at the Interface of Shaft and Bore (Kori)

## 4.2 FINITE ELEMENT ANALYSIS OF YUNGKWANG PLANT

The LP turbine of Yungkwang nuclear power plant consists of six stages and the first stage has three sets of blades, the second and third stages have two sets of blades and forth, fifth and sixth stages have a set of blades.

The analysis procedure is similar to that of Kori, and axisymmetric model and temperature distribution used in analysis are shown in Fig. 6 and Table 3, respectively. In axisymmetric analysis, 5254 nodes and 4955 rectangular elements are used and the rest of analysis is similar to that of Kori.

In Fig. 10 and 11, resultant contact and tangential stress distributions are illustrated along axis, which shows that tangential stress increases and contact stress decreases as rotating speed increases similarly to Kori. Also, temperature distribution does not have much contribution in resultant contact stress.

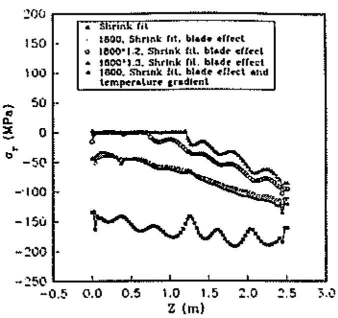


Fig. 10 Contact Stress Distribution along Shaft at the Interface of Shaft and Bore (Yungkwang)

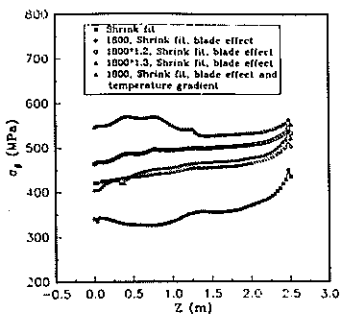


Fig. 11 Circumferential Stress Distribution along Shaft at the Interface of Shaft and Bore (Yungkwang)

### 4.3 FRACTURE ANALYSIS

Based on the stress analysis results, fracture analysis is performed on turbine rotor discs of Kori 1 and 2 plants. In this analysis, singular elements are used at the crack tip and 8 node elememts are used elsewhere as shown in Fig. 7. Stress intensity factors are obtained assuming various cracks with eight to ten kinds of crack sizes from 0.3mm to 100mm at each stage and bore.

In order to utilize stress intensity factor in calculating remaining lifetime, resultant stress intensity factors are curve fitted by least square method. In Fig. 12, stress intensity factor of the forth rotor disc with radial crack is shown along arbitrary crack size. In Fig. 13, stress intensity factor at the surface between forth and fifth discs is illustrated. Since relative crack size, $a/W$, is much smaller than that of bore surface without disc, stress intensity factor shows asymptotic behavior of $a^{1/2}$. On the other hand, at bore surface without disc, stress intensity factor does not show such asymptotic behavior because of smaller size of uncracked ligament and larger relative crack size.

Next, similar fracture analysis is performed on turbine rotor discs of Yungkwang 1 plant. Stress intensity factors are obtained assuming various cracks at inlet and outlet of each stage. In Fig. 14 and 15, illustrated are resultant stress intensity factors, which do not show asymptotic behavior since relative crack size is large.

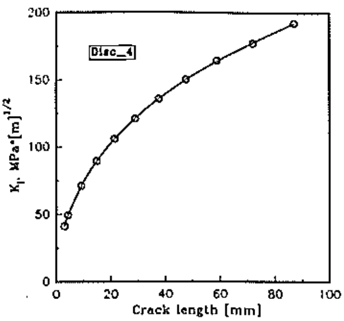


Fig. 12 Stress Intensity Factor along Crack Length at Disc No. 4 (Kori)

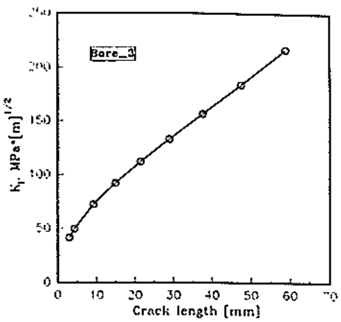


Fig. 13 Stress Intensity Factor along Crack Length at Bore No. 3 (Kori)

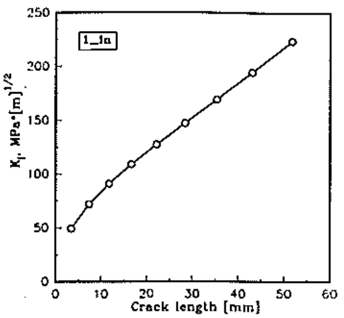


Fig. 14 Stress Intensity Factor along Crack Length at Disc No. 1 (Yungkwang)

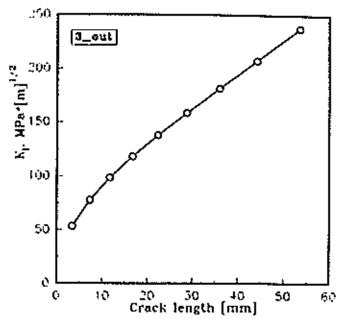


Fig. 15 Stress Intensity Factor along Crack Length at Disc No. 3 (Yungkwang)

## 5. DEVELOPMENT OF COMPUTER PROGRAM FOR RELIABILITY AND REMAINING LIFETIME

Based on resultant stress intensity factors, a computer program was developed to evaluate reliability and predict remaining lifetime of turbine discs. For convenience of plant operators, this program utilizes GUI as shown in Fig. 16.

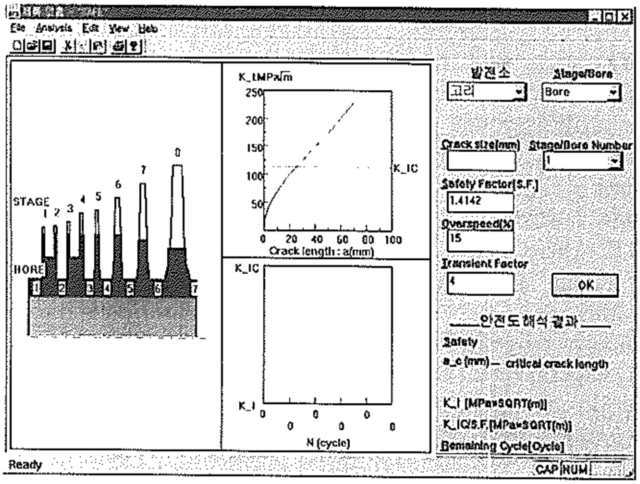


Fig. 16 GUI Data Input Display of SAFE (Kori)

### 5.1 RELIABILITY

There are many codes concerning brittle fracture such as ASME Sec. X1 (Boiler and Pressure Vessel Code), BSI PD 6493 of Standard Institution and WES 2805. This computer program, named SAFE, evaluate reliability according to ASME Sec. XI as follows:

$$K_I < \frac{1}{\sqrt{2}} K_{IC}\ , \qquad K_I < \frac{1}{\sqrt{10}} K_{Ia} \tag{1}$$

where $K_{IC}$ and $K_{Ia}$ indicate critical and arrest fracture toughness; respectively.

Fracture toughness, $K_{IC}$, for the material mentioned above was obtained by experiments, details of which is not included in this paper. In general, $K_{IC}$ depends on temperature, but in this study the smallest value of 135 MPa $\sqrt{m}$ at room temperature is used to avoid a large number of experiments and to keep results conservative.

### 5.2 REMAINING LIFETIME

The following describes Paris's law, which is commonly used to calculate remaining lifetime

$$\frac{da}{dN} = C(\Delta K)^{m} \tag{2}$$

where $C$ and $m$ are found to be $2.20 \times 10^{-9}$ and 3.33 by experiments. The program SAFE calculates remaining lifetime by integration of this Paris's law with $\Delta K$ obtained transient stress analysis during transient state.

## 6. CONCLUSION

In this study, stress and fracture analyses are performed on defects or cracks occurring at turbine rotor discs.
Based on stress analysis result, centrifugal force is found to be most effective during steady state and 130% of overspeed compensates shrink-fitting in both of Kori and Yungkwang plants.

From fracture analysis, as expected, stress intensity factor shows asymptotic behavior of $a^{1/2}$ where crack size is relatively small. And it is found that bore surface, where radius and centrifugal force are small, has smaller stress intensity factor than key-way.

Also, a computer program is developed, which contains these computational results combined with experimental properties. This program is convenient and useful in evaluating reliability and predicting remaining lifetime of the turbine discs with given crack size and location by nondestructive inspection and transient state stresses.

## 7. REFERENCE


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