Evaluation on the Structural Integrity of an Annular Structure Having Partially Contact Surfaces

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ABSTRACT

A half-scaled large test model was tested to verify its structural integrity. The temperatures and strains of a flexure were measured during a thermal cyclic test. A dye penetration test was carried out after the test, there was no evidence that cracks had been initiated and propagated from the test model. The heat transfer and the structural analysis models of a reactor cavity seal were developed with the test data. The analyses were performed with the loading conditions. Due to the high stress level from the analysis results, the cumulative usage factor was evaluated. Its value is less than 1.0 from the analysis results and design bases of an adjacent major component. The reactor cavity seal has turned out to keep the structural integrity during its service lifetime.

INTRODUCTION

Structural design is generally bound up with the service limits which define the stress levels in an elastic limit. Only a few structures are extended to their service limits beyond the elastic limit when hostile operating conditions are encountered. One of these structures is the annular structure which is affected by thermal expansion, earthquakes, and/or hydraulic pressure. Combination of thermal expansion and seismic loads for the annular structure yields a stress beyond the elastic limit.

This paper describes the test model [1] of an annular structure that was constructed for the thermal cyclic test. The test temperature was derived by numerical analyses with operating conditions. The test cycle was defined from the design bases of plants. The test model was inspected by a dye penetration test after thermal cyclic tests. The temperatures were measured. A reactor cavity seal being an annular structure is introduced, which is expected to have high stress levels beyond the elastic limit. The thermal and structural analysis models of the reactor cavity seal were developed with the test results for reducing uncertainties of modeling parameters. From the analysis results, structural integrity using the cumulative usage factor was evaluated.

TEST MODEL

Model Description

The test model consists of a seal ledge, a flexure, a seal plate, and column supports. The seal ledge is heated up as a source of thermal loads, which is in contact with the flexure and welded to its end (a in Figure 1). The flexure is designed to allow the thermal expansion of the seal ledge.

The diameter of the test model (C_d = 2700 mm) was determined to a half scale of the annular structure, but the height (C_h =140 mm) was the same as the real one; the initiation and the propagation of cracks would be due to local stresses rather than the similarity of a structure. Materials of the test model were selected with those of the annular structure. The flexure and seal ledge materials are made of A304-240 and A516 Gr70, and their thickness is 4 mm and 12 mm, respectively.

Test Condition and Analysis Method

The annular structure is subjected to thermal loads, pressure, and/or relative displacements. The equilibrium equation of the annular structure in Cartesian coordinates can be simply expressed as Eq. (1).

$$[K]\{u\} = \{F_p\} + \{F_f\} + \{F_t\}, \tag{1}$$

where $[K]$ is the stiffness matrix, and $\{u\}$ is the displacement vector of the annular structure. $\{F_p\}$, $\{F_f\}$ and $\{F_t\}$ are the hydraulic pressure, the seismic displacement load, and the thermal load acting on the annular structure, respectively.

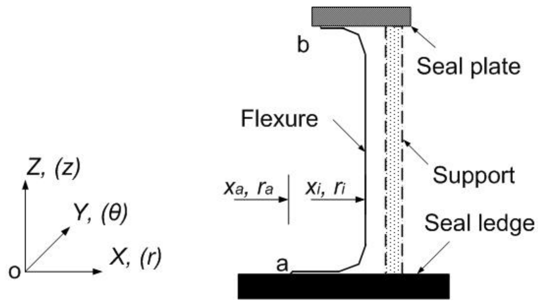


Figure 1. Section of a Test Model

The loading conditions of the annular structure are classified into two cases: One is combined with thermal and seismic displacement loads, and the other is with the hydraulic pressure and seismic displacement loads. The flexure is expected to have the highest stress level when the thermal and seismic loads are acting on the annular structure.

In order to determine test conditions, the annular structure which is a reactor cavity seal was simulated by numerical methods [2] for the severest loading conditions, and then a test model was simulated with the same technique. The test temperature for the test model was determined from the highest stress level of the annular structure with the thermal and seismic displacement loads. The test temperature is shown in Eq. (2).

$$T_f(r,\theta,0) = 288 \text{ ℃}. \qquad (2)$$

The number of thermal cycles for the test model was 200 which were defined from the design bases of an adjacent major component [3]. One thermal cycle was defined that the seal plate of the test model was heated up to 288℃ from room temperature, and then cooled down to room temperature.

THERMAL TESTS

Apparatus and Measurement

The test apparatus consist of electric heating plates, cooling coils, a temperature controller, strain gauges, data recording equipment, thermocouples and thermometers. The electric heating plates (Fig. 2 [a]) were specially ordered to fit the seal ledge of the test model. The temperature controller was installed to control the temperature of the seal ledge. Cooling coils made of copper pipes were installed at inside and outside (Fig. 2 [b]) of the flexure on the seal ledge in order to reduce the cooling time. Foil strain gauges (gage length 5 mm) for elevated temperature were selected to measure strains. Special treatment for cementing the strain gauges was performed with a special adhesive. The strains were taken with System 400 of the Measurement Group, which has multi-channels.

Strain and Fatigue Tests

Total 66 strains were measured at 6 circumferential locations shown in Table 1. In the terminal classification of the strain gauges, the first numbers are for circumferential locations, the second capitals are for the direction (H: the horizontal direction along the circumference, V: the vertical direction along the section), the third numbers are for the positions, and the fourth capitals stand for inside (I) or outside (O). For example, 1H2I stands for location 1, horizontal direction, position 2 and inside of the flexure. The measuring positions of strain gauges were determined from the analyses of the test model.

The seal ledge was heated up to 288℃, and then the temperature was maintained for a steady state of 10 minutes. The strain data were measured at each interval of 10 minutes.

Due to the thermal cyclic loads resulting in the high stress level beyond the elastic limit, the flexure of the test model was tested with a dye twice; before and after thermal cyclic tests.

Temperature Measurement

The temperatures of the flexure were measured locations I, III, and V around the circumference and at similar positions along the section of the flexure as in Figure 3 during thermal cyclic tests.

The measured data were for the verification of the thermal analysis of the annular structure at the natural convection.

Table 1. Nomenclature and Terminal Classification

Circumferential locations	Sectional positions						No. of terminals
	1	2	3	4	5	6	
I	1H1I, 1V1I	1H2I, 1V2I 1H2O, 1V2O	1H3I, 1V3I 1H3O, 1V3O	1H4I, 1V4I 1H4O, 1V4O	1H5I, 1V5I	1H6I, 1V6I	18
III	3H1I, 3V1I	3H2I, 3V2I 3H2O,3V2O	3H3I, 3V3I 3H3O,3V3O	3H4I, 3V4I 3H4O, 3V4O	3H5I, 3V5I	3H6I, 3V6I	18
V	5H1I, 5V1I	5H2I, 5V2I 5H2O, 5V2O	5H3I, 5V3I 5H3O, 5V3O	5H4I, 5V4I 5H4O, 5V4O	5H5I, 5V5I	5H6I, 5V6I	18
II, IV, VI	2H4I, 2H4O 4H4I, 4H4O, 6H4I, 6H4O, 2V4I, 2V4O, 4V4O, 4V4O, 6V4I, 6V4O						12

DISCUSSIONS

Pre-test

A pre-test was carried out to verify the performance of the strain gauge which would be adhered to the test model with the special adhesive for elevated temperature. The strain gauge for the pre-test was attached to a cantilever beam whose material was the same as that of the flexure.

Voltage to the longitudinal direction from the strain gauge was linearly proportional to the loads acting on the cantilever beam during the pre-test, but the voltage to the width direction was negligible. The results are shown in Figure 4.

Strains

The measured data at the same locations on each position had relatively large deviations, but showed the same trends. These deviations are evident that the half-scaled model is closer to a real structure than an experimental scaled one in a laboratory.

The strains at positions 4Is and 4Os had the maximum values among the measured data, and some of them exceeded the elastic limit by 0.2%. However, the average strains did not exceed the elastic limit. Strains measured outside (O) of the flexure had larger values than those of inside (I) because of the bending effects due to the thermal expansion. The average strains at Location 4 were slightly increased proportionally with the increase in the number of thermal cycles. The strain increments seemed to be a cumulative plastic deformation of the flexure from a macroscopic point of view, because the strains at all other locations except for Location 4 were slightly increased or decreased proportionally to the number of thermal cycles. An example of measured strains for the flexure is shown in Figure 5.

The measured values were less than the analysis results; thus, the analysis results were conservative from the design point of view. One thermal cycle during the test took more than 4 hours. The heat-up of the test model took about 90 minutes.

Temperature

The temperature profiles were well trended to each other; therefore, the measured data can be regarded as authentic.

Thermal analyses for the test model were carried out on the basis of the measured temperatures. By using the equation for the heat transfer coefficients [4] and conduction elements [2], the thermal analysis model was verified by comparison of the measured with analysis data for the natural convection, as shown in Figure 6. When the inside of the test model is exposed to the forced convection with 1.2 m/s, the temperature profile is shown as indicated “operation” in Figure 6. The measured temperatures from the thermal tests can be utilized for the reliability of a thermal analysis.

Dye Penetration Tests

The surfaces [5,6] of the flexure were inspected by a dye penetration test after the fatigue test. The inspection was done in 20 minutes after spraying the developing solution. There were no indications or symptoms that cracks had been initiated or propagated. Only a grinding surface on the weld has been spotted with the dye locally.

APPLICATION

Analysis Models and Stresses

A reactor cavity seal, which is a kind of the annular structure, is installed on the seal ledge of a reactor vessel in nuclear power plants. The reactor cavity seal consists of two flexures, one seal plate, and several column supports. The flexures, which are an annular shape, are designed to allow the relative motion from thermal loads and/or seismic loads.

One of them is welded to the seal ledge of the reactor vessel and the seal plate, and the other is welded to the seal plate and the embedment in a refueling pool floor. The seal plate having several holes is installed on and welded to the flexures. The holes in the seal plate are the air path for cooling the heat from the reactor vessel during the power operation and sealed by covers with O-rings during the refueling operation. The supports relieve the loads acting on the flexures by keeping the distance between the seal plate and the seal ledge. The reactor cavity seal is shown in Figure 7.

The diameter of the reactor cavity seal is about 5400 mm, and the height is about 140 mm. The materials are SA240-304 austenitic stainless steel. The heat transfer and the structural analysis models are developed. Test data are reflected into the heat transfer and the structural analysis models in order to reduce uncertainties of modeling parameters.

The loads acting on the reactor cavity seal are classified as the dead weight, the thermal loads from the reactor vessel, the hydraulic pressure and the seismic loads. The seismic loads are defined from operating basis earthquake and the safety shutdown earthquake, respectively. These earthquake events are defined by an occurrence probability. The loading conditions are divided into two cases: One is for the power operation, and the other is for the refueling operation of the nuclear power plant. Based on the loading conditions, the load combination is done and applied to the analysis models.

(a) Heating Plate (b) Setup for Heating Plates and Cooling Coils

Figure 2. Heating and Cooling Apparatus

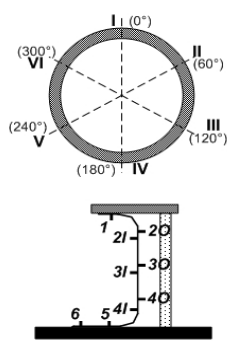


Figure 3. Nomenclature of Strain Measuring Positions for Elevated Temperature

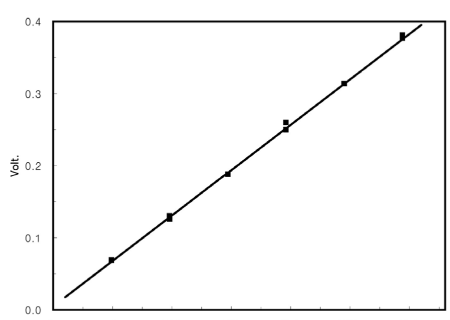
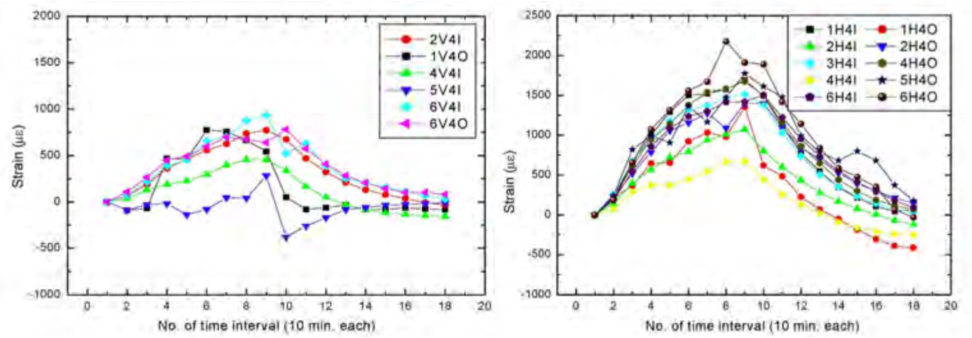


Figure 4. Voltage from the Strain Gauge depending on Thermal Loads



(a) Vertical Direction (b) Horizontal Direction

Figure 5. Measured Strains on Location 4 at the 165th Cycles

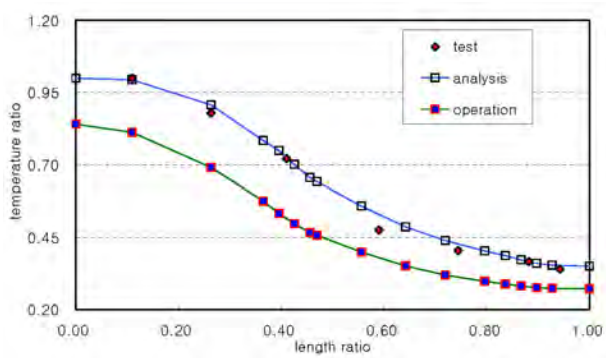


Figure 6. Comparison of Temperature Ratio with the Experimental and Numerical Analysis Data

Stress intensity resulted from numerical analyses with the loading conditions is shown in Figure 8. These stress levels exceed the allowable stress limits [7,8] except for the load case of the dead weight and hydraulic pressure (Fig. 8 [c]). Due to the high stress intensity level, each stress in Figure 8 is separated into primary, secondary and thermal bending stresses. The highest stress level except the thermal bending stress, which is for the load combination of the dead weight, thermal load and operating basis earthquake, is turned out to be less than 3 times the allowable stress limit at the temperature. Accordingly, a simplified elastic-plastic analysis [7] may apply to the evaluation of structural integrity for the reactor cavity seal during its service lifetime.

Cumulative Damage

The stress level of the reactor cavity seal is higher than 3 times in total, and less than 3 times except the thermal bending stress from the allowable stress limit [8] point of view. Accordingly, structural integrity for the reactor cavity seal could be evaluated by using the cumulative usage factor. The cumulative usage factor is a criterion whether failure in a structure would occur or not during its service lifetime.

In order to evaluate the cumulative usage factor, the alternating stress intensity which is generally a half of the stress intensity, and the number of occurrence for repeating loads should be identified for each load case. The alternating stress intensity applying to the design fatigue curve is multiplied by the factor K_e depending upon the range of primary plus secondary stress intensity and materials due to the high stress level of the reactor cavity seal. The reactor cavity seal has three kinds of stress cycles from repeating loads: One is the thermal load from the heating-up and cooling-down of the reactor vessel, another is the seismic load from the operating basis earthquake, and the other is the hydraulic load from the refueling operation for the reactor vessel. The number of occurrence for repeating loads is 200 for the thermal load, 20 for the operating basis earthquake and 80 for the hydraulic load [3].

The cumulative usage factor (U) is calculated from Equation (3);

$$U = \sum \frac{n_i}{N_i}, \qquad (3)$$

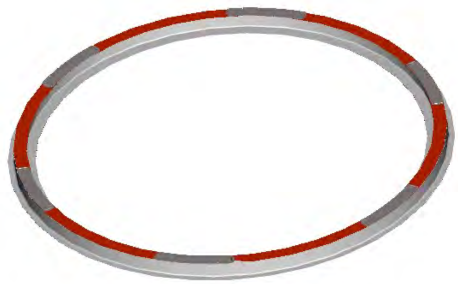
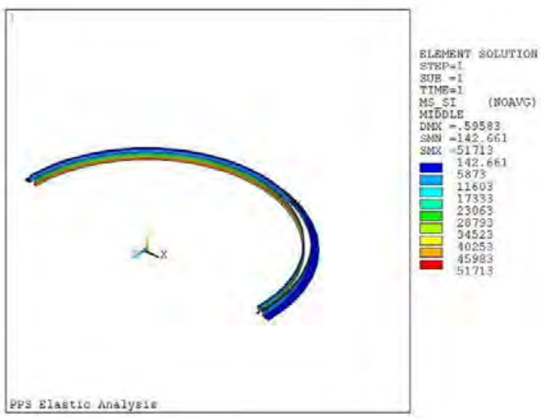
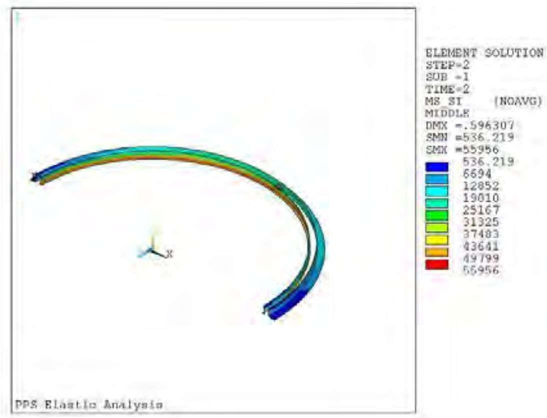


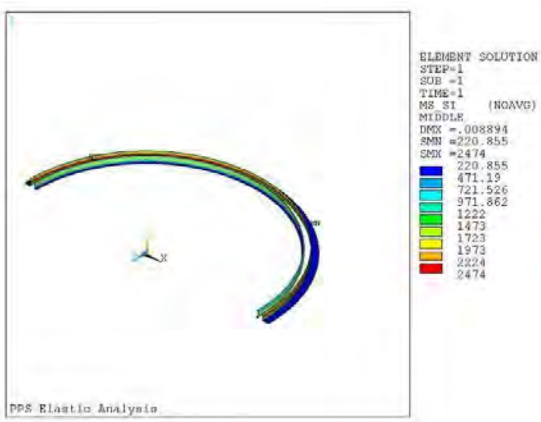
Figure 7. A Reactor Cavity Seal



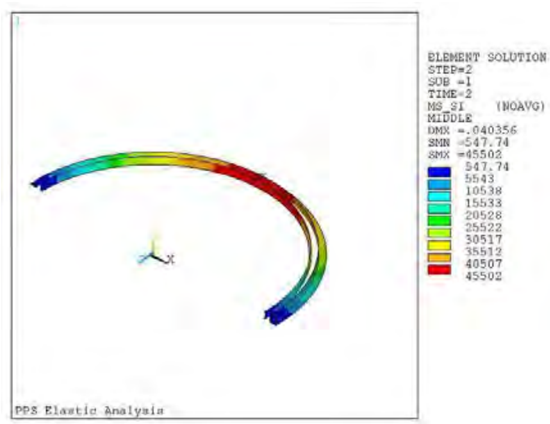
(a) Dead Weight and Thermal Load



(b) Dead Weight, Thermal Load and Operating Basis Earthquake



(c) Dead Weight and Hydraulic Pressure



(d) Dead Weight, Hydraulic Pressure and Safety Shutdown Earthquake

Figure 8. Stress Levels of the Flexure in the Reactor Cavity Seal (unit: ksi)

where n_i is the number of stress cycle, and N_i is the maximum number of repetitions for the applicable alternating stress intensity in the applicable design fatigue curve.

The cumulative usage factor is estimated to be 0.53 with the correction of the elastic modulus for the material of the flexure. The cumulative usage factor derived is less than 1.0, and thus the reactor cavity seal keeps structural integrity during its service lifetime. In addition, the stress level by the elasto-pastic analysis is turned out to be just above the yielding point of the material when the safety shutdown earthquake occurs during the power operation. It is evident that the reactor cavity seal securely maintains structural integrity with no failure during its service lifetime.

CONCLUSIONS

A half-scaled large test model for an annular structure was tested to scrutinize its behaviors by thermal cyclic loads. The test model and test conditions of the annular structure were determined by numerical analyses with the thermal and mechanical loads acting on a reactor cavity seal. Temperatures and strains of the test model were measured during the test. A dye penetration test was carried out after the thermal cyclic tests, there was no evidence that cracks had been initiated and propagated from the test model. The heat transfer and structural analysis models of the reactor cavity seal were developed with the test data to remove uncertainties. The analyses were performed with the loading conditions. Due to the high stress level from the analysis results, the cumulative usage factor was estimated. Its value is less than 1.0 from the analysis results and design bases of an adjacent major component. The reactor cavity seal has turned out to keep structural integrity during its service lifetime.

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