Elastic Follow-up Test of FBR Piping System at High Temperature

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Abstract

The elastic follow-up test was conducted on a one fourth scale model of the hot leg piping of the primary heat transport system (PHTS) of the Japanese Prototype FBR 'MONJU'. The test was performed at 600°C, and the prescribed end displacements were imposed which simulated thermal expansion load, and the both ends of the piping were fixed for approximately 5,000 hours. Measured were moments and forces at both ends, the rotation of the piping, and strains. Through the test and the associated analyses, it was made clear that strain accumulation of the 'MONJU' piping due to thermal expansion stress is small and that the 'MONJU' Design Guide is conservative for evaluating elastic follow-up of piping systems. Moreover it was shown that the computer program 'PISAC' for elastic-creep analysis of piping systems can predict fairly well elastic follow-up behaviors of piping systems.

1. Introduction

Cares must be directed to elastic follow-up in the design of piping system. This is particularly true for the Liquid Metal Fast Breeder Reactor (LMFBR) pipings where plastic or creep deformations of specific components such as elbows are, in general, unavoidable. ASME Code Case N-47/1/ does not specify any definite criteria for elastic follow-up. As for elastic follow-up of piping systems, Dhalla/2/ investigated inelastic behaviors of several piping systems by inelastic analyses. Dhalla/3/ and Severud/4/ proposed simplified methods for evaluating elastic follow-up effects in high temperature pipelines.

Power Reactor and Nuclear Fuel Development Corporation (PNC) established in 1978 the first draft of the 'Structural Design Guide for Class 1 Components of Prototype Fast Breeder Reactor for Elevated Temperature Service' ('MONJU' Design Guide) to be applied to the 'MONJU'. The final version was settled in 1984. The principal provisions for Class 1 Piping are unchanged from the first version to the last. The criteria for the evaluation of elastic follow-up of piping systems due to thermal expansion stresses are given in the 'MONJU' Design Guide. This has been accomplished by a lot of analytical as well as experimental efforts. An elastic follow-up test was conducted on a one fourth scale model of the hot leg piping of PHTS of the 'MONJU' at O-arai Engineering Center of PNC.

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The objectives of the test are to demonstrate that strain accumulation in the piping due to elastic follow-up is small, and that the elastic follow-up criteria provided in 'MONJU' Design Guide is conservative. Furthermore, the experimental results were compared with the simplified inelastic analyses.

2. Model Piping and Test Set-up

The model piping is illustrated in Fig. 1 and is arranged mainly in the horizontal plane between the reactor vessel and the IHX. It consists of one 180 deg. elbow, six 90 deg. elbows, two 60 deg. elbows and straight pipes of 8 inches in diameter. The nominal thickness is 2.8 mm, and the material is type 316 austenitic stainless steel. 7 constant-hangers are installed and one load cell for each hanger is attached to monitor the load carried by the hanger. 3 mechanical snubbers are fitted to protect against excessive motion by earthquake during the test. 18 blocks of heaters are attached to the outside surface of the model piping to heat up and maintain the aimed temperature. The special devices are provided for applying end displacements in three directions (axial, vertical and horizontal directions) to both ends (reactor vessel and IHX ends) of the piping for simulating the thermal expansion movement. Horizontal displacements and rotations of the piping are measured by displacement transducers at several locations of the piping. The change of ovality of elbows are measured by specially designed devices. Registance type weldable high temperature strain gages are attached to the outside surface of the selected elbows. Thrusts, shear forces and moments at the ends of the model are measured by specially developed load cells. Coolers with fins are provided between the piping and the load cell to cool the load cells. The piping is installed at room temperature free from expansion stresses (no cold spring). Fig. 2 shows the view of the testing.

3. Test Condition and Test Procedure

The normal operating temperature of the 'MONJU' piping is 529°C, and the duration is 210,000 hours. To meet the requirements for the test mentioned in chapter 1, the following should be achieved by the test.

(1) Similar stress and strain distributions to those of the 'MONJU' piping.

(2) Larger strain accumulation than that of the 'MONJU' piping.

Moreover, the test period is, in general, limited, say to half a year.

The computer program 'PISAC'/5/ which had been developed by PNC was used to determine the test condition. The program is based on simplified elastic-creep analyses and adopts the beam type modelling of the piping system, introducing creep flexibility factors for elbows.

First, 600°C was adopted as the test temperature. Elastic-creep analyses were conducted for the 'MONJU' piping and the model piping. End displacements having three components of the model piping were adjusted so that it may have similar stress distribution to that of the 'MONJU' piping, and have 1.25 larger elastically calculated stresses than those of the 'MONJU' piping. Fig. 3 shows the comparison of the moment-rotation relations of the elbow for the 'MONJU' and the model piping, where the stress based on C_2 index is used instead of moment. Only the specific 60 deg. elbow (60-1 elbow) and 90 deg. elbow (90-3 elbow) which had shown the maximum stresses were depicted in the figure. The location of both elbows are shown in Fig. 1. It can be understood from Fig. 3 that the creep deformation of the elbows of the model piping accumulated during the test period of 5,000 hours is larger than that of the 'MONJU' piping expected during the design life of 210,000 hours at 529°C. In the calculation of the model piping, the rigidity of the load cells and coolers is taken into account. The test condition was thus determined.

The temperature and load histories are illustrated in Fig. 4. Prior to the high temperature test, the room temperature was performed. In the high temperature test, the piping was heated up gradually, and meanwhile end displacements were applied to free thermal expansion load. After the aimed temperature of 600°C was reached, the prescribed ends displacements were imposed. After the hold time of 5,040 hours, the end displacements were set to the initial values and then reloaded again. In 380 hours, the piping was unloaded.

4. Test Results

The temperatures of the model piping during the test were within 600°C ± 10°C except the locations just near both ends. However, temperature drop was experienced once around the 90-3 elbow due to the trouble of the temperature controller, and it was repaired during the test.

Fig. 5 shows the change of the shearing force at the reactor vessel nozzle. The dotted points are values measured by the load cells. The broken line is those calculated by 'PISAC'. Both are very close and show the decreace of the force. As described before, the piping is arranged mainly in the horizontal plane. In-plane bending, therefore, is the dominant load. The measured rotation γ_Y in this plane of the 90-3 eblow is depicted in Fig. 6 in comparison with the calculated values. Both take the tendency to increase the rotation slightly, which indicates elastic follow-up of the piping. The observed rotation was a little larger than that predicted by 'PISAC' after 2,000 hours. The variation of the measured values will be attributed to the effect of changes of temperature on the output of displacement transducers. Fig. 7 illustrates the comparison of the hoop strain on the outside surface at the crown of the 90-3 elbow. In this case, the disturbance due to the trouble of the temperature controller is clearly observed, because the effect of temperature change on the output of the high temperature strain gage is generally large. It can be said PISAC predicts the local deformation fairly well. Some amount of elastic follow-up is observed.

5. Description of the 'MONJU Design Guide'

The procedure for the evaluation of elastic follow-up of piping systems provided in the 'MONJU' Design Guide is shown in Fig. 8. It utilizes the modified piping thermal expansion flexibility analysis method for the gloval analysis of piping systems. The method enables to estimate elastic follow-up behaviors of the piping by using increased flexibility factor in consideration of plastic or creep deformation of the specific elbow which has the maximum thermal expansion stress Pe in the piping. In this process, the moment level is decreased to 0.2 of the initial value, which accounts for the sufficient progress of elastic follow-up. This is illustrated in Fig. 9. The second step is to estimate the accumulated strain resulting from elastic follow-up. This is made based on the correlation between the maximum strain and the rotation of the elbow $G(\lambda)$ where $G(\lambda)$ is obtained from Clark and Reissner's equation/6/ by elastic analysis and α is bend angle of an elbow. The correction factor f (f=1.5) considering the creep and plastic behaviors of the elbow is introduced. The criteria for the judgement of the classification of the thermal expansion stress as primary or secondary stress is whether or not the accumulated strain derived in this way is larger than 0.5%. What is to be noted in evaluating Strain Limit, is the enhanced creep strain should be added to the one thus obtained. As described above, the classification of thermal expansion stresses and the estimation of accumulated strains due to elastic follow-up can be made only by elastic calculations in the 'MONJU' Design Guide.

6. Discussions

Fig. 10 shows the relationship between the moment expressed in terms of stress and the rotation of the critical elbow (90-3 elbow), where the resultant moment M is adopted for the moment, and the resultant rotation γ is used for the calculation while the dominant component γ_Y is utilized for the experiment, since other components are not measured. The knuckled line is seen in the figure. This is because the components of the moment change the sign at the loading and unloading stage. A very small amount of elastic follow-up is observed in this piping system. At the Phase 1 loading stage, the measured moment is a little higher than the calculations. This will be attributed to the possible decreased flexibility of the piping because of the restraining effect of heaters attached to the outside surface of the piping. After the hold time, the measured moment and rotation reached nearly the predicted values. The slope of the moment-rotation relation during the hold time estimated by 'MONJU' Design Guide is close to the experimental and analytical values, however, the point corresponding to 0.2 of the initial moment level is too conservative. In the same figure, the curve estimated by 'PISAC' for the 'MONJU' piping is illustrated. It was demonstrated that even after 210,000 hours, elastic follow-up of the 'MONJU' piping is very small.

7. Conclusion

The elastic follow-up test was conducted on a one fourth scale model of the hot leg piping of PHTS of the 'MONJU'. Through the test and the associated analyses, the following conclusions were obtained. First, strain accumulation of the 'MONJU' piping due to thermal expansion stress is small. Second, the 'MONJU' Design Guide is conservative for evaluating elastic follow-up of piping systems. Third, the computer program 'PISAC' for elastic-creep analysis of piping systems can predict fairly well elastic follow-up behaviors of pipings.

References

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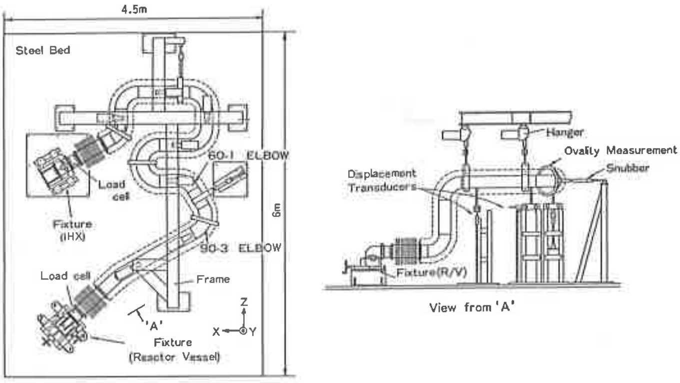

Fig. 1 Model of Hot Leg Piping of 'MONJU'

Fig. 2 View of Testing

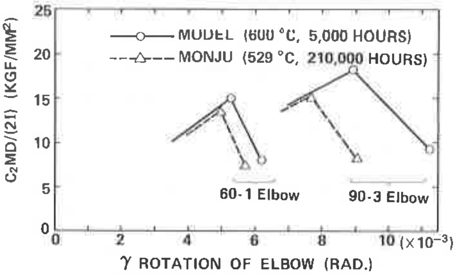

Fig. 3 Comparison of Moment-Rotation Relations between 'MONJU' and Model Piping

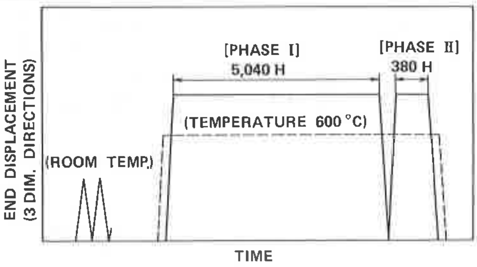

Fig. 4 Temperature and Load History of Test

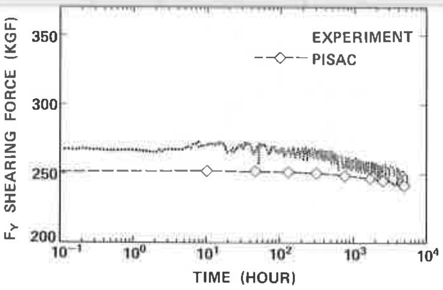

Fig. 5 Change of Shearing Force at Reactor Vessel Nozzle with Time

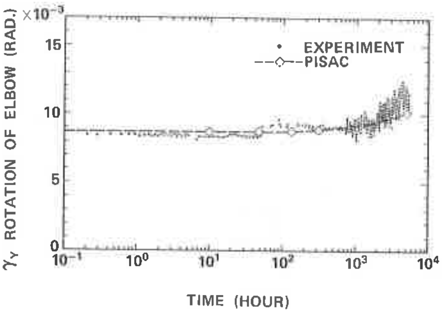

Fig. 6 Change of Rotation of Elbow with Time

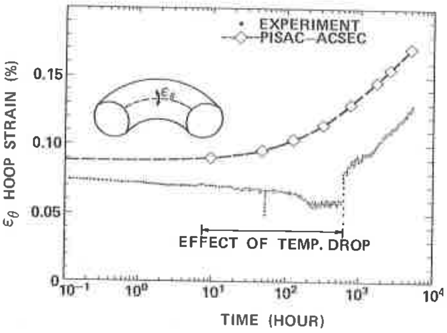

Fig. 7 Change of Hoop Strain at Crown of Elbow with Time

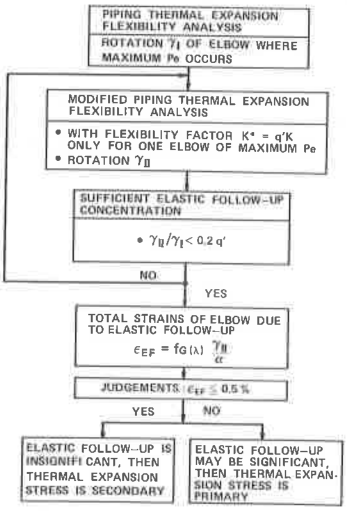

Fig. 8 Procedure for Evaluation of Elastic Follow-up in 'MONJU' Design Guide

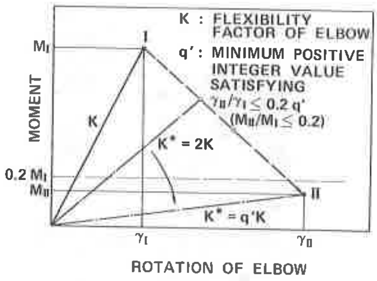

Fig. 9 Concept of Modified Piping Thermal Expansion Flexibility Analysis

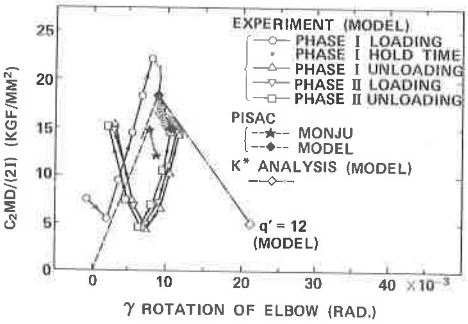

Fig. 10 Relation between Moment and Rotation of Elbow