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Elastic follow-up evaluation in pipes and elbows under displacement controlled loads at elevated temperature

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ABSTRACT

An analytical study has been performed to predict elastic follow-up behavior in elbows and straight pipes attached to nozzle under displacement controlled loading at elevated temperature. The evaluation method of elastic follow-up behavior employs pseudo inelastic analyses in which the stiffness of elbows or straight pipes with inelastic response is reduced. In this paper, formulae to define adequate stiffness reduction and to estimate maximum local strain in elbows and straight pipes from their angular deformations are proposed.

INTRODUCTION

A piping layout mainly governed by a thermal expansion stress range (Se) to be limited below 3Sm in the ASME code [1]. However, the piping integrity can be maintained without satisfying the Se limitation, when the inelastic behavior of piping under thermal expansion is evaluated accurately. A design procedure based on elastic analysis has been proposed to predict inelastic response of piping systems and local strains [2]. Local strains are used to evaluate strain and creep fatigue damage.

The procedure employs pseudo inelastic analysis using linear elastic analysis with the stiffness reduction at selected piping components (elbows and straight pipes) to estimate inelastic deformation conservatively.

EVALUATION PROCEDURE

The proposed piping design procedure for thermal expansion loading at elevated temperature is proposed in [2]. The outline of evaluation on elastic follow-up deformation is as follows.

1. Choose elbows or straight pipes which are expected to show inelastic behavior. ($M>M_L$)
2. Perform elastic thermal expansion analysis when the stiffness of only one chosen piping element is reduced. The stiffness is reduced until the calculated moment in the element is less than M_L.
3. Choose the piping element which enhance the angular deformation of evaluation points when stiffness of the piping element is reduced.
4. Calculate angular deformations due to the elastic follow-up by summing up the increase of angular deformation for each chosen case.
5. Estimate local strain by the proposed formula from the above calculated angular deformation.

In this study, finite element analyses were carried out in order to examine formulae evaluating the moment limit (M_L) and formulae estimating maximum local strains in elbows and straight pipes from their angular deformations. These formulae are used in 1., 2. and 5. in the above procedures.

ANALYSIS

Large-displacement inelastic analyses were performed using the structural analysis program MARC. Three dimensional shell elements were used. The analytical cases of straight pipes and elbows are shown in Table-1 and Table-2 respectively. The analysis models are shown in Figure-1 and Figure-2. The level of moment relaxation limit and strain evaluation formulae were proposed from those analytical results. Details of the analyses are described below.

Straight pipes

The outline of the analysis model is shown in Figure-1. The ratios of radius to thickness (r/t) equal to 13.9, 30 and 43. The ratios of length to radius (L/r) equal to 7.5 and 15 were employed. These values were chosen as representative shapes in sodium circuits in the demonstration fast breeder reactor (DFBR) in Japan. The boundary conditions were fixed on one side and give transverse displacement on the other side. In the case B-2', rotational springs were attached on fixed side. In the case B-3, a rotational displacement was given on loaded side. Material and temperature of straight pipes are 316FR stainless steel at 550℃ except that they are 316FR at 600℃ in the case B-4 and 304 stainless steel at 550℃ in the case B-5.

The displacement is equal to the design allowable displacement δ_H and kept for 300,000 hours. The design allowable displacement δ_H is the maximum allowable displacement in the proposed standards for preventing displacement controlled buckling deformation [3]. In the case that one end is fixed, δ_H is given as follows:

$$\delta_H=\frac{1}{f_B}\left\{\frac{1.27\sigma_y L^2}{3Er}+L\left(0.003+0.15\frac{t}{r}\right)\right\} \qquad (1)$$

where f_B is safety factor, f_B=1.67 (for operation conditions 1 and 2 corresponding to level A and B in ASME load), E is Young's modulus and σ_y is yield stress. L is pipe length and r is pipe radius. δ_H values of the models are shown in Table-3.

The relation of loads versus displacements are shown in Figure-3 for several analysis cases. The loads are dimensionless value of bending moment M on the fixed end divided by the product of modulus of section Z and allowable stress intensity value Sm, where Sm is defined as 0.9Sy. Sy is the yeild stress. The displacement δ is represented by the dimensionless value of elastic beam stress $3Er\delta/L^2$(=Sn) divided by Sm. All the analysis cases can be plotted on the same line in elastic-plastic region. This line is approximated to bi-linear curve which consists of the elastic straight line and a horizontal line (M/Z=1.27Sy). This approximation is used for elastic follow-up evaluation of piping system. The stiffness of the evaluating point (and possibly some of other components) is reduced until the bending moment at the evaluating point calculated by elastic analysis is decreased below the horizontal. Hence the lower the horizontal line is, the greater safety margin the elastic follow-up evaluation produces.

As for creep behavior, the moment is assumed to be relaxed from 1.27SyZ to $\alpha \times 1.27$SyZ. α is written as the next equation.

$$\alpha=\frac{Sr(t/p)}{1.5Sm} \qquad (2)$$

Sr(t/p) is creep relaxation stress for time t/p. The factor p discribes the creep relaxation of the moment is slower than that of the uniaxial stress. Creep analysis results were compared with relaxation stress Sr. An example of the analysis results is shown in Fig-4. Relaxation factor α (= σ (t)/Sy) is calculated by the formula (2).

The factor p in the above depends on the material and temperature. The value of p is decided from the analytical results. Typical results are shown in Fig-4. Factor p is summarized in Table-4. The results lead to that the moments estimated by the proposed formula are smaller (safer) than the results of FEM analysis in all cases. In this study, for straight pipes, the factor p is defined as formula (3) except the case where the material is 316FR and its temperature is more than 550℃.

$$p=4 \qquad (3)$$

As for 316FR with temperature higher than 550℃, the factor p is described as follows where T is temperature in degree C.

$$p = 4 - \frac{2.2(T-550)}{50} \qquad (4)$$

The physical meaning of p is an elastic follow-up parameter which represents the delay of stress relaxation compared to the purely strain controlled condition.

The bending moment discussed above is denoted M_L. The evaluation formulae of M_L are proposed as:

Without creep : $M_L=1.27Sy \cdot Z$ (5)
With creep : $M_L=1.27Sy \cdot Z \cdot Sr(t/p)/1.5Sm$ (6)

Sr(t/p) means the Sr value after 1/p times the holding time t at elevated temperature.

Elastic follow-up evaluation for straight pipes uses a method in which the increase of rotational displacement is calculated by reducing the spring constant at the relevant component in elastic analysis model having a rotational spring at the evaluation point. The evaluation method was studied to calculate the local maximum strain in a straight pipe element from this rotation of the spring. The strain is increased according to the increasing of elastic follow-up deformation. The relation between evaluated strains and analytical results can be written as the formula (7).

$$\varepsilon = f\frac{M_E}{EZ} + \beta(\theta - \theta_E) \qquad (7)$$

β is a factor depending on L/r and the stiffness of fixed end. In order to erase the effect of geometry or stiffness, a simplified strain evaluation formula for straight pipes is proposed as:

$$\varepsilon = f\left\{\frac{M_E}{EZ} + g\frac{1}{\dfrac{EZ}{M_E - M} + \dfrac{1}{\theta - \theta_E}}\right\} \qquad (8)$$

M_E, bending moment at evaluation element, is calculated by normal elastic analysis. θ_E is rotation of the spring. M is bending moment with reduced stiffness and should be lower than M_L. θ is rotation of the spring calculated by elastic follow-up analysis. The f is a factor of strain in elastic deformation, f=1.5 at completely fixed elements. The g is a factor for non-linear strain (g=5). Figure-5 shows comparison between strain evaluation formulae and FEM analysis results. Evaluation results are consevative in all the analysis cases.

Elbows

Stiffness reduction ratio, together with evaluation formula to calculate elastic follow-up strain for elbow, is proposed. They are proposed according to the same procedure as straight pipes in the case that thermal stress in elbows is beyond the shake-down region. Inelastic analyses were performed in order to propose M_L and strain evaluation formula. The analysis cases are shown in Table-2. The analysis model and boundary conditions are shown in Figure-2. In-plane bending displacements were loaded up to the level where elastically calculated maximum stress in elbows is equal to 2.5 times 3Sm. The displacements were kept for 300,000 hours. Material was type 304 stainless steel at 550℃ and 316FR at 600℃.

Relative angler deformations between both ends of elbows versus moments are shown in Figure-6. The value of M_L (=$1.27SyZ/B_2$ for elbows) is obtained from dividing that for straight pipes by B_2 index given in ASME Section III [1]. The collapse moment of long radius elbows and short radius elbows are shown to be at least more than 1.2 times that indicated by the above formula from the collapse experiments of elbows [4]. Therefore, M_L for elbows is proposed as follows:

Without creep : $1.27SyZ/B_2 \times 1.2 = 1.52SyZ/B_2$ (9)
With creep : $1.52SyZ/B_2 \times Sr(t/p)/1.5Sm$ (10)

Stress relaxation of elbows from Sy is shown in Figure-7 compared with Sr. It appears that moment relaxation of elbows is slower than that of straight pipes. Factors of p of elbows are larger than that of straight pipes. The p factor is tabulated in Table-5 for elbows. The M_L values in Figure-6 are compared with non-linear analysis results. The M_L values are smaller than the calculated moments in the case of plastic and creep region. It has been confirmed that the M_L values estimate the moment conservatively in non-linear region.

An evaluation formula of elastic follow-up strain from angular deformation between both ends of elbows was proposed conservatively in comparison with non-linear analysis results. The elastic follow-up strain in elbows is the growing of strain caused by increasing of angler deformation when the flexibility factor k is increased in elastic analysis model. The formula is as follows.

$$\varepsilon = f \cdot C_2 \frac{M_E}{EZ} \left\{ 1 + g \frac{\theta - \theta_E}{C_2 \frac{M_E}{EZ}} \right\} \qquad (11)$$

C_2 is the stress index in ASME Section III [1]. Factor f and g are shown in Table-6. Factor g which indicates the increase of strain in plastic region and elastic follow-up depends on pipe material or temperature. Evaluated strains were compared with FEM analytical results as shown in Figure-8. Hoop strain gives the maximum membrane plus bending strain at the point where the maximum stress is caused in an elbow. And axial strain gives the maximum membrane strain at the point where the maximum stress is caused in an elbow. These two types of strain are conservative to the FEM calculated results.

CONCLUSION

The evaluation methods of elastic follow-up behavior have been proposed. The formulae to estimate the moment M_L and maximum strain for elbows and straight pipes were defined from the results of non-linear analyses. Validity of the method was confirmed being compared with non-linear analyses and experiments [2].

ACKNOWLEDGMENT

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Table-1 Analysis cases of straight pipes

r/t	13.9	30	43	Material & Temp.
L/r=7.5	A-1	B-1	C-1	316FR,550℃
L/r=15	A-2	B-2, B-2'	C-2	
	-	B-3	-	
	-	B-4	-	316FR,600℃
	-	B-5	-	SUS304,550℃

Note: B-2'; Stiffness of Y-junction is considered.
B-3; Rotational deformation is loaded

Table-2 Analysis cases of elbows

r/t	13.9	30	43	Temperature
316FR	A-1	B-1	C-1	550 ℃
	-	B-2	-	600 ℃
SUS304	-	-	C-2	525 ℃
	-	B-3	-	550 ℃

Note: Short radius elbows (R=2r) are employed.

Table-3 δ_H values

Case	δ_H (mm)	δ_y (mm)
A-1	9.340	1.757
A-2	21.35	7.028
B-1	22.02	6.462
B-2	53.87	25.85
B-4	53.98	26.00
B-5	52.83	24.49
C-1	18.84	6.495
C-2	47.57	25.98

Note: δ_y is yield displacement

Table-4 p values for straight pipes

Temperature ℃	p	
	316FR	SUS304
450	12	12
500	8	9
550	4	7
575	3	6
600	1.8	5.5

Table-5 p values for elbows

Temperature ℃	p	
	316FR	SUS304
425	-	33
450	-	50
500	30	150
550	50	67
600	5	33

Table-6 Factor f and g for elbows

Strain	Temperature ℃	f	g	
			316FR	SUS304
Membrane + bending	≦550	1	2.5	3.0
	>550		3.5	-
Membrane	≦550	1/3	-	1
	>550		3.5/3	-

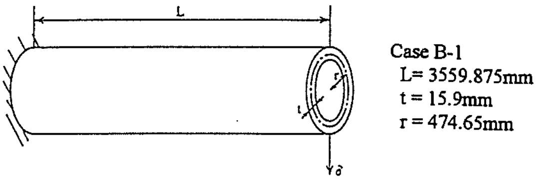

Figure-1 Analysis model for straight pipe

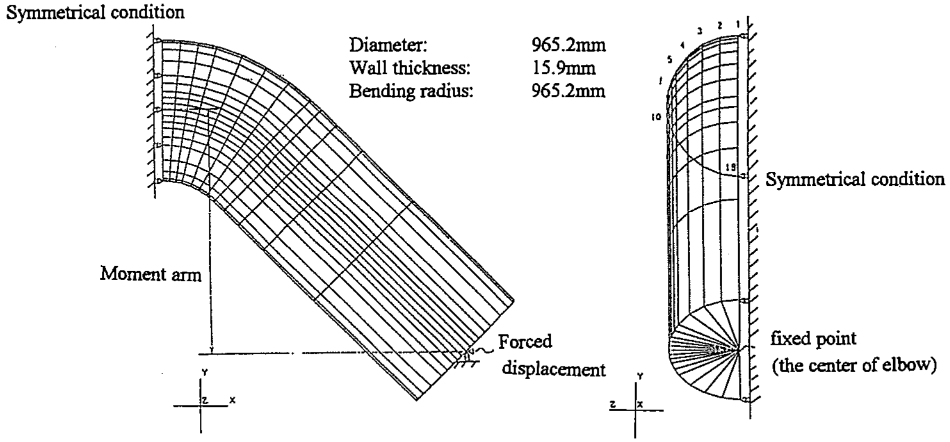

Figure-2 Analysis model and boundary condition for elbow

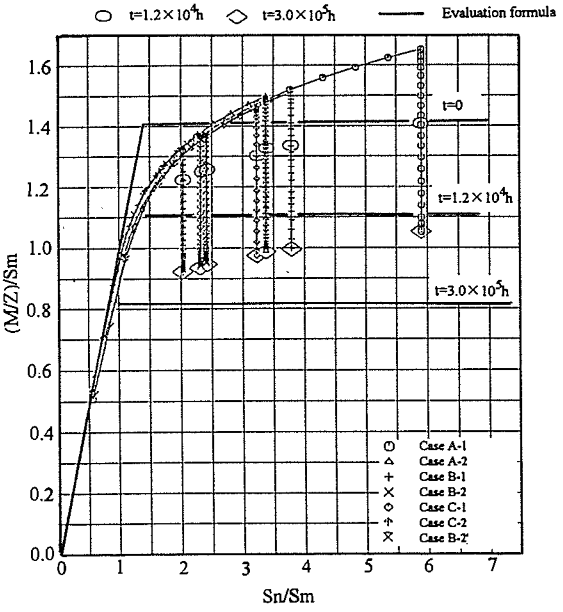

Figure-3 Relation of loads versus displacements (straight pipes)

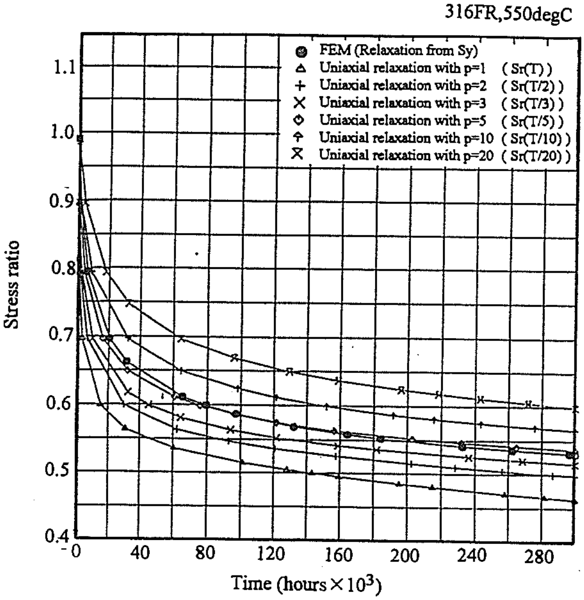

Figure-4 Comparison between Sr and relaxation stress from Sy

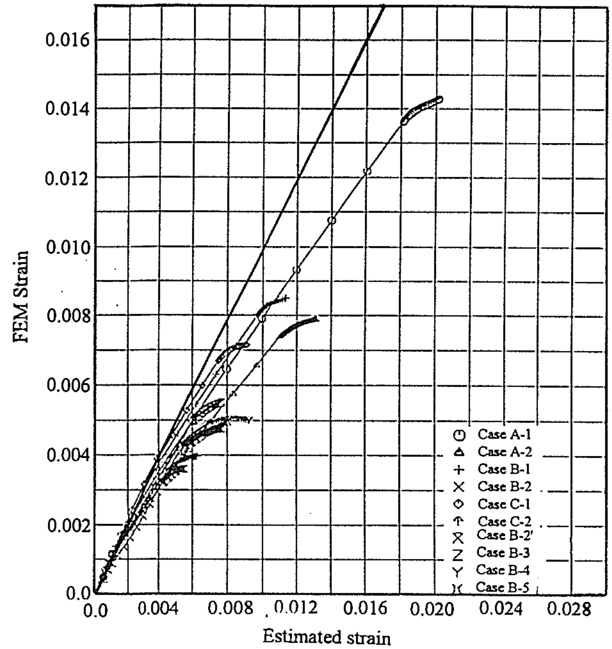

Figure-5 Comparison between evaluated strain and FEM analysis results

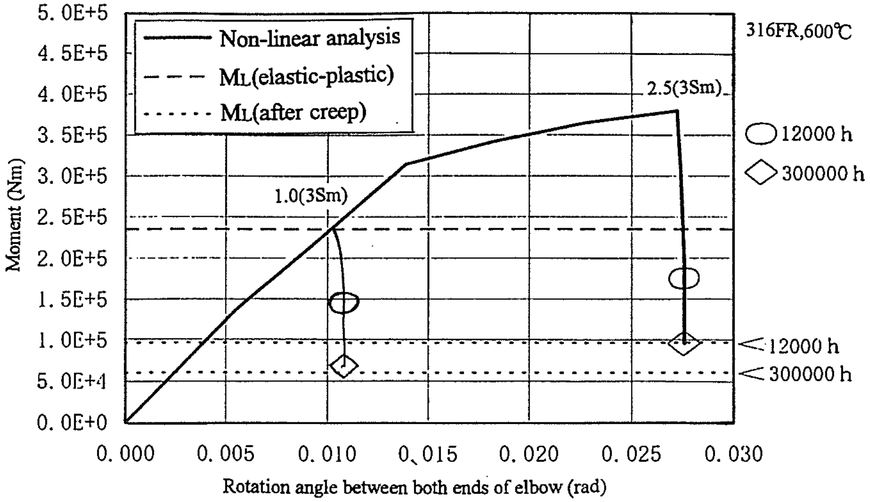

Figure-6 Angular deformations versus moment

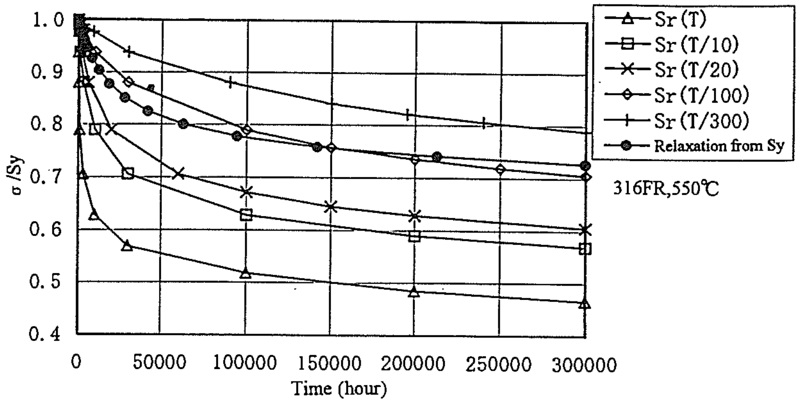

Figure-7 Comparison between Sr and behaviors of stress relaxation Sy

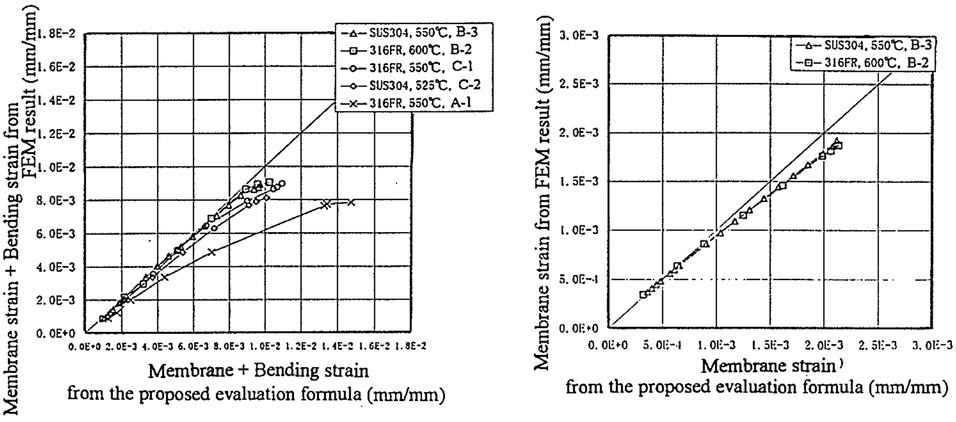

Figure-8 Comparison between evaluated strain and FEM analysis results