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A simplified design method of piping subjected to thermal loads at elevated temperature

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ABSTRACT

As piping systems used at elevated temperature suffer severe thermal expansion loads, the thermal expansion stress range Se is restricted severely for piping in current design standards. Advanced evaluation procedures are desired to shorten pipe length by eliminating the Se limitation. In this paper, a new design procedure for piping under thermal expansion loads is proposed considering inelastic behaviour of piping systems.

INTRODUCTION

Piping systems used at elevated temperature in nuclear and fossil power plants suffer thermal expansion loads. Current design codes such as ASME Section III[1] restrict the thermal expansion stress Se in piping to shakedown stress 2 σy or 3Sm, where σy is a yield stress and Sm is a design stress intensity value. This restriction is one of the most critical limitations in piping design at elevated temperature. To satisfy this Se limitation, piping systems tend to have complex routing using a lot of elbows. Long routing increases the number of piping supports. More advanced evaluation procedure is desired to shorten piping length and reduce plant construction cost, especially for fast breeder reactors whose piping systems are used at temperature higher than 500℃.

The Se limitation is introduced into design codes as a conservative rule to avoid inelastic behaviour in piping systems under thermal expansion loads. Inelastic behaviour of piping system is very complicated and difficult to predict accurately because the compliance in piping system is usually very large, and yielding and creep phenomena may cause significant elastic follow-up. If inelastic behaviour of piping under thermal expansion is estimated appropriately in design procedure, the integrity of piping systems can be assured beyond shake down region.

In this paper, a piping design procedure based on pseudo inelastic analyses is proposed to predict inelastic response of piping system and local strains in pipe components under cyclic thermal expansion loading. The detailed evaluation methods and their background data are explained separately in [2-5].

OBJECTIVES

More rational design of piping system is made possible by developing appropriate methods to predict local strains and ratchetting behaviour in inelastic situation, instead of the conventional Se limitation. To address this need, followings are investigated for developing a new design procedure.

(1) Establish an evaluation method using pseudo inelastic analyses to predict inelastic deformation of piping systems and local strains in straight pipes and elbows
(2) Define design criteria to prevent excessive strain due to ratchetting in straight pipes and elbows under cyclic deformation
(3) Define design criteria to prevent buckling of straight pipes and elbows under displacement controlled loads

The outline of the proposed design procedure is shown in Figure 1 with R&D programmes carried out. The details of the proposed design procedures are explained in the following subsections.

PROPOSED DESIGN PROCEDURE FOR PIPING

Prediction of Elastic Follow-Up in Piping Systems

Because of recent improvement of analysis codes and computational environment, elastic follow-up behaviour of piping systems can be estimated using inelastic analysis methods. However, as actual piping has deviations of stiffness from nominal values of piping components and support, inelastic analysis results are not always conservative for design. Therefore, a prediction method using pseudo inelastic analyses with conservative assumptions of inelastic behaviour of piping components is considered to be more practical in piping design.

The proposed prediction method employs pseudo inelastic analysis based on elastic analysis with the stiffness reduction at selected pipe components (straight pipes or elbows) to estimate possible maximum deformations in a piping system. The procedure to predict elastic follow-up in a piping system is outlined in Figure 2 and described as follows.

1. Choose elbows and/or straight pipes which are expected to show inelastic behaviour.
2. Perform elastic analyses in which the stiffness of one of the chosen elbows or straight pipes is reduced. The analyses are carried out reducing the stiffness of each elbow or straight pipe which is chosen above. The reduction of stiffness is determined so that the moment at the selected pipe component reaches the lower bound of relaxed moment ML showing inelastic response.
3. In evaluating the elastic follow-up deformation of an elbow or a straight pipe, chose the analysis case in which the stiffness of that particular element is reduced as well as those cases where the deformation of the element increases by reducing the stiffness of another elbow or straight pipe.
4. Estimate angular deformation with elastic follow-up by summing up the individual increase of angular deformations in the chosen analytical cases.

Reduction of stiffness due to plasticity and/or creep is simulated by the change of flexibility factors or Young's modulus of elbows and the change of spring constants at the end of straight pipes. The lower bound of relaxed moment ML is defined as[2];

For straight pipes,

$$M_L=1.27Sy \bullet Z \qquad \text{in plastic regime} \tag{1}$$

$$M_L=1.27Sy \bullet Z \bullet Sr(t/p) / 1.5Sm \qquad \text{in creep regime} \tag{2}$$

For elbows,

$$M_L=1.52Sy \bullet Z / B_2 \qquad \text{in plastic regime} \tag{3}$$

$$M_L=1.52Sy \bullet Z / B_2 \bullet Sr(t/p) / 1.5Sm \qquad \text{in creep regime} \tag{4}$$

where Sy, Sm, Z and Sr(t/p) are yield stress of material, design intensity value, section modulus and stress after creep relaxation, respectively. t is time duration at creep temperature, and p is a factor, which considers elastic follow-up for creep relaxation. The factor p is given in tables depending on material, geometry and temperature[2]. B_2 is the stress index determined in ASME B&P code Section III[1].

The prediction procedures were validated for various type of piping systems. Examples of the investigated piping systems are shown in Figure 3, including both in-plane and out-of-plane routings. The comparison between the prediction by the proposed method and inelastic analysis results is shown in Figure 4. The proposed method gives conservative predictions for the increase of angular deformation due to elastic follow-up.

Prediction of Local Strains in Pipe Components

Local strains have to be predicted to calculate creep-fatigue damage. Prediction formulae for strains are proposed by approximating inelastic analysis results of pipe components for straight pipes and elbows. Local strains can be calculated from the rotation angle predicted by the method above mentioned. The formulae are described in a separate paper. [2]

Once the local strains are obtained in pipe components, creep-fatigue damage can be evaluated following the same procedures for vessel design[6].

Prediction of Ratchetting Strains in Pipe Components

Thermal expansion loads are cyclically applied to piping systems representing start-up and shut-down of plant operation. The loads are displacement controlled, and ratchetting by this cyclic loading is concerned. Experimental and analytical studies have been performed to propose criteria for preventing ratchetting in pipe components. Formulae to predict ratchet strains in straight pipes and elbows are proposed as functions of rotation angle and the number of cycles[3]. As a simplified evaluation, the onset angular deformation θ of ratchetting phenomena is estimated as;

$$\theta / \theta_{cr} = 0.3 \qquad \text{for straight pipes} \qquad (4)$$

$$\theta / \theta_0 = 0.45 \qquad \text{for elbows} \qquad (5)$$

where θ_{cr} is a critical rotation angle for displacement controlled buckling of a straight pipe[4] and θ_0 is a reference rotation which is the twice of the elastic rotation angle corresponding to the collapse moment of an elbow.

Prevention of Buckling under Thermal Expansion

Buckling criteria are generally given for load-controlled loads in design standards. It is too conservative to evaluate buckling under displacement-controlled loads like thermal expansion by the same criteria for load-controlled loads. Therefore, buckling criteria for straight pipes and elbows under displacement were investigated.

For straight pipe, buckling can be prevented if rotation angle at the end of a pipe is restricted to critical angle $\theta_{cr} = 0.003+0.15(t/R)$ [4]. The buckling was defined as separation point from small deformation theory. On the other hand, buckling phenomena of elbows are not evident in both experiments and analyses[5]. If rotation corresponding to maximum load is defined as buckling deformation, the rotation of an elbow to catastrophic failure by deformation-controlled loading is large enough as engineering. Thus, no limitation is necessary to prevent buckling of elbows against thermal expansion loads.

VALIDATION OF THE DESIGN PROCEDURE

In order to validate the proposed design procedures, experiments using a piping system model were performed. The purpose of the experiments was to demonstrate that no excessive gross deformation or ratchetting would occur even at maximum allowable stress conditions determined by the proposed design procedures.

The piping system shown in Figure 5 was chosen because remarkable elastic follow-up behaviour was predicted from beam model analyses. The material of the piping was type 304 stainless steel, and the dimensions were 114.3mm in diameter and 3mm in thickness. The experiments were carried out at room temperature as well as at 600℃ with 10 hour holding. Thermal expansion was simulated by forced displacement at one end, while the other end was fixed. Strain gauges were attached to measure the strains of elbows, and in-plane angular deformation of elbows were measured.

The experimental results were compared with the predictions by three dimensional inelastic analyses and the proposed evaluation method. Figure 6 shows the comparison of the local rotation angles between the experiment and predictions. The prediction by the inelastic analyses agree with the experimental result. The proposed design method predicts the test results conservatively. No excessive ratchetting strains or gross deformations of the system were observed in the experiments, and it was confirmed that allowable stress level by the proposed procedure was acceptable even at elevated temperature.

CONCLUSIONS

A new design procedure for piping at elevated temperature under thermal expansion loads has been proposed. Methods using pseudo inelastic analyses to predict elastic follow-up in piping systems and local strains in pipe components have been developed, and criteria to prevent ratchetting and buckling are clarified in the procedure.

It was confirmed that the procedure conservatively predicts inelastic behaviour of piping under displacement-controlled loading at elevated temperature by comparison the predicted results with experiments. Allowable stress level of piping against thermal expansion is expected to be expanded by applying the new procedure where the conventional Se limitation is eliminated.

ACKNOWLEDGEMENT

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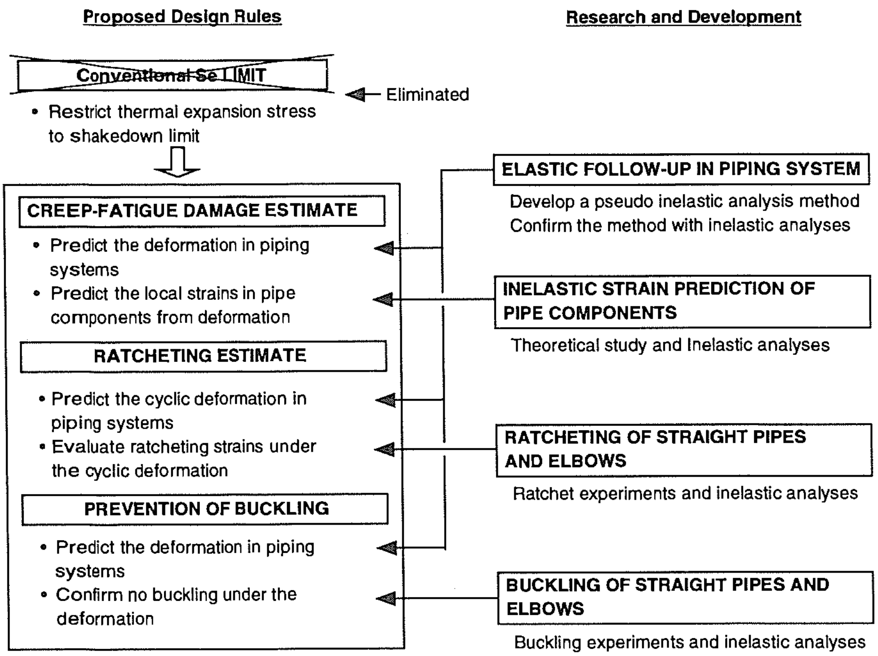


Figure 1 Proposed design procedure and R&D programmes

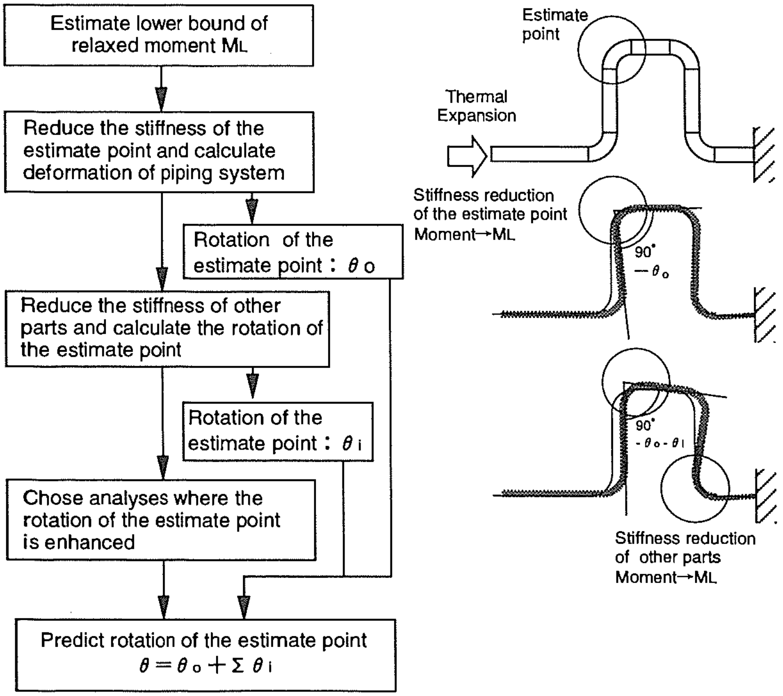
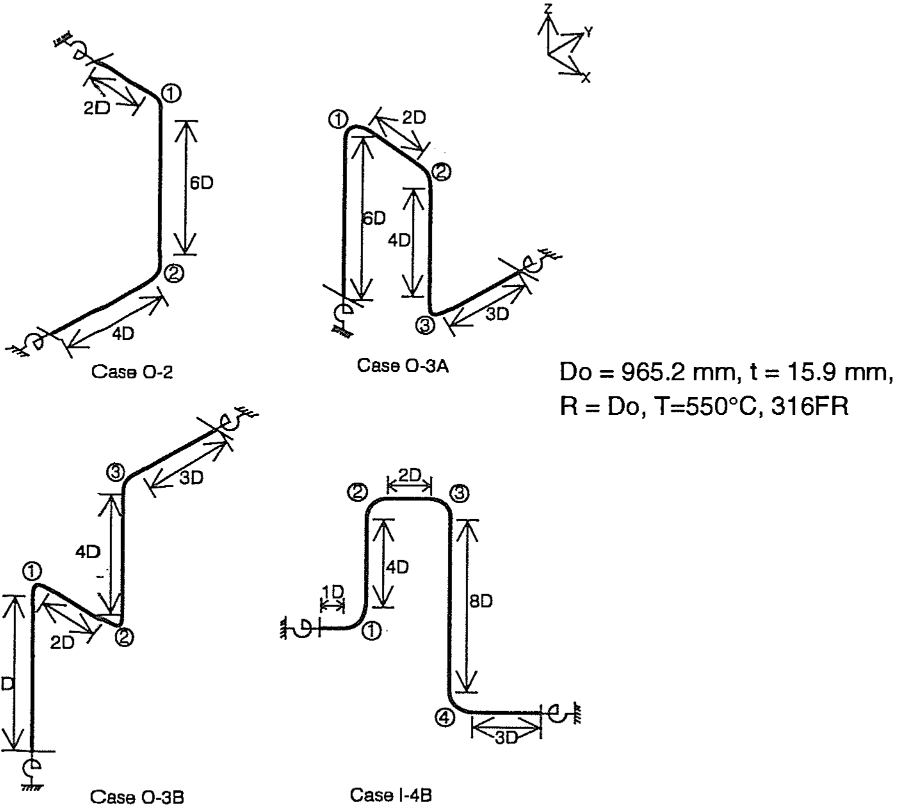
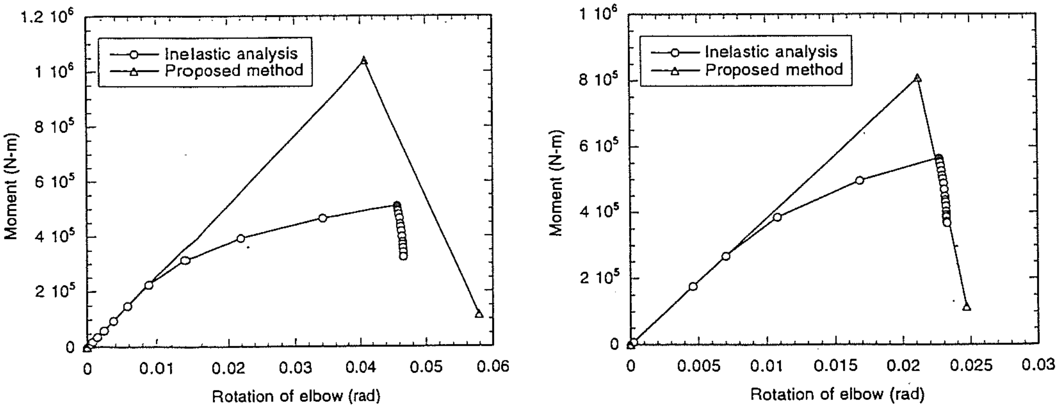


Figure 2 Pseudo inelastic analysis method to evaluate elastic follow-up



Do = 965.2 mm, t = 15.9 mm,
R = Do, T=550°C, 316FR

Figure 3 Examples of piping systems to investigate elastic follow-up



In-plane case (I-4B)

Out-of-plane case (O-2)

Figure 4 Comparison of elastic follow-up behaviour between the prediction by the proposed method and inelastic analyses

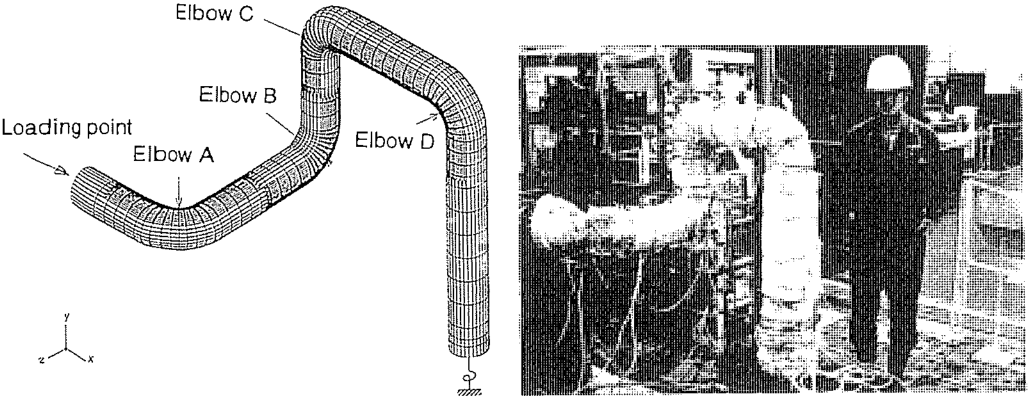


Figure 5 Piping system and overview of validation experiments

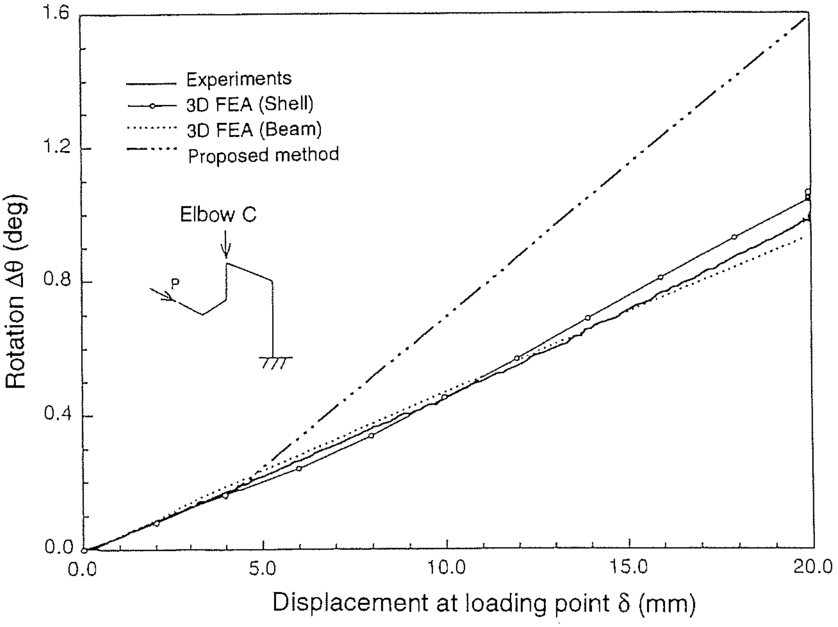


Figure 6 Comparison of the rotations of an elbow between experiment, inelastic analysis and the prediction by the proposed procedure