DEVELOPMENT OF ANALYTICAL PROCEDURE FOR THE DESIGN OF 1.5 Mwt HELIUM GAS INTERMEDIATE HEAT EXCHANGER

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Summary

This paper reports the structural integrity study of 1.5 Mwt helium gas intermediate heat exchanger performed as a part of "Research and Development of Direct Steel Making Technology Utilizing High Temperature Reducing Gas" which is one of the National Research and Development Programs by Agency of Industrial Science and Technology, Ministry of International Trade and Industry, Japan. The normal operation temperature of the heat exchanger exceeds 1000°C which is beyond the scope covered by the existing design code, e.g. ASME Code Case 1592. Therefore, a special analytical and experimental procedure should be developed to establish design rules of unprecedented components operating at extremely high temperature.

Developmental efforts have been focussed on (1) compilation of the finite element analysis program for detailed analysis of two and/or three dimensional structures, and (2) the establishment of simplified methods for elevated temperature design. The latter includes, a simplified transient creep analysis procedure, application of the reference stress method, and a simplified solution technique of creep buckling behavior. In addition, various experimental schemes have been worked out for the verification of the detailed and/or simplified methods being developed.

This paper first outlines the efforts in the above directions and describes next the method for elastic-plastic-creep analysis which incorporates the pseudo stress concept in some detail. The concept originally proposed by Cry et al. for the bilinear isotropic hardening material is extended to the kinematic and combined hardening materials. Numerical example shows that the accuracy of detailed finite element solution is considerably improved by the technique using the pseudo stress as a kind of correcting load vector.

1. Introduction

The project "Research and Development of Direct Steel Making Technology Utilizing High Temperature Reducing Gas" started in 1973 as one of the National Research and Development Program by Agency of Industrial Science and Technology, Ministry of International Trade and Industry, Japan. The crucial component of the direct steel making system is the helium gas intermediate heat exchanger which is operated at a high temperature exceeding 1000°C. Thus the establishment of rules is imperative to meet design requirements at elevated temperature beyond the scope of existing design codes, e.g. ASME Code Case 1592.

To this end, two task groups have been formed. One, named sub-committee IHX-M, has been engaging in the material aspect so that the efforts are reflected to the design rules. Paper F/9/1[1] in the Transactions of this Conference outlines the works and provisional conclusions of S/C IHX-M. Complementary to it, the present paper summarizes the activities of S/C IHX-A, the objective of which is the establishment of theoretical and experimental bases for elevated temperature design.

Both the detailed numerical analysis procedures and the simplified methods have been investigated. An outline of the efforts in these directions is given briefly in the next section. Then follows the section describing the detailed analysis technique adopting the pseudo stress concept of Cry et al.[2] and numerical results in due order.

2. Development of Methods for Inelastic Analysis

2.1 Finite Element Elastic-Plastic-Creep Analysis

A general purpose program using the finite element method has been compiled for the two and/or three dimensional structural analysis. It features the incorporation of the effect of tertiary creep, dependency of material constants on temperature, and a correction utilizing the pseudo stress concept of Cry et al. [2]. As will be detailed in next section, the correction has been proved to be effective to improve the accuracy of numerical results. In an auxiliary effort, a program for large deformation analysis of axi-symmetric thin shell and beam structure has been developed. This program is useful for the elastic-plastic buckling as well as creep buckling analysis of these structures.

2.2 Simplified Method

The existing design codes are principally based on the simplified methods and there still remains a strong demand for these methods in almost every phases of the design process. Various methods in this category have been examined in the present project of designing 1.5 Mwt helium gas intermediate heat exchanger and novel techniques are developed, when need arises.

The method established first is a simplified creep analysis procedure combining the solution to the steady creep problem with that to decay of the stress field ($\sigma_{ij}^{e} - \sigma_{ij}^{s}$), where σ_{ij}^{e} , σ_{ij}^{s} are elastic and steady creep stress fields respectively. The solution to the complete creep problem is decomposed into those of two complementary problems, i.e. the steady creep under specified loading and the decay of stress field ($\sigma_{ij}^{e} - \sigma_{ij}^{s}$). An approximate solution for the decay of the stress field ($\sigma_{ij}^{e} - \sigma_{ij}^{s}$) is obtained by a rate type of variational principle applied to the homogeneous equilibrium equations (i.e.

under zero load). The final solution is the superposition of two solutions.

A second method developed concerns with the application of reference stress method [3] and/or energy bounding theorems [4] which have been recognized as useful tools in the simplified analysis of creep. An accurate estimate of creep deformation can be made, if the solutions of the finite element analysis are incorporated in these methods. In the procedure we examined, the collapse load of the relevant structure is determined by the finite element analysis and used as a representative stress in the reference stress method or a statically admissible stress field in the application of energy theorems.

In the simplified method for creep buckling, the following cumulative damage rule is proposed and compared with the prediction by various theoretical procedures as well as the test results obtained by the experimental shemes of the project

$$\sum \frac{t_i}{t_{cri}} = 1$$

where t_i is the time duration of the load condition i and t_{cri} denotes the time for occurrence of creep buckling under the same load condition i.

3. Finite Element Elastic-Plastic-Creep Analysis of Structure with Temperature Dependent Material Properties

The tangent modulus methods have been usually taken in finite element elastic-plastic-creep analysis. In this case, it is important to obtain the accurate relations between stress and strain increments. Especially, the temperature dependency of material properties must be taken into consideration accurately in elevated temperature. The pseudo stress concept was originally proposed by Cry et al. for the bilinear isotropic hardening materials.

In this chapter this concept of pseudo stress is extended to kinematic hardening materials, combined hardening materials and the multi-linear isotropic hardening materials. Then using this extended pseudo stress, accurate relations between strain and stress increments are obtained.

3.1 Constitutive Relations Between Plastic Strain and Stress Increments

It is assumed that the total strain increment can be expressed as the sum of the elastic, plastic, creep and thermal strains. It is further assumed that the plastic strain increment is completely independent of the creep strain increment. Then the total strain increment $\Delta \varepsilon_{ij}$, at time t_i and temperature θ_i, is described as follows:

$$\Delta \varepsilon_{ij} = \Delta \varepsilon_{ij}^{e} + \Delta \varepsilon_{ij}^{\theta} + \Delta \varepsilon_{ij}^{p} + \Delta \varepsilon_{ij}^{c} \qquad (1)$$

where $\Delta \varepsilon_{ij}^{e}$, $\Delta \varepsilon_{ij}^{\theta}$, $\Delta \varepsilon_{ij}^{p}$ and $\Delta \varepsilon_{ij}^{c}$ are elastic, thermal, plastic and creep strain increments, respectively.

Constitutive relations between plastic strain and stress increments for isotropic hardening rule, kinematic hardening rule and combined hardening rule are described herein.

3.1.1 Plastic Strain Increment for Isotropic Hardening Materials

Von Mises's yield condition for isotropic hardening materials is represented as follows,

$$f(\sigma_{ij}) = F(\eta, \theta) \;; \quad f(\sigma_{ij}) = \frac{3}{2}\sigma'_{ij}\sigma'_{ij} \quad (= \bar{\sigma}^2) \tag{2}$$

where f, η , σ'_{ij} and $\bar{\sigma}$ are yield function, accumulated plastic strain, deviatoric stress tensor and equivalent stress, respectively. Assuming the associated flow rule to be valid, the plastic strain increment can be expressed as follows:

$$d\varepsilon_{ij}^{p} = \frac{3}{4\bar{\sigma}^2 H'}\left(3\sigma'_{kl}\cdot d\sigma_{kl} - \frac{\partial F}{\partial \theta}d\theta\right)\cdot\sigma'_{ij} \tag{3}$$

where H', $d\varepsilon_{ij}^{p}$, $d\sigma_{kl}$ and $d\theta$ are work hardening modulus, increments of plastic strain, stress and temperature respectively. In the case of uniaxial stress state, eq. (3) is written as

$$d\varepsilon^{p} = \frac{1}{H'}\left(d\sigma - \frac{\sigma_i}{\bar{\sigma}_i}\cdot\frac{\partial\bar{\sigma}}{\partial\theta}d\theta\right) \tag{4}$$

where σ_i and $\bar{\sigma}_i$ are uniaxial and equivalent stresses at temperature $\theta = \theta_i$. Assuming that the material properties don't vary during the temperature increment $\Delta\theta$, plastic strain increment $\Delta\varepsilon_{ij}^{p}$ can be obtained as follows:

$$\Delta\varepsilon_{ij}^{p} = \frac{3}{4\bar{\sigma}^2 H'}\left(3\sigma'_{kl}\,\Delta\sigma_{kl} - \frac{\partial F}{\partial\theta}\Delta\theta\right)\cdot\sigma'_{ij} \tag{5}$$

Accuracy of eq. (5), however, is not enough when the temperature increment is not sufficient small, or material constants complicatedly depend on temperature. Fig. 1 illustrates two stress-strain curves for a temperature dependent linear isotropic hardening material corresponding to θ_i and θ_{i+1}. The uniaxial relation between finite plastic strain increment $\Delta\varepsilon^{p}$ and finite stress increment $\Delta\sigma$ is given exactly by following equation.

$$\Delta\varepsilon^{p} = \frac{1}{H'_{i+1}}\left(\Delta\sigma + \Delta\sigma^{*}\right) \tag{6}$$

where H_{i+1}' is work hardening modulus at $\theta = \theta_{i+1}$. In eq. (6), $\Delta\sigma^{*}$ referred to as the pseudo stress by Cry and et al., is expressed as

$$\Delta\sigma^{*} = \sigma_i - \sigma_{0,i+1} - H'_{i+1}\cdot\bar{\varepsilon}_i^{p} \tag{7}$$

where and are initial yield stress at = i+1 and equivalent plastic strain at = i respectively. Exact relation between plastic strain and stress increments in the so-called transition range can be expressed by the pseudo stress, as illustrated in Fig. 2 and Fig. 3. From these figures, eqs. (6) and (7) are extended and generalized as follows:

$$\Delta\varepsilon^{p} = \frac{1}{H'_{i+1}}\cdot\left(\Delta\sigma + \frac{\sigma_i}{\bar{\sigma}_i}\Delta\sigma^{*}\right) \tag{8}$$

where

$$\Delta\sigma^* = \begin{cases} \bar{\sigma}_i - \sigma_{o,i+1} - H'_{i+1}\cdot\bar{\varepsilon}_i^P , & \sigma_{ij}\Delta\varepsilon_{ij}^P \geq 0 \\ \bar{\sigma}_i + \sigma_{o,i+1} + H'_{i+1}\cdot\bar{\varepsilon}_i^P , & \sigma_{ij}\Delta\varepsilon_{ij}^P < 0 \end{cases} \tag{9}$$

Comparing eq. (8) with eq. (4), the following correspondences can be recognized.

$$\frac{1}{H'} \text{ in eq. (4)} \longrightarrow \frac{1}{H_{i+1}} \text{ in eq. (8)}$$

$$-\frac{\partial\bar{\sigma}}{\partial\theta}d\theta \text{ in eq. (4)} \longrightarrow \Delta\sigma^* \text{ in eq. (8)}$$

Namely, the accurate incremental form of eq. (8) can be obtained by applying the above replacements in eq. (4). And substituting these relations into eq. (3), the accurate incremental form in multi axial stress state can be expressed as

$$\Delta\varepsilon_{ij}^P = \frac{9}{4\bar{\sigma}^2 H'_{i+1}}\left(\sigma'_{kl}\Delta\sigma_{kl} + \frac{2}{3}\bar{\sigma}\Delta\sigma^*\right)\cdot\sigma'_{ij} \tag{10}$$

Cry derived a pseudo stress $\Delta\sigma^*$ only for $\sigma_{ij}\Delta\varepsilon_{ij}^P \geq 0$ in eq. (9). Using imaginary yield stress $\sigma_{o,i+1}$ shown in Fig. 4, eqs. (9) and (10) are valid for multi linear hardening materials.

3.1.2 Incremental Formulation of the Plastic Strain for Kinematic Hardening Materials

Fig. 5 illustrates the relation between plastic strain increment $\Delta\varepsilon^P$, translation increment of the origin $\Delta\alpha$ and stress increment $\Delta\sigma$ in unaxial stress state of kinematic hardening material. Fig. 6 shows the plastic strain increment and stress increment replations in transition range for $(\sigma_i - \alpha_i)\Delta\varepsilon^P > 0$. From these figures, the following equations can be obtained.

$$\Delta\varepsilon^P = \frac{1}{H_{i+1}}\left(\Delta\sigma + \frac{\sigma_i - \alpha_i}{\sigma_{o,i}}\Delta\sigma^*\right) \tag{11}$$

$$\Delta\alpha = \Delta\sigma + \frac{\sigma_i - \alpha_i}{\sigma_{o,i}}\Delta\sigma^* \tag{12}$$

$$\Delta\sigma^* = \begin{cases} \frac{\sigma_{o,i}}{\bar{\sigma}_\alpha}(\bar{\sigma}_\alpha - \sigma_{o,i+1}) , & (\sigma_i - \alpha_i)\Delta\varepsilon^P \geq 0 \\ \frac{\sigma_{o,i}}{\bar{\sigma}_\alpha}(\bar{\sigma}_\alpha + \sigma_{o,i+1}) , & (\sigma_i - \alpha_i)\Delta\varepsilon^P < 0 \end{cases} \tag{13}$$

$$\bar{\sigma}_\alpha^2 = \sqrt{3(\sigma'_{ij} - \alpha'_{ij})(\sigma'_{ij} - \alpha'_{ij})/2}$$

where $\Delta\sigma^*$ is the pseudo stress.

Using the similar approach as in the case of isotropic hardening materials, accurate incremental relations in multiaxial stress state can be derived as follows

$$\Delta\varepsilon_{ij}^P = \frac{9(\sigma'_{ij} - \alpha'_{ij})}{4\bar{\sigma}_\alpha^2 H'_{i+1}}\left\{(\sigma'_{kl} - \alpha'_{kl})\Delta\sigma_{kl} + \frac{2}{3}\bar{\sigma}_\alpha\Delta\sigma^*\right\} \tag{14}$$

$$\Delta\alpha_{ij} = \frac{3(\sigma_{ij} - \alpha_{ij})}{2\bar{\sigma}_\alpha^2}\left\{(\sigma'_{kl} - \alpha'_{kl})\Delta\sigma_{kl} + \frac{2}{3}\bar{\sigma}_\alpha\Delta\sigma^*\right\} \tag{15}$$

3.1.3 Incremental Formulation of the Plastic Strain for Combined Hardening Materials

The similar way in the previous paragraph 3.1.2 leads accurate incremental relation between $\Delta \varepsilon_{ij}^{p}$, $\Delta \sigma_{ij}$ and $\Delta \sigma_{ij}$ in multi-axial stress state for combined hardening materials. Detailed description is omitted here.

3.1.4 Incremental Stress Strain Relationship

Equation (10) is substituted into eq. (1), which yields an incremental stress strain relationship for isotropic hardening material. This is given by the following,

$$\{\Delta\sigma\} = [D_{i+1}^{p}]\{\Delta\varepsilon\} - [D_{i+1}^{p}][\Delta C]\{\sigma\} - [D_{i+1}^{p}]\{\Delta\varepsilon^{\theta}\}$$
$$- [D_{i+1}^{p}]\{\Delta\varepsilon^{c}\} - \frac{2\bar{\sigma}\Delta\sigma^{*}}{3S_{o}}[D_{i+1}]\{\sigma'\} \qquad (16)$$

where $[\Delta C]$ and $[D_{i+1}]$ are the increment of strain stress and stress strain matrices at $\theta = \theta_{i+1}$, respectively. The expressions for S_o and $[D_{i+1}^{p}]$ are given by the following equations.

$$S_{o} = \frac{4}{9}\bar{\sigma}^{2}H'_{i+1} + \{\sigma'\}^{T}[D_{i+1}]\{\sigma'\}$$

$$[D_{i+1}^{p}] = [D_{i+1}] - \frac{1}{S_{o}}[D_{i+1}]\{\sigma'\}\{\sigma'\}^{T}[D_{i+1}]$$

Stiffness equation using the pseudo stress is obtained by using material constants at state θ_{i+1} and replacing $-\frac{\partial F}{\partial \theta}\Delta\theta$ in the stiffness equation of first order approximation with $\Delta\sigma^{*}$. Simularly expressions for incremental stress strain relationship using the pseudo stress are given for the cases of kinematic hardening and combined hardening when $\bar{\sigma}$ and $\{\sigma'\}$ are replaced by $\bar{\sigma}_{\alpha}$ and $\{\sigma'_{\alpha}\}$.

3.2 Example Problem

A computer program for thermal elastic-plastic-creep analysis was developed using the pseudo stress concept described in the previous section and structural analysis of the 1.5 Mwt helium heat exchanger was conducted by this program. The basic example is analysed to verify the above mentioned pseudo stress concept. The example is thermal elastic-plastic analysis of an axially constrained rod subjected to uniform heating. In the case where both Young's modulus and yield stress depend on temperature, calculation results are shown in Fig. 7. This figure shows that the present solution is more accurate than that of the first order approximation for the same increment.

4. Conclusion

Various method of inelastic analysis developed for designing the 1.5 Mwt high-temperature heat exchanger are outlined. In the methods, an extended pseudo stress method is developed and discussed in detail. The pseudo stress concept originally proposed by Cry et al. is extended to be applied for the kinematic and combined hardening materials. Numerical examples shows that the accuracy of detailed finite element solution is considerably improved by the technique using the extended pseudo stress.

Acknolegement

The authors express sincere thanks for guidance provided by the members of the Engineering Research Association of Nuclear Steelmaking, the High Temperature Heat Exchanger Strength Special Committee chaired by the top author and the Heat Exchanger Working Group of Direct Steel Making Chaired by Prof. Y. Mori.

Reference

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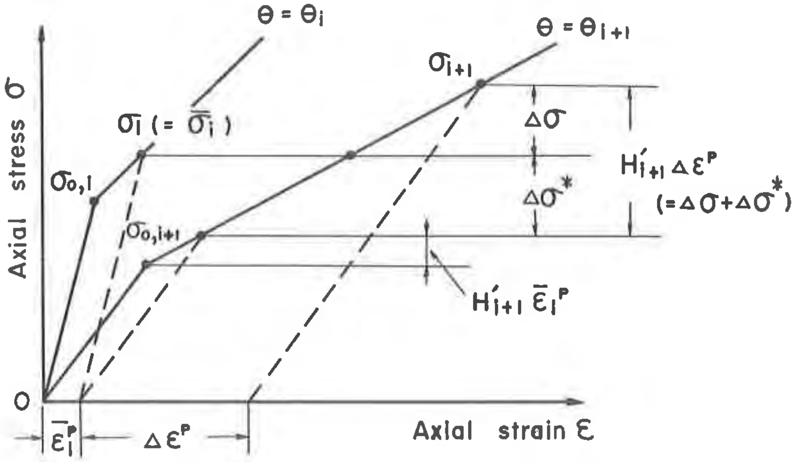

Fig. 1 Pseudo Stress $\Delta\sigma^*$ (Isotropic Hardening, $\sigma_i\,\Delta\varepsilon^p > 0$)

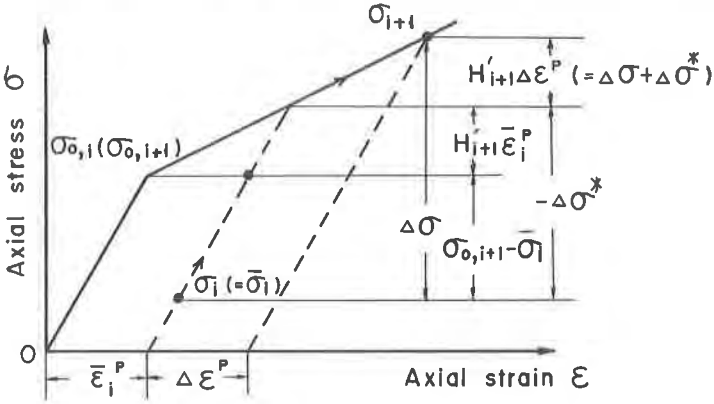

Fig. 2 Pseudo Stress $\Delta\sigma^*$ (Transient Range, Istropic Hardening, $\sigma_i\,\Delta\varepsilon^p > 0$)

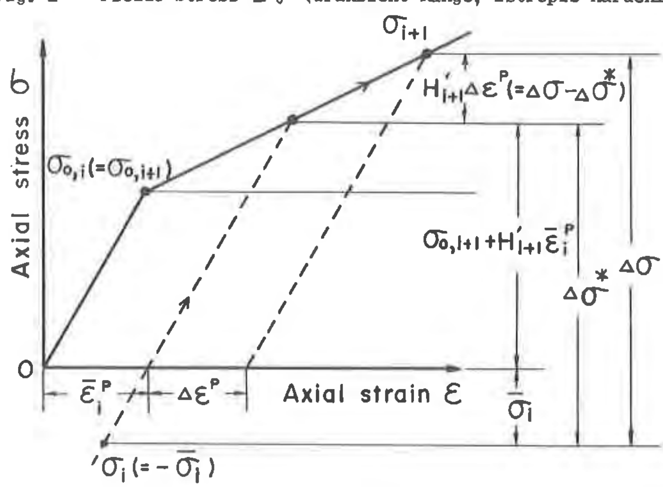

Fig. 3 Pseudo Stress $\Delta\sigma^*$ (Transient Range, Istropic Hardening, $\sigma_i\,\Delta\varepsilon^p < 0$)

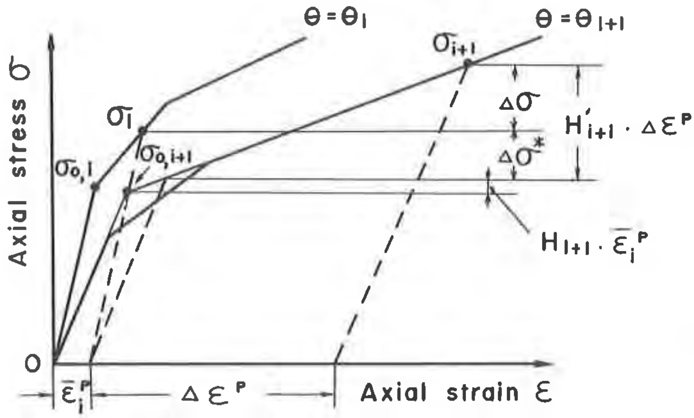

Fig. 4 Pseudo Stress $\Delta\sigma^*$ (Multi-Linear Curve)

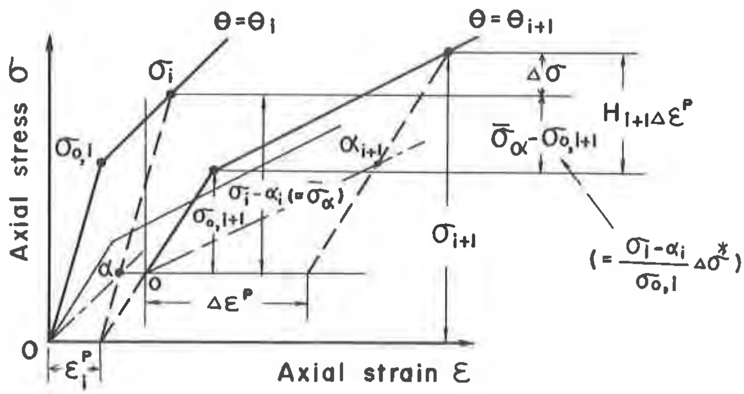

Fig. 5 Pseudo Stress $\Delta\sigma^*$ (Kinematic Hardening, $(\sigma_i - \alpha_i)\Delta\varepsilon^P > 0$)

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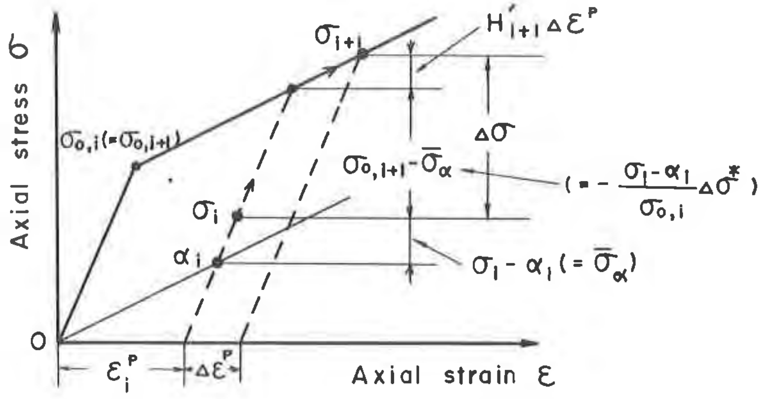

Fig. 6 Pseudo Stress $\Delta\sigma^*$(Transient Range, Kinematic Hardenig, $(\sigma_i-\alpha_i)\Delta\varepsilon^p>0$)

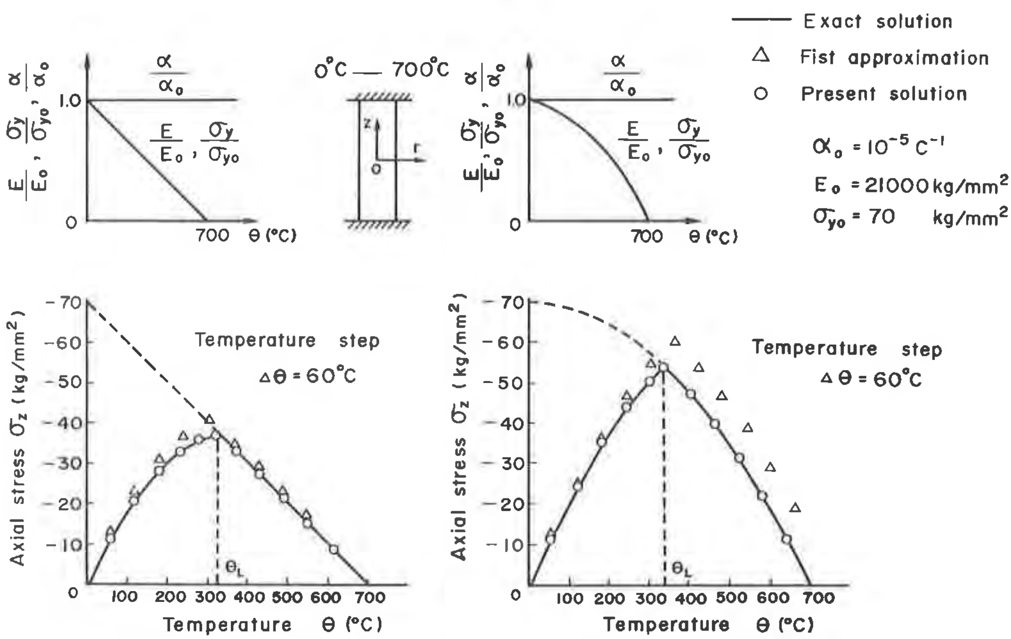

Fig. 7 Uniform Heating of an Axialy Constrained Rod

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