Development of Simplified Evaluation Methods of Structural Design and Remaining Life Assessment for Thermal and Nuclear Power Components

Background

The current Japanese design codes *[1] for pressurized power components such as boilers and pressure vessels employ simplified structural integrity assessment methods including linearization of stresses where performance of two-dimensional stress analysis is assumed. Procedures treating three-dimensional analysis resultant have not, therefore, been established. Detailed inelastic analysis-route method employed in the US fast reactor design code *[2] needs linearization of strains, and the problem is the same. In addition to being costly and laboring, detailed inelastic analysis-route approach may lead to assessment results dependent on expertise of the design engineer, because treatment of loading path effects has not been made clear. These problems are common in remaining life assessment of crack-like damage, which is getting more and more important in maintenance and life management of components.

Objectives

To develop simplified evaluation methods of structural design and remaining life assessment of crack-like damage based on elastic stress analysis which are able to be applied straight-forwardly to high temperature pressurized power components even if three-dimensional stress analysis is performed.

Principal Results

Various simplified structural integrity assessment methods have been developed. The methods proposed use structural response parameters which can be determined by performing simple inelastic analysis with simple power-law type inelastic constitutive equations *[3]. These parameters do not depend on dimensions of the component assessed or loading level, and can be reused for structural integrity assessment only from elastic stress analysis of different sized components if the necessary parameters are given. In addition, the parameters determined from elastic-plastic analysis can be used for creeping components if the stress exponent *[3] of the creep law is the same as that of the plastic law.

1. Structural Design Methods

Simplified evaluation methods eliminating the premise of two-dimensional analysis for limitations of primary stress, creep-fatigue damage and cumulative strains, which are needed in the current design codes, have been developed.

(1) Limit analysis approach for the primary stress limit in the US light water reactor design code *[4] was investigated, and treatment of multiple loads, which some consider to be ambiguous, has been theoretically articulated In addition, the twice elastic slope method employed in the code, which is said to be inconsistent with the limit analysis approach, has been modified. The newly proposed "reduced elastic slope method" has been validated by confirming consistency with the corresponding limit analysis resultant (Fig.1-(1)).

(2) Characteristics of "elastic follow-up factor", which is employed in the Japanese fast breeder reactor design code *[5], have been investigated, and it has been demonstrated that elastic follow-up factors converge as secondary stresses increase. Then simplified methods for estimating peak strain range and stress relaxation history during creep using the converged values of elastic follow-up factors constantly regardless of stress levels have been proposed and validated (Fig.1-(2)).

(3) A method based on "relative elastic core size" for cumulative strain limitation has been proposed to eliminate the necessity of linearization of strains employed in the US fast reactor design code, and its validity has been confirmed by comparing allowable stresses given by this with those by the current code.

2. Inelastic *J*-integral Estimation Methods

Applicable range of the existing methods simply estimating inelastic *J*-integrals (elastic-plastic *J*-integral for fatigue and creep *J*-integral for creep) has been expanded, and the accuracy of these has been improved.

(1) Net section stress correction factor and limit load correction factor have been introduced for improving the accuracy of the reference stress approach *[6] under load-controlled loading, and the effectiveness of these has been confirmed. In addition, a method to estimate high creep *J*-integral in small-scale creep condition before reaching the steady state has been proposed, and the validity of the method has been confirmed. (Fig.2-(1)).

(2) A method to determine elastic follow-up factor in displacement-controlled loading such as thermal expansion loading has been proposed together with theoretically clear definition. The same converging trend in these factors as that for peak strain estimates has been observed. In addition, a simplified method using the constant elastic follow-up factor at the convergence has been proposed. The method proposed has been validated by confirming accurate estimates of inelastic *J*-integral (Fig.2-(2)). A creep *J*-integral estimation method without the premise of two-dimensional analysis has also been proposed along with its numerical validation (Fig.2-(3).

Future Developments

The structural design methods developed shall be proposed for the advancement of the Japanese design codes, and shall be applied to rational design of over 700C degree class advanced USC power boilers and other power components. The crack-like damage evaluation methods shall be employed for the improvement and simplification of remaining life assessment of thermal power components.

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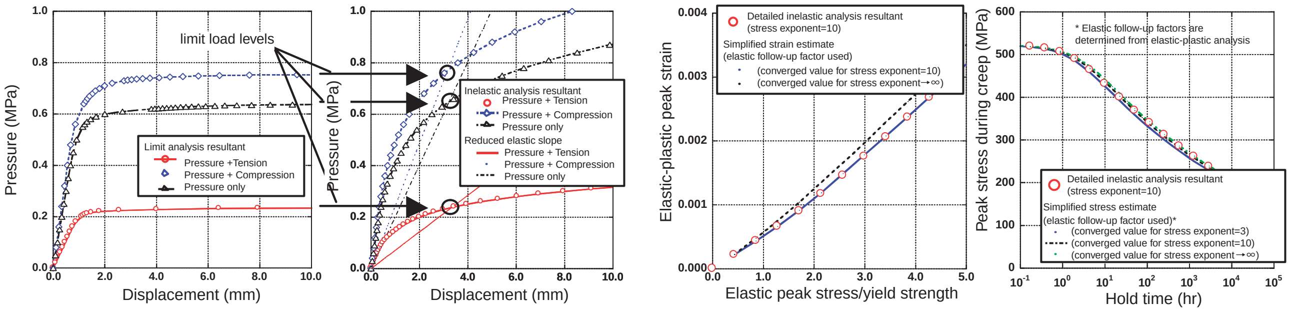
Reference

T. Fujioka, 2007, "Development of simplified structural integrity assessment methods for high temperature pressurized power components based on dimensionless structural response parameters", CRIEPI Report M03. (in Japanese)

The newly proposed reduced elastic slope method in place of the twice elastic slope method, where limit load is defined by the cross section between the reduced elastic slope and the inelastic analysis result, has been confirmed consistent with the limit analysis even under multiple loading conditions.

Accuracy of peak strain in elastic-plastic situation and peak stress relaxation during creep estimated by the proposed simplified method using a constant elastic follow-up factor obtained as the converged value by an elastic-plastic analysis with simple power law type stress-strain curves has been confirmed by an analysis of a nozzleshaped component containing stress concentration portion.



(1) Assessment method of primary stress

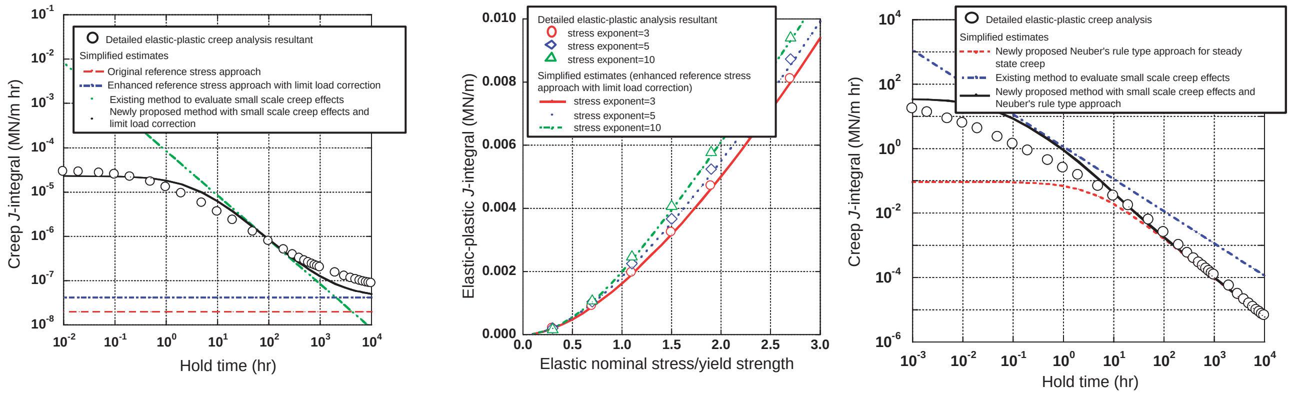
(2) Simplified estimates of peak strain and peak stress relaxation history under thermal loading

Fig.1 Validations of the structural design methods without the premise of two-dimensional stress analysis

Accuracy of the newly proposed method to incorporate effects friom small scal e creep has been comfirmed by estimating creep *J*-integral in a cracked cylinder under constant loading regardless of hold time.

Accuracy of the newly proposed method to determine elastic follow-up factor under displacement-controlled loading has been confirmed by estimating elasticplastic *J*-integral in cracked plates.

Accuracy of the newly proposed method to estimate creep *J*-integral without the premise of two-dimensional stress analysis has been confirmed by estimating creep *J*-integralin a cracked cylinder under thermal loading.



(1) Creep *J*-integral under constant loading with effects of small scale creep

(2) Elastic-plastic *J*-integral under displacement-controlled loading

(3) Creep *J*-integral under thermal loading

Fig.2 Validations of the simplified inelastic *J*-integral estimation methods without the premise of two-dimensional stress analysis

＊1：JSME, 2001, Codes for Nuclear Power Generation Facilities - Rules for Design and Construction for Nuclear Power Plants, JSME S NC1-2001. (in Japanese)

＊2：ASME, Boiler and Pressure Vessels Code, Section III - Rules for Construction of Nuclear Facility Components, Subsection NH - Class 1 Components Elevated Temperature Services, 2004.

＊3：Ramberg-Osgood law for elastic-plastic body and Norton's law for creep.

＊4：ASME, 2004, Boiler and Pressure Vessels Code, Section III - Rules for Construction of Nuclear Facility Components.

＊5：K. Iida, Y. Asada, K. Okabayashi and T. Nagata, 1987, “Simplified Analysis and Design for Elevated Temperature Components of Monju”, Nuclear Engineering and Design, Vol. 98, pp. 305-317.

＊6：Simplified method to estimate inelastic *J*-integral employed in British assessment procedures R5 and R6.