JNC TN9400 99-035

SIMULATION OF CREEP TEST ON 316FR STAINLESS STEEL IN SODIUM ENVIRONMENT AT 550°C

April 1999

O-ARAI ENGINEERING CENTER

JAPAN NUCLEAR CYCLE DEVELOPMENT INSTITUTE

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SIMULATION OF CREEP TEST ON 316FR STAINLESS STEEL IN SODIUM ENVIRONMENT AT 550°C

Ari SATMOKO[1], Tai ASAYAMA[2]

Abstract

In sodium environment, material 316FR stainless steel risks to suffer from carburization. In this study, an analysis using a Fortran program is conducted to evaluate the carbon influence on the creep behavior of 316FR based on experimental results from uni-axial creep test that had been performed at temperature 550 °C in sodium environment simulating Fast Breeder Reactor condition. As performed in experiments, two parts are distinguished. At first, elastic-plastic behavior is used to simulate the fact that just before the beginning of creep test, specimen suffers from load or stress much higher than initial yield stress. In second part, creep condition occurs in which the applied load is kept constant. The plastic component should be included, since stresses increase due to section area reduction. For this reason, elastic-plastic-creep behavior is considered. Through time carbon penetration occurs and its concentration is evaluated empirically. This carburization phenomena are assumed to affect in increasing yield stress, decreasing creep strain rate, and increasing creep rupture strength of material. The model is capable of simulating creep test in sodium environment. Material near from surface risks to be carburized. Its material properties change leading to non-uniform distribution of stresses. Those layers of material suffer from stress concentration, and are subject to damage. By introducing a damage criteria, crack initialization can thus be predicted. And even, crack growth can be evaluated. For high stress levels, tensile strength criterion is more important than creep damage criterion. But in low stress levels, the latter gives more influence in fracture. Under high stress, time to rupture of a specimen in sodium environment is shorter than in air. But for stresses lower than 26 kgf/mm^2, the time to rupture of creep in sodium environment is the same or little longer than in air. Quantitatively, the carburization effect at 550°C is not important. This corresponds well with experimental results.

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JNC TN9400 99－035
1 9 9 9 年　4 月

高速炉構造用SUS316（316FR）の550℃における ナトリウム中クリープ試験のシミュレーション

Ari SATMOKO[1], 浅山 泰[2]

要 旨

本研究ではFortranを用いた解析により、高速炉条件を模擬して550℃のナトリウム中で行われた単軸クリープ試験結果をシミュレートし、浸炭が316FRのクリープ挙動に及ぼす影響を評価した。解析は試験と同様に、2段階で実施した。第1段階として、クリープ試験の直前に負荷される降伏応力よりも大きい荷重あるいは応力を弾塑性挙動で模擬した。第2段階では負荷荷重が一定に保たれクリープが生じる。断面減少により応力が増加するため、塑性成分も考慮する必要がある。これを、弾塑性クリープ挙動を用いて模擬した。時間の経過とともに浸炭が生じるが、これは経験的式により評価した。浸炭により、降伏応力の増加、クリープひずみ速度の減少およびクリープ破断強度の増加が生じる。このようにして作成したモデルにより、ナトリウム中クリープ試験のシミュレーションを行うことができる。表層近傍の材料では浸炭が生じると、材料特性が変化し、応力分布が一様でなくなる。これにより応力集中が生じ、損傷を受ける。損傷クライテリアを導入することにより、き裂発生およびき裂進展の評価が可能となる。高応力では、クリープ強度ではなく引張り強さが破損クライテリアとなる。しかし、低応力では、クリープ強度が破損クライテリアとなる。この結果、高応力では、ナトリウム中クリープ破断時間は大気中よりも短い予測となるが、26kgf/mm^{2}以下の応力では、ナトリウム中クリープ破断時間は大気中と等しいかやや長い予測となる。定量的には、浸炭の影響は550℃では大きくない。この結果は試験と良く一致した。

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1 INTRODUCTION

In Fast Breeder Reactor, liquid sodium flows in primary and secondary systems. Especially in secondary system where the design temperature is above 500°C, $2^1/_4$ Cr-1Mo steel is used for the evaporator, and austenitic stainless steels (SUS 321, SUS 304 and SUS 316) for other components. Recently, JNC has developed 316FR stainless steel, designed for FBR plant. This material has better performance than SUS 304 or SUS 316, especially in creep behavior.

In sodium environment, material $2^1/_4$ Cr-1Mo steel risks to be decarburized. Carbon element goes into liquid sodium which then flows and in contact with other materials. In this condition, carbon may penetrate into austenitic steel causing carburization effect. This influence might be important and has to be taken into account in FBR design. To study the carbon influence on the creep behavior, uniaxial mechanical creep tests on 316FR were performed at temperature 550 °C in liquid sodium environment simulating Fast Breeder Reactor condition. The results are given in Figure 1.1. In the range from 1000 to 10000 hours the creep rupture time in sodium is shorter than in air. For long range creep, there may be little difference between creep rupture time in air and in sodium.

In this report, analytical evaluation will be conducted to simulate carburization effect in creep experiment. Carbon element in liquid sodium may penetrate in material leading to carbide formation. As it is known, the phenomenon gives affect on plasticity and creep behaviors. The first hardens material by increasing yield stress. The second causes the decrease of steady creep strain rate and the increase of creep rupture strength. The magnitude of those influences will be discussed in Chapter 4.

In creep test, specimens are a smooth round rod with 6 mm of diameter. Constant axial load is applied until the failure occurs. Considering axisymetric model, this geometry will be modeled by dividing into 129 elements as shown in Figure 1.2. The first 29 elements have 0.1 mm of width, and the last 100 elements have 0.001 mm of width. Exterior elements suffer from carbon inclusion coming from sodium environment. Through time, distance affected by carbon increases followed by mechanical property changes.

The analysis treats two parts corresponding to experimental phenomena. At first, before being under creep condition, a certain load higher than elastic limit is applied. Specimen is assumed at this step to suffer elastic-plastic phenomenon. The load rate is applied as quickly as possible. Consequently, the elastic-plastic appearing at this step is not the same as ordinary one. Considering linear strain-hardening material, we have to determine a new hardening coefficient.

In the second part, where the load is maintained after the wanted load is reached, creep condition is performed until rupture. Plastic behavior is also taken into account. In this step, carbon inclusion and its effect are considered. Specimen has no longer uniform behavior: exterior elements suffer from carbon inclusion. Creep rate, creep rupture strength, and yield stress become different from one element to others, and finally stress distribution is not uniform. Fracture criteria due to both creep damage and tensile strength are also evaluated for each element. Elements receiving high stresses tend to be the first part in fracture.

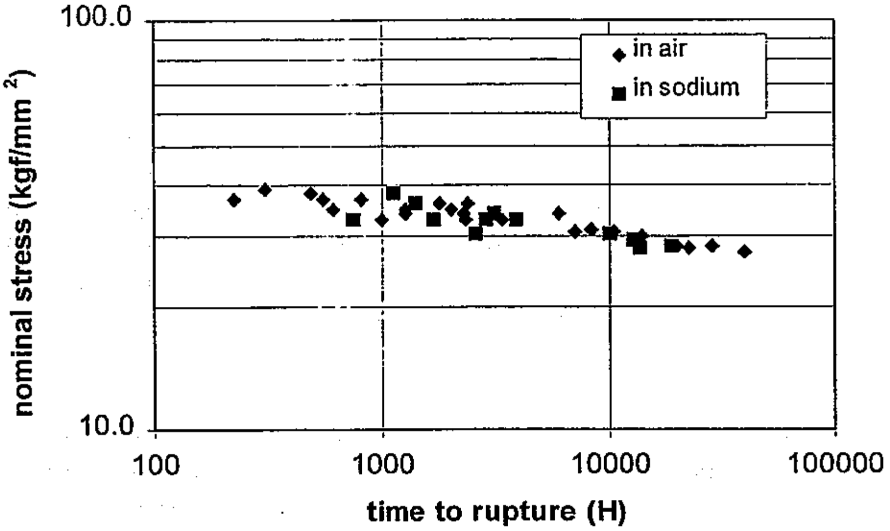

Figure 1.1 Experimental results of uni-axial creep test for 316FR stainless steel at 550°C

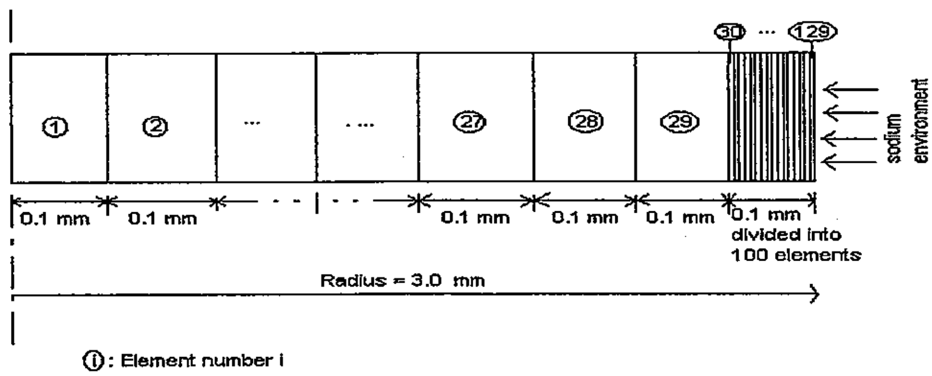

Figure 1.2 Analysis model

2 FIRST PART: ELASTIC-PLASTIC BEHAVIOR

Before being under creep condition, specimens have elastic-plastic behavior. Plastic deformation depends not only on the applied load value but also on load path. Lower displacement or load rates applied, material becomes easier to give plastic strain. This phenomenon has big influence and can not be neglected in creep analysis. Generally, experiment data are reported using nominal stress, i.e. load applied divided by initial section area. But, because of incompressible material, the increase of plastic strain in longitudinal direction will be compensated by reduction of section area. Consequently, at constant load material will receive a higher stress value (called true stress) than the nominal one. This analysis will use the true stress for calculation. Data reported with nominal stress are converted into true stress. This is possible to be done, because needed parameters are fortunately stored and available in SMAT Data Base.

In creep experiments a certain time is needed to reach wanted stress value. During this time and which the temperature condition is already 550°C, creep strain might occur. For this reason, the load is applied as quickly as possible to minimize pre-creep phenomenon. But, as stated before, when faster load is applied, material becomes difficult to give plastic strain.

The elastic-plastic behavior is characterized by hardening phenomenon. Many experiments on tensile test conducted to some formula involving constant values showing the relationship between stress and strain. Generally, experiments were performed by controlling displacement in low rate. Results are of course different from elastic-plastic phenomenon found in the first step of creep test. Therefore, constants showing elastic-plastic behavior obtained by usual tensile test can not be used in creep analysis. Here below are equations needed for determining hardening coefficient and then true stress.

To model elastic-plastic in high strain rate, material is considered having linear strain-hardening. At any time under applied load P, material receives true stress σ, which is given by following equation:

$$P = \sigma A \qquad \text{(Eq. 2.1)}$$

where A is section area of the material. In elastic-plastic behavior, total strain ε^T is the sum of elastic strain ε^e and plastic strain ε^p.

$$\varepsilon^T = \varepsilon^e + \varepsilon^p \qquad \text{(Eq. 2.2)}$$

Elastic behavior is related by Hooke law using Young's modulus E (Equation 2.3) and the plastic one is given by introducing hardening coefficient H (Equation 2.4).

$$\varepsilon^e = \sigma / E \qquad \text{(Eq. 2.3)}$$

$$\varepsilon^p = (\sigma - \sigma^y) / H, \text{ if of course } \sigma - \sigma^y > 0 \qquad \text{(Eq. 2.4)}$$

where σ^y is yield stress. E is equal to 15691 kgf/mm^2 at 550 °C, but H is still unknown variable. Because of incompressible material, positive incremental plastic strain will be compensated by section area reduction, so that:

$$A = A_0 e^{-\varepsilon p} \qquad \text{(Eq. 2.5)}$$

where A_0 is initial section area.

Now, solve the above five unknown variables. Introduction of Equation 2.3 to Equation 2.4 and then combined with Equation 2.2 give:

$$H\,\varepsilon^p = E\,\varepsilon^T - \sigma^y - E\,\varepsilon^p \qquad \text{(Eq. 2.6a)}$$

$$(H+E)\,\varepsilon^p = E\,\varepsilon^T - \sigma^y \qquad \text{(Eq. 2.6b)}$$

In the other hand, Equations 2.1, 2.5, and 2.4 can be combined to eliminate variable σ:

$$P = (H\,\varepsilon^p + \sigma^y)\,A_0\,e^{-\varepsilon p} \qquad \text{(Eq. 2.7)}$$

Finally Equation 2.6a can be included to the last equation. Considering nominal stress σ_0 as load applied divided by initial area, we have then:

$$\sigma_0 = (\varepsilon^T - \varepsilon^p)\,E\,e^{-\varepsilon p} \qquad \text{(Eq. 2.8)}$$

Young's modulus and nominal stress are known. Nominal total strain, e, is given in experimental data by measuring strain off set. True total strain can be easily obtained by using equation $\varepsilon^T = \ln(1+e)$. We have now only one unknown variable. Nevertheless, it is difficult to obtain mathematically variable ε^p. Trial and error or computational iterative methods can be used to solve this problem.

Once plastic strain is calculated, other variables, especially true stress and hardening coefficient, can be determined. Calculation leads to the following results. Figure 2.1 gives well comparison of elastic-plastic behavior in usual tensile test and in creep test. It is clear that the points obtained from creep experiments have higher curve than those obtained in usual tensile test.

An effort was tried to obtain the relationship between hardening coefficient and load or strain rate. Hardening coefficient tends to increase when load rate applied is faster as showed in Figure 2.2, but it is still doubtfully to conclude mathematical equation. For future calculation, we will use the average hardening coefficients, i.e. H = 250.8 kgf/mm^2. By using this average hardening coefficient, the curve of tensile test should follow the Figure 2.3.

Meanwhile, Figure 2.4 predicts the true stress in material when certain nominal stress is applied. It is clear that the difference between nominal and true stress becomes bigger when the load applied is much higher than yield stress. If the load applied is still in elastic zone, the nominal and true stresses are the same. This is explained by null plastic strain leading to the absent of section area reduction.

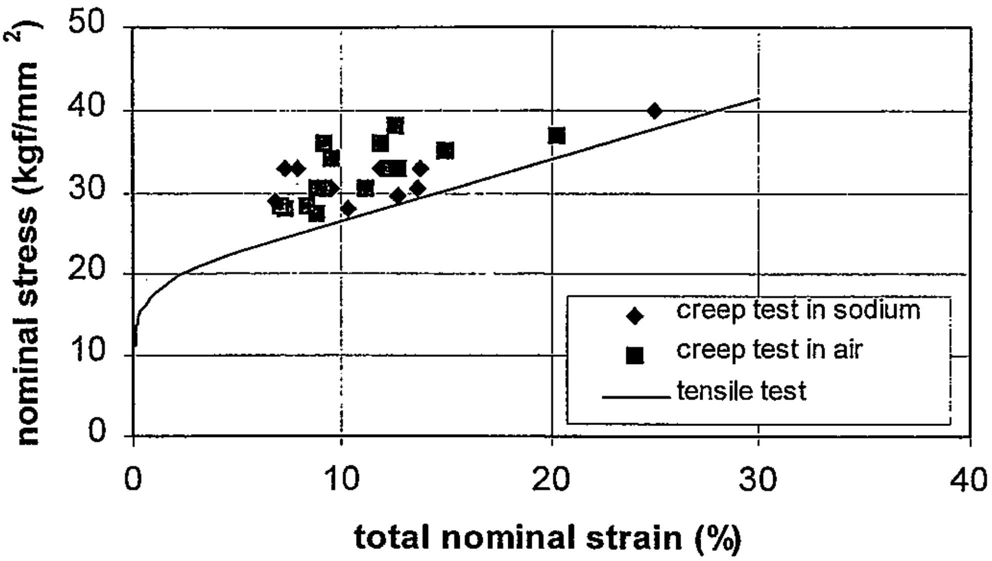

Figure 2.1 Comparison of elastic-plastic behavior in usual tensile test and in creep test

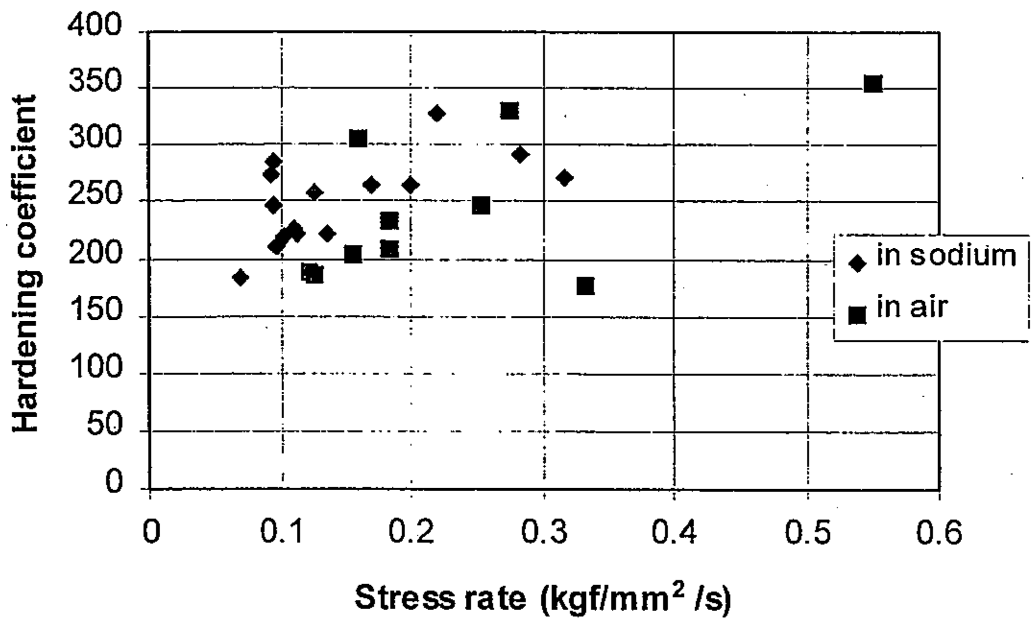

Figure 2.2 Calculated hardening coefficient in creep experiments

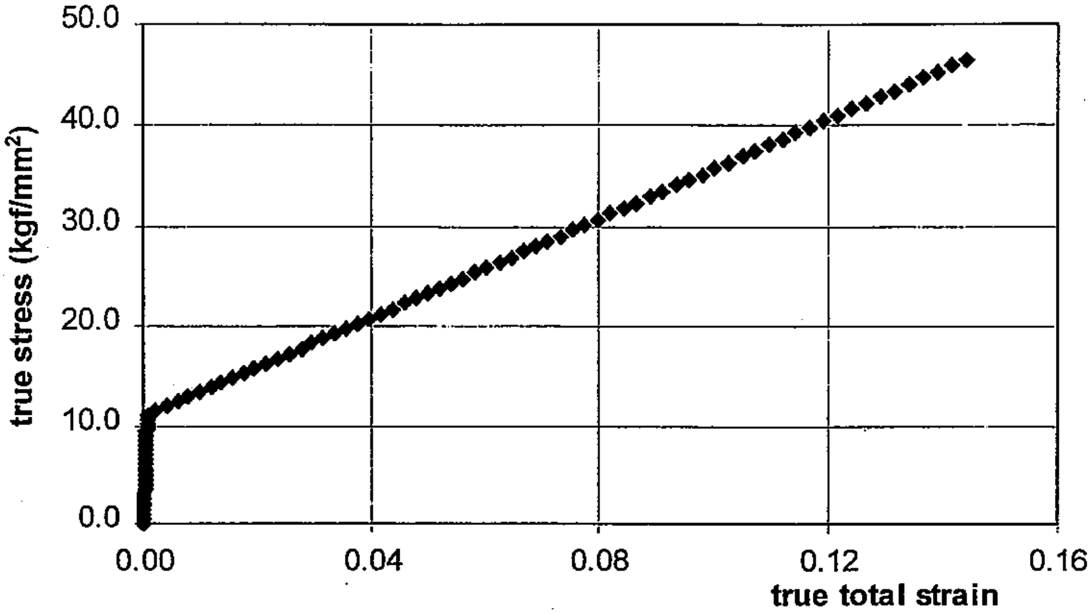

Figure 2.3 Tensile strength curve by using H = 250.8 kgf/mm^2

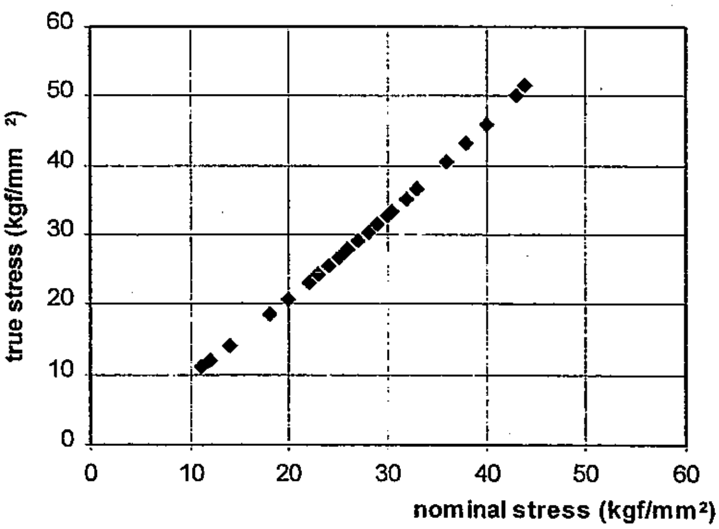

Figure 2.4. The relationship between true stress and nominal stress

3 SECOND PART: ELASTIC-PLASTIC-CREEP BEHAVIOR

After elastic-plastic is reached, specimen is now going under creep condition where load is kept constant until the rupture occurs. The axial creep strain increases. And then section area decreases. Consequently, stress in material becomes higher, and in turn plastic strain occurs. In this step elastic-plastic-creep behavior should be considered.

Because of sodium environment, carbon element might diffuse into specimen and these affects the creep strain rate, creep rupture strength, and yield stress of material. Inside material is not affected by carbon inclusion. So, the material no longer has uniform behavior. Considering N elements, analytical steps and its solution are below.

During time interval, dt, carbon inclusion occurs. Each element has three types of strain increment and the total increment $d\varepsilon^T_i$ (i is index for element number i) becomes:

$$d\varepsilon^T_i = d\varepsilon^e_i + d\varepsilon^c_i + d\varepsilon^p_i \qquad \text{(Eq. 3.1)}$$

Assuming that during this dt, creep strains $d\varepsilon^c_i$ can be calculated by using creep strain equation discussed in the next chapter. While, elastic strain increment is related to Hooke law:

$$d\sigma_i = E\, d\varepsilon^e_i \qquad \text{(Eq. 3.2)}$$

Concerning $d\varepsilon^p_i$, it is determined by stress and yield stress. Plastic strain occurs only if $\sigma_i + d\sigma_i$ is higher than $\sigma^y_i + d\sigma^y_i$. Yield stress depends on carbon concentration. So, verification should be done for each element and this makes analytical solution difficult. Due to the difficulties, two cases are distinguished:

- for all elements, $d\varepsilon^p_i = 0$
- at least in one element, $d\varepsilon^p_i > 0$

3.1 Elastic-creep behavior

Considering now the first case where only elastic-creep behavior occurs. Due to null plastic strain, Equation 3.1 becomes:

$$d\varepsilon^T_i = d\varepsilon^e_i + d\varepsilon^c_i \qquad \text{(Eq. 3.3)}$$

Total deformations of all elements are uniform, then:

$$d\varepsilon^T = d\varepsilon^T_1 = d\varepsilon^T_2 = \ldots\ldots = d\varepsilon^T_i = \ldots\ldots = d\varepsilon^T_N \qquad \text{(Eq. 3.4)}$$

The exterior load will be distributed at each element:

$$P = \Sigma P_i \qquad \text{(Eq. 3.5)}$$

where P is total applied load, P_i is load distributed to element i, and Σ means the sum for N elements. This leads to:

$$P = \Sigma\, \sigma_i A_i \qquad \text{(Eq. 3.6)}$$

with A is section area.

In creep experiment, P is constant. The last equation can be derived and becomes:

$$0 = \Sigma\, \sigma_i\, dA_i + \Sigma\, A_i\, d\sigma_i \qquad \text{(Eq. 3.7)}$$

The axial elongation is followed by the radius reduction. Assuming incompressible material, $dA_i = -(dl/l)\, A_i$, where dl is creep elongation increment, and l is length of specimen. dl/l represents the creep strain increment at instantaneous point. By using the incremental strain it is equivalent to $d\varepsilon^c_i$.

$$dA_i = - d\varepsilon^c_i A_i$$

Equation 3.7 can be rewritten as follows:

$$\Sigma A_i d\sigma_i = \Sigma \sigma_i d\varepsilon^c_i A_i \qquad \text{(Eq. 3.8)}$$

By combining all above equations (see below), unknown variables can be resolved.

Because of strain component variation, stress distribution in all elements becomes non-uniform, and this:

$$\sigma_{i(\text{after increment})} = \sigma_{i(\text{old value})} + d\sigma_i \qquad \text{(Eq. 3.9)}$$

Calculation can be continued for the next step dt by using renewed stress.

Solution in elastic-creep behavior

Due to Equations 3.2 to 3.4:

$$\begin{aligned} d\varepsilon^T &= d\varepsilon^e{}_1 + d\varepsilon^c{}_1 \\ &= d\sigma_1 / E + d\varepsilon^c{}_1 \end{aligned} \qquad \text{(Eq. 3.10)}$$

From Equation 3.8, developing now $\Sigma\{A_i d\sigma_i\}$,

$$\begin{aligned} A_i d\sigma_i &= A_i E\, d\varepsilon^e{}_i \\ &= A_i E\, [d\varepsilon^T - d\varepsilon^c{}_i] \\ &= A_i E\, [d\varepsilon^e{}_1 + d\varepsilon^c{}_1 - d\varepsilon^c{}_i] \\ &= A_i d\sigma_1 + A_i E\, [d\varepsilon^c{}_1 - d\varepsilon^c{}_i] \end{aligned} \qquad \text{(Eq. 3.11)}$$

Equation 3.8 can be rewritten:

$$\begin{aligned} & \Sigma \{ A_i\, d\sigma_1 + A_i E\, [d\varepsilon^c{}_1 - d\varepsilon^c{}_i]\} = \Sigma\, \sigma_i d\varepsilon^c{}_i A_i \\ \Leftrightarrow\ & \Sigma A_i\, d\sigma_1 + \Sigma \{A_i E\, [d\varepsilon^c{}_1 - d\varepsilon^c{}_i]\} = \Sigma\, \sigma_i d\varepsilon^c{}_i A_i \\ \Leftrightarrow\ & \Sigma A_i\, d\sigma_1 = \Sigma\, \sigma_i d\varepsilon^c{}_i A_i - \Sigma \{A_i E\, [d\varepsilon^c{}_1 - d\varepsilon^c{}_i]\} \\ \Leftrightarrow\ & d\sigma_1 = \{ \Sigma\, \sigma_i d\varepsilon^c{}_i A_i - \Sigma \{A_i E\, [d\varepsilon^c{}_1 - d\varepsilon^c{}_i]\} \} / \Sigma A_i \end{aligned} \qquad \text{(Eq. 3.12)}$$

Knowing all parameters needed, $d\sigma_1$ can be calculated. In the next turn, others $d\sigma_i$ can be found by using simply:

$$\begin{aligned} d\sigma_i &= E\, d\varepsilon^e{}_i \\ &= E\, \{ d\varepsilon^T - d\varepsilon^c{}_i \} \\ &= E\, \{ d\varepsilon^e{}_1 + d\varepsilon^c{}_1 - d\varepsilon^c{}_i \} \\ &= d\sigma_1 + E\, \{ d\varepsilon^c{}_1 - d\varepsilon^c{}_i \} \end{aligned} \qquad \text{(Eq. 3.13)}$$

Other parameters i.e. $d\varepsilon^T$, $d\varepsilon^e{}_i$, and A_i can be calculated if needed.

3.2 Elastic-plastic-creep behavior

Equations 3.12 and 3.13 are valuable only when plastic strain is absent. As stated before, if at least in one element $d\varepsilon^p{}_i > 0$, the analytical solution becomes difficult. The problem becomes more complex when the total element number of model increases. To solve this problem, trial and error method is used based on the following evaluation.

Consider elastic-plastic behavior as drawn in Figure 3.2.1. Assuming that at instantaneous time t, the position is in point R. During dt, due to carbon inclusion the yield stress σ^y_i increases. At the same time incremental creep strain $d\varepsilon^c_i$ is given by creep rate equation. The method of trial and error is to give incremental total strain approximation (for example the point S) and then this approximation is evaluated to minimize error. By giving $d\varepsilon^T$, $d\varepsilon^T$-$d\varepsilon^c_i$ can be found. This value is reported to Figure 3.2.1, so that the incremental stress $d\sigma_i$ is obtained. This calculation is done for each element, and final evaluation is to verify Equation 3.6 by comparing the applied exterior load P and the sum $\Sigma A_i\sigma_i$. If the difference between these values are so small, the point S is a good approximation. The calculation can be continued for the next step dt. If the difference between P and $\Sigma A_i\sigma_i$ is not small, the point S is not a good solution. The evaluation must be repeated with approximation giving another $d\varepsilon^T$.

Based on the above evaluation, two methods were used: iterative method and bisection method. With iterative method, approximation of total strain is given from zero and then incremented with certain value until that the difference between load P and the sum $\Sigma A_i\sigma_i$ is minimum. The inconvenient of this method is taking a long time and then is not be used.

With bisection method, minimum and maximum approximation of total strain are given. Analogue to the iterative method, middle point between the minimum and the maximum is evaluated. By evaluating the difference between load P and the sum $\Sigma A_i\sigma_i$, the minimum or the maximum approximation of total strain is renewed by changing with the middle point. Therefore, the interval between the minimum and the maximum approximations becomes small, and the difference between load P and the sum $\Sigma A_i\sigma_i$ is minimized. Compared to iterative model, bisection method saves time. The flow-chart of bisection method is included in Appendix A1.7.

3.3 Fracture Criteria

In order to evaluate material damage, two fracture criteria are used. The first is short range criteria based on tensile strength in which material recognizes its fracture if the stress becomes larger than limit stress σ_L,i.e.:

$$\sigma \geq \sigma_L \qquad \text{(Eq. 3.14)}$$

Creep tests were performed with different values of applied load. The experimental data show that at 550°C under nominal stress 43.0 kgf/mm^2, the specimen was in rupture immediately. Converted to true stress, this value is equivalent to 50.2 kgf/mm^2 and will be considered as σ_L.

The second method is long range criterion in which material is in fracture if the creep damage D_c becomes larger than unity, i.e.:

$$D_c = dt/t_r \geq 1 \qquad \text{(Eq. 3.15)}$$

where t_r is creep rupture time and as a function of stress as follows:

$$\log(t_r) = \alpha + \beta \log(\sigma) \qquad \text{(Eq. 3.16)}$$

α and β are obtained by plotting time to rupture vs. true stresses in logarithmic scales (see Figure 3.3.1). Instead of nominal stress, true stress should be used because during computation, D_c is evaluated for each element and at any time. Furthermore α and β obtained by linear regression in logarithmic scales should be corrected to avoid accumulated computational error due to stresses having tendency to increase through time. For creep in air where there is no carburization effect (carbon concentration is maintained at about 0.012 % weight), the following values are used for the calculation [see Appendix B]:

$\alpha = 19.78$

$\beta = -10.21$ (Eq. 3.17)

The influence of carbon penetration on creep rupture strength will be discussed in Chapter 4.

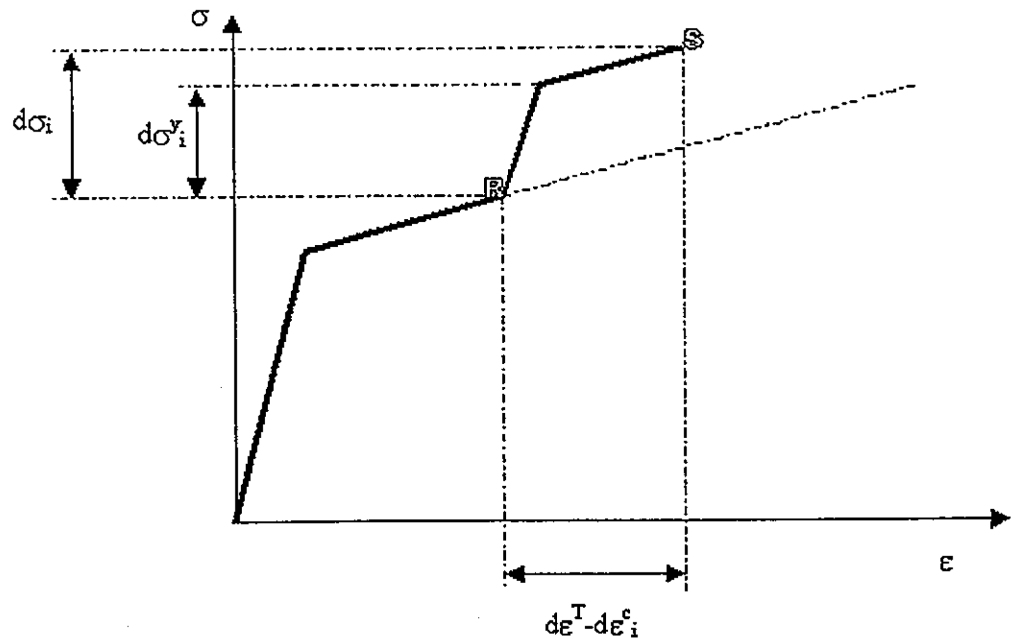

Figure 3.2.1 Elastic-plastic evaluation

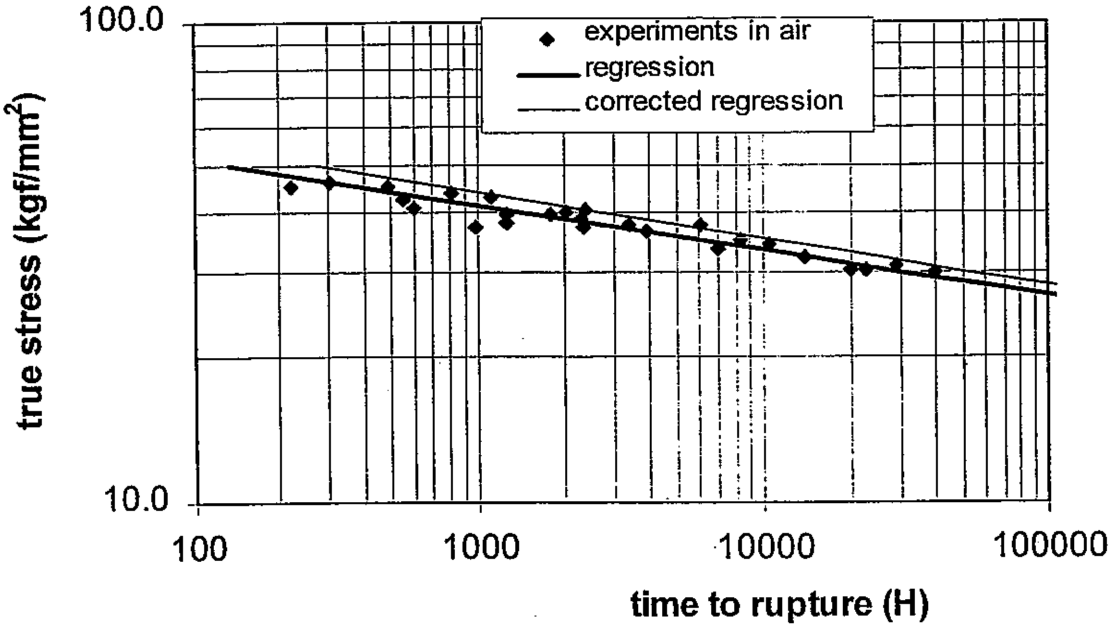

Figure 3.3.1 The relationship between time to rupture and true stress for determining α and β values

4 EFFECT OF CARBON INCLUSION

4.1 Carbon Diffusion

Material in Fast Breeder Reactor is subject to sodium exposure at temperature 550°C. 316 FR stainless steel in this condition suffers from carburization due to carbon inclusion. In order to study these phenomena, after creep tests in sodium environment, metallurgical examinations are carried out using a Scanning Electric Microscope. Based on these results, empirical mathematical equations are evaluated. Therefore, the magnitude of carbon penetration is can be simulated.

Figures 4.1.1 and 4.1.2 show zones affected by carbon inclusion. Comparing both figures, it is clear that exterior stress has a role in favoring element inclusion. The affected area can be divided into 3 zones. The first zone is between surface to point P_1. In logarithmic scale the concentration is approximately linear. The second covers from P_1 to P_2 distance. The behavior is also linear but changes the value. The last one after P_2 is not affected by sodium environment. In this region carbon concentration remains equal to initial one i.e. 0.012 % weight. In this study P_2 are assumed dependent only on time and stress applied, and in order to simplify the problem P_1 is assumed to have 1/10 distance of P_2.

Without exterior stress (material aged in sodium exposure, see Figure 4.1.1), the depth of x affected by carbon inclusion is given by diffusion theory:

$$x = (K_D\, t)^{1/2} \qquad \text{(Eq. 4.1)}$$

where K_D is diffusion coefficient and is determined by experimental results. The line of 0.013 %C is assumed as limit whether an area is affected by exterior carbon inclusion. We have then for P_2:

$$K_D = 12^2/5000 = 0.0288$$

This is initial value. Due to stress applied as shown in Figure 4.1.2, K_D varies. Table 4.1.1 resumes K_D values for different stress applied.

Many parameters influence on diffusion coefficient, but for this analysis when temperature is maintained 550°C, K_D is assumed dependent only on stress. For different stress, the approximation is using linear interpolation between points as follows:

i. For $\sigma \leq 30.5$ kgf/mm^2,

$$K_D(\sigma) = 0.0288 + 0.003590\, \sigma \qquad \text{(Eq. 4.2a)}$$

ii. For $\sigma > 30.5$ kgf/mm^2

$$K_D(\sigma) = 0.1383 + 0.2036\, (\sigma - 30.5) \qquad \text{(Eq. 4.2b)}$$

By this parameter, it may be predicted whether a layer inside material is affected by carbon inclusion during sodium exposure time t. Even, three zones affected could be determined.

Carbon concentration in the first region

At first, the carbon concentration at material surface should respect the equilibrium of carbon in fluid. This is given by Figure 4.1.3 [Ref. 2].

$$C_0 = C_{eq} \qquad \text{(Eq. 4.3)}$$

where C_0 : carbon concentration in surface

C_{eq} : predicted carbon concentration in equilibrium

In the first region the plot of ln C vs. ln x is linear. It is difficult to obtain carbon concentration exactly on the surface. To simplify this problem, we consider only 0.1 μm of deep. At any point, carbon concentration will be given by:

$$\ln(C) = \ln(C_0) + \text{slope} * [\ln(x) - \ln(0.1)] \qquad \text{(Eq. 4.4)}$$

where

slope = linear tangent

Determine now the slope. In order to obtain linear characteristic, points for x = 0.1 μm and x = 1.0 μm of distance from material surface are manipulated leading to Table 4.1.2. The slope depends on stress and time. At initial time, the slope tends to be parallel to the surface line. Due to lack of experimental data, time variable could be included by using the following relation (similar to carbon diffusion):

$$\text{angle of slope} = -90° + K_t * t^{1/2}$$

where

t : time (hour), and

It was not a smooth equation, but it is enough to simplify the problem. The Table 4.1.3 shows K_t calculated by this formula for certain stresses.

For other stresses, the constant approximation K_t is given by linear interpolation between points as follows:

$$K_t = 0.3606 + 0.030919\,\sigma \qquad \text{for } \sigma \leq 30.5 \text{ kgf/mm}^2,$$

$$K_t = 1.3036 + 0.52308\,(\sigma - 30.5) \qquad \text{for } \sigma > 30.5 \text{ kgf/mm}^2 \qquad \text{(Eq. 4.5)}$$

Thank to equation 4.4, the carbon concentration in the first zone can be predicted for any time when stress applied is known, especially at point P_1.

Carbon concentration in the second and third regions

The second zone covers from P_1 to P_2. Along this region, carbon concentration can be calculated by:

$$\ln(C) = \ln(C_{Pt.1}) + \text{slope} * [\ln(x) - \ln(X_1)] \qquad \text{(Eq. 4.6)}$$

where $C_{Pt.1}$: carbon concentration at point P_1,

slope = $[\ln(0.012) - \ln(C_{Pt.1})] / [\ln(X_2) - \ln(X_1)]$

X_1 : distance of P_1 (and assumed to be 1/10 of X_2)

X_2 : distance of P_2

At P_2 and in the third region the carbon concentration must be equal to 0.012 % weight.

Using above empirical formula, **Fortran** program was created to simulate carbon diffusion. To verify and validate all assumptions, Figure 4.1.4 predicts carbon concentration calculated by the program along inside material for different times when stress applied is 33.0 kgf/mm^2.

4.2 Relation between yield stress and carbon inclusion

Carbon inclusion affects material behavior. In microstructure point of view, diffusion of atom causes local plastic deformation. Consequently, material hardens and its elastic zone increases. Figure 4.2.1 shows the relationship between yield stress of 316FR stainless steel and carbon concentration. The curve tends to be linear.

Since for initial material containing 0.012 % C weight the yield stress is well known as 11.2 kgf/mm^2, the approximation should pass by this point. The following method performs the linear regression. Assume an equation

$\sigma^y = a * C + b,$

where σ^y is yield stress in kgf/mm^2, C is carbon concentration in % weight, a and b are constant and which are related by

$b = 11.2 - 0.012a$

The residual (or the error R_i) for each point can be expressed by

$R_i = \sigma^y{}_i - a * C_i - b$

$R_i = \sigma^y{}_i - a * C_i - (11.2 - 0.012a)$

$R_i = \sigma^y{}_i - 11.2 + a\,(0.012 + C_i)$

The sum of residual square for all points becomes:

$\Sigma\, R_i^2 = \Sigma\, \{\sigma^y{}_i - 11.2 + a\,(0.012 + C_i)\}^2$

The sum will be minimum when its derivation in function of a is zero. This leads to:

$\sigma^y = 23.6\,C + 10.9$ (Eq. 4.7)

The experimental data are given until carbon concentration 0.3 % weight. After this point, data are not available. The extrapolation in this region using Equation 4.7 leads to strength results because the calculated yield stress is too high. For this reason, an assumption is adopted that for carbon concentration higher than 0.3 %, the yield stress of material is considered constant (Figure 4.2.1).

4.3 Relationship between creep strain rate and carbon inclusion

Creep strain increment is obtained by using Norton's law for steady creep strain rate equation:

$d\varepsilon^c/dt = D\,(\sigma / G)^n$ (Eq. 4.8)

where D, G and n are material constants to be determined. D and n are assumed invariable with environment and only G varies with the alloy element diffusion. Considering carburization effect, parameter G is in function with C which is carbon concentration (in % weight) in material and is assumed to follow the Equation 4.9.

$G = G_1 * C^{p/n}$ (Eq. 4.9)

where G_1 and p are constants.

Based on experimental data, Figure 4.3.1 shows the relationship between stress and creep rate. In logarithmic scale, the curve tends to be linear and in a good path as predicted by Equation 4.8. Parameter n can be obtained easily.

Other experimental data give the relationship between creep rate and carbon concentration in material. After manipulating data, the curve of $\ln(d\varepsilon^c/dt)$ vs. $\ln(C)$ could be considered as linear (Figure 4.7). The decreasing slope represents p.

Parameters D and G_1 can not be determined by this experimental data, but we have the relationship between them. This is enough to evaluate creep behavior. We have then:

$n = 10.7$
$p = 3.5$
$D/G_1^n = 5.079E\text{-}29$

4.4 Influence of carbon concentration on creep rupture strength

Creep damage criterion is characterized by α and β. Using Equation 3.16,

$\log(t_r) = \alpha + \beta \log(\sigma)$

those parameters can be determined by plotting time to rupture vs. stresses curve in logarithmic scales. However, carburization phenomena influence on these parameters. Unfortunately, no sufficient data are available for evaluating precisely both α and β parameters.

Wada et al. [Ref. 5], have evaluated the mechanical properties on 316FR steel. It was found that the creep rupture strength for 10,000 hours increased linearly with the carbon and nitrogen concentration. This data could be used for evaluating the carburization effect. Based on these results, the linear relationship between creep rupture strength and carbon concentration (nitrogen effect is neglected) is as follows,

$$\sigma_R = A + B * \%C \quad \text{(Eq. 4.11)}$$

where σ_R is creep rupture strength for 10,000 hours, both A and B are constants, and %C is carbon concentration. Equation 4.11 can be derived giving:

$$\Delta\sigma_R = B * \Delta\%C \quad \text{(Eq. 4.12)}$$

The value of B is about 80 kgf/mm^2 /%weight. This value is in fact a linear tendency in the carbon and nitrogen concentration region less than 0.14 %. Higher than this region, the same linear extrapolation is considered as still valuable.

If σ_R is creep rupture strength, it should respect to Equation 3.16, so that:

$$\log(t_r) = \alpha + \beta \log(\sigma_R) \quad \text{(Eq. 4.10)}$$

Using values from Equation 3.17, the time to rupture for 10,000 hours can be predicted. This leads to 35.1 kgf/mm^2 (true stress). In term of nominal stress, it is equivalent to 31.9 kgf/mm^2.

Due to lack of data, both α and β can not be determined in function of carbon concentration. The following assumption is taken into account. The slope in time to rupture vs. stress curve in logarithmic scales is not influenced by carburization phenomena. In other words, only α varies in function of carbon concentration. By this assumption, parameter α can be evaluated using Equation 4.10:

$$\alpha = 4 - \beta \log (\sigma_R + B * \Delta \%C) \qquad \text{(Eq. 4.10)}$$

where, β is the same value as in Equation 3.17, σ_R is creep rupture stress for 10,000 hours, and Δ %C is obtained from carbon diffusion calculation. Knowing both α and β parameters, damage criteria can be evaluated.

Table 4.1.1 K_D values for different stress

σ (kgf/mm²)	$K_D(\sigma)$
0	0.0288
30.5	0.1383
33.0	0.6473

Table 4.1.2 Carbon concentration rate in logarithmic scale for the first region

σ (kgf/mm²)	% C weight		Ln (% C weight)		Time (hours)	Angle of slope (°)
	x = 0.1	x = 1.0	Ln x = -2.3026	Ln x = 0.0		
0	4.0	0.032	1.3863	-3.4420	5000	-64.5037
30.5	1.3	0.48	0.2624	-0.7340	2610	-23.3996
33.0	1.15	0.53	0.1398	-0.6349	747.7	-18.5950

Table 4.1.3 K_t values for different applied stress

σ (kgf/mm²)	K_t
0	0.3606
30.5	1.3036
33.0	2.6113

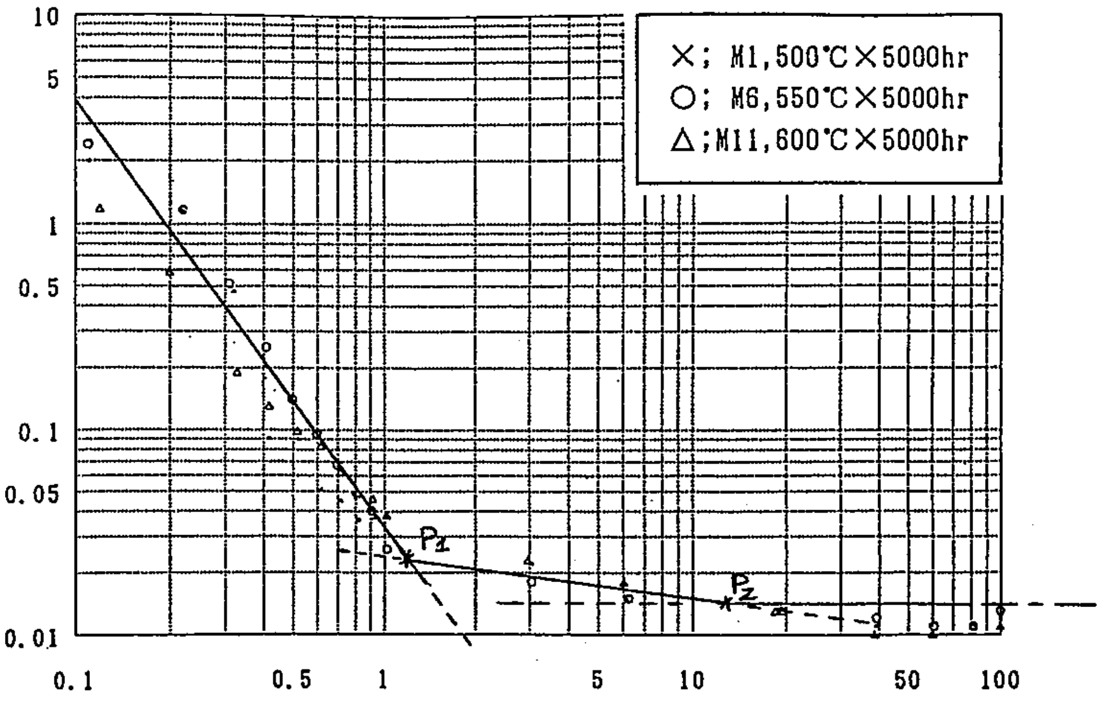

Figure 4.1.1 Carbon concentration profile on specimen exposed in sodium

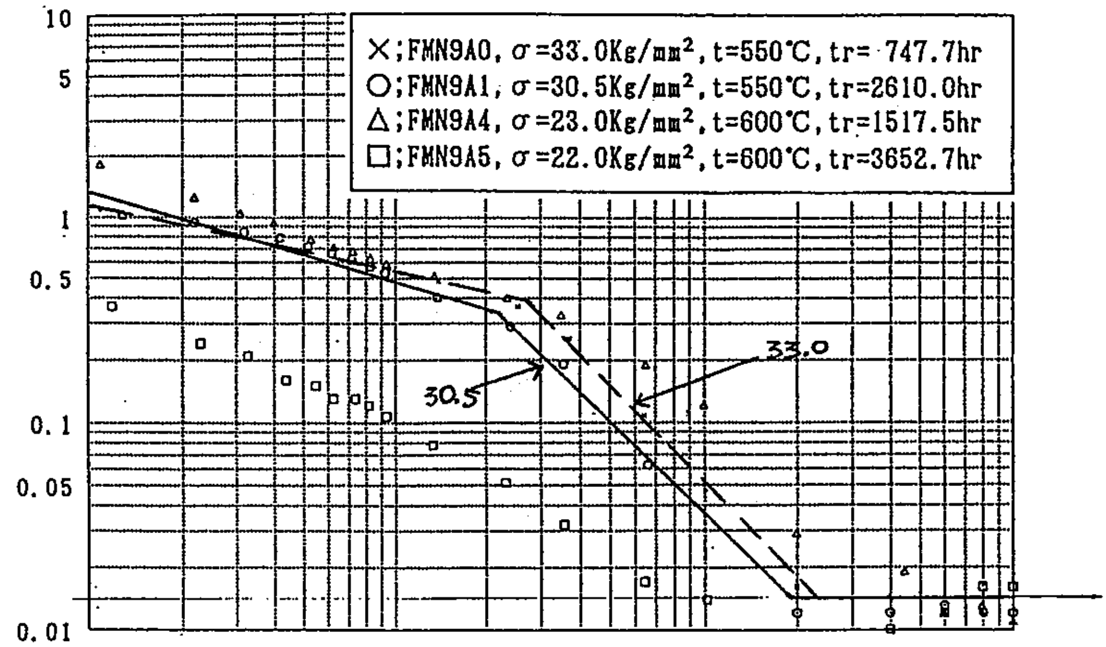

Figure 4.1.2 Carbon concentration profile on specimen after creep rupture in sodium

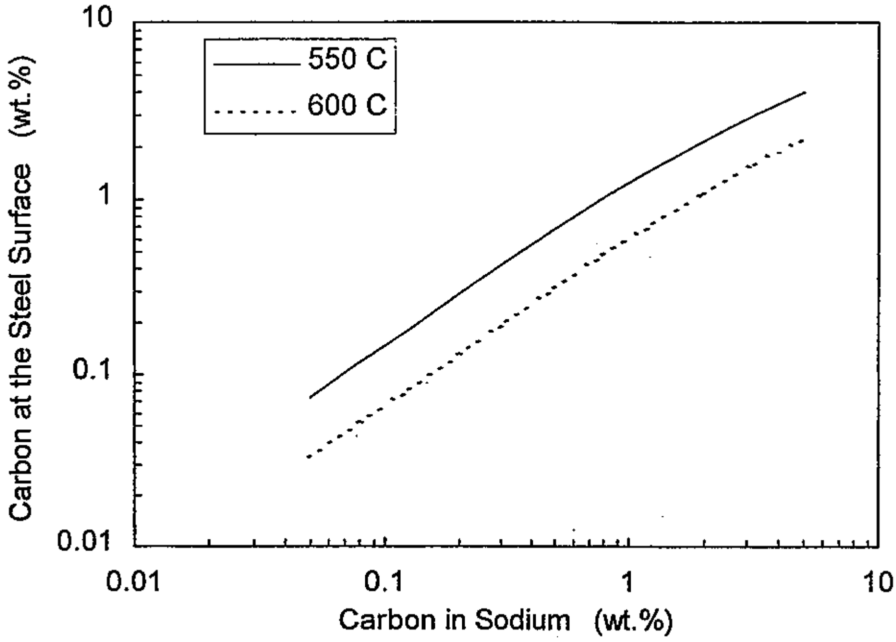

Figure 4.1.3 Equilibrium between carbon concentration in steel surface and in liquid sodium

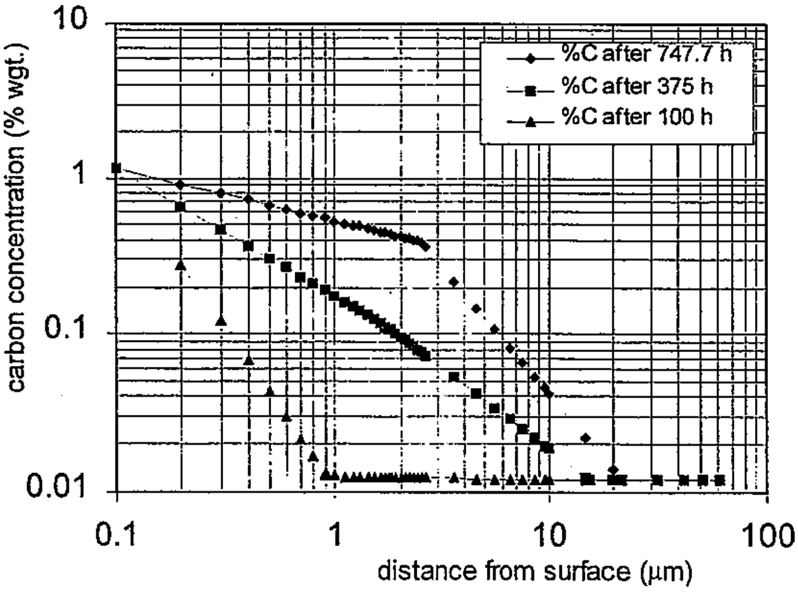

Figure 4.1.4 Influence of time on carbon inclusion in 316 FR

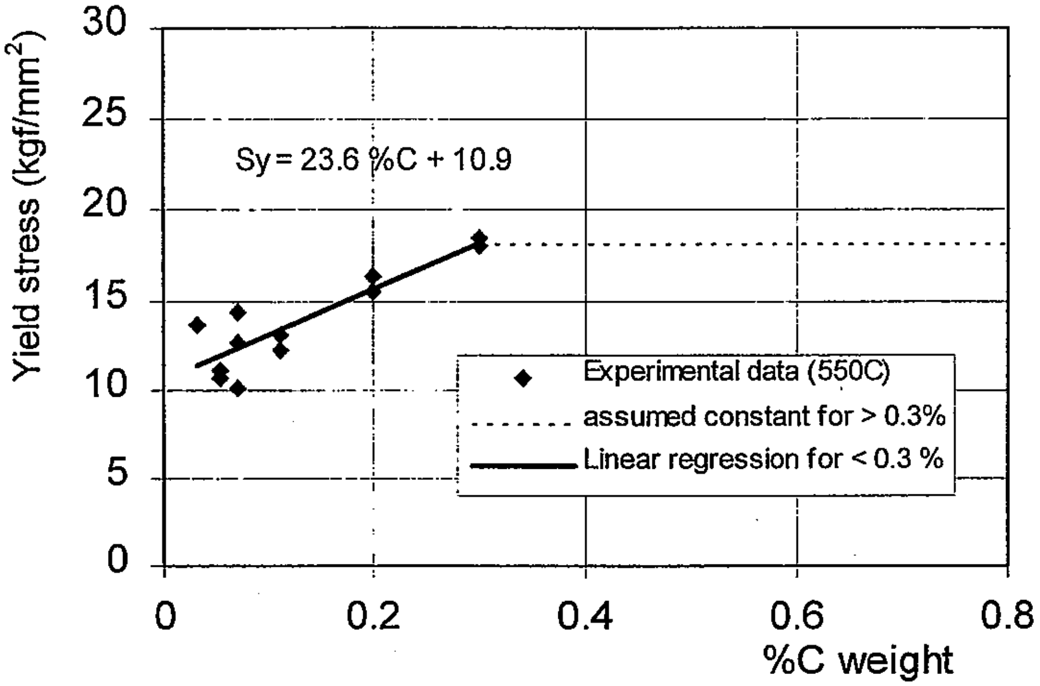

Figure 4.2.1 The relationship between carbon concentration and yield stress

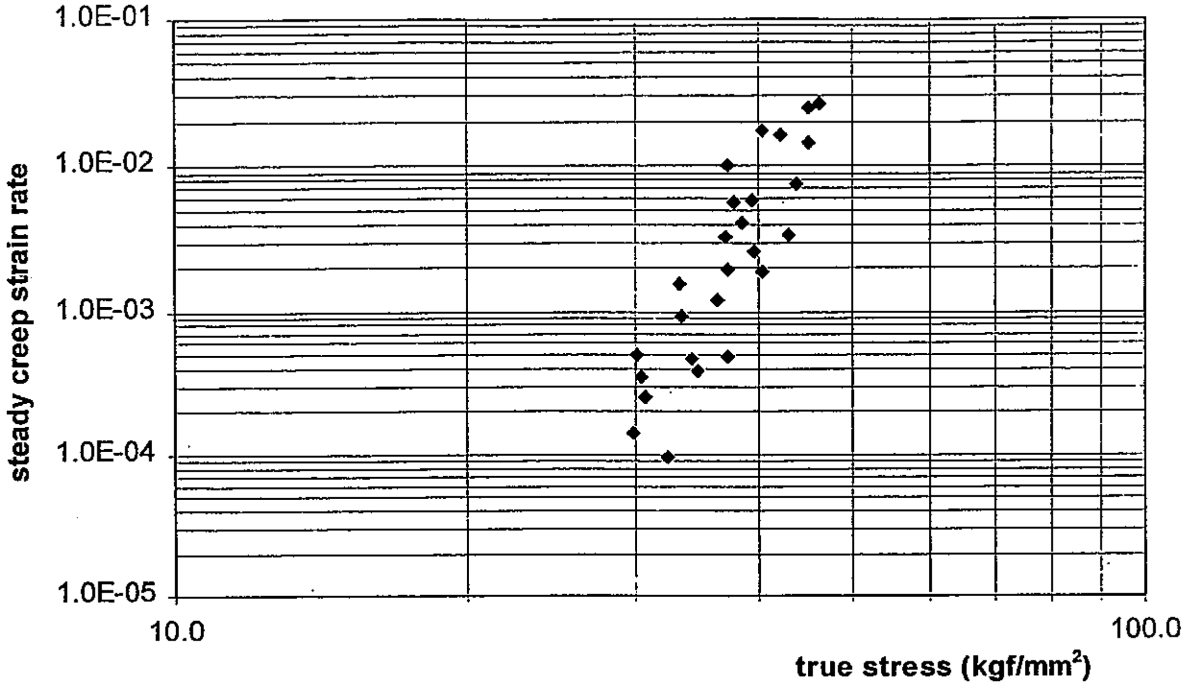

Figure 4.3.1 The curve of steady creep strain rate vs. true stress

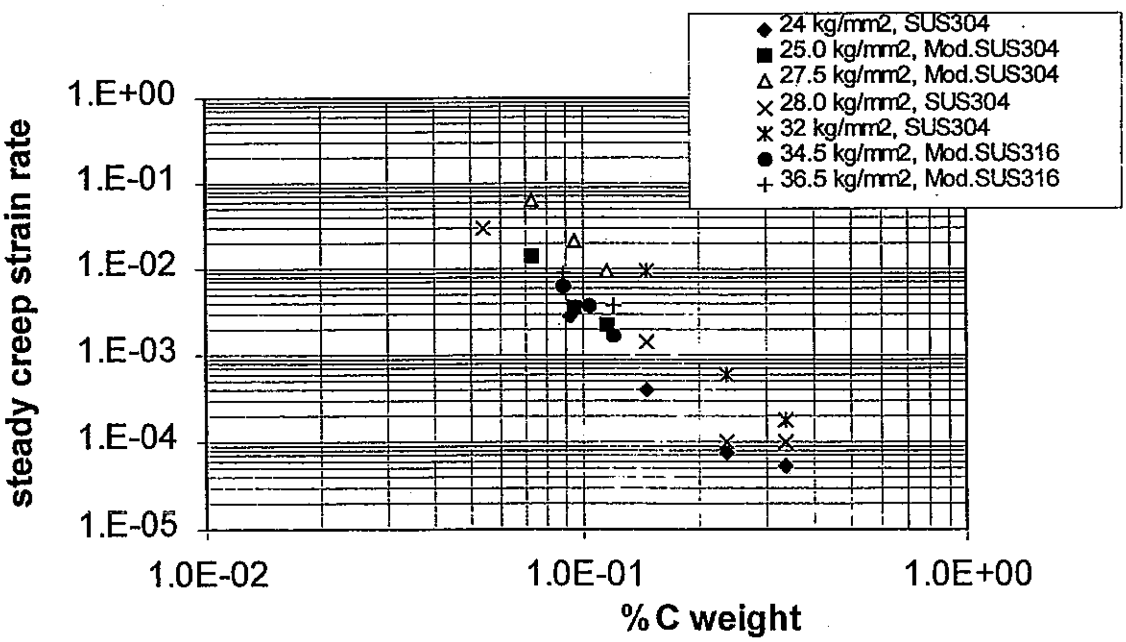

Figure 4.3.2 The relationship between creep strain rate and carbon concentration

5 RESULTS AND DISCUSSIONS

The analysis model as shown in Figure 1.2 is prepared. An axial load equivalent certain nominal stress is applied. Results are here. Only element numbers 1, 29, 60, 100, 125, 126, 127, 128, 129 are discussed. Element 1 is the deepest element, and element 129 is the most exterior element which is in contact directly with liquid sodium and is subjected to carburization.

5.1 Creep under Stress Higher than 33.0 kgf/mm^2

At first when the load equivalent to 33.0 Kgf/mm^2 of nominal stress is applied, plastic strain occurs. This axial elongation is compensated by section area reduction. Because of constant load, material receives a true stress higher than nominal stress. In a deal with Figure 2.3 prediction, the true stress is about 36.5 Kgf/mm^2. All elements have the same value under elastic-plastic condition. After certain time, stress distribution is not uniform as shown in Figure 5.1.1. The most exterior element suffers under a high stress. For comparison, after 500 hours of creep the stress in element 129 is about 41.6 Kgf/mm^2 instead of 36.9 Kgf/mm^2 inside material.

This phenomenon is explained by Figure 5.1.2 showing carbon concentration in different elements due to carbon penetration from liquid sodium environment. As discussed in Chapter IV, carbon inclusion affects the creep strain rate and this is shown by Figure 5.1.3. Creep experiment is performed so that total strain of all elements is uniform. Lower creep strain rate in exterior elements is compensated by higher elastic strain. For this reason, stresses in exterior elements are higher than inside material. Quantitatively, the difference of stress values is related to the difference of yield stress of material affected by carbon inclusion.

If creep analysis is continued, exterior elements suffer from high stress and risk to be first in fracture. Figure 5.1.4 shows stress distribution through time. The first fracture occurs in element 129 after 1301 hours. Stress disappearing from this element will be distributed to all elements explaining why stresses in all elements increase. Fracture in element 129 means also that now element 128 is the most exterior element and is in contact directly with liquid sodium. This phenomenon is repeated continuously until rupture of all elements.

After 1000 hours of creep, elements 60 and 100 have not been yet affected by carbon inclusion, so their stresses are the same as inside material. But after 1500 hours, carburization begins to give influence in element 100. For element 60, carbon penetration effect becomes important after about 2800 hours, but then rupture occurs at 3327 hours. This is explaining why the stress curve in element 60 is little different from in elements 1 or 29.

Figure 5.1.5 shows time to fracture from elements 129 to 1. The fracture begins from the element the most exterior and it moves to inside direction. Exterior elements recognize fracture because they suffer stress higher than tensile strength criteria. For inside elements, fractures are due to creep damage. Each element has 1 μm of width. Figure 5.1.6 is obtained by converting Figure 5.1.5. It shows the crack rate occurring in the material. The crack spreads with the rate becomes higher and higher.

Figure 5.1.5 predicts also that the whole specimen will be in rupture after 3378 hours. This is faster than in air where the rupture occurs after 3637 hours as shown in Figure 5.1.7. Creep curve in sodium and in air have the same curve at the beginning because at this time carburization has not had significant influence yet. Its effect becomes significant after about 2500 hours where micro-cracks spread about 20 μm.

Creep under stresses higher than 33.0 kgf/mm^2 were also evaluated. The results give similar phenomena as just discussed. However, higher applied stresses, tensile strength criteria become more important than creep damage criteria. Even, in creep under nominal stress 40 kgf/mm^2 all elements are in rupture due to tensile strength criteria.

5.2 Creep under Stress Lower than 30.5 Kgf/mm^2

For creep under nominal stress of 30.5 kgf/mm^2, similar curves as discussed above are obtained. First fracture, as shown in Figure 5.2.1, occurs in the most exterior element. However, crack growth is not absolutely from surface to inside direction. There is a moment where fracture occurs in elements which are not in direct contact with sodium environment. In the other words, voids might be created. This phenomena is clearly shown if applied stresses are less than 30.5 kgf/mm^2. In this region, the role of creep damage criteria becomes more important than tensile strength criteria.

For example in creep under nominal stress of 24.0 kgf/mm^2, stress distribution until rupture is given by Figure 5.2.2. At first, exterior elements receive higher stresses than inside due to the increase of carbon concentration. After certain time, elements from 129 to 125 reach and have the same carbon concentration as maximum limited by the equilibrium on surface. Consequently, the curve stresses of these elements coincide. But, those values have not exceeded tensile strength criteria yet. In the same time, creep strength of exterior elements increases due to carburization. For these reasons, the first fracture does not occur in the most exterior element, but in element 71 creating a void (Figure 5.2.3). After this initiation, crack spreads in both inside and outside directions. Due to creep damage in elements 85 to 30, exterior applied load will be distributed to the remaining elements. Unfortunately for elements 129 to 86, they receive stresses exceeding tensile strength criteria. There is discontinuity of curve between elements 30 and 29 because in the model inside elements have 100 μm of width instead of 1 μm in exterior elements.

5.3 Comparison of Creep Test between in Sodium and in Air

A series of tests was run for different nominal stress to simulate creep test in sodium and in air. The results are compared with experimental results. As seen in Table 5.3.1, in high stress range the time to rupture for creep in sodium environment is shorter than that in air. But, in low stress range, the time to rupture in sodium environment is longer than in air. These phenomena are in a great deal with well-known behavior. According to these results, the influence of sodium environment is not quantitatively important except for very high stresses. Compared to experimental data as shown in Figure 5.3.1, the analytical model discussed in this analysis gives good approximation. Anyway, assumptions [see Appendix C] being taken account into the model should be verified by experiments or other methods.

Table 5.3.1 Calculated time to rupture in creep for different stress

Nominal Stress (kgf/mm^2)	Time to Rupture (Hours)		in sodium / in air (%)
	in air	in sodium	
24.0	166290	168190	101.1
26.0	64950	62000	95.5
28.0	26900	25400	94.4
30.5	9572	9127	95.4
33.0	3637	3378	92.9
36.0	1223	1114	91.1
40.0	235.4	182	77.3

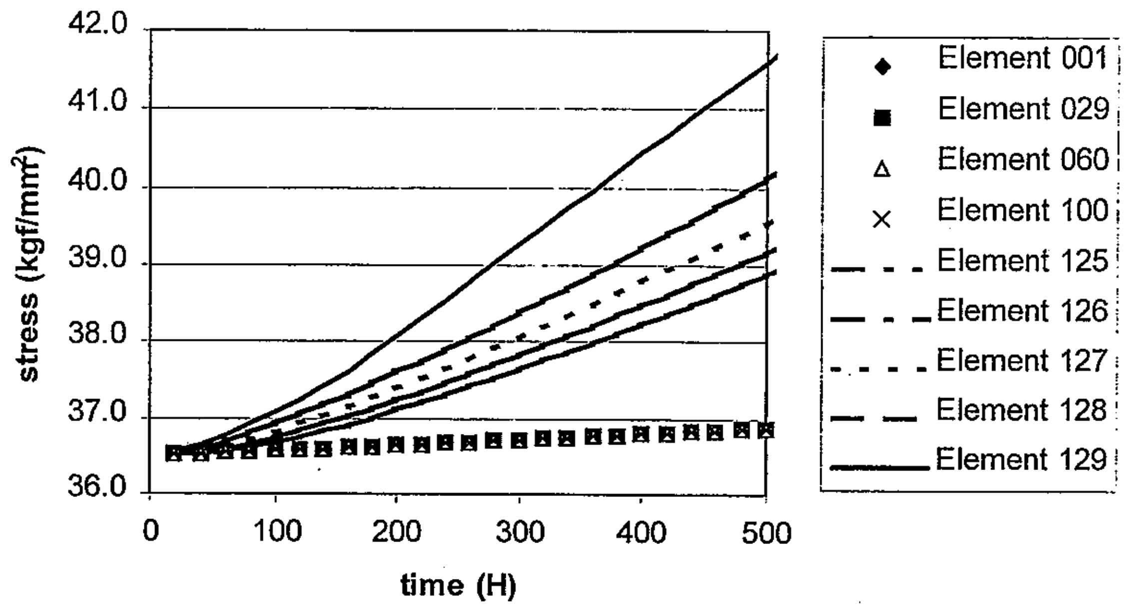

Figure 5.1.1 Stress distribution at 500 hours in creep test under 33.0 kgf/mm^2

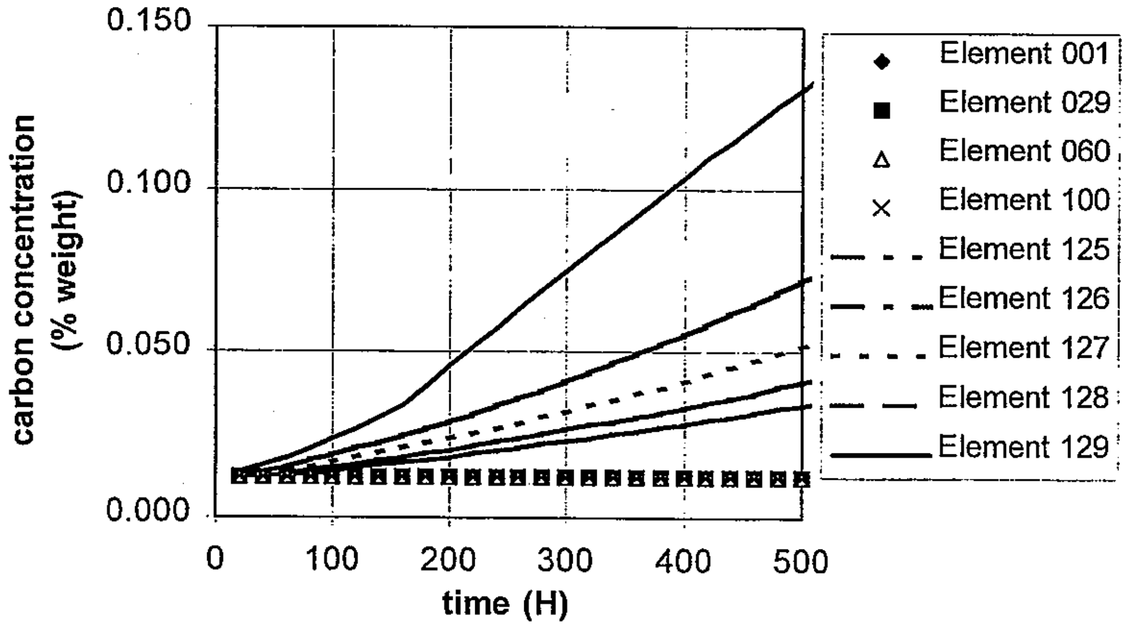

Figure 5.1.2 Carbon penetration through time for different elements

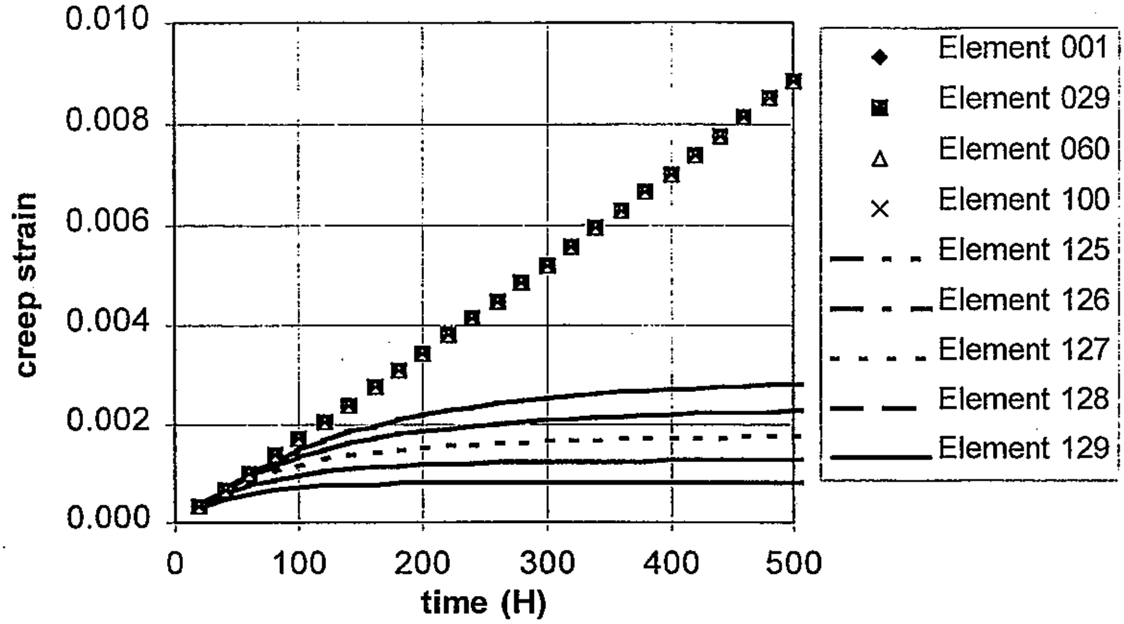

Figure 5.1.3 Different creep strain due to carburization effect

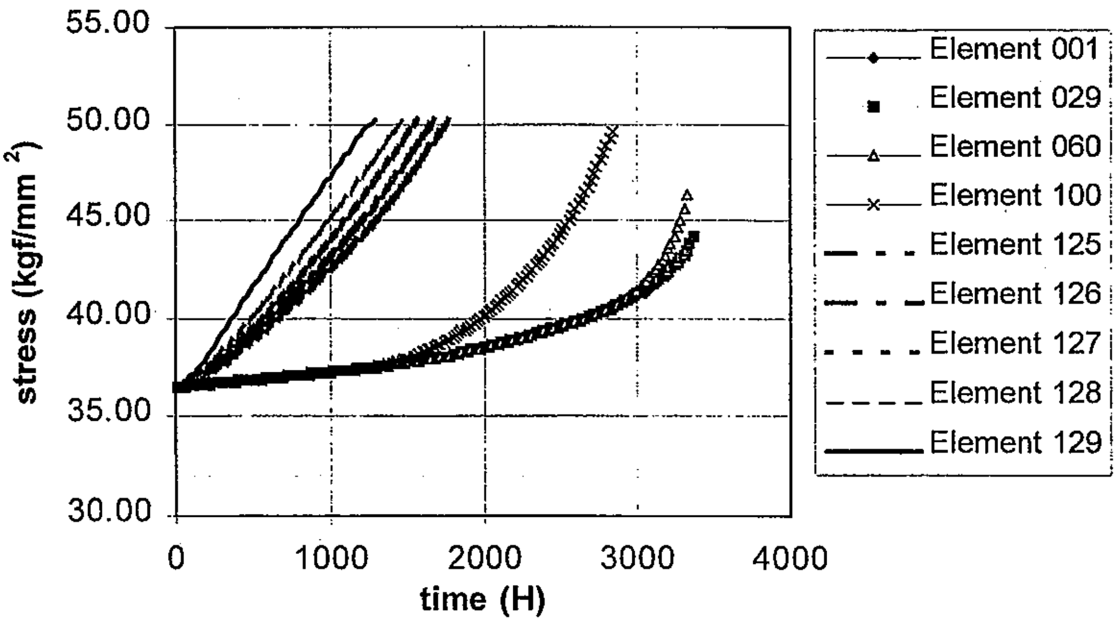

Figure 5.1.4 Stress distribution through time until rupture in creep test under 33.0 kgf/mm^2

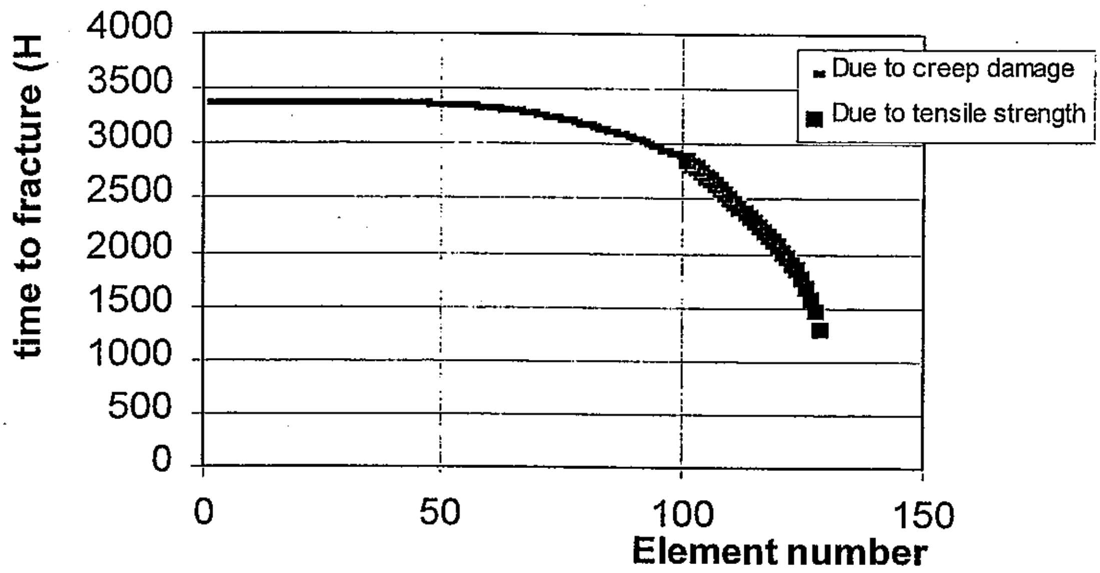

Figure 5.1.5 Time to fracture for all elements

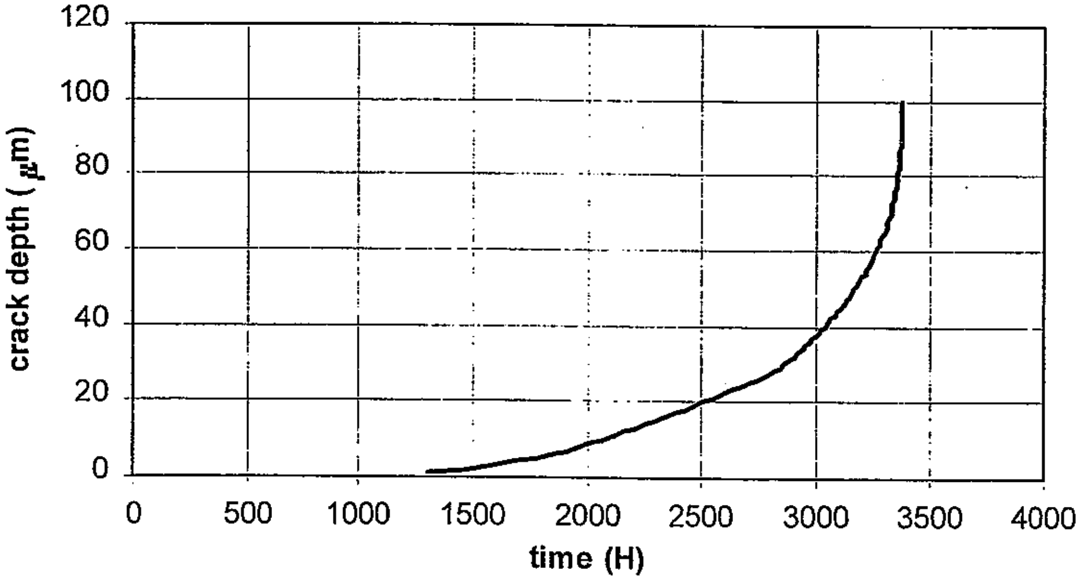

Figure 5.1.6 Crack growth through time

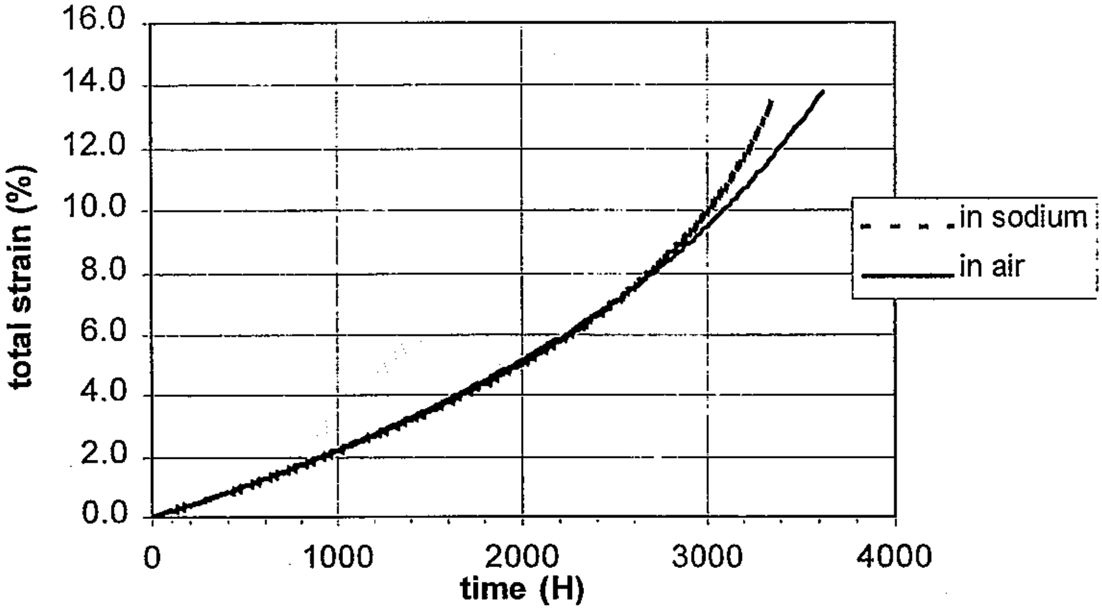

Figure 5.1.7 Comparison of creep curve under 33.0 kgf/mm^2 between in sodium and in air

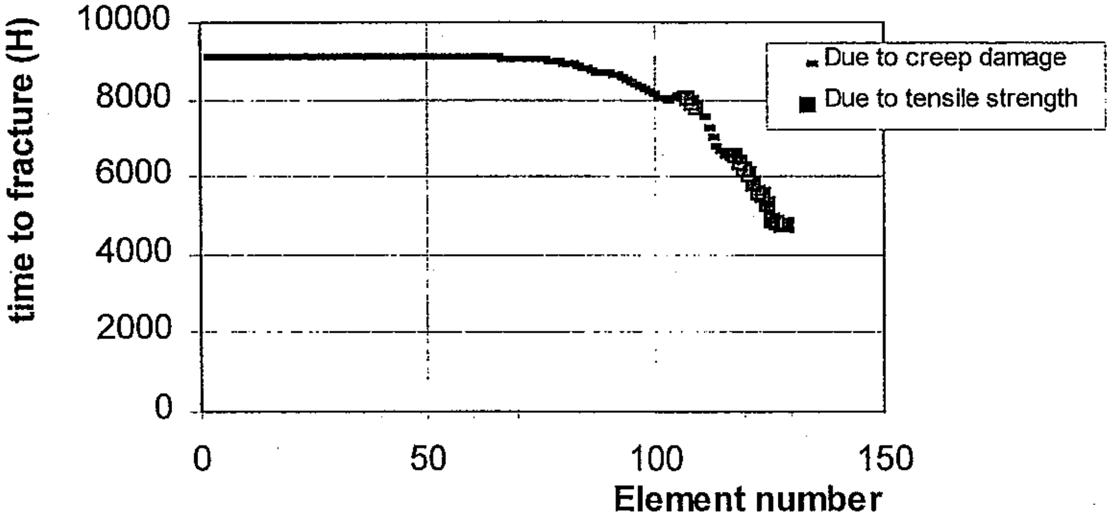

Figure 5.2.1 Fracture in creep under 30.5 kgf/mm^2

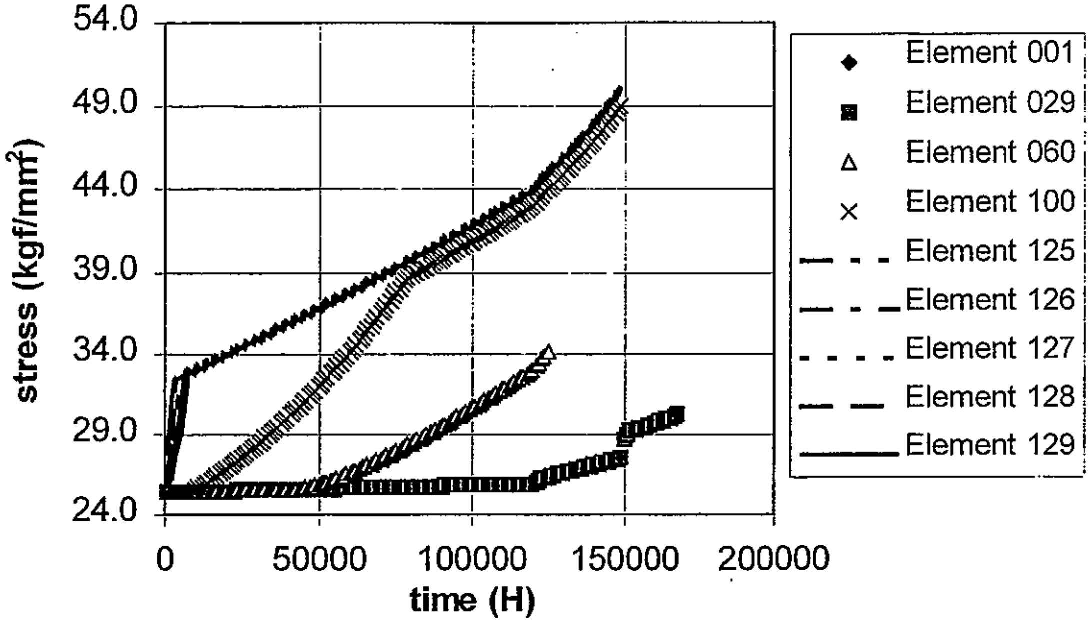

Figure 5.2.2 Stresses distribution in creep under 24.0 kgf/mm2

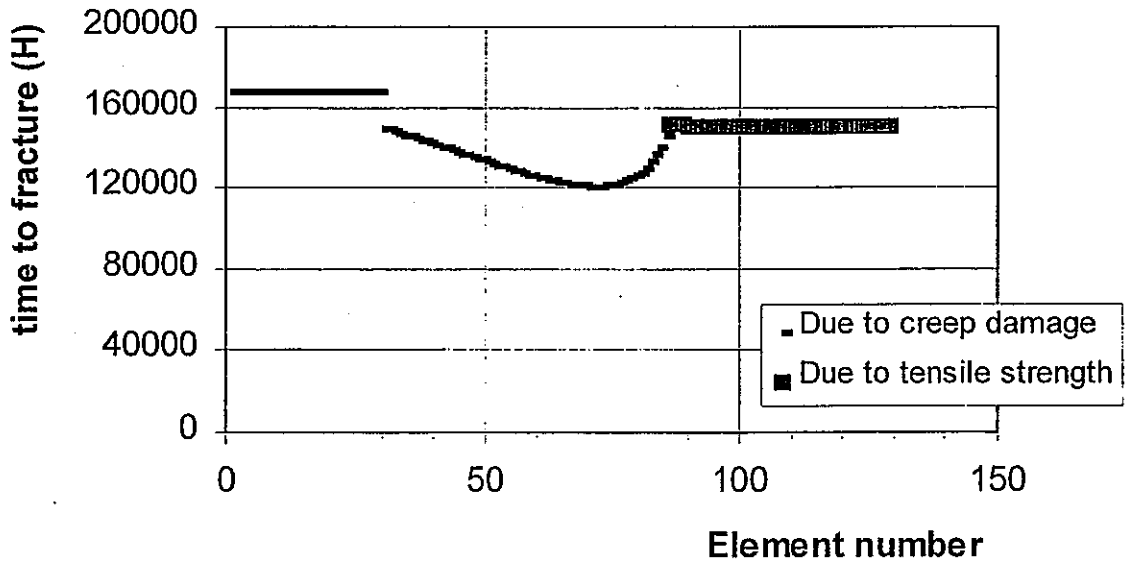

Figure 5.2.3 Fracture in creep under 24.0 kgf/mm^2

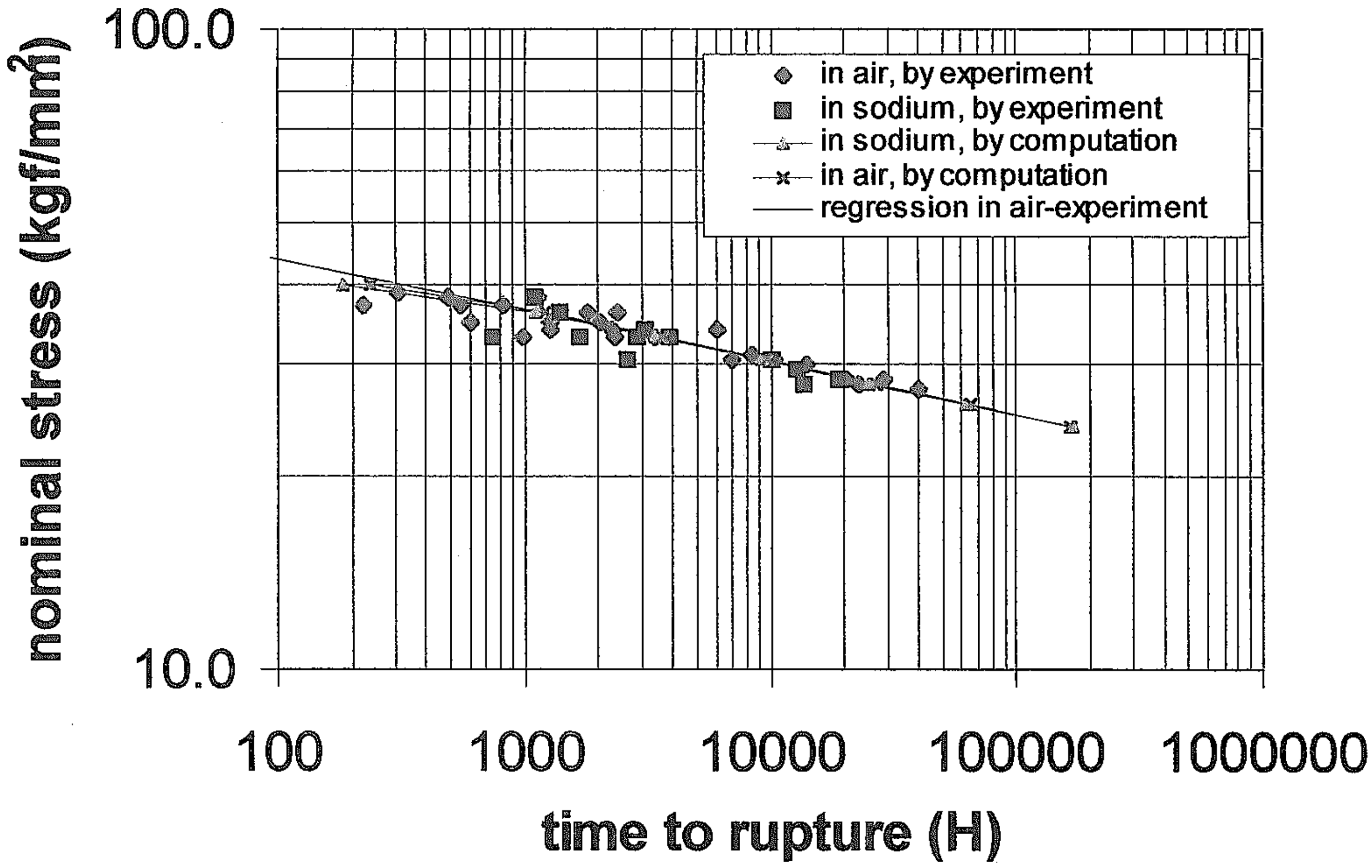

Figure 5.3.1 Time to rupture in creep predicted by the analytical model and compared with experimental data

6 GENERAL REMARKS DURING ANALYSIS WORK

6.1 Improvement of Watashi's Model

The numerical analysis performed is an extension of Watashi's model. The principle is the same in which geometrical model is divided into elements and each element is evaluated through time. Here below are some points of view that were modified.

Carbon penetration rate

In Watashi's model, elements affected by carbon are determined by diffusion coefficient, but the carbon concentration in all elements are the same. In the recent model, the carbon concentration in each element is predicted by equation based on empirical data. So, if affected by carbon inclusion, each element has different carbon concentration from others.

General Formulation

Watashi's model distinguished matrix and grain boundary. This might need assumption that constant values for matrix and grain boundary are the same. The difference might be only in carbon concentration affecting material. Even, carbon concentration in grain boundary should be adjusted because of lack of data.

The recent model considers that one element represents matrix and grain boundary combination. The use of constant values is therefore not more questionable. The recent model has also disadvantage that it is not able to distinguish between the intergranular and transgranular fractures.

Phenomenal model

Watashi's model uses nominal stress as reference. In the recent model, two parts are distinguished. First part is a situation where material is in way to be under wanted stress or load applied. In the other words, it is a moment just before the beginning of creep condition. In this step, material has elastic-plastic behavior. Consequently, true stress is distinguished from nominal stress. True stress is then used as reference to calculate creep constants and also fracture criteria.

6.2 Problems Found during Fortran Program Construction

Carbon diffusion

It is very difficult to obtain mathematical model to simulate carbon diffusion rate in material especially 316FR stainless steel. Many authors have studied these phenomena but generally in condition where material is exposed naturally to liquid sodium. Or, in our case, material in sodium exposure is subjected to exterior force. This parameter has of course influence in favoring element inclusion from the surface in contact with liquid sodium.

To resolve the problem, simplification formula is taken based on the experiments. It is needless to say that the empirical formula is not for general cases.

Possibility in using FINAS for the analysis

The treated problem is a specific case. **FINAS** or other general software based on finite element method does not generally provide such analysis. First of all, a new subroutine is needed for evaluating carbon diffusion. As known, this phenomenon has effect on mechanical material properties, especially on three parameters: creep strain rate, creep rupture strength, and yield stress. The first and the second are related to creep behavior. The last parameter represents elastic-plastic behavior. Since **FINAS** provides subroutine **XCREEP**, difficulties with creep parameters can thus be resolved. But in elastic-plastic case, the variation of yield stress remains a problem. In order to perform the special case discussed in this report by using **FINAS**, some modifications are needed, so that evolving parameters especially yield stress could be handled.

7 CONCLUSION

The numerical analysis was developed to simulate creep phenomena of 316FR stainless steel in sodium environment at 550°C. As performed in experiments, two parts are distinguished. Elastic-plastic behavior is used to simulate the fact that just before the beginning of creep test, specimen suffers from load or stress higher than initial yield stress. It is also found that load is applied as quickly as possible. This is different from usual tensile test. In the second part, creep condition is produced. The incremental strain in axial direction will be compensated by section area reduction. Consequently, stress increases because the load applied is kept constant. Plastic strain might occur. This phenomena lead to the use of elastic-plastic-creep model.

Material in contact with liquid sodium suffers from carburization effect due to carbon inclusion. The influence of this phenomena is assumed in increasing yield stress, decreasing steady creep rate, and increasing creep rupture strength. The model can successfully simulate creep experiments in sodium environment. The non-uniform of stress distribution in material can be predicted. Material affected by carbon risk to suffer from stress concentration. By damage criteria evaluation, crack initialization can be predicted, and also crack growth can be analyzed.

Some assumptions were adopted to simplify the complexity of the problem. Extrapolations in predicting yield stresses, creep strain rate, and creep rupture strength were also used due to lack of data. These are the points that should be improved in the future. In addition, with necessary modification and needing correspondent parameter values, this model can be applied for other phenomena such as decarburization effect, oxydation and or other element penetration. General finite element method will be welcomed, since the recent model treats only special case for creep test with specific specimen. Another analysis can also be combined, such as fatigue and creep-fatigue phenomena.

ACKNOWLEDGEMENTS

Incomparable valuable thanks are addressed to Mr. Hitoshi Negishi who spend time aiding to solve many problems.

The authors wish to thank Mr. Takehiko Kato for his help in compilation of data from SMAT Database.

The authors thank also to all members of KOZAI Group and their manager Dr. Masaki Morishita for their support during work.

REFERENCES

[1] Mimura H., Ito T., Yoshida E., Tsuchida Y., Kano S., Nihei I.,"*An Assessment of Carburization Behavior of SUS304 Stainless Steel in FBR Secondary System*", Fourth International Conference on Liquid Metal Engineering and Technology, Tome 2, 17-21 October 1988, Avignon, France.

[2] Watashi K., Wakai T., "*Simulation of Sodium Effect on Creep Fracture of 316FR*", Fracture, Fatigue and Life Prediction, Rio de Janeiro, August 9 – 11, 1995, Brasil.

[3] Kobayashi T., Itou T., Katou S., Aoki M., Eyoshida E., Wada Y.,"*EFFECT OF SODIUM ON 316FR (1): Creep Properties of 316FR in Sodium*", PNC Report ZN9410 93-021, February 1993

[4] George E. Dieter,"*Mechanical Metallurgy*", Second Edition, McGraw-Hill, 1976.

[5] Wada Y., Yoshida E., Kobayashi T., Aoto K.,"*Development of New Materials for LMFBR Components: Evaluation on Mechanical Properties of 316FR Steel*", International Conference on Fast Reactors and Related Fuel Cycles, October 28 - November 1, 1991, Kyoto, Japan

APPENDIX

APPENDIX A

FLOW CHART OF FORTRAN PROGRAM

Program uses **Fortran** language (see Pages from A-8 to A-17). All parameters that evolve through time are stored in variable **TABLE01** which is a two dimensional array with size (129,19), since there are 129 elements and 19 parameters needed for the calculation. The following table shows the components of **TABLE01.**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
i \ v	σ	$d\sigma$	ε^e	ε^p	ε^c	ε^T	$d\varepsilon^e$	$d\varepsilon^p$	$d\varepsilon^c$	$d\varepsilon^T$	$\sigma^{y\sigma}$	σ^{yc}	A	dA	%C	d%C	xx	fr	Dm
1																			
2																			
...																			
128																			
129																			

Table A.1 **TABLE01** variable used in the program

Here are the explanation for all variables used in Table A.1 and also in Figures A.1 to A.8.

i : index for element number
v : variable evaluated
σ : stress
$d\sigma$: incremental stress
ε^e : accumulated elastic strain
ε^p : accumulated plastic strain
ε^c : accumulated creep strain
ε^T : accumulated total strain
$d\varepsilon^e$: incremental elastic strain
$d\varepsilon^p$: incremental plastic strain
$d\varepsilon^c$: incremental creep strain
$d\varepsilon^T$: incremental total strain
$\sigma^{y\sigma}$: yield stress (renewed due to stress higher than the initial yield stress)
σ^{yc} : yield stress (renewed due to %C and thus due carburization effect)
A : section area
dA : incremental section area
%C : carbon concentration
d%C : incremental carbon concentration
xx : column not used
Fr : fracture index (= 1 if fracture, = 0 if not in fracture)
Dm, or DAMAGE : damage criteria
P : load applied
dP : incremental load applied
H : hardening coefficient
TIME : time under which material is under creep condition
dTIME: incremental time
IELM : element number
SumP : variable used in *trial and error method.*
n, p, D/G_I^n : constants in Norton's law

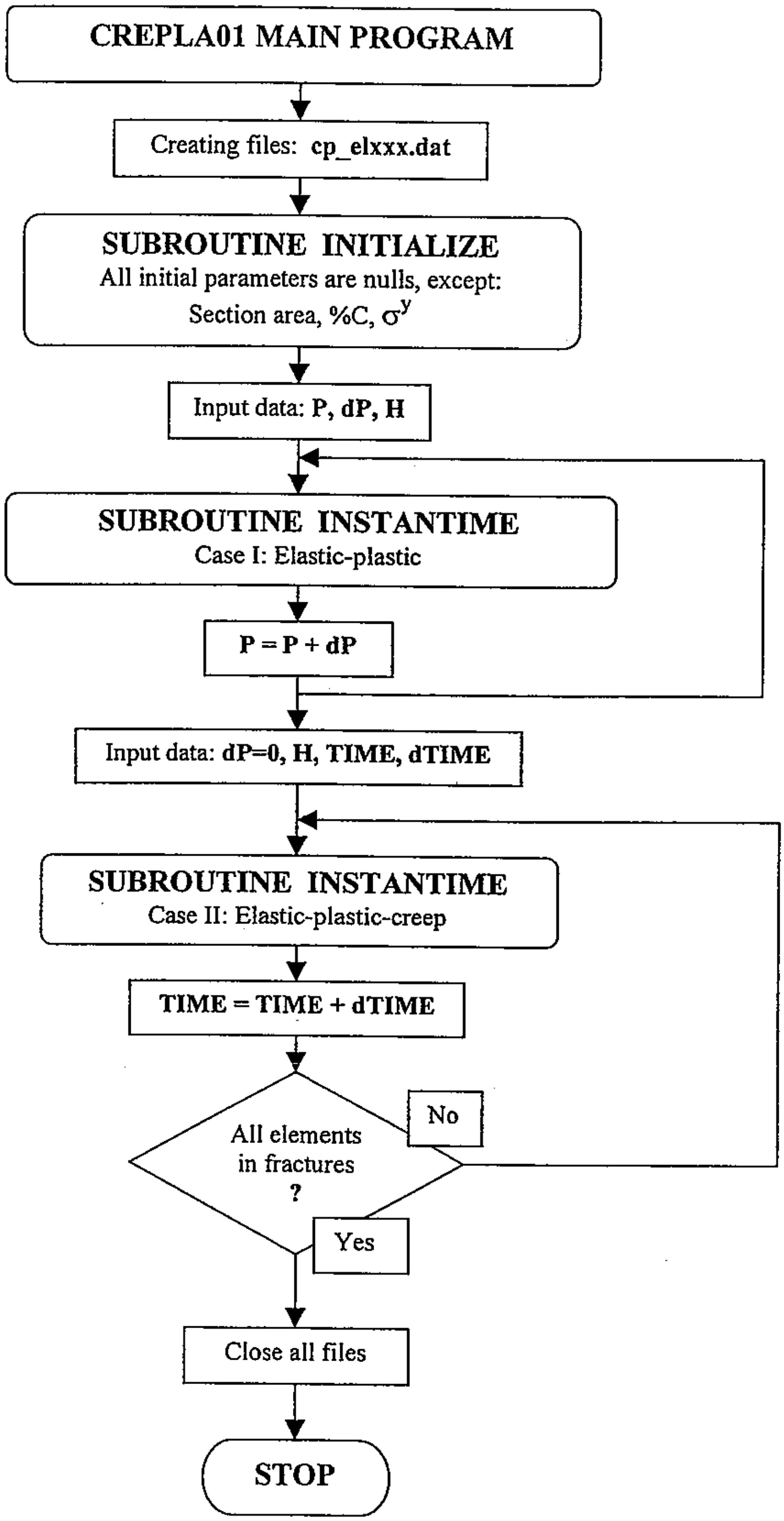

Figure A.1 Main program flow chart

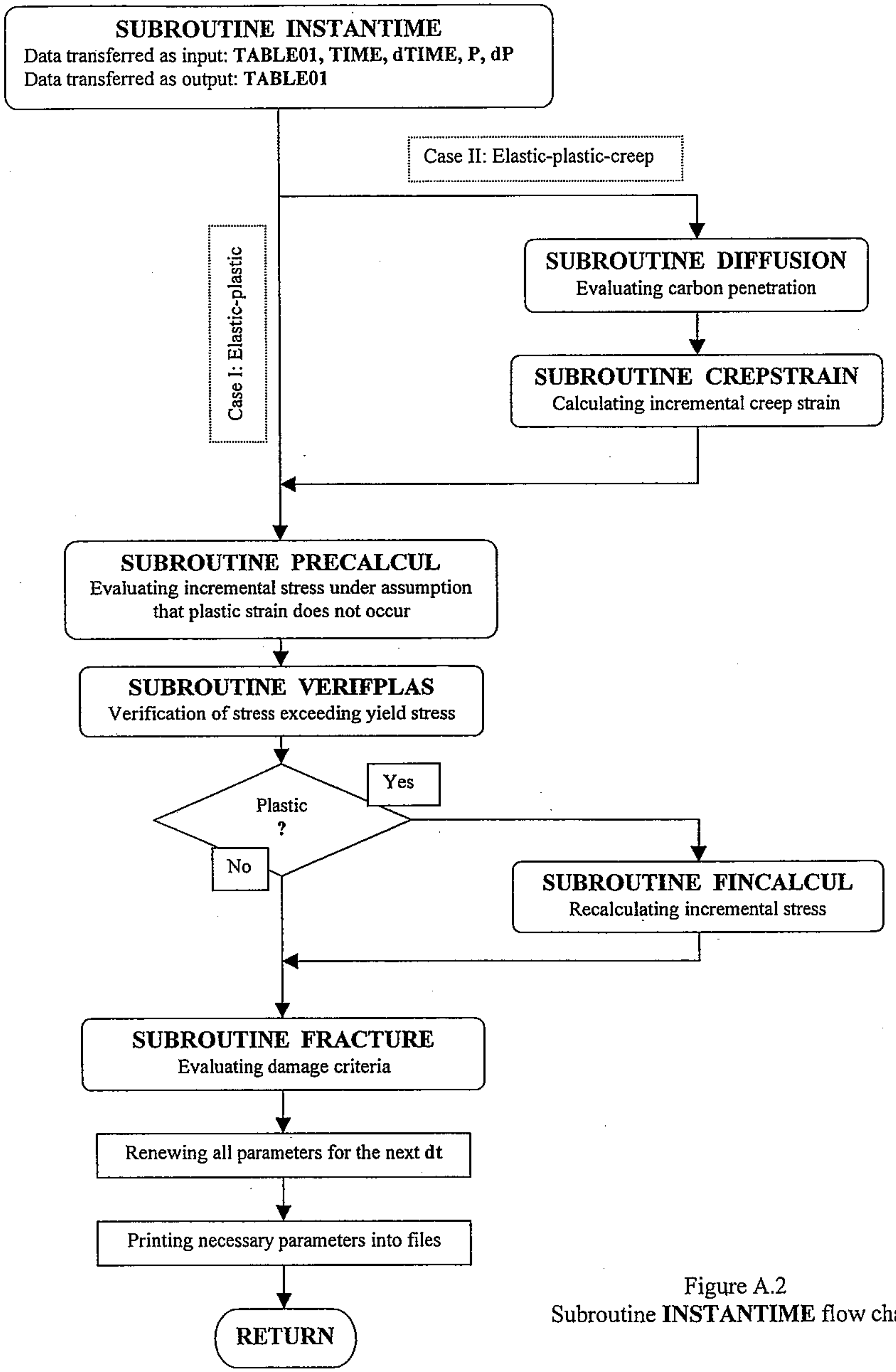

Figure A.2
Subroutine **INSTANTIME** flow chart

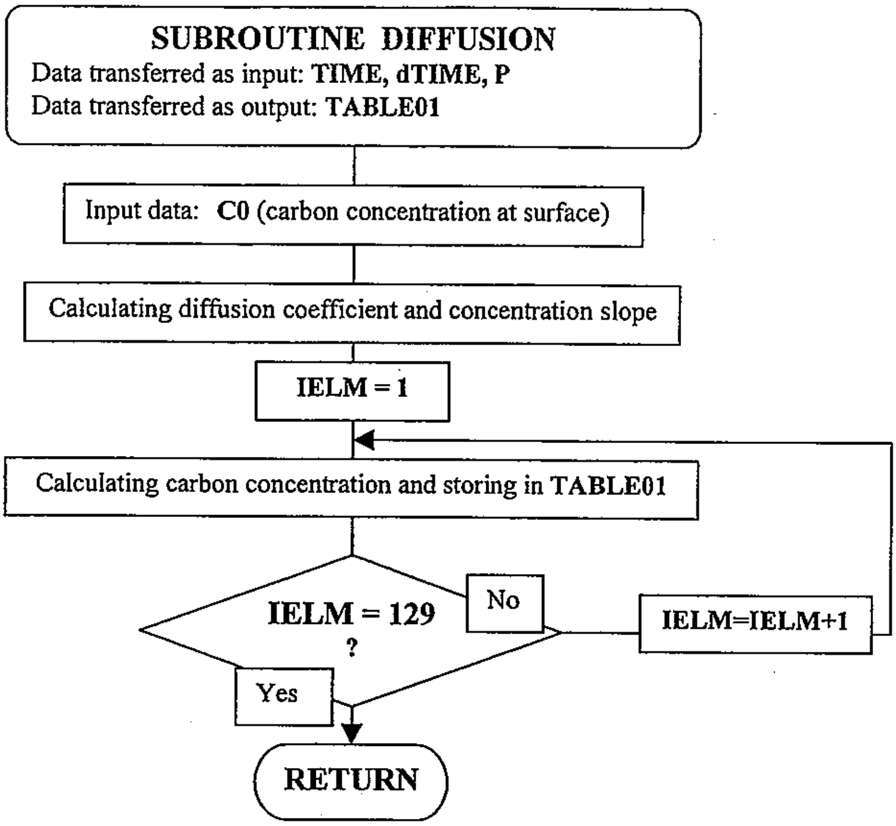

Figure A.3 Subroutine **DIFFUSION** flow chart

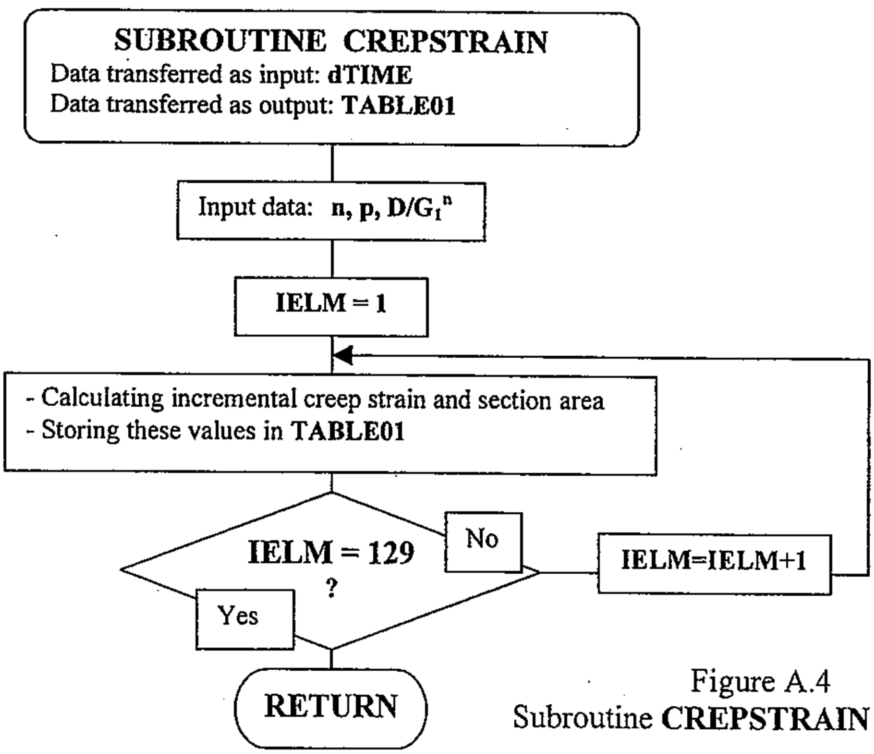

Figure A.4
Subroutine **CREPSTRAIN** flow chart

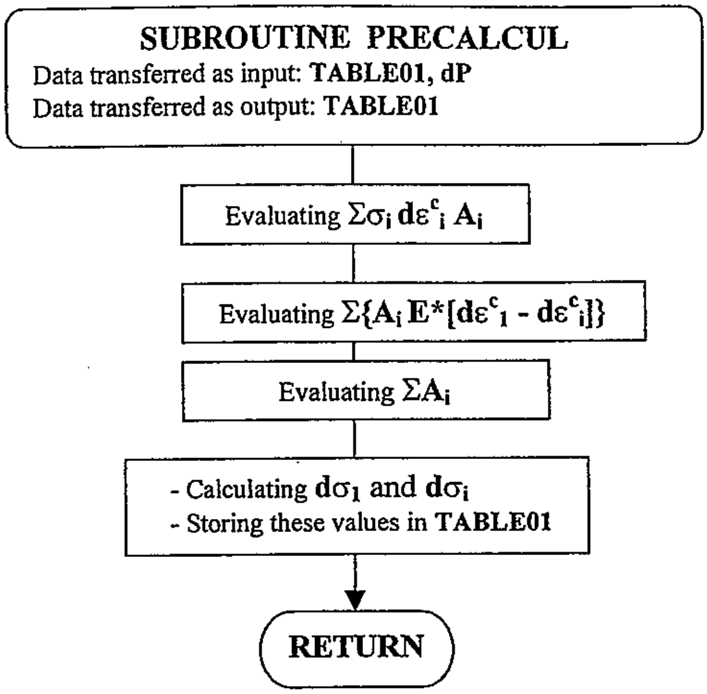

Figure A.5 Subroutine **PRECALCUL** flow chart

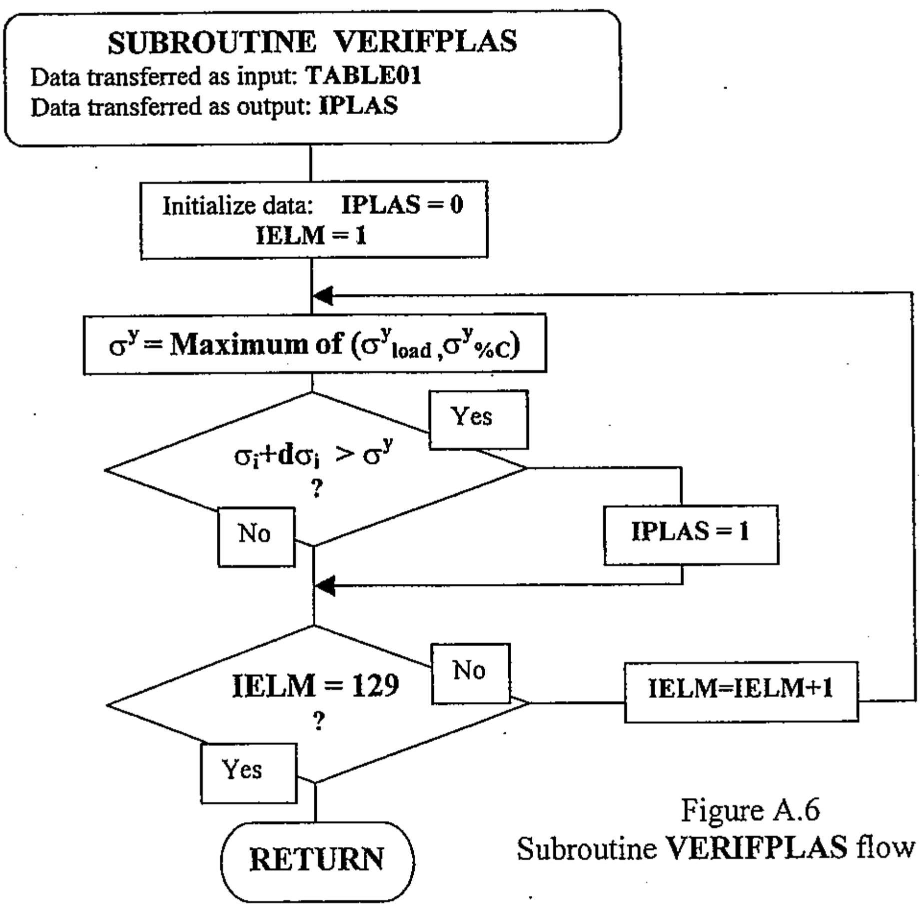

Figure A.6
Subroutine **VERIFPLAS** flow chart

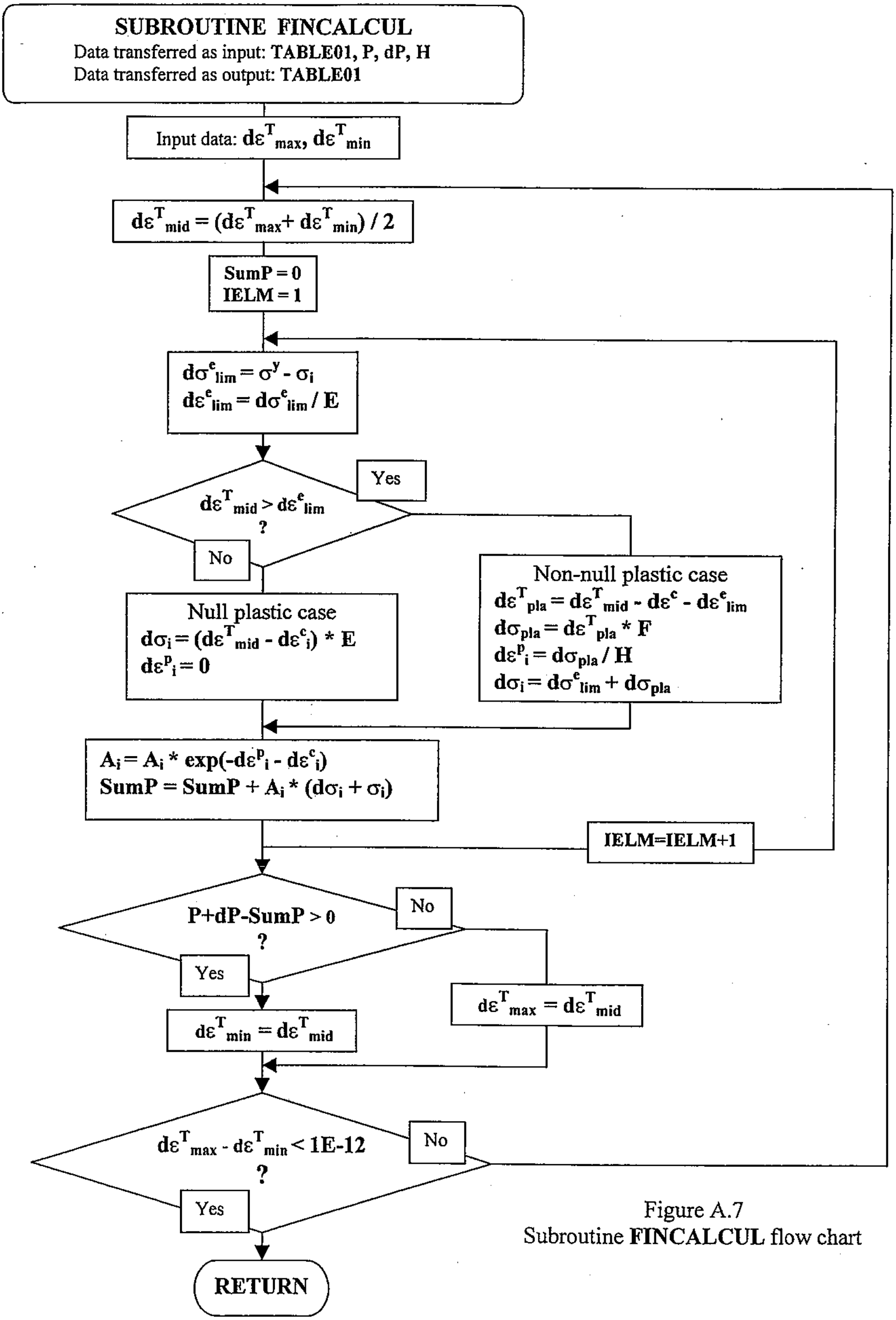

Figure A.7
Subroutine **FINCALCUL** flow chart

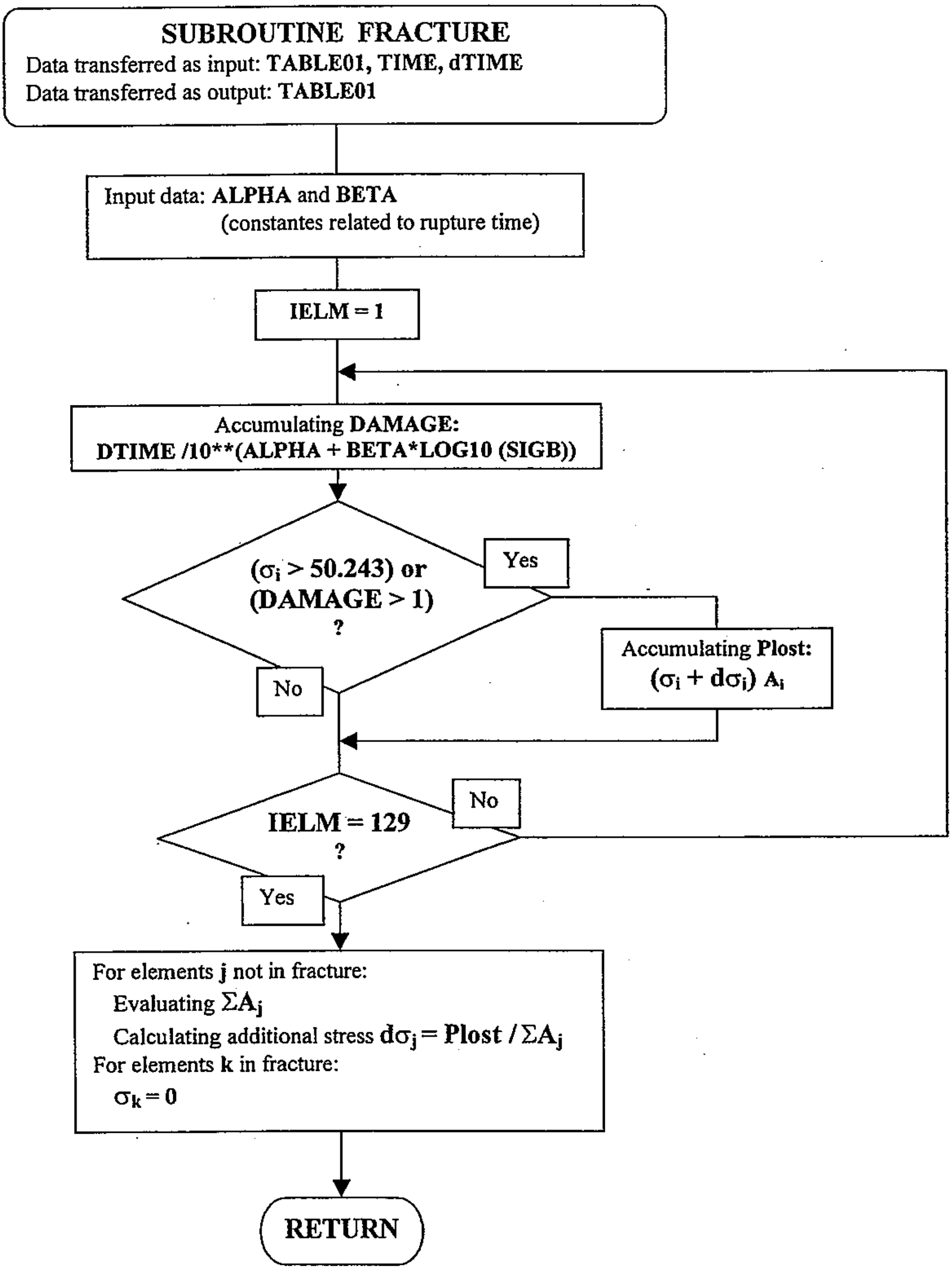

Figure A.8 Subroutine **FRACTURE** flow chart

Fortran Program List (file name: CREPLA01.for)

```
C*********************************************************************
      program CREPLA01
C*********************************************************************
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19),TBC(129)
      NELEM = 129
      OPEN(1,FILE='CP_EL001.DAT')
      OPEN(2,FILE='CP_EL029.DAT')
      OPEN(3,FILE='CP_EL060.DAT')
      OPEN(4,FILE='CP_EL100.DAT')
      OPEN(5,FILE='CP_EL125.DAT')
      OPEN(6,FILE='CP_EL126.DAT')
      OPEN(7,FILE='CP_EL127.DAT')
      OPEN(8,FILE='CP_EL128.DAT')
      OPEN(9,FILE='CP_EL129.DAT')
      OPEN(20,FILE='FRACTURE.DAT')
      CALL INITIALIZE(TABLE01,TBC)
      WRITE (1,11)  'STRESS 1','ELASTIC 1','PLASTIC 1','CREEP 1',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 1','% C 1',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(2,11)'STRESS 029','ELASTIC 029','PLASTIC 029','CREEP 029',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 029',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(3,11)'STRESS 060','ELASTIC 060','PLASTIC 060','CREEP 060',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 060',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(4,11)'STRESS 100','ELASTIC 100','PLASTIC 100','CREEP 100',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 100',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(5,11)'STRESS 125','ELASTIC 125','PLASTIC 125','CREEP 125',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 125',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(6,11)'STRESS 126','ELASTIC 126','PLASTIC 126','CREEP 126',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 126',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(7,11)'STRESS 127','ELASTIC 127','PLASTIC 127','CREEP 127',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 127',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(8,11)'STRESS 128','ELASTIC 128','PLASTIC 128','CREEP 128',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 128',
     1              'FRACT','DAMMAGE','TIME'
      WRITE(9,11)'STRESS 129','ELASTIC 129','PLASTIC 129','CREEP 129',
     1              'TOTAL STRAIN','YIELD STRESS','SURF AREA 2','% C 129',
     1              'FRACT','DAMMAGE','TIME'
11    FORMAT(11A12)
      WRITE(20,13)'THIS FILE CONTAINS TIME TO RUPTURE FOR EACH ELEMENT'
      WRITE(20,13)'IELM TIME                                           '
13    FORMAT(A52)
      CONSPP = 0.0D0
      CONSPVERIF=TABLE01(1,1)*TABLE01(1,13)+TABLE01(2,1)*TABLE01(2,13)
      WRITE(1,12)  TABLE01(1,1),TABLE01(1,3),TABLE01(1,4),TABLE01(1,5),
     1            TABLE01(1,6),TABLE01(1,11),TABLE01(1,13),TABLE01(1,16),
     1            TABLE01(1,18),TABLE01(1,19)
      WRITE(2,12)  TABLE01(29,1),TABLE01(29,3),TABLE01(29,4),
     1              TABLE01(29,5),TABLE01(29,6),TABLE01(29,11),
     1              TABLE01(29,13),TABLE01(29,16),TABLE01(29,18),
     1              TABLE01(29,19)
      WRITE(3,12)  TABLE01(60,1),TABLE01(60,3),TABLE01(60,4),
     1              TABLE01(60,5),TABLE01(60,6),TABLE01(60,11),
     1              TABLE01(60,13),TABLE01(60,16),TABLE01(60,18),
     1              TABLE01(60,19)
      WRITE(4,12)  TABLE01(100,1),TABLE01(100,3),TABLE01(100,4),
     1              TABLE01(100,5),TABLE01(100,6),TABLE01(100,11),
```

```
     1              TABLE01(100,13),TABLE01(100,16),TABLE01(100,18),
     1              TABLE01(100,19)
      WRITE(5,12) TABLE01(125,1),TABLE01(125,3),TABLE01(125,4),
     1              TABLE01(125,5),TABLE01(125,6),TABLE01(125,11),
     1              TABLE01(125,13),TABLE01(125,16),TABLE01(125,18),
     1              TABLE01(125,19)
      WRITE(6,12) TABLE01(126,1),TABLE01(126,3),TABLE01(126,4),
     1              TABLE01(126,5),TABLE01(126,6),TABLE01(126,11),
     1              TABLE01(126,13),TABLE01(126,16),TABLE01(126,18),
     1              TABLE01(126,19)
      WRITE(7,12) TABLE01(127,1),TABLE01(127,3),TABLE01(127,4),
     1              TABLE01(127,5),TABLE01(127,6),TABLE01(127,11),
     1              TABLE01(127,13),TABLE01(127,16),TABLE01(127,18),
     1              TABLE01(127,19)
      WRITE(8,12) TABLE01(128,1),TABLE01(128,3),TABLE01(128,4),
     1              TABLE01(128,5),TABLE01(128,6),TABLE01(128,11),
     1              TABLE01(128,13),TABLE01(128,16),TABLE01(128,18),
     1              TABLE01(128,19)
      WRITE(9,12) TABLE01(129,1),TABLE01(129,3),TABLE01(129,4),
     1              TABLE01(129,5),TABLE01(129,6),TABLE01(129,11),
     1              TABLE01(129,13),TABLE01(129,16),TABLE01(129,18),
     1              TABLE01(129,19)
12    FORMAT(10E12.5)
      CONSPP=0.0D0
       SN = 24.D0
      DCONSPP=SN*9.0D0
       DTIME=1.0D0
       CONSHH = 250.80081D0
      DO 20 TIME= -1.0D0,-1.0D0,DTIME
        CALL INSTANTIME(TABLE01,CONSPP,DCONSPP,TIME,DTIME,CONSHH,TBC,SN)
20    CONTINUE
      DCONSPP=0.0D0
       DTIME=.100D0
      DO 22 TIME= -1.0D0,-1.D0,DTIME
        CALL INSTANTIME(TABLE01,CONSPP,DCONSPP,TIME,DTIME,CONSHH,TBC,SN)
22    CONTINUE
      DCONSPP = 0.0D0
      DTIME = 10.D0
      DO 30 TIME= 0.0D0,9000000.0D0,DTIME
        CALL INSTANTIME(TABLE01,CONSPP,DCONSPP,TIME,DTIME,CONSHH,TBC,SN)
           IFRACTURE = TABLE01(1,18)
           IF (IFRACTURE .EQ. 1) GOTO 40
30    CONTINUE
      GOTO 43
40    WRITE(*,41)'MATERIAL IS IN RUPTURE AFTER ',TIME,' HOURS'
41    FORMAT(A33,F7.1,A6)
43    CLOSE(1)
      CLOSE(2)
      CLOSE(3)
      CLOSE(4)
      CLOSE(5)
      CLOSE(6)
      CLOSE(7)
      CLOSE(8)
      CLOSE(9)
      CLOSE(20)
      STOP
      END
C
C***********************************************************************
      SUBROUTINE INITIALIZE(TABLE01,TBC)
C***********************************************************************
C
```

```
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19),AREAINIT(129),TBC(129)
      NELEM = 129
      DO 210 III=1,NELEM
         DO 205 JJJ=1,19
            TABLE01(III,JJJ) = 0.0D0
205      CONTINUE
         TBC(III)=0.012D0
210   CONTINUE
      CARBON=0.012D0
      SIGY=CARBON*23.64517D0+10.91625D0
      DO 220 IELM=1,NELEM
         IF(IELM .LE. 29) THEN
             RINT=(IELM-1)*0.1D0
             REXT=RINT+0.1D0
          ELSE
             RINT=2.9D0 + (IELM-30)*0.001D0
             REXT=RINT+0.001D0
         END IF
         AREA = REXT*REXT - RINT*RINT
C         AREA = AREA * 1000.0D0
         TABLE01(IELM,11) = SIGY
         TABLE01(IELM,13) = AREA
         TABLE01(IELM,15) = CARBON
          AREAINIT(IELM) = AREA
220   CONTINUE
      RETURN
      END
C
C***********************************************************************
      SUBROUTINE INSTANTIME(TABLE01,CONSPP,DCONSPP,TIME,DTIME,CONSHH,
     1                   TBC,SN)
C***********************************************************************
C
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19),TBC(129)
      NELEM=129
       WRITE (*,38) 'TIME',TIME
38    FORMAT(A5,F10.2)
      IF (TIME .GE. 0.0D0) THEN
c           CALL DIFFUSION(TABLE01,TIME,DTIME,TBC,SN)
          CALL CREPSTRAIN(TABLE01,DTIME)
       END IF
      CALL PRECALCUL(TABLE01,DCONSPP)
      CALL VERIFPLAS(TABLE01,IPLAS)
c      IF (TIME .GE. 0.0D0) GOTO 39
      IF (IPLAS .EQ. 1) CALL FINCALCUL(TABLE01,CONSPP,DCONSPP,CONSHH,
     1                          RESIDU)
39      IF (TIME .GE. 0.0D0) CALL FRACTURE(TIME,DTIME,TABLE01,DCONSPP)
C ********* UNTIL THIS POINT, THE SITUATION ARE AT TIME T + DT *********
C ********* SOME FOLLOWING EXECUTIONS ARE USED FOR THE NEXT STEP DT ****
      CONSPP = CONSPP + DCONSPP
      DO 130 III = 1,NELEM
         TABLE01(III,1) = TABLE01(III,1)+TABLE01(III,2)
         TABLE01(III,3) = TABLE01(III,3)+TABLE01(III,7)
         TABLE01(III,4) = TABLE01(III,4)+TABLE01(III,8)
         TABLE01(III,5) = TABLE01(III,5)+TABLE01(III,9)
         TABLE01(III,6) = TABLE01(III,6)+TABLE01(III,10)
         TABLE01(III,13) = TABLE01(III,13)+TABLE01(III,14)
         TABLE01(III,15) = TABLE01(III,15)+TABLE01(III,16)
         IF (TABLE01(III,1).GE.(TABLE01(III,11)+TABLE01(III,12))) THEN
             TABLE01(III,11)=TABLE01(III,1)
          ELSE
```

```
            TABLE01(III,11)=TABLE01(III,11)+TABLE01(III,12)
         END IF
130   CONTINUE
      CONSPVERIF = 0.0D0
       DO 135 IELM=NELEM,1,-1
          CONSPVERIF = CONSPVERIF + TABLE01(IELM,1)*TABLE01(IELM,13)
135   CONTINUE
C      RESIDUPP = CONSPVERIF - 274.5D0
      RESIDUPP = CONSPVERIF - CONSPP
       LTIME = (TIME+DTIME)*10.0D0
C      DELTIM = TIME - LTIME
       IF (MOD(LTIME,10000) .NE. 0) GOTO 136
      WRITE(1,150) TABLE01(1,1),TABLE01(1,3),TABLE01(1,4),TABLE01(1,5),
     1         TABLE01(1,6),TABLE01(1,11),TABLE01(1,13),TABLE01(1,15),
     1         TABLE01(1,18),TABLE01(1,19),TIME+DTIME,RESIDUPP
      WRITE(2,150) TABLE01(29,1),TABLE01(29,3),TABLE01(29,4),
     1           TABLE01(29,5),TABLE01(29,6),TABLE01(29,11),
     1           TABLE01(29,13),TABLE01(29,15),TABLE01(29,18),
     1           TABLE01(29,19),TIME+DTIME,RESIDUPP
      WRITE(3,150) TABLE01(60,1),TABLE01(60,3),TABLE01(60,4),
     1           TABLE01(60,5),TABLE01(60,6),TABLE01(60,11),
     1           TABLE01(60,13),TABLE01(60,15),TABLE01(60,18),
     1           TABLE01(60,19),TIME+DTIME,RESIDUPP
      WRITE(4,150) TABLE01(100,1),TABLE01(100,3),TABLE01(100,4),
     1           TABLE01(100,5),TABLE01(100,6),TABLE01(100,11),
     1           TABLE01(100,13),TABLE01(100,15),TABLE01(100,18),
     1           TABLE01(100,19),TIME+DTIME,RESIDUPP
      WRITE(5,150) TABLE01(125,1),TABLE01(125,3),TABLE01(125,4),
     1           TABLE01(125,5),TABLE01(125,6),TABLE01(125,11),
     1           TABLE01(125,13),TABLE01(125,15),TABLE01(125,18),
     1           TABLE01(125,19),TIME+DTIME,RESIDUPP
      WRITE(6,150) TABLE01(126,1),TABLE01(126,3),TABLE01(126,4),
     1           TABLE01(126,5),TABLE01(126,6),TABLE01(126,11),
     1           TABLE01(126,13),TABLE01(126,15),TABLE01(126,18),
     1           TABLE01(126,19),TIME+DTIME,RESIDUPP
      WRITE(7,150) TABLE01(127,1),TABLE01(127,3),TABLE01(127,4),
     1           TABLE01(127,5),TABLE01(127,6),TABLE01(127,11),
     1           TABLE01(127,13),TABLE01(127,15),TABLE01(127,18),
     1           TABLE01(127,19),TIME+DTIME,RESIDUPP
      WRITE(8,150) TABLE01(128,1),TABLE01(128,3),TABLE01(128,4),
     1           TABLE01(128,5),TABLE01(128,6),TABLE01(128,11),
     1           TABLE01(128,13),TABLE01(128,15),TABLE01(128,18),
     1           TABLE01(128,19),TIME+DTIME,RESIDUPP
      WRITE(9,150) TABLE01(129,1),TABLE01(129,3),TABLE01(129,4),
     1           TABLE01(129,5),TABLE01(129,6),TABLE01(129,11),
     1           TABLE01(129,13),TABLE01(129,15),TABLE01(129,18),
     1           TABLE01(129,19),TIME+DTIME,RESIDUPP
150    FORMAT(12E12.5)
136   RETURN
      END
C
C***********************************************************************
      SUBROUTINE PRECALCUL(TABLE01,DCONSPP)
C***********************************************************************
C
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19)
      NELEM = 129
      CONSEE = 15691.0D0
C ******* CALCULATING DELTA SIGMA ELEMENT 1 ****************************
C ******* IN THIS CASE PLASTIC STRAIN IS ASSUMED NUL *******************
      SUM1 = 0.0D0
        DO 250 III=NELEM,1,-1
```

```
            IFRACTURE = TABLE01(III,18)
            IF (IFRACTURE .EQ. 1) GOTO 250
           SUM1 = SUM1 + TABLE01(III,1)*TABLE01(III,9)*TABLE01(III,13)
250     CONTINUE
        SUM2 = 0.0D0
          DO 260 III=NELEM,2,-1
            IFRACTURE = TABLE01(III,18)
            IF (IFRACTURE .EQ. 1) GOTO 260
           SUM2=SUM2+CONSEE*TABLE01(III,13)*(TABLE01(1,9)-TABLE01(III,9))
260     CONTINUE
        CONSAA = 0.0D0
          DO 270 III=NELEM,1,-1
            IFRACTURE = TABLE01(III,18)
            IF (IFRACTURE .EQ. 1) GOTO 270
           CONSAA = CONSAA + TABLE01(III,13)
270     CONTINUE
        DSIGMA1 = (DCONSPP + SUM1 - SUM2)/CONSAA
         TABLE01(1,2) = DSIGMA1
C ******* CALCULATING DELTA SIGMA ELEMENT i ****************************
          DO 280 III=NELEM,2,-1
            IFRACTURE = TABLE01(III,18)
            IF (IFRACTURE .EQ. 1) GOTO 280
           DSIGMAIII = DSIGMA1 + CONSEE*(TABLE01(1,9)-TABLE01(III,9))
           TABLE01(III,2) = DSIGMAIII
280     CONTINUE
C ******* STORE DELTA EPSILON ELASTIC,PLASTIC,TOTAL,AREA VARIATION
C ******* FOR ALL ELEMENTS
          DO 290 III=1,NELEM
            IFRACTURE = TABLE01(III,18)
            IF (IFRACTURE .EQ. 1) GOTO 290
           TABLE01(III,7) = TABLE01(III,2)/CONSEE
           TABLE01(III,8) = 0.0D0
           TABLE01(III,10) = TABLE01(III,7)+TABLE01(III,9)
           AREANEW = TABLE01(III,13)*EXP(-TABLE01(III,9))
           TABLE01(III,14) = AREANEW - TABLE01(III,13)
290     CONTINUE
        RETURN
         END
C
C***********************************************************************
        SUBROUTINE CREPSTRAIN(TABLE01,DTIME)
C       CALCULATING DELTA EPSILON CREEP BY NORTON EQUATION *************
C***********************************************************************
C
        IMPLICIT REAL * 8 (A-H,O-Z)
        DIMENSION TABLE01(129,19)
        NELEM = 129
        CONSNN = 10.716D0
C        CONSDD = 10.9D0
        CONSDGN = 5.07931D-29
         CONSPDIVN = 0.3293113D0
C        CONSPDIVN = 0.3379220D0
c        CONSGG1 = 588.247350D0
        DO 300 IELM=1,NELEM
           CARBON = TABLE01(IELM,15)
C           CONSGG = CONSGG1*(CARBON**CONSPDIVN)
           CARBONPDIVN = CARBON**CONSPDIVN
           SIGMA = TABLE01(IELM,1)
           DCREEP = CONSDGN*((SIGMA/CARBONPDIVN)**CONSNN)*DTIME
           TABLE01(IELM,9) = DCREEP
            AREANEW = TABLE01(IELM,13)*EXP(-DCREEP)
            TABLE01(IELM,14) = AREANEW - TABLE01(IELM,13)
C           TABLE01(IELM,14) = TABLE01(IELM,13)*(-DCREEP)
```

```
300   CONTINUE
      RETURN
      END
C
C***********************************************************************
       SUBROUTINE VERIFPLAS(TABLE01,IPLAS)
C***********************************************************************
C
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19)
      NELEM = 129
       IPLAS = 0
        DO 310 III=1,NELEM
          SIGI = TABLE01(III,1)
          DSIGI = TABLE01(III,2)
          SIGYI = TABLE01(III,11)
          DSIGYI = TABLE01(III,12)
          IF ((SIGI+DSIGI) .GT. (SIGYI+DSIGYI)) IPLAS = 1
310   CONTINUE
      RETURN
       END
C
C***********************************************************************
       SUBROUTINE FINCALCUL(TABLE01,CONSPP,DCONSPP,CONSHH,RESIDU)
C***********************************************************************
C
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19)
      CALL XLIMIT(TABLE01,DEPSLOW,DEPSUP,CONSHH)
      CALL BISECT(TABLE01,DEPSLOW,DEPSUP,DEPSMID,CONSPP,DCONSPP,
     1            CONSHH,RESIDU)
      RETURN
      END
C
C***********************************************************************
       SUBROUTINE XLIMIT(TABLE01,DEPSLOW,DEPSUP,CONSHH)
C***********************************************************************
C
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19)
      NELEM = 129
c      SIGYMAX = TABLE01(1,11) + TABLE01(1,12)
c      DCREEPMAX = TABLE01(1,9)
c       IELMMAX = 1
c        DO 500 III=2,NELEM
c         IF (SIGYMAX .LT. (TABLE01(III,11) + TABLE01(III,12))) THEN
c              SIGYMAX = (TABLE01(III,11) + TABLE01(III,12))
c              IELMMAX = III
c         END IF
c         IF (DCREEPMAX .LT. (TABLE01(III,9))) THEN
c              DCREEPMAX = TABLE01(III,9)
c         END IF
c500   CONTINUE
      DEPSLOW = 0.0D0
c      DEPSUP = TABLE01(IELMMAX,2)/CONSHH
      DEPSUP = 1.0D0
      RETURN
       END
C
C***********************************************************************
      SUBROUTINE BISECT(TABLE01,DEPSLOW,DEPSUP,DEPSMID,CONSPP,DCONSPP,
       1            CONSHH,RESIDU)
C***********************************************************************
```

```
C
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19)
      NELEM = 129
      CONSEE = 15691.0D0
       CONSFF = CONSHH*CONSEE/(CONSHH+CONSEE)
610      DEPSMID = (DEPSLOW + DEPSUP)/2
      SUMPP = 0.0D0
      DO 600 III=NELEM,1,-1
          IFRACTURE = TABLE01(III,18)
          IF (IFRACTURE .EQ. 1) GOTO 600
          AREAOLD = TABLE01(III,13)
         DCREEP = TABLE01(III,9)
          SIGINIT = TABLE01(III,1)
          SIGYNEW = TABLE01(III,11)+TABLE01(III,12)
          DSIGELLIM = SIGYNEW - SIGINIT
         DEPSELLIM = DSIGELLIM / CONSEE
         IF ((DEPSMID-DCREEP) .LE. DEPSELLIM) THEN
             DSIGIII = CONSEE*(DEPSMID-DCREEP)
             DEPSPLAIII = 0.0D0
          ELSE
             DEPSPLATOT = (DEPSMID-DCREEP-DEPSELLIM)
             DSIGPLA = DEPSPLATOT*CONSFF
             DSIGIII = DSIGELLIM + DSIGPLA
              DEPSPLAIII = DSIGPLA/CONSHH
         END IF
         TABLE01(III,2) = DSIGIII
         TABLE01(III,7) = DSIGIII/CONSEE
         TABLE01(III,8) = DEPSPLAIII
         TABLE01(III,10)= TABLE01(III,7)+DEPSPLAIII+DCREEP
          AREANEW = AREAOLD * EXP(-DEPSPLAIII-DCREEP)
          TABLE01(III,14)= AREANEW-AREAOLD
         SUMPP = SUMPP + AREANEW*(SIGINIT+DSIGIII)
600   CONTINUE
       RESIDU = CONSPP + DCONSPP - SUMPP
C      IF (ABS(RESIDU/(CONSPP+DCONSPP)) .LT. 0.001D0) GOTO 690
       IF ((DEPSUP - DEPSLOW) .LT. 0.00000000000001D0) GOTO 690
       IF (RESIDU .GT. 0.0D0) THEN
           DEPSLOW = DEPSMID
         ELSE
           DEPSUP = DEPSMID
       END IF
C       DEPSMID = DEPSMID+0.000001D0
      GOTO 610
690   RETURN
      END
C
C ***************************************************************************
C ***** THE FOLLOWING SUBROUTINE EVALUATES CREEP DAMMAGE CRITERIA ************
C *****                D = INTEG (1/TR) * DT
C *****                    WITH TR = ALPHA + BETA * STRESS
C ***************************************************************************
C
      SUBROUTINE FRACTURE(TIME,DTIME,TABLE01,DCONSPP)
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19)
      NELEM = 129
C  ****************************** VALUES CALCULATED FROM TEST ******************
c       ALPHA = 19.78D0
C       BETA = -8.5087D0
C  ***************************** CORRECTED VALUES CALCULATED FROM TEST ********
      BETA = -10.21D0
      XLOSTPP = 0.0D0
```

```
      DO 695 IELM = 1,NELEM
           IFRACTURE = TABLE01(IELM,18)
           IF (IFRACTURE .EQ. 1) GOTO 695
               CONCENT = TABLE01(IELM,15)- 0.012D0
                   SIGRTRUE = 35.119D0
               DSIGRTRUE = 80.0D0*CONCENT
                   ALPHA = 4.0D0 - BETA*LOG10(SIGRTRUE+DSIGRTRUE)
         SIGI = TABLE01(IELM,1)
         DIVIDE = ALPHA + BETA * LOG10(SIGI)
         DAMMAGE = DTIME / (10**DIVIDE)
         TABLE01(IELM,19) = TABLE01(IELM,19) + DAMMAGE
         IF (((TABLE01(IELM,19).GE. 1.0D0) .OR.
C    1          ((SIGI+TABLE01(IELM,2)) .GT. 81.56D0))) THEN
     1          ((SIGI+TABLE01(IELM,2)) .GT. 50.243D0))) THEN
                   IFRACTURE = 1
                   TABLE01(IELM,18) = IFRACTURE
         END IF
          IF (IFRACTURE .EQ. 1) THEN
             AIREIELM = TABLE01(IELM,13)+TABLE01(IELM,14)
             XLOSTPP = XLOSTPP+(TABLE01(IELM,1)+TABLE01(IELM,2))*AIREIELM
            WRITE(20,694) IELM,TIME,SIGI+TABLE01(IELM,2),TABLE01(IELM,19)
694          FORMAT(I5,F10.2,F8.3,F8.5)
             TABLE01(IELM,1) = 0.0D0
             TABLE01(IELM,2) = 0.0D0
             TABLE01(IELM,3) = 0.0D0
             TABLE01(IELM,7) = 0.0D0
             TABLE01(IELM,8) = 0.0D0
             TABLE01(IELM,9) = 0.0D0
             TABLE01(IELM,10) = 0.0D0
             TABLE01(IELM,14) = 0.0D0
             TABLE01(IELM,19) = 0.0D0
C         ELSE
C            DCONSPP = 0.0D0
          END IF
695   CONTINUE
      AIRETOT = 0.0D0
      IF (XLOSTPP .NE. 0.0D0) THEN
          DO 696 IELM=NELEM,1,-1
             IFRACTURE = TABLE01(IELM,18)
             IF (IFRACTURE .EQ. 1) GOTO 696
             AIRETOT=AIRETOT+TABLE01(IELM,13)+TABLE01(IELM,14)
696      CONTINUE
         IF (AIRETOT .EQ. 0.0D0) GOTO 699
          XLOSTPERAIRE=XLOSTPP/AIRETOT
          DO 697 IELM=NELEM,1,-1
             IFRACTURE = TABLE01(IELM,18)
             IF (IFRACTURE .EQ. 1) GOTO 697
C            ADDSTRESS=(TABLE01(IELM,13)+TABLE01(IELM,14))*XLOSTPERAIRE
C            TABLE01(IELM,1)=TABLE01(IELM,1)+ADDSTRESS
             TABLE01(IELM,1)=TABLE01(IELM,1)+XLOSTPERAIRE
697      CONTINUE
      END IF
      RETURN
699   END
C
C ***************************************************************************
C ***** THE FOLLOWING SUBROUTINE EVALUATES CARBON DIFFUSION AT XDEEP POINT ****
C *****         XK2    : DIFFUSION COEFFICIENT
C *****         XKT    : SLOPE COEFFICIENT
C *****         X1    : DISTANCE OF POINT P1
C *****         X2    : DISTANCE OF POINT P1
C *****         SLOP1 : THE SLOPE IN FIRST REGION AFFECTED BY CARBON
C *****         SLOP2 : THE SLOPE IN SECOND REGION AFFECTED BY CARBON
```

```
C *****           CP1    : CARBON CONCENTRATION AT POINT P1
C *****           C0     : CARBON CONCENTRATION AT SURFACE DUE TO EQUILIBRIUM
C *****           XLN01 : LN(0.1)
C *****           XLN0012 : LN(0.012)
C ****************************************************************************
C
      SUBROUTINE DIFFUSION(TABLE01,TIME,DTIME,TBC,SN)
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19),TBC(129)
      SIGAPPL = SN
      TIMEX = TIME + DTIME
      C0 = 1.0D0
      XLN01 = -2.30258509299D0
      XLN0012 = -4.42284862919D0
C
C ********************* CALCULATE K2, KT, X1, X2
C
      IF (SIGAPPL .LE. 30.5D0) THEN
         XK2 = 0.0288 + 0.003590 * SIGAPPL
         XKT = 0.3606 + 0.030919 * SIGAPPL
         BBB = 0.00000392915D0
      ELSE
         XK2 = 0.1383 + 0.2036 * (SIGAPPL - 30.5)
C         XKT = 1.3036 + 0.52308 * (SIGAPPL - 30.5)
         BBB = 0.00000392915D0
      ENDIF
      X2 = SQRT(XK2*TIMEX)
      X1 = 0.1D0*X2
C
C *************** CALCULATE CARBON CONCENTRATION AT SURFACE AND FIRST SLOP
C
C      SLOP1 = DTAND(XKT*SQRT(TIMEX) - 90)
      CP1 = 0.012D0+(0.000002D0+BBB*SIGAPPL)*TIMEX
       XLNCP1 = LOG(CP1)
        SLOP1 = (XLNCP1 - LOG(C0))/(LOG(X1)-XLN01)
C      XLNCP1 = LOG(C0)+SLOP1*(LOG(X1) - LOG(0.1))
C      CP1 = EXP(XLNCP1)
      SLOP2 = (LOG(0.012)-XLNCP1)/(LOG(X2)-LOG(X1))
C
C *********** CALCULATE CARBON CONCENTRATION AT A POINT
C
      CALL CALCONC(TABLE01,X1,X2,SLOP1,SLOP2,CP1,C0,TBC)
      RETURN
      END
C
C ****************************************************************************
C ***** THE FOLLOWING SUBROUTINE EVALUATES CARBON CONCENTRATION AT XDEEP POINT
C *****     AND ALSO ITS INFLUENCE ON YIELD STRESS
C *****     INPUT PARAMETER  : X1, X2, SLOP1, SLOP2, CP1, C0
C ****************************************************************************
C
      SUBROUTINE CALCONC(TABLE01,X1,X2,SLOP1,SLOP2,CP1,C0,TBC)
      IMPLICIT REAL * 8 (A-H,O-Z)
      DIMENSION TABLE01(129,19),TBC(129)
      NELEM = 129
      XLN01 = -2.30258509299D0
       NFRACTURE = 0
       IELMEXT = 129
687    IF (TABLE01(IELMEXT,18) .EQ. 1) THEN
           IELMEXT = IELMEXT - 1
           GOTO 687
       END IF
       NFRACTURE = 129 - IELMEXT
```

```
C        DO 688 IELM=1,NELEM
C           IFRACTURE = TABLE01(IELM,18)
C           IF (IFRACTURE.EQ.1) NFRACTURE=NFRACTURE+1
C688     CONTINUE
         DO 700 IELM=1,NELEM
            IF (IELM .LE. 29) THEN
               XDEEP = (3.0D0 - IELM*0.1D0 + 0.1D0)*1000
            ELSE
               XDEEP = (3.0D0 - (IELM - 30)*0.001D0 - 2.90D0)*1000
            END IF
            IF (XDEEP .LE. X1) THEN
               DEXPON = SLOP1*(LOG(XDEEP) - XLN01)
               CDEEPX = C0*EXP(DEXPON)
            ELSE
               IF (XDEEP .LT. X2) THEN
                  DEXPON = SLOP2*(LOG(XDEEP) - LOG(X1))
                  CDEEPX = CP1*EXP(DEXPON)
               ELSE
                  CDEEPX = 0.012D0
               END IF
            END IF
            IF (CDEEPX .LT. 0.012D0) CDEEPX = 0.012D0
C           GOTO 750
C           CDEEPX = 0.012D0
            DELCONC = CDEEPX - TBC(IELM)
750         IF (CDEEPX .GT. C0) THEN
                CDEEPX = C0
                DELCONC = 0.0D0
            END IF
            IF ((IELM-NFRACTURE) .GE. 30) THEN
              TABLE01(IELM-NFRACTURE,16) = DELCONC
               IF (TABLE01(IELM-NFRACTURE,15)      .GE. 0.3D0) THEN
                     TABLE01(IELM-NFRACTURE,12)= 0.0D0
                 ELSE
                   TABLE01(IELM-NFRACTURE,12) = DELCONC*23.569D0
               END IF
            ELSE
              TABLE01(IELM,16) = DELCONC
               IF (TABLE01(IELM,15)  .GE. 0.3D0) THEN
                     TABLE01(IELM,12)= 0.0D0
                 ELSE
                   TABLE01(IELM,12) = DELCONC*23.569D0
               END IF
            END IF
            TBC(IELM)=CDEEPX
700      CONTINUE
         RETURN
         END
```

APPENDIX B

DETERMINATION OF α AND β PARAMETERS

In order to determine α and β, the curve of time to rupture vs. true stress is plotted in logarithmic scales. By regression, experimental data give:

$\alpha_1 = 20.02$

$\beta_1 = -10.53$

Creep damage criterion is evaluated by Equations 3.15 and 3.16:

$D_c = dt/t_r$

where t_r is creep rupture time and as a function of stress as follows:

$\log(t_r) = \alpha_1 + \beta_1 \log(\sigma)$

As seen, t_r is related to stress and, stress its-self increases through time due to section area reduction. Consequently, parameter D_c increases quicker than predicted. For these reasons, α and β values obtained by the initial regression should be corrected. Followings are necessary steps that were used.

(i) The program was run applying creep analysis in air under 24.0 kgf/mm^2 of nominal stress. Parameter α was fixed as obtained by experimental regression, but β was evaluated by trial and error method so that the calculated time to rupture corresponds to experimental regression.

(ii) The same condition was run, but this time β was fixed and α was evaluated.

(iii) Considering another load, the program was run applying creep analysis in air under 33.0 kgf/mm^2 of nominal stress. Exactly as step (i), parameter α was fixed, but β was evaluated by trial and error method so that the calculated time to rupture corresponds to experimental regression.

(iv) The same condition was run, but this time β was fixed and α was evaluated.

The above steps are plotted in the curve α versus β (see Figure B-1). The steps (i) and (ii) give first linear curve. The steps (iii) and (iv) give the second linear curve. Both curves intersect in one point that will be the corrected values of parameter α and β, as follows:

$\alpha_2 = 19.78$

$\beta_2 = -10.21$

Those above values were used to evaluate creep analysis under other stresses and gave a good approximation compared to experimental data.

Index 1: related to $\sigma = P/A_1$, where A_1 is section area at the beginning of the creep.

Index 2: related to $\sigma = P/A_2$, where A_2 is decreasing section area that we assume represents area reduction during creep.

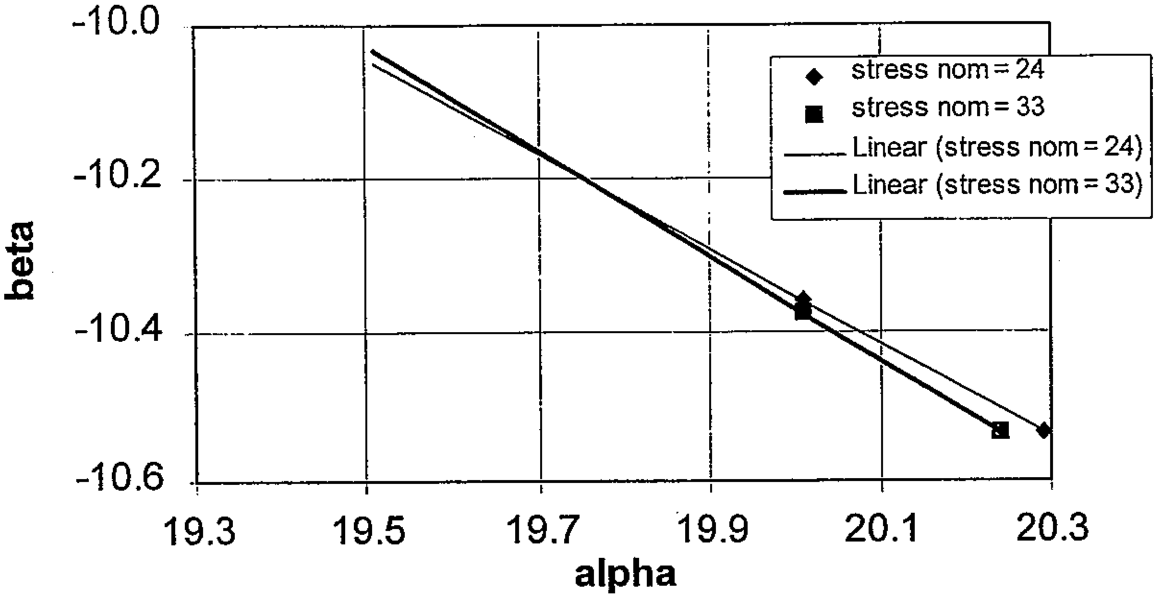

Figure B-1 Determination of α and β

APPENDIX C

ASSUMPTIONS TAKEN ACCOUNT INTO THE MODEL

To simplify the complexity of the problem or due to lack of available data, some assumptions are taken account into the model. Table C-1 summarizes these assumptions.

Table C-1 The summary of all assumptions considered in the model

Domain	Assumptions
Sodium environment	Other elements than carbon are also susceptible to penetrate into 316FR stainless steel. But only carbon effect is considered and other elements effects are neglected.
Model	Only axial direction is studied, mechanical behavior in radial and circular directions are not evaluated.
Section area reduction	Related only to plastic and creep strain.
Elastic-plastic-(creep) behavior	Young's modulus = 15691 kgf/mm^2 Hardening coefficient = 250 kgf/mm^2
Tensile strength criterion	$\sigma_L = 50.2\ kgf/mm^2$
Carbon diffusion	Modeled empirically based on a specimen that being aged under sodium exposure for 5000 hours and on others that being under creep test in sodium environment until rupture.
Carburization effect:	
• On yield stress	• $\sigma^y = 23.6\,C + 10.9$ for $C \leq 0.3$ % weight $\sigma^y = 18.0\ kgf/mm^2$ for $C > 0.3$ % weight where C is carbon concentration.
• On creep strain rate	• $d\varepsilon^c/dt = D\,(\sigma / G)^n$ where D, G and n are constants, but only G varies with the carbon concentration
• On creep rupture strength	$\log(t_r) = \alpha + \beta \log(\sigma)$ • α and β obtained by direct regression from experimental data are corrected since stress applied increases through time due to section area reduction. • only α varies in function of carbon concentration