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**A THREE-BAR MODEL FOR RATCHETING OF FUSION
REACTOR FIRST WALL**

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A THREE-BAR MODEL FOR RATCHETING OF FUSION REACTOR FIRST WALL

J. Wolters and S. Majumdar

ABSTRACT

First wall structures of fusion reactors are subjected to cyclic bending stresses caused by inhomogeneous temperature distribution during plasma burn cycles and by electromagnetically induced impact loads during plasma disruptions. Such a combination of loading can potentially lead to ratcheting or incremental accumulation of plastic strain with cycles. An elastic-plastic three-bar model is developed to investigate the ratcheting behavior of the first wall.

1. INTRODUCTION

During normal operations of tokamak fusion reactors, such as the International Thermonuclear Experimental Reactor (ITER), cyclic thermal stresses are created in the first wall by a pulsed plasma which subjects the first wall to a high intermittent surface heat flux. Depending on the design, the first wall is cooled by either pressurized water or liquid metal. Due to this cooling, the plasma-facing section of the first wall can be subjected to a steep temperature gradient which may cause high secondary stresses in the first wall. In addition to thermal stresses, high transient dynamic stresses can be induced in the first wall by large electromagnetic forces that are created during plasma disruptions and vertical disruption events. The normal disruption pressure on the first wall typically has a rise time of a few to some tens of milliseconds followed by a gradual decay and could lead to large transient dynamic bending stresses [1]. The interaction of the two cyclic loadings may lead to progressive incremental plastic deformation (ratcheting) [2].

In a recent analysis of the Next European Tokamak (NET), the interaction of disruption forces and thermal stresses in the metallic parts of the first wall was investigated [3]. The Ratcheting Investigation Testing Apparatus (RITA) has been established in Germany to experimentally study the interaction of thermal and mechanical impact loads on the first wall. Experiments have been performed to demonstrate the predicted ratcheting behavior of actively cooled beams made of stainless steel 316 under realistic loading conditions. In addition, experiments have been performed to prove that ratcheting effects are worst under constant mechanical and cyclic thermal loading conditions.

The present work was undertaken to supplement earlier experimental and theoretical work and to provide a better understanding of the ratcheting behavior of the fusion reactor first wall.

2. BACKGROUND INFORMATION ON RATCHETING

It is well known that a combination of steady primary and cyclic thermal stress, under certain conditions, can cause incremental accumulation of plastic strain, i.e., ratcheting, in a structure [4]. The ratcheting mechanism of a pressurized cylinder subjected to cyclic axisymmetric thermal stress was investigated by Miller[5], Bree [4] and Burgreen [6]. The Bree diagram was shown [7] to be significantly different for loading sequences involving steady thermal cyclic primary, in-phase cyclic thermal and primary, out-of-phase cyclic thermal and primary stress. In particular, ratcheting was shown not to occur for the case of a steady thermal and cyclic primary stress, irrespective of the magnitudes of the thermal stresses. Ratcheting due to repeated secondary bending stress and steady primary bending stress in a cantilever beam was considered by Yamashita et al. [8] and the results were applied to the analysis of ratcheting of bellows. The additional complexity in ratcheting due to thermal creep has been treated by O'Donnell and Porowski [9], whose approach forms the basis for the ratcheting analysis recommended in the ASME Code Case N47.

3. THREE BAR MODEL

A detailed two or three dimensional cyclic elastic-plastic analysis of a first wall (cp. Fig.1) can be highly complex and time-consuming. Further, a finite-element analysis by itself does not necessarily lead to a better understanding of the mechanisms underlying the problem. On the other hand, a simple model such as a two or a three-bar model considered here can sometimes give key insight to the ratcheting problem and have been used in the past [10]. Therefore, for a detailed examination of ratcheting of the first wall, a three-bar model, shown in Fig. 2, has been analyzed.

Fig. 1: Cross-section of the first wall segment considering the design outlines of [11]

Fig. 2: Three bar model for investigations on ratcheting

3.1 Assumptions

For the three bar model the following assumptions were made. The model consists of three bars with different areas of cross section (A). The distance between bar one and bar two is given by y_{12} and the distance between bar two and three by y_{23} . Moreover it is assumed that the three bars are connected in such a way, that the total strain (ϵ) is linear with the y -position of each bar. In the elastic range the stress-strain correlation is given by the Young's modulus E . If the yield limit σ_y of the material is exceeded, the correlation between the plastic strain and the stress is given by the tangent modulus E_T . If the material is assumed to be elastic-perfectly plastic (no hardening) the tangent modulus is set to zero. One of the main assumptions for the following evaluation is that for small strains the total strain is given by the sum of the elastic, the plastic and the thermal strain. The thermal expansion of the material is described by the thermal expansion coefficient α_{th} . For bar one (representing the heated side of the first wall) an increment in temperature (ΔT) is assumed for simulating the thermal load. The mechanical load is given by a single moment. It is assumed that no axial load is applied.

3.2 Analysis

3.2.1 Basic stress-strain relationships

The calculation of the mechanical behavior of the three bar model under cyclic loading conditions is based on the following three equations:

– deformation coupling of the three bars

$$y_{23} \epsilon_1 - (y_{12} + y_{23}) \epsilon_2 + y_{12} \epsilon_3 = 0 \quad (1)$$

– equilibrium of axial force

$$F_1 + F_2 + F_3 = \sum_{i=1}^3 F_i = 0 \quad (2)$$

– equilibrium of moment

$$-y_s F_1 + (y_{12} - y_s) F_2 + (y_{12} + y_{23} - y_s) F_3 = \sum_{i=1}^3 g_i F_i = g_i F_i = M; \quad g_i = \begin{pmatrix} -y_s \\ y_{12} - y_s \\ y_{12} + y_{23} - y_s \end{pmatrix} \quad (3)$$

where ϵ is the total strain and F is the force in the corresponding bar.

The height of the neutral axis is given by

$$y_s = \frac{y_{12} A_2 E_2 + (y_{12} + y_{23}) A_3 E_3}{A_1 E_1 + A_2 E_2 + A_3 E_3} \quad (4)$$

For each load cycle and irrespective of initial conditions, equations 1, 2 and 3 must be satisfied. The solution of equations 1-4 is implemented by substituting the forces in each bar in terms of the total strains.

3.2.2 Solution procedure

Noting that the force in any bar is given by the elastic strain multiplied by the Young's modulus and the area of cross section

$$F_{\alpha} = \varepsilon_{el\alpha} E_{\alpha} A_{\alpha} = \left(\varepsilon_{\alpha} - \varepsilon_{pl\alpha} - \Delta\varepsilon_{pl\alpha} - \varepsilon_{th\alpha} \right) E_{\alpha} A_{\alpha} \quad (\text{no sum on } \alpha), \quad (5)$$

where $\varepsilon_{pl\alpha}$ is the initial plastic deformation of bar α and $\Delta\varepsilon_{pl\alpha}$ is the increment of plastic deformation during the current load step. The thermal strain $\varepsilon_{th\alpha}$ is defined by the thermal expansion coefficient multiplied by the increment in temperature: $\varepsilon_{th} = \alpha_{th} \Delta T$. If none of the bars experience any incremental plastic strain during the current load step, then the forces in equation 2 and 3 can be replaced by equation 6 and the total strain in each bar can be solved from eqs. 1-3.

$$F_{\alpha} = \left(\varepsilon_{\alpha} - \varepsilon_{pl\alpha} - \varepsilon_{th\alpha} \right) E_{\alpha} A_{\alpha} \quad (6)$$

If one or more bars experience additional plastic deformations during the current load step, the force in each bar is given by the current yield stress multiplied by the area of cross section. For an elastic-ideally plastic constitutive equation (no strain hardening) the yield stress is constant and therefore the force is independent of the total strain. It is given by:

$$F_{\alpha} = \begin{cases} \sigma_{y0\alpha}^{+} A_{\alpha} & \text{for tensile} \\ \sigma_{y0\alpha}^{-} A_{\alpha} & \text{for compression} \end{cases} \quad (7)$$

If, on the other hand, the material is strain hardening, the yield stress depends on the plastic strain. For a kinematically hardening material, the relationship between yield stress and plastic strain is given by:

$$\begin{aligned} \sigma_{y\alpha}^{+} &= \sigma_{y0\alpha}^{+} + \left(\varepsilon_{pl\alpha} + \Delta\varepsilon_{pl\alpha} \right) E_{T\alpha} & \text{for } \Delta\varepsilon_{pl\alpha} \geq 0 \\ \sigma_{y\alpha}^{-} &= \sigma_{y0\alpha}^{-} + \left(\varepsilon_{pl\alpha} + \Delta\varepsilon_{pl\alpha} \right) E_{T\alpha} & \text{for } \Delta\varepsilon_{pl\alpha} < 0 \end{aligned} \quad (8)$$

Together with equation 5, a relationship between the total strain and the force can be derived:

$$F_{\alpha} = \begin{cases} \frac{A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}}\varepsilon_{\alpha} + \frac{A_{\alpha}E_{\alpha}\sigma_{y0\alpha}^{+}}{E_{\alpha} + E_{T\alpha}} - \frac{\alpha_{th\alpha}\Delta T_{\alpha}A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta\varepsilon_{pl\alpha} \geq 0 \\ \frac{A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}}\varepsilon_{\alpha} + \frac{A_{\alpha}E_{\alpha}\sigma_{y0\alpha}^{-}}{E_{\alpha} + E_{T\alpha}} - \frac{\alpha_{th\alpha}\Delta T_{\alpha}A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta\varepsilon_{pl\alpha} < 0 \end{cases} \quad (9)$$

On the other hand, for an isotropically hardening material the yield stress increases with every additional plastic deformation:

$$\begin{aligned} \sigma_{y\alpha}^{+} &= \sigma_{yv\alpha}^{+} + \Delta\varepsilon_{pl\alpha}E_{T\alpha}; \quad \sigma_{y\alpha}^{-} = -\sigma_{y\alpha}^{+} & \text{for } \Delta\varepsilon_{pl\alpha} \geq 0 \\ \sigma_{y\alpha}^{-} &= \sigma_{yv\alpha}^{-} + \Delta\varepsilon_{pl\alpha}E_{T\alpha}; \quad \sigma_{y\alpha}^{+} = -\sigma_{y\alpha}^{-} & \text{for } \Delta\varepsilon_{pl\alpha} < 0 \end{aligned} \quad (10)$$

where $\sigma_{yv\alpha}^{\pm}$ is the initial yield stress at the beginning of a new step.

As in the case of kinematic hardening, a relationship between the total strain and the force can be derived for the isotropic hardening, using equation 10 and 5:

$$F_{\alpha} = \begin{cases} \frac{A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}}\varepsilon_{\alpha} + \frac{A_{\alpha}E_{\alpha}\left(\sigma_{yv\alpha}^{+} - E_{T\alpha}\varepsilon_{pl\alpha}\right)}{E_{\alpha} + E_{T\alpha}} - \frac{\alpha_{th\alpha}\Delta T_{\alpha}A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta\varepsilon_{pl\alpha} \geq 0 \\ \frac{A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}}\varepsilon_{\alpha} + \frac{A_{\alpha}E_{\alpha}\left(-\sigma_{yv\alpha}^{-} - E_{T\alpha}\varepsilon_{pl\alpha}\right)}{E_{\alpha} + E_{T\alpha}} - \frac{\alpha_{th\alpha}\Delta T_{\alpha}A_{\alpha}E_{\alpha}E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta\varepsilon_{pl\alpha} < 0 \end{cases} \quad (11)$$

In all cases (elastic, ideally-plastic, kinematic hardening and isotropic hardening) the relationship between the total strain and the force can be described in the following generalized form:

$$F_{\alpha} = P_{\alpha}\varepsilon_{\alpha} + Q_{\alpha} + R_{\alpha}\Delta T_{\alpha} \quad (12)$$

Noting that only bar one experiences an increment in temperature ($\Delta T_1 = \Delta T$, $\Delta T_2 = \Delta T_3 = 0$), the final equations for the problem can be written as follows:

$$D_{ij}\varepsilon_j = B_i + B_i^*\Delta T + B_i^{**}M \quad (13)$$

where the tensors are given by:

$$D_{ij} = \begin{pmatrix} y_{12} & -y_{12} - y_{23} & y_{23} \\ P_1 & P_2 & P_3 \\ g_1P_1 & g_2P_2 & g_3P_3 \end{pmatrix}; \quad (14)$$

$$B_i = \begin{pmatrix} 0 \\ -Q_1 - Q_2 - Q_3 \\ -g_1Q_1 - g_2Q_2 - g_3Q_3 \end{pmatrix}; \quad B_i^* = \begin{pmatrix} 0 \\ -R_1 \\ -g_1R_1 \end{pmatrix}; \quad B_i^{**} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (15)$$

From a knowledge of whether additional plastic deformation occurs in each bar, the solution for the total strain can be derived as follows:

$$\varepsilon_k = D_{ki}^{-1} (B_i + B_i^* \Delta T + B_i^{**} M) \quad (16)$$

In order to determine the parameters (P_i , Q_i , R_i), it is necessary to establish for each bar whether compression or tensile strain will occur. The problem is solved iteratively by first assuming that none of the bars experiences any additional plastic deformation. In this case the tensors are of the following form:

$$D_{ij} = \begin{pmatrix} y_{12} & -y_{12} - y_{23} & y_{23} \\ E_1 A_1 & E_2 A_2 & E_3 A_3 \\ g_1 E_1 A_1 & g_2 E_2 A_2 & g_3 E_3 A_3 \end{pmatrix} \quad (17)$$

$$B_i = \begin{pmatrix} 0 \\ \sum_{\alpha=1}^3 E_{\alpha} A_{\alpha} \varepsilon_{pl\alpha} \\ \sum_{\alpha=1}^3 g_{\alpha} E_{\alpha} A_{\alpha} \varepsilon_{pl\alpha} \end{pmatrix}; B_i^* = \begin{pmatrix} 0 \\ -E_1 A_1 \alpha_{th1} \\ -g_1 E_1 A_1 \alpha_{th1} \end{pmatrix}; B_i^{**} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (18)$$

For a given moment M , an upper and a lower limit for the temperature-increment in bar one ΔT can be found such that the yield stress is not exceeded in any bar:

$$\sigma_{\alpha} < \sigma_{y\alpha}^+ \quad \wedge \quad \sigma_{\alpha} > \sigma_{y\alpha}^- \quad (19)$$

$$\Rightarrow \Delta_{\alpha l}^{-1} (B_l + B_l^* \Delta T + B_l^{**} M) - \varepsilon_{\pi l \alpha} - \alpha_{\pi l \alpha} \Delta T_{\alpha} < \frac{\sigma_{y\alpha}^+}{E_{\alpha}} \quad \wedge \quad \Delta_{\alpha l}^{-1} (B_l + B_l^* \Delta T + B_l^{**} M) - \varepsilon_{\pi l \alpha} - \alpha_{\pi l \alpha} \Delta T_{\alpha} > \frac{\sigma_{y\alpha}^-}{E_{\alpha}} \quad (20)$$

$$\Rightarrow \Delta T > \Delta T_1^- = \frac{\frac{\sigma_{y1}^+}{E_1} - D_{1l}^{-1} (B_l + B_l^{**} M) + \varepsilon_{pl1}}{D_{1l}^{-1} B_l^* - \alpha_{th1}} \quad \wedge \quad \Delta T < \Delta T_1^+ = \frac{\frac{\sigma_{y1}^-}{E_1} - D_{1l}^{-1} (B_l + B_l^{**} M) + \varepsilon_{pl1}}{D_{1l}^{-1} B_l^* - \alpha_{th1}} \quad \text{for} \quad \text{bar 1} \quad (21a)$$

$$\Rightarrow \Delta T > \Delta T_2^- = \frac{\frac{\sigma_{y2}^-}{E_2} - D_{2i}^{-1} (B_i + B_i^{**} M) + \varepsilon_{pl2}}{D_{2i}^{-1} B_i^*} \quad \wedge \quad \Delta T < \Delta T_2^+ = \frac{\frac{\sigma_{y2}^+}{E_2} - D_{2i}^{-1} (B_i + B_i^{**} M) + \varepsilon_{pl2}}{D_{2i}^{-1} B_i^*}$$

for bar 2

(21b)

$$\Rightarrow \Delta T > \Delta T_3^- = \frac{\frac{\sigma_{y3}^+}{E_3} - D_{3i}^{-1} \left(B_i + B_i^{**} M \right) + \varepsilon_{pl2}}{D_{3i}^{-1} B_i^*} \wedge \Delta T < \Delta T_3^+ = \frac{\frac{\sigma_{y3}^-}{E_3} - D_{3i}^{-1} \left(B_i + B_i^{**} M \right) + \varepsilon_{pl3}}{D_{3i}^{-1} B_i^*}$$

for bar 3

(21c)

If the given ΔT exceeds one of the upper limits (ΔT_i^+), additional plastic deformation will occur for the bar with the smallest upper limit. If the given ΔT falls below one of the lower limits (ΔT_i^-), additional plastic deformation will occur for the bar with the largest lower limit. In the first case, the increment in plastic strain will be negative if bar one or bar three has the smallest upper limit; it will be positive if bar two has the smallest upper limit. In the second case (temperature increment falls below one of the lower limits), the increment in plastic strain will be negative if bar two has the largest lower limit and it will be positive if bar one or three have the largest lower limit. In both cases for the next iteration, the parameters (P_i , Q_i , R_i) have to be evaluated using the updated values of plastic strains. For the two bars that are still in the elastic range, the limits for the increment in temperature can be determined using the same equations as for the previous iteration (eq. 21). If the material is elastic-ideally plastic, the three bar model will collapse if the given temperature increment for bar one exceeds one of the updated limits. If the material is either kinematically or isotropically hardening, the parameters P_i , Q_i , R_i have to be recalculated as in the first step if one of the limits is exceeded and then the same procedure has to be repeated for the last bar.

If after one of the described three steps no limit for the increment in temperature is exceeded, the total strain can be calculated using equation 16. If the total strain is known, the additional plastic strain for each bar, if any, can be determined. For an elastic-ideally plastic constitutive equation formula 22 can be used to calculate the incremental plastic strain

$$\Delta \varepsilon_{pl\alpha} = \begin{cases} \varepsilon_{\alpha} - \varepsilon_{pl\alpha} - \alpha_{th\alpha} \Delta T_{\alpha} - \frac{\sigma_{y0\alpha}^+}{E_{\alpha}} & \text{for } \Delta \varepsilon_{pl\alpha} \geq 0 \\ \varepsilon_{\alpha} - \varepsilon_{pl\alpha} - \alpha_{th\alpha} \Delta T_{\alpha} - \frac{\sigma_{y0\alpha}^-}{E_{\alpha}} & \text{for } \Delta \varepsilon_{pl\alpha} < 0 \end{cases}, \quad (22)$$

while for kinematic hardening equation 23

$$\Delta \varepsilon_{pl\alpha} = \begin{cases} \varepsilon_{\alpha} \left(1 - \frac{E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} \right) - \varepsilon_{pl\alpha} - \alpha_{th\alpha} \Delta T_{\alpha} \left(1 - \frac{E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} \right) - \frac{\sigma_{y0\alpha}^+}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta \varepsilon_{pl\alpha} \geq 0 \\ \varepsilon_{\alpha} \left(1 - \frac{E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} \right) - \varepsilon_{pl\alpha} - \alpha_{th\alpha} \Delta T_{\alpha} \left(1 - \frac{E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} \right) - \frac{\sigma_{y0\alpha}^-}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta \varepsilon_{pl\alpha} < 0 \end{cases} \quad (23)$$

and for isotropic hardening equation 24

$$\Delta \varepsilon_{pl\alpha} = \begin{cases} \frac{E_{\alpha} \left(\varepsilon_{\alpha} - \varepsilon_{pl\alpha} - \alpha_{th\alpha} \Delta T_{\alpha} \right) - \sigma_{yv\alpha}^+}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta \varepsilon_{pl\alpha} \geq 0 \\ \frac{E_{\alpha} \left(\varepsilon_{\alpha} - \varepsilon_{pl\alpha} - \alpha_{th\alpha} \Delta T_{\alpha} \right) - \sigma_{yv\alpha}^-}{E_{\alpha} + E_{T\alpha}} & \text{for } \Delta \varepsilon_{pl\alpha} < 0 \end{cases} \quad (24)$$

has to be used. In the last step of the evaluation, the total strain or the increment in plastic strain can be used to determine the new yield stress if kinematic or isotropic hardening is used:

–kinematic hardening:

$$\left. \begin{aligned} \sigma_{y\alpha}^+ &= \frac{E_{\alpha} E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} \varepsilon_{\alpha} + \left(\sigma_{y0\alpha}^+ - \alpha_{th\alpha} \Delta T_{\alpha} E_{T\alpha} \right) \frac{E_{\alpha}}{E_{\alpha} + E_{T\alpha}} \\ \sigma_{y\alpha}^- &= \sigma_{y\alpha}^+ - \left(\sigma_{y0\alpha}^+ - \sigma_{y0\alpha}^- \right) \end{aligned} \right\} \text{for } \Delta \varepsilon_{pl\alpha} \geq 0 \quad (25 a, b)$$

$$\left. \begin{aligned} \sigma_{y\alpha}^- &= \frac{E_{\alpha} E_{T\alpha}}{E_{\alpha} + E_{T\alpha}} \varepsilon_{\alpha} + \left(\sigma_{y0\alpha}^- - \alpha_{th\alpha} \Delta T_{\alpha} E_{T\alpha} \right) \frac{E_{\alpha}}{E_{\alpha} + E_{T\alpha}} \\ \sigma_{y\alpha}^+ &= \sigma_{y\alpha}^- + \left(\sigma_{y0\alpha}^+ - \sigma_{y0\alpha}^- \right) \end{aligned} \right\} \text{for } \Delta \varepsilon_{pl\alpha} < 0$$

–isotropic hardening:

$$\begin{aligned} \sigma_{y\alpha}^+ &= \sigma_{yv\alpha}^+ + \left| \Delta \varepsilon_{pl\alpha} \right| E_{T\alpha} \\ \sigma_{y\alpha}^- &= \sigma_{yv\alpha}^- - \left| \Delta \varepsilon_{pl\alpha} \right| E_{T\alpha} \end{aligned} \quad (26)$$

After the new plastic strain and the new yield limit have been determined, the above procedure can be used to calculate the mechanical behavior for a new loading condition.

3.2.3 Deflection of the beam

For a simply supported beam the deflection in the middle of the beam might be of interest. For a given beam-length L the deflection can be calculated using equation (27):

$$d = \text{SGN}(R) \left(|R| - \sqrt{R^2 - \frac{L^2}{4}} \right), \quad (27)$$

where the radius of curvature R is given by equation 28:

$$R = \frac{(\varepsilon_1 + 1)(y_{12} + y_{23})}{\varepsilon_1 - \varepsilon_3} - y_s \quad (28)$$

The deflection can also be used to determine whether ratcheting occurs or not. If there is no increment in the deflection for a new load cycle then there is no ratcheting.

4. PROGRAM TO DETERMINE THE LOAD LIMITS FOR PLASTIC DEFORMATION, CYCLIC PLASTIFICATION AND RATCHETING

In order to determine the load limits for the elastic range, plastic deformation, cyclic plastification and ratcheting the procedure described in section 4 was incorporated in a computer program (see appendix). The model data are input at the beginning of the program. In the next step, the bending moment needed for the onset of plasticity without any thermal load M_y and the collapse bending moment (if no hardening is assumed) are calculated. Moreover, the temperature needed for the onset of plastic deformation without any mechanical load T_y is determined. In order to generalize the results, the load limits for each type of material behavior are related to M_y and T_y and the results are stored in the result file of the program. Different types of load cycles are used for the investigation on ratcheting. The load cycles are defined as follows:

type of load cycle	description	schematic
1	constant mechanical and cyclic thermal load
2	cyclic mechanical and constant thermal load
3	mechanical and thermal load in phase
4	mechanical and thermal load out of phase
5	mechanical load applied during heating phase

Table 1: Definition of different load cycles

The limits for the elastic range are calculated first by dividing the range of bending moment between the negative and the positive collapse moments into a number of equally spaced bending moments and calculating the temperature needed to cause first yielding for each using eq. 21. The only exception is load cycle type 4 in which the mechanical and thermal loads are applied out-of-phase. In this case, the range of bending moment is limited to the positive and negative yield moments, while the thermal load is limited by T_Y .

Next, for each mechanical moment, the limit in temperature for shake down in one cycle is determined. For a given temperature, the program checks whether additional plastic deformation occurs in any of the three bars during the second cycle. If additional plastic deformation occurs, the temperature increment is reduced, if not, the temperature increment is increased and the calculation is repeated. This iterative procedure is continued until the temperature increment converges to within a preset tolerance.

The last step in the development of the Bree-like diagram is to distinguish between cyclic plastification and ratcheting. For both, cyclic plastification and ratcheting, additional plastic deformation occurs during each load cycle. Therefore, the increment in the deflection (without thermal load) between the second and the third load cycle is used to determine whether or not ratcheting occurs under the given loading conditions. For the calculation, a constant increment of temperature is used and for each temperature the minimum bending moment needed to cause ratcheting is calculated iteratively. The reason for using a given temperature instead of a given moment (as in the cases for elastic range and shake down) is, that for some types of load cycle (especially for a constant mechanical and cyclic thermal load, using kinematic hardening), proceeding in this fashion enables determination of the Bree-like diagram more efficiently.

To avoid failure by ratcheting or cyclic plastification, it is sufficient that the loading conditions lie inside the shakedown boundary (shakedown here is defined as that occurring in one cycle). If they exceed the limits for shakedown, a more precise analysis is needed., because shakedown may occur after a finite or infinite number of cycles of ratcheting and the total accumulated plastic deformation may still be within a permissible limit. Moreover if the limits for ratcheting are reached for high thermal and small mechanical loads, ratcheting effect may sometimes be neglected compared to the effect of cyclic plastification. In order to carry out a more precise analysis the program provides the option to conduct single calculations for a given loading condition. For each type of load cycle the development of the plastic strain and the deflection is calculated.

5. RESULTS

5.1 Symmetrical three-bar model

To explore the mechanical behavior of the three bar model for different types of load cycles, the first set of calculations were done for a symmetric arrangement:

$$A_1 = A_3 = 1/2 A_2$$

$$y_{12} = y_{23}$$

$$E_1 = E_2 = E_3$$

$$\sigma_{y01} = \sigma_{y02} = \sigma_{y03}$$

$$E_1/E_{T1} = E_2/E_{T2} = E_3/E_{T3} = 10 \text{ for isotropic and kinematic hardening}$$

5.1.1 Constant mechanical and cyclic thermal load

Of all the load cycle types considered, load cycle type 1 (constant mechanical and cyclic thermal load) is the most susceptible to ratcheting. It is the only loading type for which ratcheting occurs even for an elastic–ideally plastic (cp. Fig. 3) or a kinematically hardening material (cp.

Fig. 5 and 6). Using an elastic–ideally plastic constitutive equation, ratcheting occurs if $|M/M_y| + T/2T_y$ exceeds 1 (cp. Fig. 3). The mechanism for ratcheting in this case is quite simple. Assuming a positive moment (compression for bar 1, tensile stresses for bar 3), there will be no plastic deformation if $M < M_y$. If in addition to the mechanical moment the thermal load is applied, the stress in bar 1 will increase and that in bar 3 will decrease, so that plastic deformation (compression) will occur for bar 1 if the yield limit is exceeded. On removal of the thermal load, the stress in bar 1 will be relieved due to the plastic deformation and bar 3 has to bear a larger share of the moment. For those loading conditions where ratcheting occurs, the stress in bar 3 reaches the yield limit and plastic deformation (tensile) occurs. This procedure is repeated for every load cycle (cp. Fig. 4) and for every load cycle the increment in plastic deformation is the same (infinite ratcheting). If hardening is assumed, the Bree–like diagrams change. For both types of hardening the shake down region is extended (cp. Fig. 5 and 6). For a kinematically hardening material, at high thermal loads, cyclic plastification instead of ratcheting occurs.

Fig. 3: Bree–like diagram for constant mechanical and cyclic thermal load using an elastic–ideal plastic constitutive equation

Fig. 4: Development of plastic strain for a constant mechanical and cyclic thermal load using an elastic ideal plastic constitutive equation.

Fig. 5: Bree-like diagram for a constant mechanical and cyclic thermal load using kinematic hardening.

Fig. 6: Bree-like diagram for a constant mechanical and cyclic thermal load using isotropic hardening

To investigate the influence of hardening on the development of plastic deformation, deflections were calculated for two loading conditions; $M/My=.5$; $T/Ty=2$ and $M/My=.5$; $T/Ty=4$ (cp. Fig. 7a and b). For an elastic-ideally plastic material, the increment in deflection is the same for each cycle (infinite ratcheting); for a hardening material, the increment decreases with each cycle. For $M/My=.5$ and $T/Ty=2$ there is no difference between kinematic and isotropic hardening, because the plastic deformation in each bar increases monotonically. For $M/My=.5$ and $T/Ty=4$ the situation changes. For a kinematically hardening material, cyclic plastification is reached without any increment of the deflection between two load cycles; for an isotropically hardening material, the increment of the deflection between two load cycles increases compared to the first loading condition.

Fig. 7a and b: Development of the deflection for constant mechanical load and cyclic thermal load:
a: $M/My=0.5$ and $T/Ty=2$
b: $M/My=0.5$ and $T/Ty=4$

5.1.2 Cyclic mechanical and constant thermal load

For a cyclic mechanical and a constant thermal load no ratcheting and no cyclic plastification can occur. If $|M/My| + T/Ty$ is greater than 1, plastic deformation will occur in at least one bar during the first load cycle, but for all the following load cycles there will be no further plastic deformation. The Bree-like diagram is the same for no hardening, kinematic and isotropic hardening (cp. Fig. 8).

Fig. 8: Bree-like diagram for cyclic mechanical and constant thermal load

5.1.3 Mechanical and thermal load in phase

For this type of load cycle the Bree-like diagram is the same for a kinematically hardening and an elastic-ideally plastic material (cp. Fig. 9). If the sum of T/T_y and $|M/My|$ exceeds 1, plastic deformation will occur and if this sum exceeds 2 there will be cyclic plastification. For isotropic hardening the situation changes. Compared to the Bree-like diagram for the previous cases, the shake-down regime is enlarged. If the limits for shake-down are exceeded, ratcheting instead of cyclic plastification occurs (cp. Fig. 10).

Fig. 9: Bree-like diagram for mechanical and thermal load in phase using an elastic-ideal plastic constitutive equation or kinematic hardening

Fig. 10: Bree-like diagram for mechanical and thermal load in phase using isotropic hardening

5.1.4 Mechanical and thermal load out of phase

The Bree-like diagram in this case is again the same for no hardening and kinematic hardening (cp. Fig. 11). The limits for the elastic regime are given by $|M/M_y| \leq 1$ and $T/T_y \leq 1$. Cyclic plastification occurs if the sum of $|M/M_y|$ and T/T_y exceeds 2. Using isotropic hardening the

shake-down regime is enlarged again compared to no hardening and kinematic hardening and for loading conditions that exceed the limits for shake down, ratcheting instead of cyclic plastification occurs (cp. Fig. 12).

Fig. 11: Bree-like diagram for mechanical and thermal load out of phase using an elastic-ideal plastic constitutive equation or kinematic hardening

Fig. 12: Bree-like diagram for mechanical and thermal load out of phase using isotropic hardening

5.1.5 Mechanical load applied during heating phase

This kind of load cycle is the relevant one for the first wall segment of a fusion reactor. The results of the calculation are again presented in a Bree-like diagram. Fig. 13 shows the regions of different mechanical behavior using no hardening or kinematic hardening and Fig. 14 shows the different regions for isotropic hardening.

Fig. 13: Bree-like diagram for the relevant kind of load cycle (mechanical load applied during the heating phase) using an elastic-ideal plastic constitutive equation or kinematic hardening

Fig. 14: Bree-like diagram for the relevant kind of load cycle (mechanical load applied during the heating phase) using isotropic hardening

Again for isotropic hardening ratcheting may occur while for ideal plasticity and kinematic hardening there is no ratcheting. Due to the relevance of this type of load cycle for ITER, further ratcheting calculations were performed. In Fig. 15a the stress and in Fig. 15b the plastic deformations are shown for each bar as a function of the cycle number. For the calculation, a relative bending moment (M/M_y) of 0.5 and a relative thermal load (T/T_y) of 3 were used. In the first step, the thermal load is applied which puts bars 1 and 3 into compression and bar 2 into tension. The absolute value of the plastic strain and the increase of the yield stress is the same for each bar. In the second step, the mechanical moment is applied and therefore additional plastic deformation occurs in the first bar, while the stresses in the other bars are decreased. Due to the additional plastic deformation in bar 1 the yield stress for this bar increases. If in the next two loading steps the mechanical and thermal loads are removed again, tensile stresses occur in bars 1 and 3. Because of the higher yield stress of bar 1, tensile strain appear first in bar 3, so that the initial compression due to the thermal load is decreased for this bar. The plastic deformations in bar 2 are of minor interest and they are not important for the ratcheting mechanism. For the next load cycles the procedure is almost the same as that for the first load cycle, so that the plastic deformation is progressive.

5.2 Fusion reactor first wall

In order to apply the three-bar model to the first wall design of [11], first a finite element analysis was performed using a typical temperature distribution to calculate the thermal (or secondary) stress distribution. As can be seen in Fig. 16 for the thermal stress there are three different zones. The upper and lower surfaces of the first wall are subjected to compressive stresses, while tensile stresses occur in the middle. These three zones are now represented by the three bars (cp. Tab. 2).

Three-Bar-Model	
A ₁	396.1 mm ²
A ₂	1063.1 mm ²
A ₃	586.9 mm ²
y ₁₂	15.3 mm
y ₂₃	15.0 mm

Table 2: Geometric data for the three bar model

Fig. 15 a and b: Plastic deformation and stresses are presented for each bar as a function of cycle number.

The distances between the bars was set equal to the distance between the centers of gravity of each zone. For the following calculations using the three-bar model it is assumed, that the material properties do not change with temperature, so that each bar has the same yield stress, Young's modulus and hardening characteristics. The influence of temperature-dependent material properties on the mechanical behaviour and especially on the ratcheting of the three-bar model will be investigated in the future.

Fig. 16: Elastic calculated compression and tensile zones due to the thermal load.

For every load cycle, a Bree-like diagram was developed using ideal plasticity and kinematic and isotropic hardening with $E/E_T=10$.

5.2.1 Constant mechanical and cyclic thermal load

The Bree-like diagrams in this case (cp. Fig. 17, 18 and 19) are similar to the diagrams for the symmetrical three-bar model. However for ideal plasticity, for small mechanical moments and $T/T_y > 2$, cyclic plastification occurs (cp. Fig. 17) which is in contrast to the symmetrical arrangement where ratcheting occurs as soon as a mechanical moment is present and the relative thermal load (T/T_y) exceeds 2.

Fig. 17: Bree-like diagram for constant mechanical and cyclic thermal load using an elastic-ideal plastic constitutive equation.

Fig. 18: Bree-like diagram for a constant mechanical and cyclic thermal load using kinematic hardening.

Fig. 19: Bree-like diagram for a constant mechanical and cyclic thermal load using isotropic hardening

5.2.2 Cyclic mechanical and constant thermal load

For a constant thermal load the Bree-like diagram (cp. Fig. 20) is, as in the case for the symmetric arrangement, very simple. Neither cyclic plastification nor ratcheting occurs, and the Bree-like diagram is the same for ideal plasticity, isotropic hardening and kinematic hardening.

Fig. 20: Bree-like diagram for cyclic mechanical and constant thermal load

5.2.3 Mechanical and thermal load in phase

In contrast to the symmetrical arrangement, in this case there are ratcheting regimes for both elastic-ideally plastic and kinematically hardening materials. For ideal plasticity, ratcheting occurs for high thermal loads if the relative moment (M/My) is smaller than -0.2 (cp. Fig. 21). In case of ratcheting, the plastic strain increment is the same for every load cycle (infinite ratcheting). For a kinematically hardening material, there is also a ratcheting regime for negative mechanical moments and high thermal loads (cp. Fig. 22), but in contrast to ideal plasticity, the ratcheting effect is much smaller. The increment in plastic deformation almost vanishes after the first load cycles and so ratcheting is much less important than cyclic plastification. The Bree-like diagram for isotropic hardening is again similar to the one for the symmetrical arrangement (cp. Fig. 23).

Fig. 21: Bree-like diagram for mechanical and thermal load in phase using an elastic-ideal plastic constitutive equation.

Fig. 22: Bree-like diagram for mechanical and thermal load in phase using kinematic hardening.

Fig. 23: Bree-like diagram for mechanical and thermal load in phase using isotropic hardening.

5.2.4 Mechanical and thermal load out of phase

As in the case where the mechanical and thermal loads are in phase, there is a ratcheting regime for ideal plasticity and kinematic hardening, but in this case ratcheting occurs for a positive mechanical moment (cp. Fig. 24 and 25). In contrast to the symmetrical arrangement, for isotropic hardening cyclic plastification may occur (cp. Fig. 26). More detailed examinations showed that, upon removal of the thermal load, for the isotropically hardening material the deflection of a beam can even increase due to hardening to the opposite of the mechanical moment.

Fig. 24: Bree-like diagram for mechanical and thermal load out of phase using an elastic-ideal plastic constitutive equation .

Fig. 25: Bree-like diagram for mechanical and thermal load out of phase using kinematic hardening.

Fig. 26: Bree-like diagram for mechanical and thermal load out of phase using isotropic hardening.

5.2.5 Mechanical load applied during heating phase

Again, there is a ratcheting regime for an elastic-ideally plastic material whereas for a symmetrical arrangement no ratcheting can occur (cp. Fig. 27). Due to the relevance of this type of load cycle for the first wall of a fusion reactor, additional investigations were carried out. Fig. 28 shows the plastic strain as a function of the load cycle for a relative mechanical moment of -1 and a relative thermal load of 4 . If in the first step the thermal load is applied, compressive stresses occur in bars 1 and 3. Due to its smaller area of cross section plastic deformation occurs in bar 1 (Fig.28-1). If a negative mechanical moment is subsequently applied, the stress in bar 3 is increased causing it to plastically deform (Fig.28-2). On removal of the mechanical and thermal load, tensile stresses occur in bars 1 and 3 due to the plastic compressive strains present in them. In bar 1, the stress even exceeds the yield limit so that plastic deformation occurs. If the thermal load is now applied in the second load cycle, there is again compression for bar 1. But due to the plastic compressive strain in bar 3, there is an increment in the plastic strain of bar 1 between removal and application of the thermal load (Fig.28-3). This increment leads to additional plastic deformation in bar 3 when the mechanical moment is applied again (Fig.28-4). This sequence of events is now repeated for every load cycle, so that ratcheting occurs.

Fig. 27: Bree-like diagram for the relevant kind of load cycle (mechanical load applied during the heating phase) using an elastic-ideal plastic constitutive equation.

Fig. 28: Development of plastic strain for the relevant load cycle (mechanical load applied during heating phase) using an elastic ideal plastic constitutive equation.

For kinematic hardening there is also a ratcheting regime (cp. Fig. 29), but due to the hardening this effect is very small and nearly disappears after a few cycles. If isotropic hardening is used there is again ratcheting as soon as the limits for shakedown are exceeded (cp. Fig. 30).

Fig. 29: Bree-like diagram for the relevant kind of load cycle (mechanical load applied during the heating phase) using kinematic hardening.

Fig. 30: Bree-like diagram for the relevant kind of load cycle (mechanical load applied during the heating phase) using isotropic hardening.

6. DISCUSSIONS AND CONCLUSIONS

A simplified model (3-bar model) was developed to investigate the ratcheting of a fusion reactor first wall and to study the influence of hardening (kinematic and isotropic) on its mechanical behaviour under cyclic loading conditions. This model was incorporated in a computer program in order to determine Bree-like diagrams for various loading sequences and for two different geometrical configurations of the three-bar model; a symmetrical arrangement and an arrangement that was fitted to the first wall design of [11].

The loading sequence has a major influence on the ratcheting behavior. The first type of load cycle (constant mechanical and cyclic thermal load) usually leads to the severest ratcheting. For a constant thermal and a cyclic mechanical load no ratcheting or cyclic plastification can occur. For the other three types of load cycles (mechanical and thermal load in phase, out of phase and mechanical load applied during heating phase), ratcheting depends on the geometry and the kind of material hardening. In general, ratcheting for these loading cases is smaller than that for a constant mechanical and cyclic thermal load.

The effects of kinematic and isotropic hardening on ratcheting were included in the program. Hardening limits the accumulation of ratcheting strain by decreasing the increment in plastic strain with each cycle so that ratcheting is reduced especially for a constant mechanical and cyclic thermal load. On the other hand, for those types of load cycles where the mechanical load as well as the thermal load are cyclic, there is a ratcheting effect due to isotropic hardening, whereas for ideal plasticity or kinematic hardening no ratcheting occurs.

7. REFERENCES

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APPENDIX A

List of Symbols

A_{α}	area of cross section of bar α
y_{12}	distance between bar 1 and 2
y_{23}	distance between bar 2 and 3
y_s	height of the neutral axis
F_{α}	force in bar α
M	mechanical moment
ΔT	temperature increment for bar 1
E_{α}	Young's modulus for bar α
E_T	tangent module for bar α
ε_{α}	total strain in bar α
$\varepsilon_{el\alpha}$	elastic strain in bar α
$\varepsilon_{pl\alpha}$	plastic strain in bar α
$\Delta\varepsilon_{pl\alpha}$	increment in plastic strain for bar α
$\varepsilon_{th\alpha}$	thermal strain in bar α
$\alpha_{th\alpha}$	thermal expansion coefficient for bar α
$\sigma_{y\alpha}^+$	tensile yield stress of bar α
$\sigma_{y\alpha}^-$	compressive yield stress of bar α
$\sigma_{y0\alpha}^+$	initial tensile yield stress of bar α
$\sigma_{y0\alpha}^-$	initial compressive yield stress of bar α
$\sigma_{yv\alpha}^+$	tensile yield stress at the beginning of a new load-step (used for isotropic hardening)
$\sigma_{yv\alpha}^-$	compressive yield stress at the beginning of a new load-step (used for isotropic hardening)

APPENDIX B

Program Listing

```
REM Programme for evaluating the      'THREE BAR MODEL'
REM Author:                          Joerg Wolters
                                      Argonne National Laboratory /
                                      KFA-Juelich GmbH - IWE 1

REM Advisor:                         Saurin Majumdar
                                      Argonne National Laboratory

REM last change: August 15,1994

'*****
**
**                                  VARIABLES
**
'*****
**
'E()          Young's modulus [N/mm^2]
'A()          area of cross section [mm^2]
'alpha        thermal expansion coefficient of bar 1 [1/K]
's()          actual stress [N/mm^2]
'F()          actual force [N]
'sy()         original yield stress [N/mm^2]
'syp#()       yield stress for tension [N/mm^2]
'syn#()       yield stress for pressure [N/mm^2]
'hkind%()     kind of hardening, 0=kinematic, 1=isotropic
'ET()         hardening parameter [N/mm^2]
'eps ges#()   total plastic strain [mm/mm]
'epspl#()     plastic strain [mm/mm]
'depspl#()    increment in plastic strain [mm/mm]
'plastic#(x,y) plastic strain for bar x and subcycle y (to determine
               cyclic plastification) [mm/mm]
'T0           difference in temperature for bar 1 [K]
'T0s          temperature difference for single calculation [K]
'T            actual temperature between bar 1 and the other two bars
               (T=0 or T=T0) [K]
'Tsub()       defines the load cycle regarding temperature [K]
'dTstart      initial increment in temperature [K]
'dT           increment in temperature [K]
'Tlim#(x,y)   temperature limits for additional plastic deformation
(bar x) [K]
'Tmin         minimal temperature so that no further plastic
               deformation occur [K]
'Tmax         maximum temperature so that no further plastic
               deformation occur [K]
'M0           mechanical moment [Nmm]
'M0s          mechanical moment for single calculation [Nmm]
'M            actual mechanical moment [Nmm] (M=0 or M=M0)
'Msub()       defines load cycle regarding mechanical load [Nmm]
'Myn          negative yield moment [Nmm]
'Myp          positive yield moment [Nmm]
'Mmax         maximum moment before collapse (using ideal plasticity)
[Nmm]
```



```

'Mmin          minimal moment before collapse (using ideal plasticity)
[Nmm]
'mincrn        number of increments for the moment
'dM0           increment in moment
'l             beam length [mm]
'R             radius of curvature [mmm]
'ro            curvature [1/mm]
'defl#         deflection in the middle of the beam [mm]
'mdefl#()      mean deflection for one load cycle [mm]
'D#(,)         matrix
'Dl#(,)        inverse of D
'B, Bst        vector that includes the deformation of all bars
'P#(),Q#(),R#() vectors describing stress strain relation
'y12           distance between bar 1 and 2 [mm]
'y23           distance between bar 2 and 3 [mm]
'g()           geometry vector
'azcycl%       number of cycles
'cycl%         actual cycle
'azsubc%       number of subcycles
'subc%         actual subcycle
'ckind%        kind of cycle:      1 - cyclic thermal load, constant
                                   mechanical load
                                   2 - cyclic mechanical, constant
                                   thermal load
                                   3 - cyclic mechanical and thermal
                                   load, in phase
                                   4 - cyclic mechanical and thermal
                                   load, out of phase
                                   5 - no load->thermal load-
                                   >thermal+mechanical load-
                                   >thermal load->no load
'erg$( )       string needed to combine all results in one file
'total         variable needed for estimating the total time of the
               calculation
'azread        "
'cyclf         "
'mon, day, hour, min, sec  actual time
'mon0, day0, hour0, min0, sec0  time when the calculation started
'days()        days per month
'cograph%      control variable for graphic display:  0 - no graphic
                                                         display
                                                         1 - graphic
                                                         display
'conplast%     control variable for occurrence of plastic deformation
'copl%         control variable for calculating the limits for the
               elastic range
'cocy%         control variable for calculating the limits for shake
               down
'corat%        control variable for calculating the limits for
               ratcheting
'cosin%        control variable for a single calculation
'copm%         control variable that indicates whether the negative or
               positive moment where ratcheting starts for a given
               temperature is calculated

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***                                PREPARATIONS
**
*****
**
'FIELD VARIABLES
DIM E(3)                        'elastic modulus
DIM a(3)                        'area of cross section
DIM sy(3)                       'yield strength for each bar at room
                                temperature
DIM syp#(3)                     'actual positive yield stress
DIM syn#(3)                     'actual negative yield stress
DIM hkind%(3)                   'kind of hardening:0=kinematic, 1=isotropic
DIM ET(3)                       'd sig/d epspl=k
DIM epsges#(3)                  'total strain
DIM epspl#(3)                   'plastic strain
DIM depspl#(3)                  'increment in plastic strain
DIM D#(3,3)                     'matrix
DIM D1#(3,3)                    'inverse matrix
DIM g(3)                        'geometry vector
DIM b#(3)
DIM Bst#(3)
DIM P#(3),Q#(3),r#(3)           'vectors for describing stress strain
                                relation
DIM Tlim#(3,2)                  'temperature limits for each bar
DIM F(3), S(3)                  'force and stress
DIM pl(3)                       'vector remaining information about
                                increment in plastic deformation
DIM Tsub(10)                    'cyclic temperature
DIM Msub(10)                    'cyclic mechanical moment
DIM mdefl#(100)                 'mean deflection during one cycle
DIM mepspl#(100)                'mean plastic strain during one cycle
DIM erg$(100,17),r$(200,3)      'results in one file
DIM days(12)
FOR i%=1 TO 12
    READ days(i%)
NEXT i%
DATA 31,28,31,30,31,30,31,31,30,31,30,31

*****
**
*****
**
***                                MAIN PROGRAMME
**
*****
**
*****
**
GOSUB einl
GOSUB maxmom
GOSUB minmom
GOSUB limT
'for a given Temperature the moment will be calculated, where plastic
deformation, cyclic plastification and ratcheting occurs
INPUT "plastic deformation (j/n) ?",jn$
IF jn$="j" THEN
    copl%=1
ELSE

```

```

        copl%=0
    END IF
    INPUT "cyclic plastification (j/n) ?",jn$
    IF jn$="j" THEN
        cocy%=1
    ELSE
        cocy%=0
    END IF
    INPUT "ratcheting (j/n) ?",jn$
    IF jn$="j" THEN
        corat%=1
    ELSE
        corat%=0
    END IF
    INPUT "single calculation (j/n) ?",jn$
    IF jn$="j" THEN
        cosin%=1
    ELSE
        cosin%=0
    END IF

    INPUT "kind of hardening (e=no, k=kinematic, i=isotropic, a=all) :",hk$
    INPUT "which load cycle (1-5, a=all) :",lc$
    IF hk$="e" THEN
        hkb%=-1
        hke%=-1
        hkf%=1
    END IF
    IF hk$="k" THEN
        hkb%=0
        hke%=0
        hkf%=1
    END IF
    IF hk$="i" THEN
        hkb%=1
        hke%=1
        hkf%=1
    END IF
    IF hk$="a" THEN
        hkb%=-1
        hke%=1
        hkf%=3
    END IF
    IF lc$="a" THEN
        lcb%=1
        lce%=5
        lcf%=5
    ELSE
        lcb%=VAL(lc$)
        lce%=VAL(lc$)
        lcf%=1
    END IF

    IF cocy%=1 OR copl%=1 OR corat%=1 THEN
        'input-data for calculation:
        PRINT "negative yield moment" : ",Myn
        PRINT "positive yield moment" : ",Myp
        PRINT
    
```

```

PRINT "negative collapse moment      :",Mmin
PRINT "positive collapse moment      :",Mmax
INPUT "number of increments for the moment:",mincrnr
PRINT
PRINT "negative yield temperature    :",Tyn
PRINT "positive yield temperature    :",Typ
INPUT "maximum temperature for the calculation :",T0max
INPUT "number of increments for the temperature:",Tincrn
dM0=(Mmax-Mmin)/mincrnr
total=(cocy%*(mincrnr)*2/3+corat%*(Tincrn+1)*2*2)*hkf%*lcf%
END IF
IF cosin%=1 THEN
PRINT "negative yield moment          :",Myn
PRINT "positive yield moment          :",Myp
PRINT
PRINT "negative collapse moment      :",Mmin
PRINT "positive collapse moment      :",Mmax
INPUT "related moment                :",M0sr
M0s=M0sr*Myp
PRINT
PRINT "negative yield temperature    :",Tyn
PRINT "positive yield temperature    :",Typ
INPUT "related temperature           :",T0sr
T0s=T0sr*Typ
INPUT "number of cycles for single calculation :",azcyc%
cyc%lcf=azcyc%/3/16
total=total+hkf%*lcf%*cyc%lcf
END IF

INPUT "File-name (max. 5 characters):",file$
CLS
mon0=VAL(LEFT$(DATE$,2))
day0 =VAL(MID$(DATE$,4,2))
hour0=VAL(LEFT$(TIME$,2))
min0=VAL(MID$(TIME$,4,2))
sec0=VAL(RIGHT$(TIME$,2))

FOR hk%=hkb% TO hke%
IF hk%=-1 THEN
hkind%(1)=0
hkind%(2)=0
hkind%(3)=0
ELSE
hkind%(1)=hk%
hkind%(2)=hk%
hkind%(3)=hk%
END IF
IF hk%=0 THEN
hard$="k"
ELSE
IF hk%=1 THEN
hard$="i"
ELSE
hard$="e"
END IF
END IF
FOR ckind%=lcb% TO lce%
IF copl%=1 THEN

```

```

        GOSUB plastic
    END IF
    IF cocy%=1 THEN
        GOSUB cyclic
    END IF
    IF corat%=1 THEN
        GOSUB ratcheting
        GOSUB ratch2
    END IF
    IF cosin%=1 THEN
        GOSUB single
    END IF
NEXT ckind%
NEXT hk%
IF copl%=1 AND cocy%=1 AND corat%=1 THEN
    GOSUB file
END IF
IF cosin%=1 AND hk$="a" THEN
    GOSUB Fils
END IF
END

```

```

plastic:
' P L A S T i C   D E F O R M A T i O N
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_p.dat" FOR OUTPUT AS #1
PRINT #1,"M/My";",",";Tmax/Ty"
FOR M=Mmin+dM0/2 TO Mmax-dM0/2+.1 STEP dM0
    IF ckind%=1 THEN
        GOSUB fit
        GOSUB res
        GOSUB tensor
        GOSUB inverse
        GOSUB calcT
        IF Tmin<=0 AND Tmax>=0 THEN
            PRINT #1,M/My;",";Tmax/Typ
        ELSE
            PRINT #1, M/My;",";0
        END IF
    END IF
    IF ckind%=2 OR ckind%=5 THEN
        GOSUB fit
        GOSUB res
        GOSUB tensor
        GOSUB inverse
        GOSUB calcT
        IF Tmax<=Typ THEN
            PRINT #1, M/My;",";Tmax/Typ
        ELSE
            PRINT #1,M/My;",";1
        END IF
    END IF
    IF ckind%=3 THEN
        GOSUB fit
        GOSUB res
        GOSUB tensor
        GOSUB inverse
        GOSUB calcT
    END IF

```

```

        PRINT #1, M/Myp;",";Tmax/Typ
    END IF
    IF ckind%=4 THEN
        IF M<Myn OR M>Myp THEN
            PRINT #1,M/Myp;",";0
        ELSE
            PRINT #1,M/Myp;",";1
        END IF
    END IF
NEXT M
CLOSE #1
RETURN

cyclic:
' C Y C L I C   P L A S T I F I C A T I O N
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_c.dat" FOR OUTPUT AS #1
PRINT #1,"M/My";",";"T/Ty"
dTstart=T0max/8
T0=0
FOR M0=Mmin+dM0/2 TO Mmax-dM0/2+.1 STEP dM0
    azread=azread+2/3
    dT=dTstart
    cyciter:      'beginning of iteration to find the moment for a
                  given temperature where ratcheting occurs
    GOSUB fit
    GOSUB setsub      'definition of the load cycle
    azcycl%=2
    FOR cycl%=1 TO azcycl%
        FOR subc%=1 TO azsubc%
            T=Tsub(subc%)
            M=Msub(subc%)
            GOSUB res      'resets all variables
            iterate:
                ' switch on / off graphic display with g-button
                IF INKEY$="g" THEN
                    IF cograph%=0 THEN
                        cograph%=1
                    ELSE
                        cograph%=0
                    CLS
                END IF
            END IF
            GOSUB tensor      'determination of D, B, Bst tensors
            GOSUB inverse     'calculation of the inverse of D
            IF conplast%=1 AND ((pl(1)<>0 AND ET(1)=0) OR (pl(2)<>0 AND
ET(2)=0) OR (pl(3)<>0 AND ET(3)=0)) THEN
                'PRINT "plastic deformation without hardening"
                GOSUB epsges
                GOTO conl
            END IF
            GOSUB calct      'calculation of temperature limits
                            for additional plastic deformation
            GOSUB evaluation  'evaluating stress strain situation
            'remark: if additional plastic deformation occur, the matrix
            D has to be changed

```

```

        IF conplast%=1 THEN GOTO iterate      'additional plastic
                                              deformation occurs -->
                                              new calculation

        con1:
        GOSUB newyield
        FOR i%=1 TO 3
            plastic#(i%,subc%)=epspl#(i%)
        NEXT i%
        IF cograph%=1 THEN
            GOSUB graph      'graphic presentation of the results
        END IF
    NEXT subc%
NEXT cycl%

'all cycles are calculated-> evaluation of the results
re=1000000&      'resolution for determination of cyclic
                  plasticity
IF (INT(plastic#(1,azsubc%)*re)=INT(plastic#(1,azsubc%/2)*re)) AND
(INT(plastic#(2,azsubc%)*re)=INT(plastic#(2,azsubc%/2)*re)) AND
(INT(plastic#(3,azsubc%)*re)=INT(plastic#(3,azsubc%/2)*re)) THEN
    'no cyclic plastification
    IF T0>T0max THEN
        GOTO nextM
    END IF
    IF cosearch=1 THEN
        dT=dT/2
        IF dT<Typ/10000 THEN
            dT=dTstart
            GOTO nextM
        END IF
    END IF
    T0=T0+dT
    GOTO cyciter
ELSE
    'cyclic plastification
    cosearch=1
    dT=dT/2
    IF dT<Typ/10000 THEN
        dT=dTstart
        GOTO nextM
    END IF
    T0=T0-dT
    GOTO cyciter
END IF
GOSUB sleep
nextM:
'the temperature, where cyclic plastification for the given
mechanical moment occurs has been found
PRINT #1,M0/Myp;" ";T0/Typ
T0=0
cosearch=0
GOSUB time
NEXT M0
CLOSE#1
RETURN

```

ratcheting:

```

' R A T C H E T T I N G
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_r.dat" FOR OUTPUT AS #1
PRINT #1,"M/My";",","T/Ty"
minus:
IF copm%=0 THEN
    dMstart=Mmax/16-dM0/32
ELSE
    dMstart=Mmin/16+dM0/32
END IF
M0=0
Tstep=T0max/Tincrn
FOR T0=0 TO T0max+.1 STEP Tstep
    azread=azread+1
    dM=dMstart
    ratchiter:          'beginning of iteration to find the moment for a
                        'given temperature where ratcheting occurs

    GOSUB fit
    FOR i%=1 TO 3
        mdefl#(i%)=0
    NEXT i%
    GOSUB setsub        'definition of the load cycle
    azcycl%=3
    FOR cycl%=1 TO azcycl%
        FOR subc%=1 TO azsubc%
            T=Tsub(subc%)
            M=Msub(subc%)
            GOSUB res    'resets all variables
            iteration:

            ' switch on / off graphic display with g-button
            IF INKEY$="g" THEN
                IF cograph%=0 THEN
                    cograph%=1
                ELSE
                    cograph%=0
                    CLS
                END IF
            END IF

            GOSUB tensor    'determination of D, B, Bst tensors
            GOSUB inverse    'calculation of the inverse of D
            IF conplast%=1 AND ((pl(1)<>0 AND ET(1)=0) OR (pl(2)<>0 AND
ET(2)=0) OR (pl(3)<>0 AND ET(3)=0)) THEN
                'PRINT "plastic deformation without hardening"
                GOSUB epsges
                GOTO con2
            END IF
            GOSUB calct      'calculation of temperature limits
                        'for additional plastic deformation
            GOSUB evaluation 'evaluating stress strain situation
            'remark: if additional plastic deformation occur, the matrix
            D has to be changed
            IF conplast%=1 THEN GOTO iteration    'additional plastic
            deformation occurs --> new calculation
            con2:
            GOSUB curvat
            IF T=0 THEN
                mdefl#(cycl%)=defl#

```



```

        ELSE
            IF mdefl#(cycl%)=0 AND subc%=azsubc% THEN
                mdefl#(cycl%)=defl#
            END IF
        END IF
        GOSUB newyield
        IF cograph%=1 THEN
            GOSUB graph           'graphic presentation of the results
        END IF
    NEXT subc%
NEXT cycl%

'all cycles are calculated-> evaluation of the results
IF
INT(mdefl#(2)*100000&+.5)*SGN(M0)<=INT(mdefl#(3)*100000&+.5)*SGN(M0) AND
h#<>L/2 THEN
    'no ratcheting
    IF M0>=Mmax-dM0/2 OR M0<=Mmin+dM0/2 THEN
        GOTO nextT0
    END IF
    IF cosearch=1 THEN
        dM=dM/2
        IF (copm%=0 AND dM<Myp/10000) OR (copm%=1 AND dM>-Myp/10000)
THEN
            dM=dMstart
            GOTO nextT0
        END IF
    END IF
    M0=M0+dM
    GOTO ratchiter
ELSE
    'ratcheting
    cosearch=1
    dM=dM/2
    IF (copm%=0 AND dM<Myp/10000) OR (copm%=1 AND dM>-Myp/10000)
THEN
        dM=dMstart
        GOTO nextT0
    END IF
    M0=M0-dM
    GOTO ratchiter
END IF
'GOSUB sleep
nextT0:
'the mechanical moment, where ratcheting for the given temperature
occurs has been found
PRINT #1,M0/Myp;" , ";T0/Typ
M0=0
cosearch=0
GOSUB time
NEXT T0
IF copm%=0 THEN
    copm%=1
    GOTO minus
END IF
CLOSE#1
copm%=0
RETURN

```

```

ratch2:
' R A T C H E T T I N G
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_r2.dat" FOR OUTPUT AS #1
PRINT #1,"M/My";",","T/Ty"
minus2:
IF copm%=0 THEN
    dMstart=Mmin/16+dM0/32
    M0=Mmax-dM0/2
ELSE
    dMstart=Mmax/16-dM0/32
    M0=Mmin+sM0/2
END IF
Tstep=T0max/Tincrn
FOR T0=0 TO T0max+.1 STEP Tstep
    azread=azread+1
    dM=dMstart
    ratchiter2:                'beginning of iteration to find the moment for a
                                given temperature where ratcheting occurs

    GOSUB fit
    FOR i%=1 TO 3
        mdefl#(i%)=0
    NEXT i%
    GOSUB setsub                'definition of the load cycle
    azcycl%=3
    FOR cycl%=1 TO azcycl%
        FOR subc%=1 TO azsubc%
            T=Tsub(subc%)
            M=Msub(subc%)
            GOSUB res            'resets all variables
            iteration2:

            ' switch on / off graphic display with g-button
            IF INKEY$="g" THEN
                IF cograph%=0 THEN
                    cograph%=1
                ELSE
                    cograph%=0
                    CLS
                END IF
            END IF

            GOSUB tensor          'determination of D, B, Bst tensors
            GOSUB inverse         'calculation of the inverse of D
            IF conplast%=1 AND ((pl(1)<>0 AND ET(1)=0) OR (pl(2)<>0 AND
            ET(2)=0) OR (pl(3)<>0 AND ET(3)=0)) THEN
                'PRINT "plastic deformation without hardening"
                GOSUB epsges
                GOTO con22
            END IF
            GOSUB calcT           'calculation of temperature limits
                                for additional plastic deformation
            GOSUB evaluation      'evaluating stress strain situation
            'remark: if additional plastic deformation occur, the matrix
                                D has to be changed
            IF conplast%=1 THEN GOTO iteration2 'additional plastic
            deformation occurs --> new calculation
        con22:

```

```

        GOSUB curvat
        IF T=0 THEN
            mdefl#(cycl%)=defl#
        ELSE
            IF mdefl#(cycl%)=0 AND subc%=azsubc% THEN
                mdefl#(cycl%)=defl#
            END IF
        END IF
        GOSUB newyield
        IF cograph%=1 THEN
            GOSUB graph          'graphic presentation of the results
        END IF
    NEXT subc%
NEXT cycl%

'all cycles are calculated-> evaluation of the results
IF
INT(mdefl#(2)*100000&+.5)*SGN(M0)<=INT(mdefl#(3)*100000&+.5)*SGN(M0) OR
h#<>L/2 THEN
    'no ratcheting
    IF (copm%=0 AND M0<=0) OR (copm%=1 AND M0>=0) THEN
        GOTO nextT02
    END IF
    IF cosearch=1 THEN
        dM=dM/2
        IF (copm%=0 AND dM>-Myp/10000) OR (copm%=1 AND dM<Myp/10000)
THEN
            dM=dMstart
            GOTO nextT02
        END IF
    END IF
    M0=M0+dM
    GOTO ratchiter2
ELSE
    'ratcheting
    cosearch=1
    dM=dM/2
    IF (copm%=0 AND dM>-Myp/10000) OR (copm%=1 AND dM<Myp/10000)
THEN
        dM=dMstart
        GOTO nextT02
    END IF
    M0=M0-dM
    GOTO ratchiter2
END IF
'GOSUB sleep
nextT02:
'the mechanical moment, where ratcheting for the given temperature
occurs has been found
PRINT #1,M0/Myp;" ";T0/Typ
IF copm%=0 THEN
    M0=Mmax-dM0/2
ELSE
    M0=Mmin+sM0/2
END IF
cosearch=0
GOSUB time
NEXT T0

```

```

IF copm%=0 THEN
    copm%=1
    GOTO minus2
END IF
CLOSE#1
copm%=0
RETURN

single:
    azread=azread+cyclf
    M0=M0s
    T0=T0s
    OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_s.dat" FOR OUTPUT AS #1
    OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_pl.dat" FOR OUTPUT AS #2
    PRINT
#2,"cycle";",",";epspl(1)";",",";epspl(2)";",",";epspl(3)";",",";sig(1)";",",";
;sig(2)";",",";sig(3)"
    IF hk%=-1 THEN
        PRINT #1, "cycle";",",";no hardening"
    END IF
    IF hk%=0 THEN
        PRINT #1, "cycle";",",";kinematic hardening"
    END IF
    IF hk%=1 THEN
        PRINT #1, "cycle";",",";isotropic hardening"
    END IF
    GOSUB fit
    azcycl%=azcycls%
    GOSUB setsub      'definition of the load cycle
    amsubc%=0
    FOR cycl%=1 TO azcycl%
        FOR subc%=1 TO azsubc%
            amsubc%=amsubc%+1
            T=Tsub(subc%)
            M=Msub(subc%)
            GOSUB res      'resets all variables
            iterations:
            ' switch on / off graphic display with g-button
            IF INKEY$="g" THEN
                IF cograph%=0 THEN
                    cograph%=1
                ELSE
                    cograph%=0
                    CLS
                END IF
            END IF
            GOSUB tensor      'determination of D, B, Bst tensors
            GOSUB inverse      'calculation of the inverse of D
            IF complast%=1 AND ((pl(1)<>0 AND ET(1)=0) OR (pl(2)<>0 AND
            ET(2)=0) OR (pl(3)<>0 AND ET(3)=0)) THEN
                'PRINT "plastic deformation without hardening"
                GOSUB epsges
                GOTO conls
            END IF
            GOSUB calcT      'calculation of temperature limits
            'for additional plastic deformation
            GOSUB evaluation 'evaluating stress strain situation

```

```

        'remark: if additional plastic deformation occur, the matrix
                        D has to be changed
        IF conplast%=1 THEN GOTO iterations      'additional plastic
        deformation occurs --> new calculation
        conls:
        GOSUB curvat
        GOSUB newyield
        PRINT #1, amsubc%/azsubc%;",,"; defl#/L^2
        PRINT #2,
amsubc%/azsubc%;",,";epspl#(1);",,";epspl#(2);",,";epspl#(3);",,";S(1);",,";S
(2);",,";S(3)
        IF cograph%=1 THEN
            GOSUB graph                'graphic presentation of the results
            PRINT defl#
            GOSUB sleep
        END IF
    NEXT subc%
NEXT cycl%
CLOSE #1
CLOSE #2
GOSUB time
RETURN

```

```

*****
**
**                               SUBROUTINES
**
*****

```

```

*****--einl--*****
einl:

```

```

    OPEN "3bar_data" FOR INPUT AS #1
    'cross section
        INPUT #1, a$,b$
        INPUT #1,a$
        po=INSTR(a$,CHR$(9))
        a$=RIGHT$(a$,LEN(a$)-po)
        po=INSTR(a$,CHR$(9))
        a(1)=VAL(LEFT$(a$,po-1))
        a$=RIGHT$(a$,LEN(a$)-po)
        po=INSTR(a$,CHR$(9))
        a(2)=VAL(LEFT$(a$,po-1))
        a(3)=VAL(RIGHT$(a$,LEN(a$)-po))
    'Young's modulus
        INPUT #1,a$
        po=INSTR(a$,CHR$(9))
        a$=RIGHT$(a$,LEN(a$)-po)
        po=INSTR(a$,CHR$(9))
        E(1)=VAL(LEFT$(a$,po-1))
        a$=RIGHT$(a$,LEN(a$)-po)
        po=INSTR(a$,CHR$(9))
        E(2)=VAL(LEFT$(a$,po-1))
        E(3)=VAL(RIGHT$(a$,LEN(a$)-po))
    'hardening
        INPUT #1,a$
        po=INSTR(a$,CHR$(9))

```

```

a$=RIGHT$(a$, LEN(a$)-po)
po=INSTR(a$, CHR$(9))
ET1=VAL(LEFT$(a$, po-1))
a$=RIGHT$(a$, LEN(a$)-po)
po=INSTR(a$, CHR$(9))
ET2=VAL(LEFT$(a$, po-1))
ET3=VAL(RIGHT$(a$, LEN(a$)-po))
'yield stress
INPUT #1, a$
po=INSTR(a$, CHR$(9))
a$=RIGHT$(a$, LEN(a$)-po)
po=INSTR(a$, CHR$(9))
sy(1)=VAL(LEFT$(a$, po-1))
a$=RIGHT$(a$, LEN(a$)-po)
po=INSTR(a$, CHR$(9))
sy(2)=VAL(LEFT$(a$, po-1))
sy(3)=VAL(RIGHT$(a$, LEN(a$)-po))
'thermal expansion
INPUT #1, a$
po=INSTR(a$, CHR$(9))
alpha=VAL(RIGHT$(a$, LEN(a$)-po))
'distance
INPUT#1, a$
po=INSTR(3, a$, CHR$(9))
y12=VAL(RIGHT$(a$, LEN(a$)-po))
INPUT#1, a$
po=INSTR(3; a$, CHR$(9))
y23=VAL(RIGHT$(a$, LEN(a$)-po))
'length
INPUT#1, a$
po=INSTR(3, a$, CHR$(9))
L=VAL(RIGHT$(a$, LEN(a$)-po))
CLOSE #1
RETURN

*****-----fit-----
*****
fit:
IF hk%<>-1 THEN
    ET(1)=ET1
    ET(2)=ET2
    ET(3)=ET3
ELSE
    ET(1)=.1
    ET(2)=.1
    ET(3)=.1
END IF

ys=(y12*E(2)*a(2)+(y12+y23)*E(3)*a(3))/(E(1)*a(1)+E(2)*a(2)+E(3)*a(3))
g(1)=-ys
g(2)=y12-ys
g(3)=y12+y23-ys
epspl#(1)=0
epspl#(2)=0
epspl#(3)=0
FOR i%=1 TO 3
    syp#(i%)=sy(i%)
    syn#(i%)=-sy(i%)

```

```

        NEXT i%
RETURN

'*****--maxmom----
*****
maxmom:
'CALCULATION OF THE COLLAPSE MOMENT
  FOR i%=1 TO 3          'save old values of hardening
    ETs(i%)=ET(i%)
    ET(i%)=0
  NEXT i%
  GOSUB fit
  GOSUB res
  T=0
  GOSUB tensor
  GOSUB inverse
  GOSUB moment
  Myp=1E+30
  FOR i%=1 TO 3
    IF Mlim(i%,1)<Myp THEN
      Myp=Mlim(i%,1)
      ind%=i%
    END IF
  NEXT i%
  pl(ind%)=SGN(Dl#(ind%,3))
  GOSUB tensor
  GOSUB inverse
  GOSUB moment
  Mmax=1E+30
  FOR i%=1 TO 3
    IF Mlim(i%,1)<Mmax AND pl(i%)=0 THEN
      Mmax=Mlim(i%,1)
      ind%=i%
    END IF
  NEXT i%
  'PRINT Mmax,ind%
  FOR i%=1 TO 3
    ET(i%)=ETs(i%)
  NEXT i%
RETURN
'*****--minmom----
*****
minmom:
'CALCULATION OF THE COLLAPSE MOMENT
  FOR i%=1 TO 3          'save old values of hardening
    ETs(i%)=ET(i%)
    ET(i%)=0
  NEXT i%
  GOSUB fit
  GOSUB res
  T=0
  GOSUB tensor
  GOSUB inverse
  GOSUB moment
  Myn=-1E+30
  FOR i%=1 TO 3
    IF Mlim(i%,2)>Myn THEN
      Myn=Mlim(i%,2)

```

```

        ind%=i%
    END IF
NEXT i%
pl(ind%)=-SGN(D1#(ind%,3))
GOSUB tensor
GOSUB inverse
GOSUB moment
Mmin=-1E+30
FOR i%=1 TO 3
    IF Mlim(i%,2)>Mmin AND pl(i%)=0 THEN
        Mmin=Mlim(i%,2)
        ind%=i%
    END IF
NEXT i%
'PRINT Mmin,ind%
FOR i%=1 TO 3
    ET(i%)=ETs(i%)
NEXT i%
RETURN

'*****-----limT-----
'*****
limT:
    GOSUB fit
    GOSUB res
    M=0
    GOSUB tensor
    GOSUB inverse
    GOSUB calcT
    Typ=Tmax
    Tyn=Tmin
RETURN

'*****---setsub---
'*****
setsub:
    IF ckind%=1 THEN
        azsubc%=2
        Msub(1)=M0
        Msub(2)=M0
        Tsub(1)=0
        Tsub(2)=T0
    END IF
    IF ckind%=2 THEN
        azsubc%=2
        Msub(1)=0
        Msub(2)=M0
        Tsub(1)=T0
        Tsub(2)=T0
    END IF
    IF ckind%=3 THEN
        azsubc%=2
        Msub(1)=0
        Msub(2)=M0
        Tsub(1)=0
        Tsub(2)=T0
    END IF
    IF ckind%=4 THEN

```



```

        azsubc%=2
        Msub(1)=0
        Msub(2)=M0
        Tsub(1)=T0
        Tsub(2)=0
    END IF
    IF ckind%=5 THEN
        azsubc%=4
        Msub(1)=0
        Msub(2)=M0
        Msub(3)=0
        Msub(4)=0
        Tsub(1)=T0
        Tsub(2)=T0
        Tsub(3)=T0
        Tsub(4)=0
    END IF
RETURN

'*****-----res-----
'*****
res:
    FOR i%=1 TO 3
        pl(i%)=0
        pmax(i%)=0
        pmin(i%)=0
        depspl#(i%)=0
    NEXT i%
    complast%=0
RETURN

'*****---tensor---
'*****
tensor:
    'DETERMIN D-MATRIX
    'geometric connection (does not change with plastic deformation)
    D#(1,1)=y23
    D#(1,2)=-y12-y23
    D#(1,3)=y12
    FOR i%=1 TO 3
        P#(i%)=(1-
ABS(pl(i%))*E(i%)*a(i%)+ABS(pl(i%))*a(i%)*E(i%)*ET(i%)/(E(i%)+ET(i%))
        Q#(i%)=-(1-ABS(pl(i%)))*E(i%)*a(i%)*epspl#(i%)+ABS(pl(i%))*((1-
hkind%(i%))*pl(i%)*sy(i%)*a(i%)*E(i%)/(E(i%)+ET(i%))+hkind%(i%)*(a(i%)*E
(i%)/(E(i%)+ET(i%))*(pl(i%)*syp#(i%)-epspl#(i%)*ET(i%)))
        NEXT i%
        r#(1)=- (1-ABS(pl(1)))*E(1)*a(1)*alpha-
ABS(pl(1))*alpha*ET(1)*a(1)*E(1)/(E(1)+ET(1))
        FOR i%=1 TO 3
            D#(2,i%)=P#(i%)
            'P#(i%) depends on weather
            plastic deformation occur or not

            D#(3,i%)=g(i%)*P#(i%)
        NEXT i%
    'DETERMIN B-VECTOR
    FOR i%=1 TO 3
        b#(i%)=0
        Bst#(i%)=0
    NEXT i%

```

```

    FOR i%=1 TO 3
        b#(2)=b#(2)-Q#(i%)
        b#(3)=b#(3)-g(i%)*Q#(i%)
    NEXT i%
    Bst#(2)=-r#(1)
    Bst#(3)=-g(1)*r#(1)
'    PRINT
'    FOR i%=1 TO 3
'        PRINT B#(i%),Bst#(i%)
'    NEXT i%
'    PRINT
RETURN

'*****--inverse---
'*****
inverse:
'    DETERMINATION OF DETERMINANT

D#=D#(1,1)*D#(2,2)*D#(3,3)+D#(1,2)*D#(2,3)*D#(3,1)+D#(1,3)*D#(2,1)*D#(3,
2)
    D#=D#-D#(1,3)*D#(2,2)*D#(3,1)-D#(1,2)*D#(2,1)*D#(3,3)-
D#(1,1)*D#(2,3)*D#(3,2)
'    PRINT "Determinant : ",D
'    DETERMINATION OF THE INVERSE MATRIX
D1#(1,1)=(D#(2,2)*D#(3,3)-D#(2,3)*D#(3,2))/D#
D1#(1,2)=(D#(1,3)*D#(3,2)-D#(1,2)*D#(3,3))/D#
D1#(1,3)=(D#(1,2)*D#(2,3)-D#(1,3)*D#(2,2))/D#
D1#(2,1)=(D#(2,3)*D#(3,1)-D#(2,1)*D#(3,3))/D#
D1#(2,2)=(D#(1,1)*D#(3,3)-D#(1,3)*D#(3,1))/D#
D1#(2,3)=(D#(2,1)*D#(1,3)-D#(1,1)*D#(2,3))/D#
D1#(3,1)=(D#(2,1)*D#(3,2)-D#(2,2)*D#(3,1))/D#
D1#(3,2)=(D#(1,2)*D#(3,1)-D#(1,1)*D#(3,2))/D#
D1#(3,3)=(D#(1,1)*D#(2,2)-D#(1,2)*D#(2,1))/D#
'    PRINT MATRIX AND INVERSE
'    FOR i%=1 TO 3
'        FOR j%=1 TO 3
'            PRINT D#(i%,j%),
'        NEXT j%
'    PRINT
'    NEXT i%
'    PRINT
'    FOR i%=1 TO 3
'        FOR j%=1 TO 3
'            PRINT D1#(i%,j%),
'        NEXT j%
'    PRINT
'    NEXT i%
'GOSUB sleep
RETURN

'*****---moment---
'*****
moment:
'    RESPONING MOMENT FOR BEGINNING PLASTIC DEFORMATION
    IF D1#(1,3)<>0 THEN
        Mlim(1,2)=(alpha*T-D1#(1,1)*(Bst#(1)*T+b#(1))-
D1#(1,2)*(Bst#(2)*T+b#(2))-
D1#(1,3)*(Bst#(3)*T+b#(3)))+syp#(1)/E(1))/D1#(1,3)

```

```

      Mlim(1,1)=(alpha*T-D1#(1,1)*(Bst#(1)*T+b#(1))-
D1#(1,2)*(Bst#(2)*T+b#(2))-
D1#(1,3)*(Bst#(3)*T+b#(3)))+syn#(1)/E(1))/D1#(1,3)
    END IF
    IF D1#(2,3)<>0 THEN
      IF D1#(2,3)<0 THEN
        Mlim(2,2)=-
((D1#(2,1)*(Bst#(1)*T+b#(1))+D1#(2,2)*(Bst#(2)*T+b#(2))+D1#(2,3)*(Bst#(3)
)*T+b#(3)))-syp#(2)/E(2))/D1#(2,3)
        Mlim(2,1)=-
((D1#(2,1)*(Bst#(1)*T+b#(1))+D1#(2,2)*(Bst#(2)*T+b#(2))+D1#(2,3)*(Bst#(3)
)*T+b#(3)))-syn#(2)/E(2))/D1#(2,3)
      ELSE
        Mlim(2,1)=-
((D1#(2,1)*(Bst#(1)*T+b#(1))+D1#(2,2)*(Bst#(2)*T+b#(2))+D1#(2,3)*(Bst#(3)
)*T+b#(3)))-syp#(2)/E(2))/D1#(2,3)
        Mlim(2,2)=-
((D1#(2,1)*(Bst#(1)*T+b#(1))+D1#(2,2)*(Bst#(2)*T+b#(2))+D1#(2,3)*(Bst#(3)
)*T+b#(3)))-syn#(2)/E(2))/D1#(2,3)
      END IF
    ELSE
      Mlim(2,1)=1E+30
      Mlim(2,2)=-1E+30
    END IF
    IF D1#(3,3)<>0 THEN
      Mlim(3,1)=-
((D1#(3,1)*(Bst#(1)*T+b#(1))+D1#(3,2)*(Bst#(2)*T+b#(2))+D1#(3,3)*(Bst#(3)
)*T+b#(3)))-syp#(3)/E(3))/D1#(3,3)
      Mlim(3,2)=-
((D1#(3,1)*(Bst#(1)*T+b#(1))+D1#(3,2)*(Bst#(2)*T+b#(2))+D1#(3,3)*(Bst#(3)
)*T+b#(3)))-syn#(3)/E(3))/D1#(3,3)
    END IF
  RETURN

```

*****---calc-T---

calcT:

'TEMPERATURE LIMITS FOR EACH BAR FOR FURTHER PLASTIC DEFORMATION

'TENSION BAR 1, T<Tlim

Tlim#(1,1)=(syp#(1)/E(1)-D1#(1,1)*b#(1)-D1#(1,2)*b#(2)-
D1#(1,3)*(b#(3)+M)+epspl#(1))/(D1#(1,1)*Bst#(1)+D1#(1,2)*Bst#(2)+D1#
(1,3)*Bst#(3)-alpha)

'PRESSURE BAR 1, T>Tlim

Tlim#(1,2)=(syn#(1)/E(1)-D1#(1,1)*b#(1)-D1#(1,2)*b#(2)-
D1#(1,3)*(b#(3)+M)+epspl#(1))/(D1#(1,1)*Bst#(1)+D1#(1,2)*Bst#(2)+D1#
(1,3)*Bst#(3)-alpha)

'PRESSURE BAR 2, T>Tlim

Tlim#(2,2)=(syp#(2)/E(2)-D1#(2,1)*b#(1)-D1#(2,2)*b#(2)-
D1#(2,3)*(b#(3)+M)+epspl#(2))/(D1#(2,1)*Bst#(1)+D1#(2,2)*Bst#(2)+D1#
(2,3)*Bst#(3))

'TENSION BAR 2, T<Tlim

Tlim#(2,1)=(syn#(2)/E(2)-D1#(2,1)*b#(1)-D1#(2,2)*b#(2)-
D1#(2,3)*(b#(3)+M)+epspl#(2))/(D1#(2,1)*Bst#(1)+D1#(2,2)*Bst#(2)+D1#
(2,3)*Bst#(3))

'TENSION BAR 3, T<Tlim

Tlim#(3,1)=(syp#(3)/E(3)-D1#(3,1)*b#(1)-D1#(3,2)*b#(2)-
D1#(3,3)*(b#(3)+M)+epspl#(3))/(D1#(3,1)*Bst#(1)+D1#(3,2)*Bst#(2)+D1#

```

(3,3)*Bst#(3))
  'PRESSURE BAR 3, T>lim
    Tlim#(3,2)=(syn#(3)/E(3)-D1#(3,1)*b#(1)-D1#(3,2)*b#(2)-
D1#(3,3)*(b#(3)+M)+epspl#(3))/(D1#(3,1)*Bst#(1)+D1#(3,2)*Bst#(2)+D1#
(3,3)*Bst#(3))
  'PRINT "limits for temperature bar1 for further plastic
deformation"
  'PRINT "
                                minimum                maximum"
  'PRINT "bar-1 :      ",Tlim#(1,1), Tlim#(1,2)
  'PRINT "bar-2 :      ",Tlim#(2,1),Tlim#(2,2)
  'PRINT "bar-3 :      ",Tlim#(3,1),Tlim#(3,2)
Tmax=1E+20
Tmin=-1E+20
FOR i%=1 TO 3
  IF Tlim#(i%,2)<Tmax THEN
    Tmax=Tlim#(i%,2)
  END IF
  IF Tlim#(i%,1)>Tmin THEN
    Tmin=Tlim#(i%,1)
  END IF
NEXT i%
RETURN

*****-evaluation-
*****
evaluation:
  'T>Tmax?
  pmax(1)=0
  FOR i%=1 TO 3
    IF T>Tlim#(i%,2) AND pl(i%)=0 THEN
      IF pmax(1)=0 OR Tlim#(i%,2)<pmax(2) THEN
        pmax(1)=i%
        pmax(2)=Tlim#(i%,2)
        IF i%=2 THEN pmax(3)=1 ELSE pmax(3)=-1
      END IF
    END IF
  NEXT i%
  pmin(1)=0
  FOR i%=1 TO 3
    IF T<Tlim#(i%,1) AND pl(i%)=0 THEN
      IF pmin(1)=0 OR Tlim#(i%,1)>pmin(2) THEN
        pmin(1)=i%
        pmin(2)=Tlim#(i%,1)
        IF i%=2 THEN pmin(3)=-1 ELSE pmin(3)=1
      END IF
    END IF
  NEXT i%
  'PRINT "evaluation : "
  'PRINT "maximaltemperaturueberschreitung", pmax(1),pmax(2),pmax(3)
  'PRINT "minimaltemperaturunterschreitung",pmin(1),pmin(2),pmin(3)
  IF pmin(1)<>0 AND pmax(1)<>0 THEN
    'PRINT "-----> COLLAPSE"
    IF ET(1)=0 AND ET(2)=0 AND ET(3)=0 THEN
      STOP
    END IF
  END IF
  IF pmin(1)=0 AND pmax(1)=0 THEN
    'PRINT "-----> NO FURTHER PLASTIC DEFORMATION"

```

```

        conplast%=0
        GOSUB epsges
        GOTO ret1
    END IF
    IF pmin(1)<>0 OR pmax(1)<>0 THEN
        IF pmin(1)<>0 THEN
            pl(pmin(1))=pmin(3)
        END IF
        IF pmax(1)<>0 THEN
            pl(pmax(1))=pmax(3)
        END IF
        conplast%=1
    END IF
ret1:
RETURN

'*****-----epsges-----
'*****
epsges:
'CALCULATION OF THE TOTAL PLASTIC STRAIN, THE STRESSES AND THE LOAD
'PRINT
'TOTAL STRAIN
FOR i%=1 TO 3

    epsges#(i%)=Dl#(i%,1)*(b#(1)+Bst#(1)*T)+Dl#(i%,2)*(b#(2)+Bst#(2)*T)+Dl#(
    i%,3)*((b#(3)+M)+Bst#(3)*T)
    'PRINT epsges#(i%)
NEXT i%
'INCREMENT IN PLASTIC STRAIN
FOR i%=1 TO 3
    IF pl(i%)<>0 THEN
        IF hkind%(i%)=0 THEN
            depspl#(i%)=epsges#(i%)*(1- ET(i%)/(E(i%)+ET(i%)))-
            epspl#(i%)-pl(i%)*sy(i%)/(E(i%)+ET(i%))
        ELSE
            depspl#(i%)=(E(i%)*(epsges#(i%)-epspl#(i%))-
            pl(i%)*syp#(i%))/(E(i%)+ET(i%))
        END IF
    ELSE
        depspl#(i%)=0
    END IF
NEXT i%
IF pl(1)<>0 THEN
    IF hkind%(1)=0 THEN
        depspl#(1)=depspl#(1)-alpha*T*(1- ET(1)/(E(1)+ET(1)))
    ELSE
        depspl#(1)=depspl#(1)-E(1)*alpha*T/(E(1)+ET(1))
    END IF
END IF
FOR i%=1 TO 3
    epspl#(i%)=epspl#(i%)+depspl#(i%)
NEXT i%
S(1)=(epsges#(1)-epspl#(1)-alpha*T)*E(1)
S(2)=(epsges#(2)-epspl#(2))*E(2)
S(3)=(epsges#(3)-epspl#(3))*E(3)
F(1)=S(1)*a(1)
F(2)=S(2)*a(2)
F(3)=S(3)*a(3)

```

```

'PRINT "epsges", "stress", "load"
'PRINT epsges#(1), s(1), F(1)
'PRINT epsges#(2), s(2), F(2)
'PRINT epsges#(3), s(3), F(3)
'GOSUB sleep
RETURN

*****--curvat---
*****
curvat:
'CALCULATION OF CURVATURE
epsgesm#=(epsges#(1)-(epsges#(1)-epsges#(3)))/(y12+y23)*ys
ro#=(epsges#(1)-epsges#(3))/(y12+y23)/(epsgesm#+1)
IF ro#=0 THEN
    r#=1000000000000000#
ELSE
    r#=1/ro#
END IF
IF ABS(r#)>L THEN
    h#=SQR(r#^2-L^2/4)
ELSE
    PRINT r#, L, ro#
    h#=L/2
END IF
defl#=(ABS(r#)-h#)*SGN(r#)
RETURN

*****--new-yield-
*****
newyield:
'DETERMINATION OF THE NEW YIELD STRESSES
FOR i%=1 TO 3
    IF pl(i%)<>0 THEN
        IF hkind%(i%)=0 THEN
            'kinematic hardening
            IF i%=1 THEN
                'considering Temperature in bar
1
                IF pl(i%)=1 THEN
                    'tension
syp#(i%)=E(i%)*ET(i%)/(E(i%)+ET(i%))*epsges#(i%)+(sy(i%)-
alpha*T*ET(i%))*E(i%)/(E(i%)+ET(i%))
                    syn#(i%)=syp#(i%)-2*sy(i%)
                ELSE
                    'pressure
syn#(i%)=E(i%)*ET(i%)/(E(i%)+ET(i%))*epsges#(i%)+(-sy(i%)-
alpha*T*ET(i%))*E(i%)/(E(i%)+ET(i%))
                    syn#(i%)=syn#(i%)+2*sy(i%)
                END IF
            ELSE
                'other bars (without thermal
                strain)
                IF pl(i%)=1 THEN
                    'tension
syp#(i%)=E(i%)*ET(i%)/(E(i%)+ET(i%))*epsges#(i%)+(sy(i%))*E(i%)/(E(i%)+E
T(i%))
                    syn#(i%)=syp#(i%)-2*sy(i%)
                ELSE
                    'pressure
syn#(i%)=E(i%)*ET(i%)/(E(i%)+ET(i%))*epsges#(i%)+(-
sy(i%))*E(i%)/(E(i%)+ET(i%))

```

```

        syp#(i%)=syn#(i%)+2*sy(i%)
    END IF
END IF
ELSE      'isotropic hardening
    IF pl(i%)<>0 THEN
        syp#(i%)=syp#(i%)+ET(i%)*ABS(depspl#(i%))
        syn#(i%)=syn#(i%)-ET(i%)*ABS(depspl#(i%))
        'PRINT "new yield stresses: ",syp#(i%),syn#(i%)
    END IF
END IF
END IF
NEXT i%
'PRINT
'PRINT "neue Streckgrenze:"
'FOR i%=1 TO 3
    'PRINT "Balken ",i,syp#(i%),syn#(i%)
'NEXT i%
'GOSUB sleep
RETURN

'*****--control---
'*****
control:
    'CONTROL OF RESULTS
    'GEOMETRIE
        IF y23*epsges#(1)-(y12+y23)*epsges#(2)+y12*epsges#(3)<>0
THEN
            PRINT "Geometry: ",y23*epsges#(1)-
(y12+y23)*epsges#(2)+y12*epsges#(3);" <> 0"
            ELSE
                PRINT "Geometry ", "ok"
            END IF
        'LOAD
            IF F(1)+F(2)+F(3)<>0 THEN
                PRINT "Load: ",F(1)+F(2)+F(3);" <> 0"
            ELSE
                PRINT "Load ", "ok"
            END IF
        'MOMENT
            IF -ys*F(1)+(y12-ys)*F(2)+(y12+y23-ys)*F(3)<>M THEN
                PRINT "Moment: ",-ys*F(1)+(y12-ys)*F(2)+(y12+y23-
ys)*F(3);" <>";M
            ELSE
                PRINT "Moment ", "ok"
            END IF
        'STRESS-STRAIN
RETURN

'*****----graph---
'*****

graph:
    CLS
    GOSUB control
    fact=10000&
    'GRAPHIC PRESENTATION OF THE RESULTS
    LOCATE 1,40
    PRINT "Temperature      :";T

```

```

LOCATE 2,40
PRINT "Moment                ":";M
LOCATE 3,40
PRINT "cycle Nr.            ":";cycl%
LOCATE 4,40
PRINT "total plastic strain in bar 1 : ";epspl#(1)
LOCATE 5,40
PRINT "total plastic strain in bar 3 : ";epspl#(3)

'middle line
  LINE (320, (-ys)*10+190)-(320, (y12+y23-ys)*10+210)      'Middle Line

'bar 1
  'total elastic strain
  LINE (320, -ys*10+190)-(320+fact*epsges#(1), -ys*10+190)
  LINE (320, -ys*10+210)-(320+fact*epsges#(1), -ys*10+210)
  LINE (320+fact*epsges#(1), -ys*10+210)-(320+fact*epsges#(1), -
ys*10+190)
  'thermal strain
  LINE (320+fact*epsges#(1), -ys*10+200)-(320+fact*(epsges#(1)-
alpha*T), -ys*10+200)
  LINE (320+fact*(epsges#(1)-alpha*T), -ys*10+207)-
(320+fact*(epsges#(1)-alpha*T), -ys*10+193)
  'plastic strain
  LINE (320+fact*(epsges#(1)-alpha*T), -ys*10+207)-
(320+fact*(epsges#(1)-alpha*T-epspl#(1)+depspl#(1)), -ys*10+207)
  LINE (320+fact*(epsges#(1)-alpha*T), -ys*10+193)-
(320+fact*(epsges#(1)-alpha*T-epspl#(1)+depspl#(1)), -ys*10+193)
  'increment in plastic strain
  LINE (320+fact*(epsges#(1)-alpha*T-epspl#(1)+depspl#(1)), -
ys*10+200)-(320+fact*(epsges#(1)-alpha*T-epspl#(1)), -ys*10+207)
  LINE (320+fact*(epsges#(1)-alpha*T-epspl#(1)+depspl#(1)), -
ys*10+200)-(320+fact*(epsges#(1)-alpha*T-epspl#(1)), -ys*10+193)
  LINE (320+fact*(epsges#(1)-alpha*T-epspl#(1)), -ys*10+193)-
(320+fact*(epsges#(1)-alpha*T-epspl#(1)), -ys*10+207)
  'elastic strain
  LINE (320+fact*(epsges#(1)-alpha*T-epspl#(1)), -ys*10+196)-(320, -
ys*10+204)
  LINE (320+fact*(epsges#(1)-alpha*T-epspl#(1)), -ys*10+204)-(320, -
ys*10+196)

'bar 2
  'total elastic strain
  LINE (320, (-ys+y12)*10+190)-(320+fact*epsges#(2), (-ys+y12)*10+190)
  LINE (320, (-ys+y12)*10+210)-(320+fact*epsges#(2), (-ys+y12)*10+210)
  LINE (320+fact*epsges#(2), (-ys+y12)*10+210)-(320+fact*epsges#(2),
(-ys+y12)*10+190)
  'plastic strain
  LINE (320+fact*(epsges#(2)), (-ys+y12)*10+207)-(320+fact*(epsges#(2)-
epspl#(2)+depspl#(2)), (-ys+y12)*10+207)
  LINE (320+fact*(epsges#(2)), (-ys+y12)*10+193)-(320+fact*(epsges#(2)-
epspl#(2)+depspl#(2)), (-ys+y12)*10+193)
  'increment in plastic strain
  LINE (320+fact*(epsges#(2)-epspl#(2)+depspl#(2)), (-ys+y12)*10+200)-
(320+fact*(epsges#(2)-epspl#(2)), (-ys+y12)*10+207)
  LINE (320+fact*(epsges#(2)-epspl#(2)+depspl#(2)), (-ys+y12)*10+200)-
(320+fact*(epsges#(2)-epspl#(2)), (-ys+y12)*10+193)

```



```

      LINE (320+fact*(epsges#(2)-epspl#(2)), (-ys+y12)*10+193)-
(320+fact*(epsges#(2)-epspl#(2)), (-ys+y12)*10+207)
      'elastic strain
      LINE (320+fact*(epsges#(2)-epspl#(2)), (-ys+y12)*10+196)-(320,
(-ys+y12)*10+204)
      LINE (320+fact*(epsges#(2)-epspl#(2)), (-ys+y12)*10+204)-(320,
(-ys+y12)*10+196)

'bar 3
      'total elastic strain
      LINE (320, (-ys+y12+y23)*10+190)-(320+fact*epsges#(3),
(-ys+y12+y23)*10+190)
      LINE (320, (-ys+y12+y23)*10+210)-(320+fact*epsges#(3),
(-ys+y12+y23)*10+210)
      LINE (320+fact*epsges#(3), (-ys+y12+y23)*10+210)-
(320+fact*epsges#(3), (-ys+y12+y23)*10+190)
      'plastic strain
      LINE (320+fact*(epsges#(3)), (-ys+y12+y23)*10+207)-
(320+fact*(epsges#(3)-epspl#(3)+depspl#(3)), (-ys+y12+y23)*10+207)
      LINE (320+fact*(epsges#(3)), (-ys+y12+y23)*10+193)-
(320+fact*(epsges#(3)-epspl#(3)+depspl#(3)), (-ys+y12+y23)*10+193)
      'increment in plastic strain
      LINE (320+fact*(epsges#(3)-epspl#(3)+depspl#(3)),
(-ys+y12+y23)*10+200)-(320+fact*(epsges#(3)-epspl#(3)),
(-ys+y12+y23)*10+207)
      LINE (320+fact*(epsges#(3)-epspl#(3)+depspl#(3)),
(-ys+y12+y23)*10+200)-(320+fact*(epsges#(3)-epspl#(3)),
(-ys+y12+y23)*10+193)
      LINE (320+fact*(epsges#(3)-epspl#(3)), (-ys+y12+y23)*10+193)-
(320+fact*(epsges#(3)-epspl#(3)), (-ys+y12+y23)*10+207)
      'elastic strain
      LINE (320+fact*(epsges#(3)-epspl#(3)), (-ys+y12+y23)*10+196)-(320,
(-ys+y12+y23)*10+204)
      LINE (320+fact*(epsges#(3)-epspl#(3)), (-ys+y12+y23)*10+204)-(320,
(-ys+y12+y23)*10+196)

```

RETURN

```

'*****-----file-----
*****

```

```

file:
FOR hk%=hkb% TO hke%
  IF hk%=0 THEN
    hard$="k"
  ELSE
    IF hk%=1 THEN
      hard$="i"
    ELSE
      hard$="e"
    END IF
  END IF
FOR ckind%=lcb%TO lce%
  FOR i%=1 TO 100
    FOR j%=1 TO 8
      erg$(i%,j%)=""
    NEXT j%
  NEXT i%

```

```

FOR i%=1 TO 200
    r$(i%,1)=" "
    r$(i%,2)=" "
NEXT i%
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_p.dat" FOR INPUT AS #1
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_c.dat" FOR INPUT AS #2
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_r.dat" FOR INPUT AS #3
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_r2.dat" FOR INPUT AS
#4
OPEN file$+RIGHT$(STR$(ckind%),1)+hard$+"_a.dat" FOR OUTPUT AS
#5
i%=0
10 :
    i%=i%+1
    INPUT #1, erg$(i%,1),erg$(i%,2)
    INPUT #2,a$,b$
    erg$(i%,3)=b$
    IF EOF(1)=0 THEN GOTO 10
    max%=i%
    i%=0
20 :
    i%=i%+1
    INPUT #3,r$(i%,1),r$(i%,2)
    INPUT #4,a$,r$(i%,3)
    IF EOF(3)=0 THEN GOTO 20
    az%=(i%+1)/2
    FOR i%=1 TO az%
        erg$(i%,4)=r$(i%,1)
        erg$(i%,5)=r$(i%,2)
        erg$(i%,6)=r$(i%,3)
        erg$(i%,7)=r$(i%+az%-1,1)
        erg$(i%,8)=r$(i%+az%-1,2)
        erg$(i%,9)=r$(i%+az%-1,3)
    NEXT i%
    erg$(1,7)=r$(1,1)
    erg$(1,8)=r$(1,2)
    erg$(1,9)=r$(1,3)
    IF az%>max% THEN
        max%=az%
    END IF
    FOR i%=1 TO max%
        PRINT
#5,erg$(i%,1);",";erg$(i%,2);",";erg$(i%,3);",";erg$(i%,4);",";erg$(
(i%,5);",";erg$(i%,6);",";erg$(i%,7);",";erg$(i%,8);",";erg$(i%,9)
    NEXT i%
    CLOSE #1
    CLOSE #2
    CLOSE #3
    CLOSE #4
    CLOSE #5
NEXT ckind%
NEXT hk%
RETURN

Fils:
OPEN file$+"_s.dat" FOR OUTPUT AS #1
FOR i%=1 TO 100

```

```

        FOR j%=1 TO 12
            erg$(i%,j%)=""
        NEXT j%
    NEXT i%
    FOR ckind%=lcb% TO lce%
        OPEN file$+RIGHT$(STR$(ckind%),1)+"e"+"_s.dat" FOR INPUT AS #2
        OPEN file$+RIGHT$(STR$(ckind%),1)+"k"+"_s.dat" FOR INPUT AS #3
        OPEN file$+RIGHT$(STR$(ckind%),1)+"i"+"_s.dat" FOR INPUT AS #4
        i%=0
11 :
        i%=i%+1
        IF ckind%=1 THEN
            INPUT #2, erg$(i%,1),erg$(i%,2)
            INPUT #3, a$,b$
            erg$(i%,3)=b$
            INPUT #4,a$,b$
            erg$(i%,4)=b$
        ELSE
            IF ckind%=5 THEN
                INPUT #2,erg$(i%,14),erg$(i%,15)
                INPUT #3,a$,b$
                erg$(i%,16)=b$
                INPUT #4,a$,b$
                erg$(i%,17)=b$
            ELSE
                INPUT #2, a$,b$
                erg$(i%,ckind%*3-1)=b$
                INPUT #3, a$,b$
                erg$(i%,ckind%*3)=b$
                INPUT #4,a$,b$
                erg$(i%,ckind%*3+1)=b$
            END IF
        END IF
        IF EOF(2)=0 THEN GOTO 11
        CLOSE #2
        CLOSE #3
        CLOSE#4
    NEXT ckind%
    max%=i%
    FOR i%=1 TO max%
        PRINT
        #1,erg$(i%,1);",";erg$(i%,2);",";erg$(i%,3);",";erg$(i%,4);",";erg$(
        i%,5);",";erg$(i%,6);",";erg$(i%,7);",";erg$(i%,8);",";erg$(i%,9);",";e
        rg$(i%,10);",";erg$(i%,11);",";erg$(i%,12);
        PRINT
        #1,"",";erg$(i%,13);",";erg$(i%,14);",";erg$(i%,15);",";erg$(i%,16);",";e
        rg$(i%,17)
    NEXT i%
    CLOSE #1
    RETURN

*****-----time-----
*****
time:
    LOCATE 10,10
    mon=VAL(LEFT$(DATE$,2))
    day =VAL(MID$(DATE$,4,2))

```

```

hour=VAL(LEFT$(TIME$,2))
min=VAL(MID$(TIME$,4,2))
sec=VAL(RIGHT$(TIME$,2))
IF mon0=mon THEN
    time=(day-day0)*24*60+(hour-hour0)*60+(min-min0)+(sec-sec0)/60
ELSE
    time=(days(mon0)-day0+day)*24*60+(hour-hour0)*60+(min-min0)+(sec-sec0)/60
END IF
PRINT USING "###.### % ready      aprox. time to go: ###.##
min";azread/total*100,((time)*(total/azread-1))
PRINT USING "                      time : ###.## min";time
RETURN

'*****-----sleep-----
*****
sleep:
LOCATE 26,5
PRINT "press any key"
    loop:
        IF INKEY$="" THEN loop
RETURN

```

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