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Background of Advanced Procedures for Strength Assessment of WWER Equipment and Piping

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ABSTRACT : Advanced procedures for strength assessment of nuclear power plant (NPP) components when strain and stresses are calculated by finite element elastic-plastic methods. The criterion for the lower bound collapse load C_L is discussed. Problems with using of new materials for NPP components are· shown. Influence of residual stresses on strength and lifetime structures is shown.

1 INTRODUCTION

The Association of Mechanical Engineers of the Czech Republic performed the CAME STD Section III [3]. The CAME STD Section I [1] and Section II [2] will be issued in this year. The CAME STD Section IV [4] is negotiated. These CAME STDs are based on the Eastern standard for WWER Nuclear Power Plants, their philosophy is very closed to the ASME Code, Section III [5]. All modifications of the CAME STDs were aimed at a gradually bringing they near to the specifications of the Western Standards namely to the ASME Code, Section III [5]. Advanced procedures have to enable the more accessible using of elastic-plastic strain and stress analyses by finite element methods (FEM).

2 ASSESSMENT ON A STATIC STRENGTH AND ON FATIGUE

The standards usually prefer an elastic strain and stress analysis for which the principle of superposition is valid. It enables easy calculations of all stress categories : σ_m (P_m) - general membrane, σ_{mL} (P_L) - local membrane, σ_b (P_b) - general bending, σ_{bL} (Q) - local bending, σ_T (Q) - general thermal, σ_K (σ_{mK}, σ_{bK}, τ_{kK}; Q) - compensating thermal stresses, due to restriction of piping thermal expansion, σ_{TL} (F) - local thermal, (α_H-1) σ_n (F) - increment of the stress in the region of the local structures discontinuity, α_H - theoretical stress concentration factor, σ_n - nominal stress (σ_m or σ_{mL}) + σ_b + σ_{bL} + σ_T + σ_K.

Stress analyses using finite element methods determine stresses with an influence of a stress concentration factor at notches. Procedures for determination of all stress components (σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{zx}) in the structure cross section are described in [6]. They are used in our program STATES for assessment of limit states in accordance with [3] and [5]. A difficulty with determination of all stress categories can be, when the elastic-plastic stress analysis by finite element methods is used, then the principle of superposition is not valid, Fig. 1. The sum of the stress $\sigma = f(p)$ due to mechanical loads with the stress $\sigma = f(T)$ due to temperature field are not equal to stress $\sigma = f(p,T)$ due to simultaneously effected mechanical loads and temperature field, when elastic-plastic analysis is used.

New procedures inserted to CAME STD Section III [3] enable easy using of elastic-plastic analyses for stress calculation and assessment of limit states. This access is enabled thanks definition of the stress category groups $(\sigma)_1$, $(\sigma)_2$, $(\sigma)_R$ and (σ_{aF}) in Eastern standards [3] and [7]. Values of these $(\sigma)_1$, $(\sigma)_2$, $(\sigma)_R$ and (σ_{aF}) mean the equivalent stress intensity values calculated using the maximum shear stress theory. The HMH theory is possible to use for non-nuclear power plant components.

1) The stress category groups $(\sigma)_1$ and $(\sigma)_2$ are calculated from nominal (linear distribution in the structure cross section) stresses due to mechanical loads :

$$(\sigma)_1 = \sigma_m \tag{1}$$

$$(\sigma)_2 = (\sigma_m \text{ or } \sigma_{mL}) + \sigma_b \tag{2}$$

Membrane stress σ_m is possible calculate using the membrane theory. The σ_m is defined as the component of normal stress which is uniformly distributed and equal to the average value of the stress across of the structure cross section.

The values $(\sigma)_2$ are calculated for load conditions, when at least one from all six tensor stress components reaches the local extreme during service time. Steps of calculation are following :

a) Elastic or elastic-plastic analysis of strain and stresses due to mechanical loads by the FEM in used.
b) Selection of the most stressed structure parts.
c) Calculation of linear distributed equivalent stresses in the structure cross section from non-linear distributed stresses, determined by the FEM. Both stress distributions have the same resultant forces F and moments M.
d) Determination of principal stresses in the more stressed points of the structure cross section. This points are usually located on the surface of the structure.
e) Calculation of the equivalent stress intensity value $(\sigma)_2$ from principal stresses.

2) The stress category group $(\sigma)_R$ (range of stresses) is equal to the difference of algebraic max. and min. values of the equivalent stress intensity values $(\sigma_n)_{max}$, $(\sigma_n)_{min}$ due to mechanical loads and a temperature field for all service live, Fig. 2.

$$(\sigma)_R = (\sigma_n)_{max} - (\sigma_n)_{min} = (\Delta\sigma_m \text{ or } \Delta\sigma_{mL}) + \Delta\sigma_b + \Delta\sigma_{bL} + \Delta\sigma_T + \Delta\sigma_K \tag{3}$$

Steps of calculations are following :

a) Elastic or elastic-plastic analysis of strain and stresses due to simultaneously affecting mechanical loads and a temperature field by the FEM in used.
b) c) d) are the same as above.
e) Calculation of the equivalent stress intensity values of (σ_n) from principal stresses and determination of the $(\sigma_n)_{max}$ and $(\sigma_n)_{min}$.
f) Determination of the $(\sigma)_R$ using Eg. (3). The values $(\sigma_n)_{max} \geq 0$ and $(\sigma_n)_{min} \leq 0$ are used for calculation of the $(\sigma)_R$.

The procedure of the CAME STD Section III [3] does not require calculation of single stress categories, but it only requires calculation of stress category groups $(\sigma)_1$ and $(\sigma)_2$ due to mechanical loads and $(\sigma)_R$ due to mechanical loads and temperature field, see Fig. 3. The Fig. 3 was inserted to the CAME STD Section III [3].

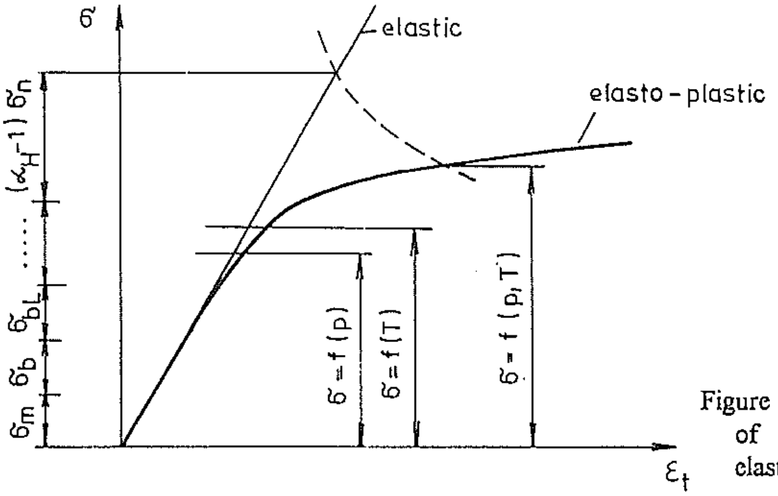


Figure 1. The validity of the principe of superposition when elastic or elastic-plastic analyses are used.

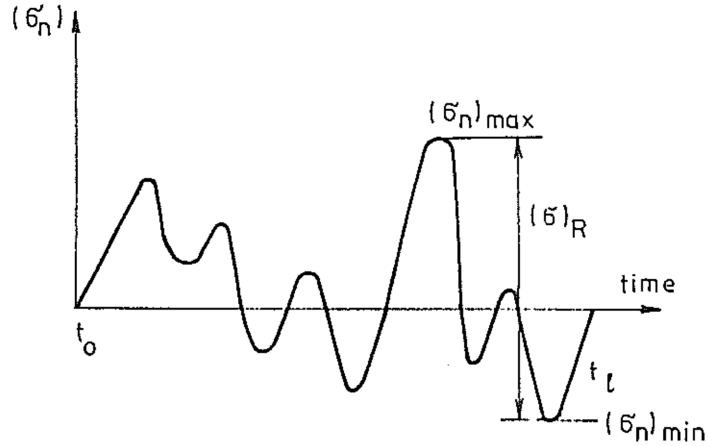


Figure 2. Determination of the range of stresses $(\sigma)_R$

3) The stress category group (σ_{aF}) means the amplitude of the fictitious stress $(\sigma_{aF}) = E \cdot (\varepsilon_{at})$, where E is Young's modulus. The equivalent total (elastic plus plastic) strain intensity amplitude (ε_{at}) due to mechanical loads and a temperature field is calculated by the elastic-plastic analysis FEM. The elastic analysis (σ_H) together with approximately determination (ε_{at}) from (σ_H) by the Number's rule is possible use too. The relationships for determination of the allowed number of cycles are shown in the [8].

$(\sigma)_1$	$(\sigma)_2$	$(\sigma)_R$	(σ_{aF})
$\leq k\,[\sigma]$	$\leq k\,k_1\,[\sigma]$ or $0.67\,k\,C_L$	$\leq \min\,\{2.5 - S_y/S_u;\ 2\}\,S_y$	$\leq [\sigma_{aF}]$

Figure 3. Assessment of stress category groups; k = 1 for NOC - normal operation conditions, k = 1.2 for AOC - abnormal operation conditions, k = 1.4 for FC - faulted conditions; $k_1 = 0.87\ W_p/W_e$, where W_p - plastic section modulus, W_e - elastic section modulus, $k_1 = 1.3$ for square or rectangular shapes of the section; allowed design stress $[\sigma] = \min\,\{S_y/1.5;\ S_u/2.6\}$.

3 THE CRITERION FOR THE LOWER BOUND COLLAPSE LOAD

Cases are known, that wall thickness of nuclear pressure vessel is designed using of national standards for classical stable pressure vessels. The design of wall thickness in accordance with the Czech standard CSN 690010 for classical stable pressure vessels is based on a plastic limit state. Three plastic hinges origin in the gross discontinuity area in this case, Fig. 4 and 6. Standards for nuclear power plant components admit only one plastic hinge in this area, when first assessment step, $(\sigma)_2 \leq k\, k_1\, [\sigma]$, [3] is used.

Usability of these pressure vessels is possible to prove using the criterion 0.67 k C_L, Fig. 3, [3] and [5]. Definition of the lower bound collapse load C_L is shown on the Fig. 5. The condition $\varepsilon_e = \varepsilon_p$ for determination of the C_L can be very strict for notches or gross discontinuity areas. The standards usually give any instructions for these cases. One case is shown on the Fig. 4 and Fig. 7.

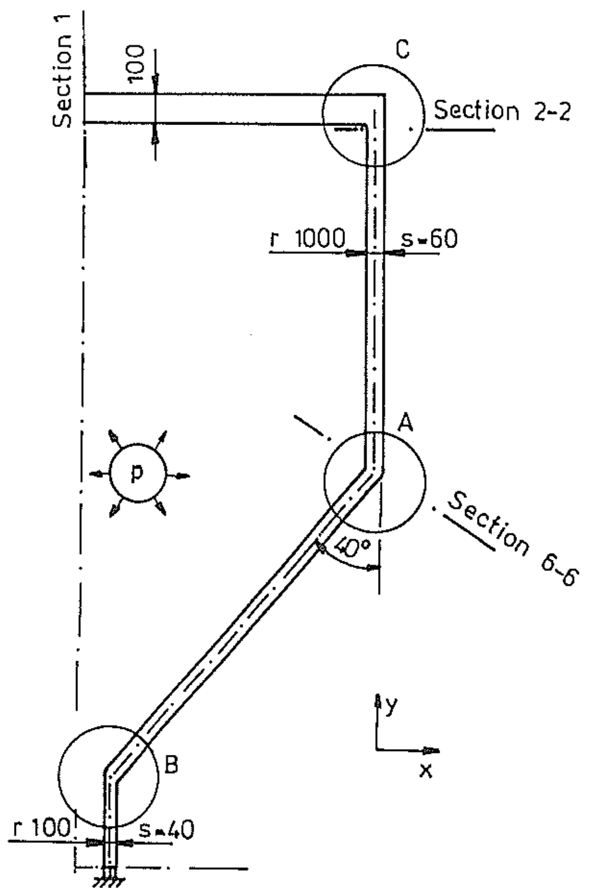


Figure 4. Analysed pressure vessel with gross discontinuity areas A, B, C loaded by a press p

Redistribution of the equivalent stress (σ) and strain (ε_t) intensities in the cross section 6-6 (Fig. 4) is shown on the Fig. 7. The condition $\varepsilon_e \leq \varepsilon_p$ does not fulfilled at the inner layer of 1.9 mm for p = 10.1 MPa and the layer of 6.35 mm for p = 15.1 MPa. The total strains are (ε_t) = 0.0105 for p = 15.1 MPa and (ε_t) = 0.00412 for p = 10.1 MPa. These values of the (ε_t) origin only in the first half cycle $0 \rightarrow p \rightarrow 0$. The amplitude of strain (ε_{at}) in the following cycles $0 \rightarrow p \rightarrow 0$ is approximately equal to $(\varepsilon_t)/4$.

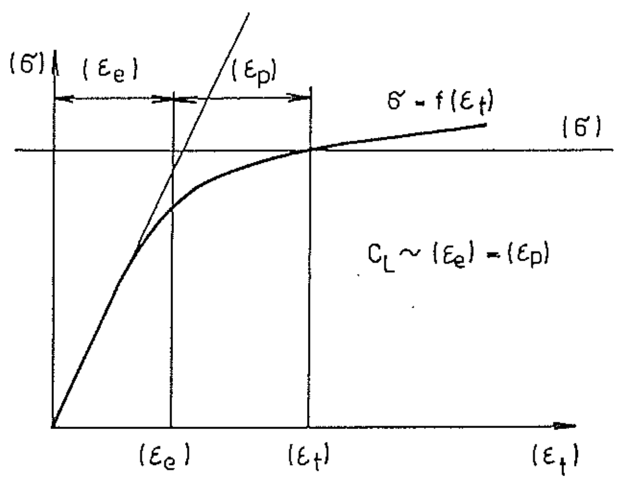


Figure 5. The criterion for the lower bound collapse load C_L

The allowed number of cycles $[N_o]$ for the continuously varying load

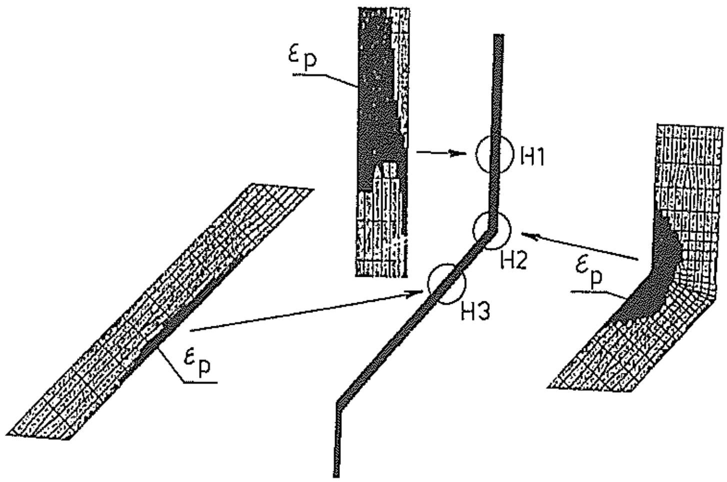


Figure 6. Redistribution of plastic strain ε_p in the gross discontinuity area; p = 19.1 MPa

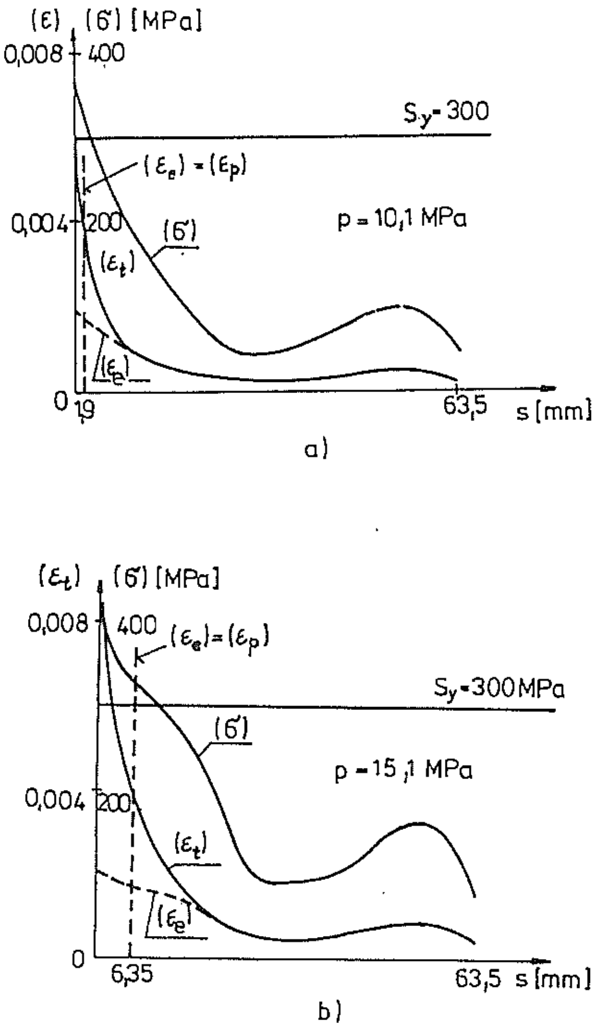
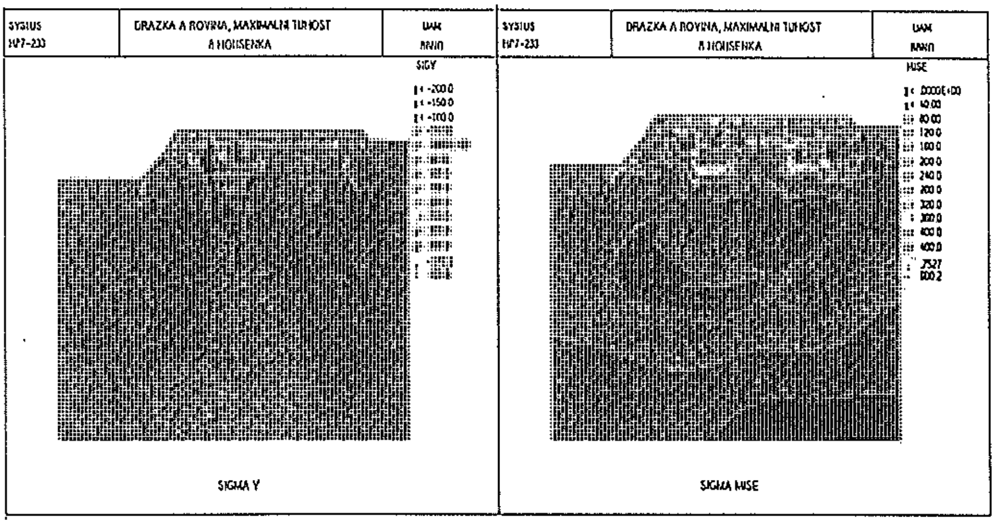


Figure 7. Redistribution of the equivalent stress (σ) and strain (ε_t), (ε_e) intensity values in the structure cross section 6-6, see Fig. 5

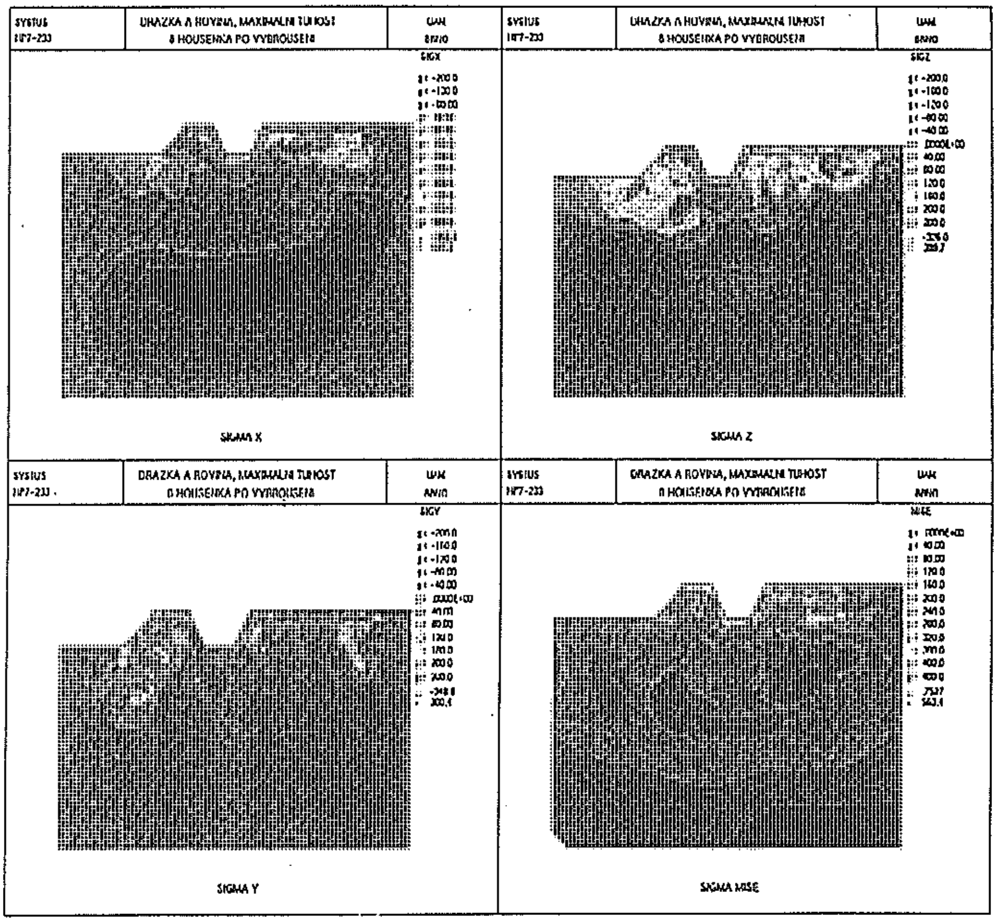
$0 \rightarrow p \rightarrow 0$ was calculated using the CAME STD Section III [3] assessment on fatigue. The $[N_o]$ = 2840 cycles was calculated for Δp = 15.1 MPa and the $[N_o]$ = 34850 cycles was calculated for Δp = 10.1 MPa, both by program STATES [8].

The condition $\varepsilon_c \geq \varepsilon_p$ for determination of C_L is demanded in the wall depth bigger than s/10, where s is thickness of the wall. Value of the s/10 is thickness of the surface layer, where can be $\varepsilon_p > \varepsilon_c$. The C_L = 15.1 MPa and s/10 = 63.5/10 = 6.35 mm are for our example, Fig. 7.

The load 0.67 C_L = 0.67 x 15.1 = = 10.1 Mpa is allowed load for the stress category group $(\sigma)_2$. Number of cycles n of the press range Δp = 10.1 MPa during all assumed life time of the structure must be less than $[N_o]$ = 34850 cycles. Possibility of crossing of the $\varepsilon_c = \varepsilon_p$ condition in the surface layer is restricted by an assessment on fatigue. It is in accordance with CAME STD Section III [3].



a)



b)

Figure 8. Distribution of residual stresses calculated by the program SYSWELD. The repaid area of the top part of the steam generator collector with the sealing slot; a) after welding of eight beats; b) after cutting of the slot.

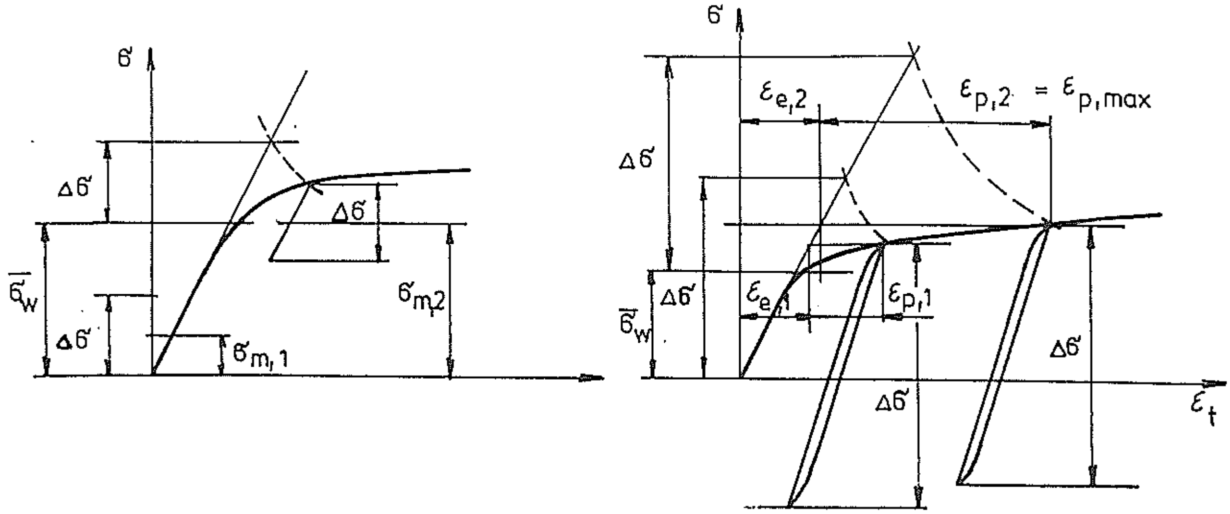


Figure 9. Influence of residual stresses $\overline{\sigma}_W$ due to welding; a) high cyclic fatigue; b) low cyclic fatigue

4 MATERIAL CHARACTERISTICS

The main problems with the CAME STD Section I [1] and Section II [2] are concentrated in the fact that only soviet type materials were allowed for use in WWER NPPs according to the former Soviet codes [7]. These steels, however, were manufactured in the Czech Republic under a mastered and im-safety supporting know-how. In this time, some of these materials are no longer produced domestically, now their import is sometimes complicated or even impossible.

The CAME STD Section I [1] and Section II [2] define conditions which must be fulfilled if a new material could be added into the list of allowable materials.

The databank of mechanical and physical characteristics of materials used for a manufacture of power plant components and pipeline was created. Measured raw characteristics are inserted into the databank. Coefficients of design fatigue curves, quantities of fracture mechanics and other are determined from these characteristics. Standard procedures are used for their determination. This databank has its manager.

5 INFLUENCE OR RESIDUAL STRESSES IN WELDS ON STRENGTH AND LIFETIME OF COMPONENTS

Residual stresses $\overline{\sigma}_W$ after welding have influence on strength and lifetime of components. We use the programme SYSWELD for determination of a material structure and residual stresses [9]. Residual stress have very complicated distribution in the weld area, Fig. 8 [10]. Their influence on strength and lifetime of structure is usually unfavourable. It is shown on the Fig. 9 for a high cyclic fatigue (influence of middle stress σ_m), and for a low cyclic fatigue (influence plastic strain $\varepsilon_{p,max}$). Residual stresses can cause a sadden fracture of static loaded structures with the crack, when the temperature decrease under the temperature T_{NDT}.

6 CONCLUSION

Definition of the stress category group $(\sigma)_1$, $(\sigma)_2$, $(\sigma)_R$ and (σ_{aF}) enables currently to use elastic-plastic analyses of strain and stresses by the FEM. The strain and stresses are calculated at first for mechanical loads for assessment of the $(\sigma)_1$, $(\sigma)_2$ and at second for simultaneously affecting mechanical loads and temperature field.

The criterion $\varepsilon_e = \varepsilon_p$ for determination of the lower bound collapse load C_L is possible to cross ($\varepsilon_p > \varepsilon_e$) in the surface layers (less then s/10, where s is thickness of wall) when condition for assessment on fatigue is fulfilled.

Influence of residual stresses calculated by the program SYSWELD on fatigue and resistance against sadden fracture is estimated by the CAME STDs Section III and Section IV.

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