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ASME AND RCC-MR COMPARISON FOR THE PREVENTION OF FATIGUE ANALYSIS

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INTRODUCTION

The purpose of this survey is to compare the simplified methods, without reference to the safety factor allowed for the mechanical properties. An application of both codes, RCC-MR and ASME, on the design of the wall mock-up of the NET project is made and also an estimation with an elastoplastic analysis.

In the case of fatigue analysis according to ASME in the plastic field, the elastic stress is magnified by a K_e factor derived from stress variation, S_n, disregarding geometrical discontinuities. According to RCC-MR, the elastic maximum strain will magnified by two coefficients accounting for plasticity and variation of Poisson ratio.

EXPERIMENTAL MOCK UP AND CALCULATION

The model is formed of a plate which is 500 mm long, 240 mm wide, and 33 mm thick. It is fastened, on two sides, through two plates which are 120 mm height (figure 1). On the top face, the model is submitted to a thermal flux whose maximal value is 0.7 MW/m^2. The heat is evacuated through a cold water circuit (15°C) machined inside the wall. The front part of the model is shown on figure 1; thermal transient and limit conditions are shown on figure 2. A bi-dimensional plane pattern of the model, in height direction, has been used. The network, shown on figure 1, includes:

- the wall,
- the noses for hanging the tiles,
- the joining and fastening of the model.

The model is symmetrical versus y-z plane; its right half is taken as pattern accordingly. The network, built with the GIBI code, comprises 1 858 nodes, 499 elements with 8 nodes, and 58 elements with 6 nodes. Nine nodes represent the minimal thickness between the top face and the tubing. This allows to calculate with sufficient accuracy the gradients of thermal peaks. The curves of temperature evolution versus curvilinear abscissa do not show discontinuities in this area. Therefore the network thinness is appropriate.
The wall is made in 316L EDF SPH steel and for Young's moduli and thermal dilatation coefficient at different temperatures come from RCC-MR IS material.

The thermal transient is shown on figure 3.

The heat flux is linearly increased from the initial value of 0.05 MW/m^2 up to the maximum value of 0.7 MW/m^2 during 60 secs, and it is held during 10 seconds before decreasing. In the technical appendix of the Net Contract, it is required to get stationary conditions for the different phases of the transient. With a rise time of 60 secs, and the normal decreasing time, it appears that, in order to get the permanent status, it is necessary to maintain the flux during 10 secs at levels of 0.7 MW/m^2 and 40 secs at level 0.05 MW/m^2.

The loading deals with temperature distribution versus time, coming from thermal calculation.

Displacements on x axis are disabled for hanging nose opposite to foot, in order to simulate the symmetry. The 8 nodes of the foot have their displacements and rotations disabled, in order to simulate embedded conditions.

Calculations are performed in generalised plane deformation. The deformation ε_z is given by:

$$\varepsilon_z = U_z + \Theta_x (y - y_o) + \Theta_y (x - x_o)$$

where x_o, y_o centre of inertia coordinates of the model

and $\Theta_x = 0, \quad \Theta_y = 0, \quad N_z = 0.$

For thermal calculation, the DELFINE code of CASTEM has been used.

For mechanical calculations, the INCA code of CASTEM system has been used.

The main results of thermal and mechanical elastic analyses are:

- the evolutions of temperature (figure 4 in Section 1), versus curvilinear abscissa for the first part of the transient (the rise and the flat top),
- the evolutions of Von Mises's stress (figure 5 in Section 1) versus curvilinear abscissa (same transient).

The Section 1 is the most loaded section.

LOW TEMPERATURE SIMPLIFIED ELASTOPLASTIC ANALYSIS

The field of application for the both codes ASME Section III and the RCC-MR comprises neither crack-like defects nor bolting. Creep shall not be significant. Maximum temperature thecycle is at 425°C for the ASME and a negligible creep curve indicates maximum temperature versus time for the RCC-MR. The equivalent stress is calculated using the TRESCA criterion for ASME and TRESCA or VON MISES criterion for RCC-MR. For each load cycle, the equivalent stress variation is calculated as follows:

ASME

$S_p = \Delta(\overline{P_L+P_b+Q+F})$

Under plastic conditions for stress S_p to be included in the fatigue curves, it has to be magnified by a factor calculated as follows:

. If $S_n = \Delta(P_L+P_b+Q) < 3S_m$ $\qquad K_e = 1$

. If $3S_m < S_n < 3mS_m$ $\qquad K_e = 1. + \frac{1-n}{n(m-1)} \left(\frac{S_n}{3S_m} - 1\right)$

. If $S_n > 3m\ S_m$

$K_e = 1/n$
$n = 0.3$)
$m = 1.7$) for austenitic steels
$S_a = K_e\ S_p$
or
$E.\overline{\Delta\varepsilon}_{alt} = K_e\ S_p$.

RCC-MR

$$\overline{\Delta\sigma}_{tot} = \Delta(\overline{P_L+P_b+Q+F})$$

Using this result, the real strain equivalent variation is estimated at each point in the structure, by the following process:

For each load cycle, the cyclic curve corresponding to the highest temperature at the point considered shall be retained. The elastic equivalent strain can then be assessed:

$$\Delta\varepsilon_1 = 2/3\ \frac{1+\nu}{E}\ (\Delta\sigma_{tot})$$

Under plastic conditions, the real strain is assessed as follows, provided there has been no strain augmentation due to primary stress variations.

$$\overline{\Delta\varepsilon} = (K_\varepsilon+K_\nu-1)\ \overline{\Delta\varepsilon_1} \qquad \text{or} \qquad \overline{\Delta\varepsilon} = (K_\varepsilon+K_\nu-1)\ \frac{2}{3}\ \frac{1+\nu}{E}\ (\Delta\sigma_{tot})$$

where K_ε is the strain plastic augmentation due to the nonlinearity between stress and strain (Neuber rule) and K_ν is the strain plastic augmentation due to the biaxiality ($\nu = 0.3$ in the elasticity and becomes 0.5 in the plasticity).

K_ε and K_ν are calculated using $\Delta\varepsilon_1$.

$$K_e \equiv (K_\varepsilon + K_\nu - 1)2/3(1 + \nu).$$

The fatigue usage factors $U_1(\Delta\sigma)$ for the ASME and $U_1(\Delta\varepsilon)$ for the RCC-MR shall be calculated from the fatigue curves.

REMARKS ON DESIGN RULES

According to ASME, the fatigue analysis is grounded on a cyclic stress assessment. In the plastic field, this stress is magnified by a factor K_e, derived from stress variation S_n, disregarding geometrical discontinuities. It shall be noted that the factor K_e is independent of the stress state, with a 20°C and 425°C and identical for all austenitic steels. It equals 1 if S_n is below S_y, whereas the material is already under plastic conditions. According to the RCC-MR, the fatigue analysis is based on a cyclic strain assessment. Under plastic conditions, this strain will be increased by two coefficients: K_ε nonlinearity between plasticity and elasticity, and K_ν, variation of the ν coefficient. These two coefficients are dependent on total strain and temperature of the material. Figure 6 shows factor K_e versus the nominal stress $S_n = \Delta(P+Q)$. It will be noted that the ASME code deals very severely with S_n values exceeding S_y. For the RCC-MR to show greater severity, the stress peaks have to reach 7 times the nominal stress. On the other hand, for S_n values below S_y, the ASME code considers the material to be elastic.

DAMAGE ANALYSIS

The maximum temperature is 407°C. Creep is neglectible, according to ASME and RCC-MR. Fatigue is the preponderant damage.

The analysis is done on Section 1, where the variations of equivalent stresses are the highest, at heaviest time.

RCC-MR PROCESS

$\overline{\Delta\sigma_e} = 918$ MPa

maximum elastic deformation:

$\overline{\Delta\varepsilon_1} = \frac{2}{3}\left(1 + \frac{\nu}{E}\right) = 0.5\%$ - $E = 161\ 000$ MPa.

Factors K_ε and K_ν are defined from 425°C characteristics. It is assumed that:

$\overline{\Delta\varepsilon_2} = 0$ (no variable primary stress)

$K_\varepsilon = 1.72$ - $K_\nu = 1.22$

$\overline{\Delta\varepsilon} = (k_\varepsilon + K_\nu - 1)\ \overline{\Delta\varepsilon_1}$; $\overline{\Delta\varepsilon} = 1.94 \times 0.5\%$; $\overline{\Delta\varepsilon} = 0.97\%$.

Number of admissible cycles: $N_a = 180$ cycles (1S RCC-MR).

ASME PROCESS

Determination of nominal stress in the whole support section

$S_n = \sigma_m + \sigma_b$

$\sigma_m = 240$ MPa (membrane stress) $S_n = 532$ MPa
$\sigma_b = 292$ MPa (bending stress) $S_m = 107$ MPa

$K_e = 1 + \left[\frac{1-n}{n(m-1)}\right]\left[\frac{S_n}{3S_m} - 1\right] = 3.19$ with $n = 0.3$ and $m = 0.7$.

$2\ S_a = K_e\ S_p = 3.19 \times 918 = 2.928$ MPa.

S_a mod $= 1.464 \times \frac{E_{20°C}}{E_{400°C}} = 1.844$ MPa (that corresponds to: $\overline{\Delta\varepsilon} = \frac{2S_a}{E} = 1.84\%$).

Number of admissible cycles: $N_a = 80$ cycles (fig. I 921 ASME)
or $N_a = 25$ cycles for $\overline{\Delta\varepsilon} = 1.84\%$
with fatigue curves of 1S material from RCC-MR.

ELASTOPLASTIC ANALYSIS

Plastic calculations are performed on one cycle and the pattern is built with a "monotonous" loading. The constitutive law is the isotropic plasticity pattern. It is based upon decomposition of total deformation ε_T into an elastic part ε_e and a plastic part ε_p. It uses the plasticity surface concept and the normality law. The plasticity surface is defined by the Von Mises's criterion in the area of stress deviator, but its radius is variable and depends on hardening. This one is represented by uniaxial cyclic curves. Mechanical characteristics (cyclic curve and Young's modulus) come from RCC-MR material 1S. Elastoplastic stresses are weaker than the ones given by elastic calculation. Maximum values occur at 70 secs: 441 MPa (maximum flux) and 501 MPa (0.05 MW/m^2 flux). The most stressed point is the surface of section 1. Stresses inside the thickness are weaker, too. The main difference between elastic and elastoplastic calculations comes from the presence of strong residual stresses. The left and right noses are less stressed. The strains are maximum on skin, on the surface submitted to flux, and on the tubing face. Residual strains remain limited. High stresses are explained by mechanical properties which are higher in the cold state than in the hot one. The most stressed is the point 1, surface submitted to heat flux between two tubings. At this point, the calculated deformation (0.54%) is very few different from the one given by an elastic calculation (0.6%). Therefore, thermal stresses are effectively of secondary nature. With the fatigue curve for the 316L EDF-SPH material given in document GTM 12, we estimate the number of cycles for crack initiation. Having no fatigue curve at 407°C, we have selected the nearest of our maximum temperature, i.e. 450°C. The number of cycles to initiate cracks, with a 0.543% deformation, could be between 15 000 and 30 000 cycles.

CONCLUSIONS

Fatigue analysis ASME section III is severe and is due to evaluation of the factor more the 3 for the maximum value. The elastic calculations of stresses have confirmed the top face is the most stressed. The analysis of fatigue damage has shown a small number of cycles for crack initiation, near hundred according to both ASME section III and RCC-MR codes. Elastoplastic calculations show weaker stresses. But we have to note non neglectible residual stresses and deformations. An estimation of the lifetime with true mechanical characteristics gives an initiation located between 15 000 and 30 000 cycles.

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THERMAL BOUNDARY CONDITIONS

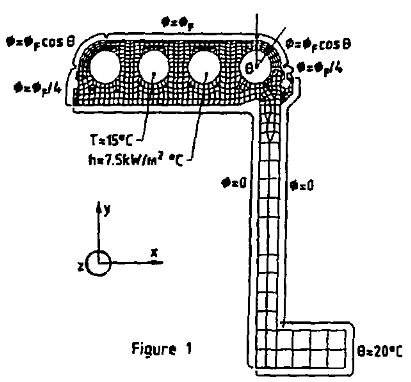


Figure 1

MECHANICAL BOUNDARY CONDITIONS

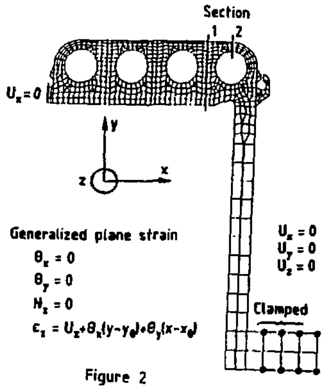


Figure 2

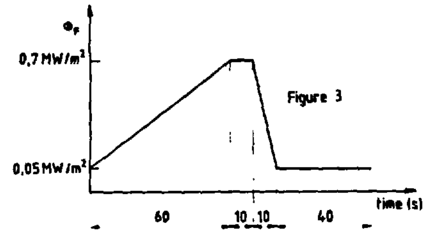
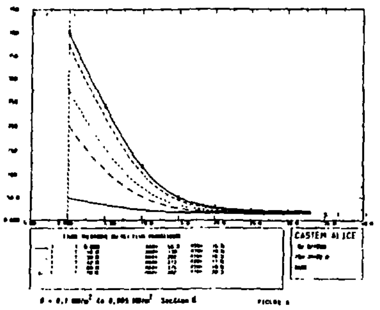
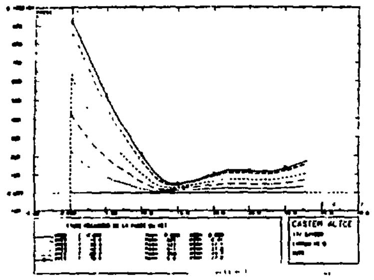


Figure 3





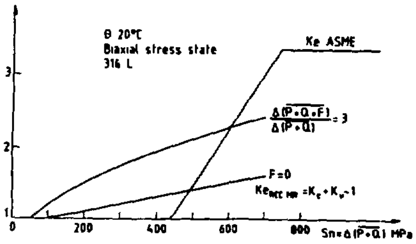


Figure 6

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