LIFE ASSESSMENT EVALUATION OF PIPING BRANCH CONNECTION UNDER CREEP & FATIGUE.

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Abstract The comparative results of fatigue life assessment analyses are presented for piping branch connection of Tee type (Tee) of power station Main Steam piping . The results are derived using the German Standard TRD with and without usage of modified finite element analyses of transient thermal stresses, occurring during power station startup or shutdown. The traditional TRD approach for Tee stress analyses is conservative because of using formulas, which are the upper estimate of transient thermal stresses. The TRD assumption about the coincidence of creep and fatigue maximum stress areas is very conservative as well. The analyses results enable us to extend the power station piping components life assessment.

1. INTRODUCTION

Two types of processes may be distinguished during operation of power station piping. The first type, called the operating process, is characterized by relatively slow changes in piping pressure and temperature. The second type, called the power station startup and/or shutdown process, is characterized by rapid changes of piping loads. This transient process leads to the development of thermal transient stresses in piping components. The total duration of startup and shutdown is negligible in comparison to the duration of the operating process.

The Tee in power station's Main Steam piping is a intricate shapes component, connecting branches and pipes. This component is subjected to creep and fatigue conditions.

The German Standard TRD [1] approach is used in this paper for life assessment calculations. The evaluation of transient thermal stresses, according to the Standard TRD rules for creep and fatigue life assessment, results in the upper estimate of stresses. Such approach leads to prohibitive cost of piping components. One of the Standard TRD assumptions is that the areas of maximum thermal stresses and maximum pressure stresses coincide for piping components. The life assessment evaluation is often reduced as a result of such conservative approach.

The method of finite elements analyses enables us to obtain a more accurate stress-strain state of piping components. These results provide a basis for a modified life assessment evaluation.

The goal of this article is to present the modified life assessment calculation of a Tee on Main Steam piping. During the operating process the Tee is subjected to external forces and moments. These external loads are caused by internal pressure, component's weight, thermal expansion of piping and its supports. All these loads are slowly changing during the operating work.

The Tee life assessment analyses are carried out in this paper by two methods:

- according to the Standard TRD in the traditional manner;
- according to the Standard TRD in a modified manner by using finite elements stress analysis.

According to the Standard TRD rules the usage damage coefficient is calculated for creep and fatigue. When the usage damage coefficient attains 100% the life assessment is exhausted.

The traditional Standard TRD approach does not take into account the force and moment distribution in Main Steam piping.

The modified TRD calculations are carried out in two steps:

-in the first step force and moment distribution for the Tee's Main Steam piping is obtained by using the special finite element program AUTOPIPE [2]. This program uses only beam elements.

-in the second step the Tee stress-strain state is found by using the finite elements program ANSYS [3] and the results of the first step. The Tee's pressure and thermal transient stresses, resulting correspondingly from pressure load and from rapid piping heating-cooling, are found. This sum of the stresses is used for the life assessment calculation.

2. TRADITIONAL CALCULATION ACCORDING TO STANDARD TRD RULES.

The calculations are made for material 10 CrMo 9 10. It is assumed that the Tee works under creep and fatigue conditions and the life assessment calculations are based on 100% achieving of usage damage coefficient e.

$$e = \sum_i e_{zi} + \sum_j e_{wj} \ , \tag{1}$$

where

e_{zi} is the usage damage coefficient of the i period due to the creep in %,

e_{wj} is the usage damage coefficient of the j cycle due to the fatigue in %.

2.1 Fatigue calculations

According to the Standard TRD designations the basic equations for fatigue stress amplitude $2\sigma_a$ due to pressure and thermal transient are:

$$\sigma_a(\theta, v_{\theta st}, v_{\theta sh}) = \frac{f_3 \Delta\sigma^2(\theta, v_{\theta st}, v_{\theta sh})}{4\sigma_{0.2}(\theta)} \tag{2}$$

where

$$\Delta\sigma(\theta, v_{\theta st}, v_{\theta sh}) = \sigma_{iMax}(\theta_{Max}, v_{\theta sh}) - \sigma_{iMin}(\theta_{Min}, v_{\theta st}) \tag{3}$$

$$\Delta\sigma_i(\theta, v) = \sigma_{pi}(P, \theta) + \sigma_{i\theta}(\theta, v) \tag{4}$$

$$\sigma_{ip}(P, \theta) = \alpha_m(P, \theta) P \frac{d_m}{2s_b} \tag{5}$$

$$\sigma_{i\theta}(\theta, v) = \frac{\alpha_\theta \beta_L(\theta) E(\theta)}{1 - \upsilon} \Theta(\theta, v) \tag{6}$$

$\Delta\sigma(\theta, v_{\theta st}, v_{\theta sh})$ is the total fatigue stress due to pressure and thermal transient, depending on temperature θ;

$v_{\theta st}, v_{\theta sth}$ are the temperature rates of startup and shutdown, respectively;

$\sigma_{0.2}(\theta)$ is the yield strength of material;

f_3 is the surface correction factor;

$\sigma_{iMax}(\theta_{Max}, v_{\theta sh}), \sigma_{iMin}(\theta_{Min}, v_{\theta st})$ are the fatigue stresses due to shutdown or startup, respectively;

$\Delta\sigma_i(\theta,v)$ is the total fatigue stress due to shutdown and startup;

$\sigma_{pi}(P,\theta),\sigma_{i\theta}(\theta,v)$ are the fatigue stresses due to pressure and thermal transient, respectively;

$\alpha_m(P,\theta)$, α_θ are the stress intensity factor (SIF) due to pressure and thermal transient, respectively;

P is the internal piping pressure;

$v, E(\theta)$ are elastic material constants (the Poison's ratio and the Young's modulus);

$\Theta(v,\theta)$ is the temperature difference between the start and the end points of the thermal process;

d_m is the pipe diameter;

s_b . is the pipe thickness.

As measurements show, there are 3 types of the Tee's fatigue cycles during power station startup and/or shutdown. During these cycles the temperature varies between its extremal values θ_{min}, θ_{max}. Each cycle may be approximated as having a constant temperature rate. The cycles characteristics are shown in Table 1.

Table 1. The charasteristic of piping fatig cycles

Cycle type	Number of cycles n_j	Temp. θ_{min} ,°C	Temp. θ_{max} ,°C	Temp. rate of startup, v_{st} °/minute	Temp. rate of shutdown, v_{sh} °/minute
1	84	250	540	4.8	- 4.8
2	63	200	540	1.5	- 1.5
3	58	20	540	2.5	- 2.5

The fatigue calculations, which results from the Standard TRD rules, are presented in Table 2.

Table 2. The Standard TRD's fatigue calculation results

Cycle type	Number of cycles, n_j	Max. therm. stresses, σ_i kg/mm^2	Stresses amplitude, $2\sigma_a$ kg/mm^2	Max. up to crack cycles number , N_j	Fatigue usage damage, e_{wj}, %
1	84	39.6	229	124	67.8
2	63	11.2	31.8	60 600	1.04
3	58	18.4	58.5	104 000	0.56
					$\sum_j e_{wj}$ =69.4

The Tee's stress intensity factor SIF = 2.9, according to the Standard TRD, is included into total fatigue transient thermal stresses (Table 2). This value provides the upper bound for the SIF. The maximum number of cycles until incipient crack formation N_j is derived from the Standard TRD fatigue curves by using the amplitude of fatigue stresses $2\sigma_a$. The value of fatigue usage damage coefficient e_{wj} is calculated as the ratio of the operating number of cycles n_j to the maximum number of cycles until crack initiation, N_j.

$$e_{wj} = \frac{n_j}{N_j} \tag{7}$$

2.2 Creep calculations

The measurements show, that there are 3 types of creep periods, in which the temperature and stresses do not change severely. The creep load data are presented in Table 3, where the creep stresses are the hoop piping ones. The results of creep calculation according to the Standard TRD are given in Table 4. The value of the usage creep damage coefficient is calculated as the ratio of load operating period duration Z_i to design life period duration Z_{Bi}.

$$e_{zi} = \frac{Z_i}{Z_{Bi}} \tag{8}$$

Table 3. The charasteristics of piping creep loads

Load period type	Load oper. period dur. Z_i, hr	Aver. pipe temperat., θ° C	Aver. steam pressure P, kg/mm^2	Aver. creep stresses σ_{gB}, kg/mm^2
1	69 000	540	1.45	4.72
2	38 000	533	1.35	4.40
3	15 500	526	1.25	4.07

Table 4. The Standard TRD's creep calculation results

Load period type	Load oper. period dur., Z_i, hr	Design life period dur., Z_{Bi}, hr	Creep usage damage, e_{zi}, %
1	69 000	408 000	16.9
2	38 000	1 060 000	3.6
3	15 500	2 980 000	0.5
	$\sum Z_i$ =122 000		$\sum e_{zi}$ =21

2.3 Total life assessment calculation.

The overall sum of creep and fatigue usage damage coefficient, calculated according to Tables 2, 4, is 90.4%.

By this means, the Tee is used essentially its life assessment at the operating period end ($\sum_i Z_i$ =122 000 hr) and there comes a time, when to decide about component's change. Modified analyses are obtained in attempt to prolongate the Tee's life assessment.

3. MODIFIED STANDARD TRD CALCULATIONS WITH FINITE ELEMENTS ANALYSES

Traditionally fatigue calculations, performed according to the Standard TRD, are modified here by using the method of finite elements. The creep calculations are carried out as in the previous parts according to the Standard TRD.

3.1 The operating process stresses

As noted above, in the first step of calculations the AUTOPIPE program [2[is used in order to obtain the forces and moments distribution in piping cross sections. The Main Steam piping system is schematically shown in fig. 1. This piping contains the Tee to be analyzed.

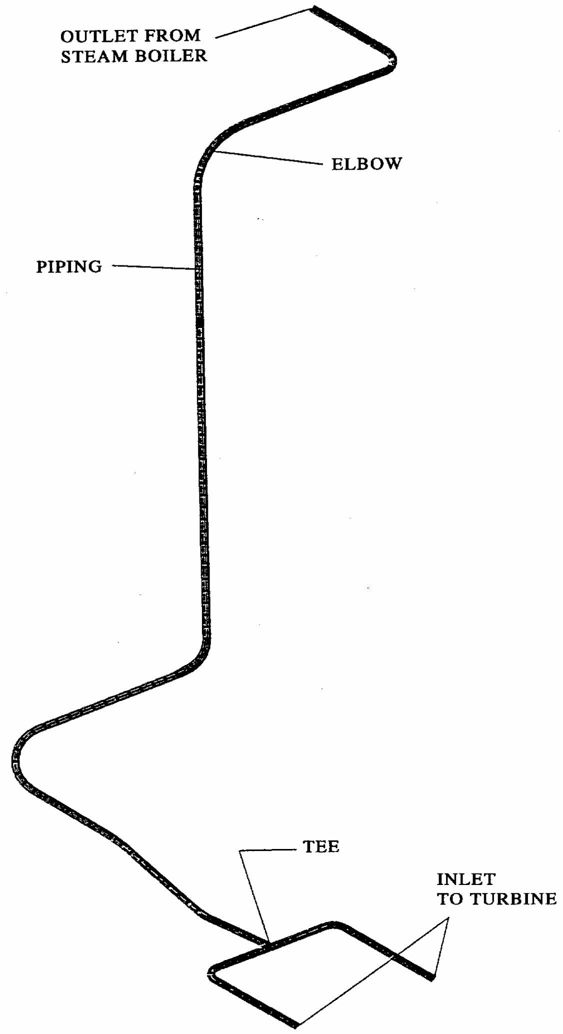

Fig. 1 Schematic illustration of the typical Main Steam piping.

The Tee end loads (fig. 2) are the force and moment vectors $\mathbf{F_1}$, $\mathbf{F_2}$, $\mathbf{F_3}$, $\mathbf{M_1}$, $\mathbf{M_2}$, $\mathbf{M_3}$. Projections of these vectors on piping longitudinal and transverse axes results from AUTOPIPE calculations. These loads are calculated regardless of internal piping pressure effect.

In order to get the Tee stress-strain state, the built finite elements model must be loaded by the pressure and ends loads. The stress-strain states of similar three-dimensional piping body are analyzed in [4-6].

Since there is a symmetry plane in Tee, one half of the component is modeled with appropriate symmetry or antisymmetry boundary conditions applied. The model with symmetry boundary conditions in symmetry plane is used, when symmetry loads (pressure and symmetry components of ends loads) are applied.

Antisymmetry boundary conditions in symmetry plane are applied to model, loaded by the antisymmetry components of the ends loads.

The finite element Solid 5 is used to generate actual element mesh. In order to increase the calculation accuracy the model is restricted to brick elements with transitional degrees of freedom per node. Mesh density is chosen so, that to be enough high in the area of expected large stress gradients.

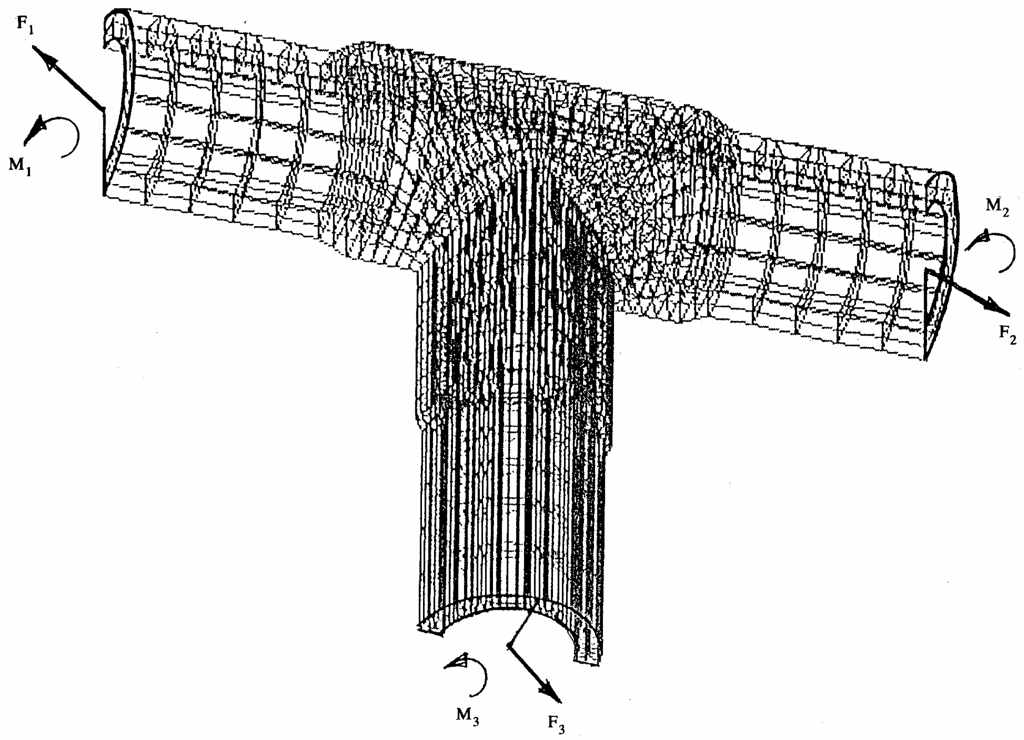

Fig. 2 The Tee external ends loads, acting on auxiliary beams.

The concentrated ends loads are transmitted to model body by building the auxiliary high rigid beams in the model end cross sections. The ends loads, which results from AUTOPIPE calculations, are applied in cross section centers of gravity. These auxiliary beams are schematically shown in fig. 2. Mesh density in vicinity of the auxiliary beams areas is chosen enough rough, because their stress distribution is not of interest.

The finite elements static solutions are obtained for each symmetry and antisymmetry models and the results (stress, deformation, displacement and etc. fields) are summed, using the ANSYS program.

In order to check the accuracy of the model, AUTOPIPE's end loads are applied to auxiliary beams. The finite elements displacements and rotations of points, where loads are applied, agree very closely with the AUTOPIPE solution. When AUTOPIPE's ends displacements and rotations are applied to auxiliary beams, the corresponding finite elements end loads accord with the AUTOPIPE solution as well.

Another checking of the model mesh accuracy is carried out. The finite elements analyses are made for a number of models with different mesh densities. The model mesh density is refined until calculation results for this model are agreed enough closely with the previous refined model. In the case of results discrepancy a new refined model is built to compare afresh. The final model mesh density is shown in fig. 3, 4.

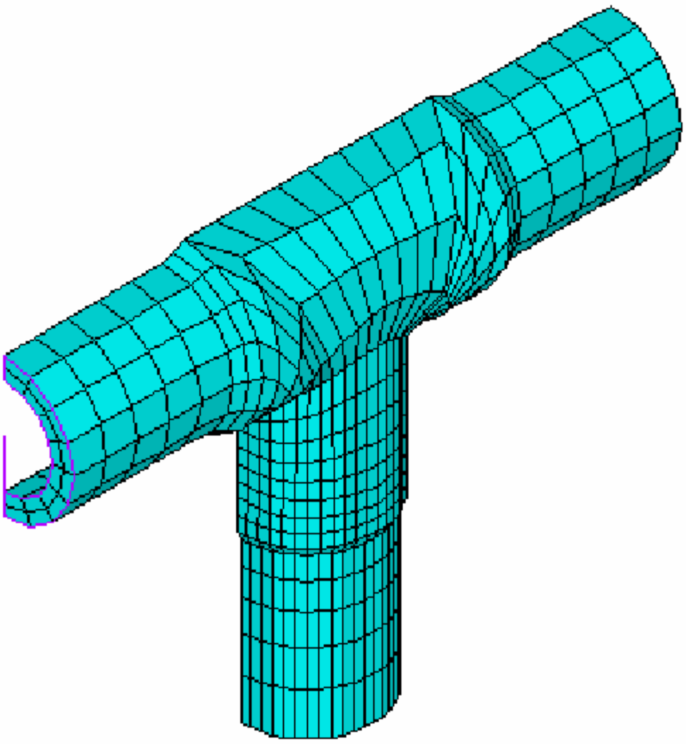

Fig. 3 The finite elements model mesh.

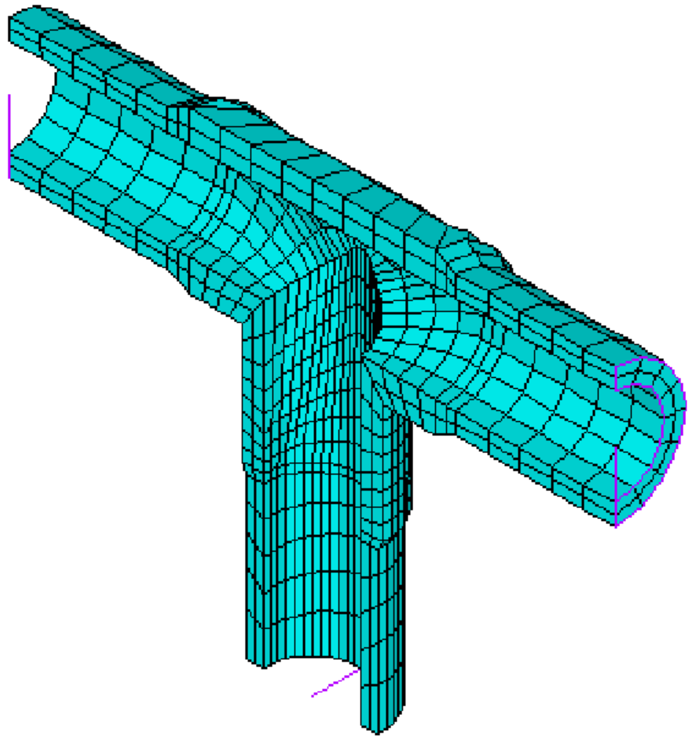

Fig. 4 The finite elements model mesh.

The calculation results (Von-Mises stresses) for pressure load, corresponding to cycle 1 (Table 1) are presented in fig. 5. Analog stress fields are obtained for any cycles. As shown by fig. 5, the maximum stresses occur on the internal surface of the Tee symmetry plane in two cylinders intersection area (maximum stresses due to pressure here are σ_{pr}=12.9 kg/mm^2). These stresses have a local character and they are peak stresses according to the Standard TRD classification.

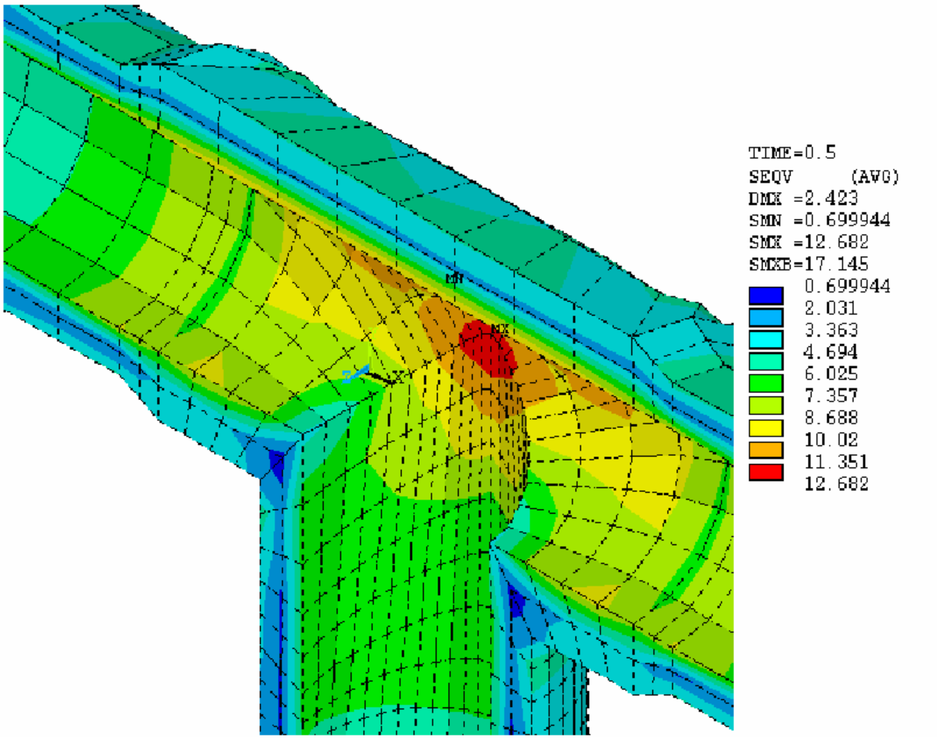

Fig. 5 The Tee pressure stresses.

3.2 Thermal transient stresses

The thermal transient stresses in Main Steam piping due to rapid steam temperature change during power station startup or shutdown. Finite elements analyses of thermal stresses for a similar problem are carried out in [7].

A typical process of steam temperature θ change with time t is schematically shown in fig. 6. The graph is characterized by a constant temperature increase rate between θ_{min} and θ_{max} on the first process step t_{tr} and by a constant temperature on the second one. The duration of the first step is negligible as compared with the second one. Analog character have the cooling steam process.

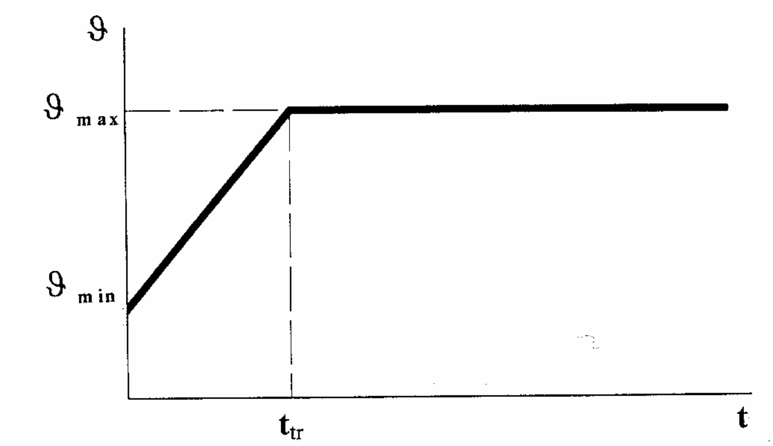

Fig. 6 The typical process of steam temperature change.

The thermal-structure solid element (Solid 5) enables us to model stress-strain state, steel thermal conductivity, thermal convection process between steel and steam. The Von-Mises thermal transient stresses, found for the cycle 1 (Table 1), are shown in fig. 7.

The maximum thermal stresses are developed on the internal surface of the Tee on the plane normal to the symmetry plane near the two cylinders intersection line (maximum stresses due to thermal transient here are σ_{th}=12.7 kg/mm^2).

As fig. 5, 7 show, the maximum stresses areas of two stress fields (pressure and thermal transient) do not correspond to each other. The maximum overall pressure and thermal transient stress field are σ_Σ=18.1 kg/mm^2.

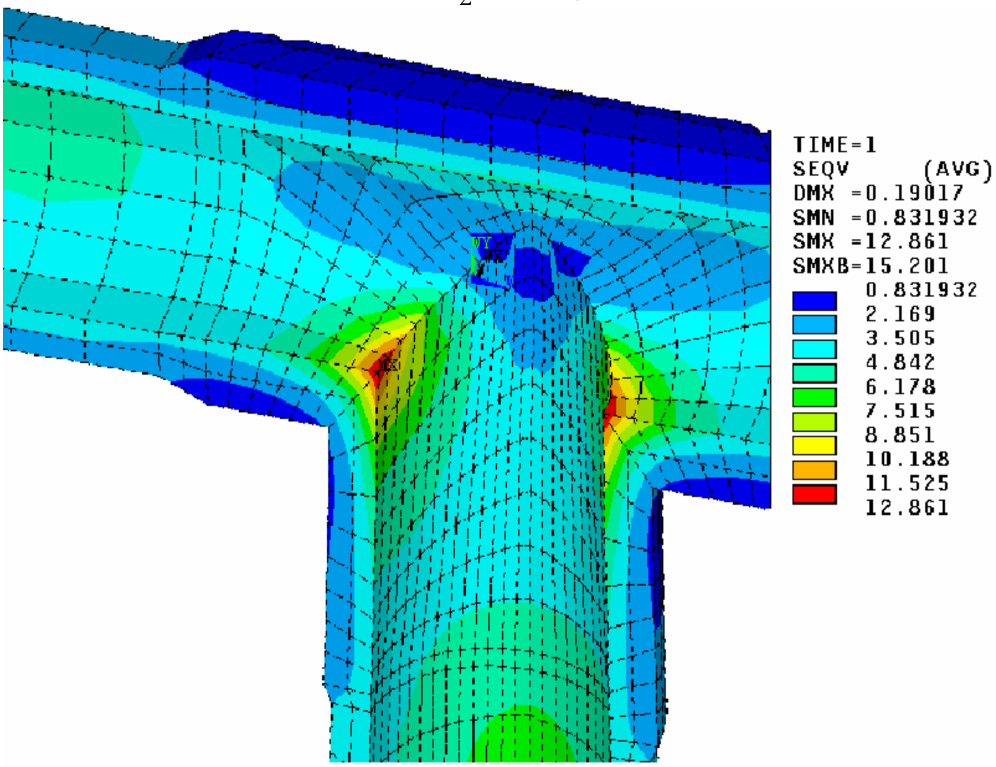

Fig. 7 The Tee transient thermal stresses.

3.3 Total life assessment calculations

The Tee's life assessment calculations are carried out with fatigue stresses, which are found by finite elements method, and creep stresses, taken from table 4 (according to the Standard TRD). The results of fatigue calculations are given in Table 5. An additional value of SIF is not accounted in these calculations, because the obtained stresses are real.

Table 5. The finite elements fatigue calculation results

Cycle type	Number of cycles n_j	Max. thermal stresses, σ_i kg/mm^2	Stresses amplitude, $2\sigma_a$ kg/mm^2	Max. up to crack cycles number , N_j	Fatigue usage damage, e_{wi} , %
1	84	12.7	36.2	105 000	0.8
2	63	6.2	17.4	315 000	0.2
3	58	8.1	22.6	145 000	0.4
					$\sum_i e_{wi}$ =1.4

The overall creep and fatigue usage damage coefficient due to stresses from tables 4, 5 is 22.4%.

4. CONCLUSIONS.

The total usage damage coefficient for life assessment is calculated for creep and fatigue stresses in traditional manner of the Standard TRD. The piping hoop stresses are used as creep stresses. The fatigue stresses involve pressure and thermal transient components. The transient thermal stresses thus computed provide the upper bound for the real stresses. The assumption of the coincidence of maximum stresses areas for pressure and thermal transient loading is taken. This method leads to the total fatigue stress amplitude 229 kg/mm^2 and total fatigue-creep usage damage coefficient 90.4%. This values are result of conservative traditional approach of the Standard TRD.

The modified finite elements calculations show:

-the upper bound of transient thermal stresses may be diminished in comparison with their Standard TRD evaluation;

-the maximum stress areas for pressure and thermal transient do not coincide.

As result of modified finite elements calculations the total fatigue stress amplitude is 36.2 kg/mm^2 (instead of 229 kg/mm^2 according to TRD) and the total fatigue-creep usage damage coefficient is 22.4% (instead of 90.4%). This values are far less than those obtained by the traditional Standard TRD method.

By this means, the modified finite elements method analyses enable us to decrease drastically the total fatigue stresses and on this way to increase (by approximately 4 times) the life assessment.

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