Inelastic Analysis and Material Tests Comparison in High-Temperature Steam Piping Life Verification

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ABSTRACT

As following-on studies on creep and fatigue analysis of high pressure SS piping, being operated for times approaching 70,000 hours at 540 °C in 660 MW thermal power plant, and developed by the Italian Electrical Board in view to reassess the structural and mechanical integrity of the line, extensive campaign of calculations has been programmed.

Different creep-relaxation cycles were introduced to simulate the effects of further long-term exposure of the piping in creep range, up to 50,000 hours, and for a better understanding of the prestress load behaviour.

The examination of cycles in creep regime describes the behaviour of the stress-strain distribution in a more stressed section, like bend, during the time, and gives some indication about the safety margin still existing in the structure.

In particular, the influence on bends of oligocyclic fatigue and creep has been evaluated and compared with some experimental data.

Sectional analysis with 3D finite element computer programme, with an elastic and elastoplastic behaviour of the material, permit to verify the congruence of theoretical approach with the experimental informations in view of assessing the possible extension of intensification factor to detailed piping analysis in creep range.

The results of design analysis of the Piping, applying ASME Sct. III, ANSI philosophy (arbitrarily extended over its natural limits of validity) and certain criteria of C.C. N-47 are presented to demonstrate the ability of these codes in covering the combination of load conditions and assuring the structure safety in stress-strain verification at elevated temperatures.
1. Introduction

The steam piping of a thermoelectric power plant (the ENEL hypercritical power plant located in La Spezia, Italy) consists of medium diameter (Ø = 10/14") and thick wall (30/60 mm) pipes made of ferritic steel (2 1/4 Cr 1 Mo) the AB line (fig. 1) and austenitic stainless steel AISI type 316H the BD line.

The object of the study is the evaluation of the ASME/ANSI rules or, in other words, an attempt to apply them both in the field of the schematization of the plant design/operation loads in a piping for thermoelectric power plants following the ASME loading categories, and in the field of the stress classification. This comparison will be limited mainly to rules recommended for the design conditions. The loads considered are therefore, the mechanical ones and those deriving from the thermomechanical flexibility with the exception of the thermal loads due to axial gradients and seismic loads.

In order to ease the comparison in the first phase, the influence of creep could be partially disregarded.

To completely verify the stress state of the piping at the application of standard rules is preliminary the evaluation of mechanical/thermal loads combination effects during the operation (start-up) transients in manner to examine the occurrence of ratchetting/shake-down regimes.

2. Loads and operating conditions

The loads considered are arbitrarily revised in order to respect the working conditions observed during operation, rather than those corresponding to theoretical analysis and hypothetical response of the plant. The design values were assumed to be the rated working loads of the steam pipe and namely: a) 250 afe pressure (24.52 N/m²); b) weight, insulation, interrelations of supports and constraints.

As regards the possible correspondence of the Normal conditions (Service Level A) of the ASME Sect. III, the following loads should be considered: design conditions, uniform average temperature of 540 °C and constraint compliance at the ends. The above operating conditions are supposed to cover: 20 years' life with a 0.8 loading factor, equal to 16 actual years; 100 cold start-ups. Transient loads are also included in upset conditions verifications. The Emergency and Faulty conditions are also disregarded.

3. Preloading and hold-time effects on oligicycle behaviour

The study of the preloading and creep influences on the stress/strain distribution along the pipe has been already presented in a previous paper /1/. It will investigated here their effect on the most stressed sections. The time-dependence of the temperature and pressure
during start-up transient combined with its expected cyclic occurrence, may induce working conditions of the steam pipe into the plasticity range. It is therefore important to evaluate whether the pipe will be in shake-down or in ratchetting regime.

In order to properly assess the pipe behaviour, the real evolution of the material should be described as close as possible; specifically a kinematic strain hardening law has been introduced, since it is acknowledged to fit better fatigue analysis. Five loading cycles (cold start-up close by shut down) has been considered. The calculations also take into account the effect of the preload, with relative intensities equal to 60, 100, 160 % of the effective stress. The way to introduce the preload effect in the calculations consists in producing a suitable shortening of the pipe line by “freezing” two central elements. The stiffness matrix keeps unchanged its characteristics, and it turns to be possible to parametrize the temperature so to obtain optimal preload conditions. The stress analysis has been performed with finite elements computer codes COCO, TEDEL, TRICO of the CASTEM system /2,3,4/ on the pipe elements n. 180 (Fig. 1).

The study of low-cycle fatigue conditions has been carried out assuming five consecutive temperature cycles. It should be pointed out that the temperature distribution evolution is strictly correlated with the pressure changes: it will therefore result the cycling of both primary and secondary stresses. Ratchetting effects are evidenced (Fig. 2 and 3), even at the fifth cycle non saturation of the total plastic strain is reached. The preload fails to originate beneficial effects on the considered element.

As known, the main purpose of the preload is to decrease the stress intensity along the pipe, when it reaches the normal design conditions at maximum allowed service temperature. Nevertheless, the effectiveness of the cold springing may be questionable. The nature of the preload and its classification still presents some uncertainties; on one hand the application procedures should attribute to the preload a mechanical - and therefore primary - characterization, on the other hand, the generated stresses are typical “strain controlled stresses” since they are induced by an initial deformation and are expected to relaxate at high temperature. Another typical point is related to the specific behaviour of the material. The AISI type 316 stainless steel is subjected to cold creep, i.e. plastic time-dependent deformation, even at room temperature, for stresses values close to its yielding point. The reduction of the total accumulated strain in the more stressed section by adopting a preload may conversely induce, at ambient temperature, where the cold springing is more important, a problem which would have been thought to be solved. Finally, it should be considered the simultaneous presence of thermal transients and the preload during the plant start-up until operational design conditions are reached. Even acceptable thermal gradients acting jointly with preload values may produce high stress/strain field. This effect has been analyzed here, where the start-up begins to occur at temperatures lower than the nominal ones. This explains why the ratchetting
effect does not seem to be favourably influenced everywhere by the preload. The plastic-strain increase with the number of cycles is reported with its distribution at the outer surface (Fig. 4).

The effect of creep has been simulated by introducing after each cycle an hold-time of 30,000 hours at design operating conditions in order to get some elements for the evaluation of the cumulative damage and for pipe line residuellife prediction. The results show (Fig. 5) that creep enhance the strain build-up for every preload, this effect being more evident with higher preloads both on outer and inner surface.

4. Stress intensification factors of bends

It is known that the bends of pipe lines are elements with a stiffness smaller than that of straight tubes and are moreover subjected to stress/strain concentration effects. The node n. 180 considered in our calculations is in fact a bend. It is therefore important to evaluate the allowance left by the analytical relations recommended by the design codes and to be used for pipe reassessment. The 3-D analysis with the TRICO code has been carried out on an elbow (BEND2 in ref. /5/) connected with two straight lines subjected to in-plane bending moment.

The results have been compared (Fig. 6) with the stress intensification factor values calculated from experimental data. The stress intensification factors resulting from tab. NB -3685-1-2 /6/ are also presented (Fig. 7). Although these relations are valid for bends with \( \lambda > 0.2 \), they have been extended to our geometry where is \( \lambda = 0.1864 \). It may be noted a very close behaviour of the stress intensification factor, as calculated from design requirements by finite elements or from experimental data. These latter provide a maximum value at the inner surface, although the numerical values give the same maximum absolute values for the outer and the inner surface. Extensive calculations on an elbow of \( R = 9" \), \( r = 3.25" \) and \( t = 0.134" \) have shown that the straight ends decrease the stress intensity by about 30 % and consequently the \( K \) flexibility is reduced by 40 % /7,8,9/. This decrease tends to zero, if geometrical non-linearities are considered. It seems that for the geometry investigated, ASME Sct. III NB-3680 procedures are well supported by numerical and experimental results on jointed bends, even if large displacement did occur.

The effect of creep has been introduced in the calculations, assuming a Norton law. The evolution of the mutual rotation angle follows a straight line. The behaviour of stress intensification factor, transverse and longitudinal, for the inner and outer surface is given in Fig. 8. A fair agreement is acknowledged for instantaneous loading and for an hold time of 3,000 hours. In conclusion, by awaiting for a more extensive investigation on creep/fatigue effect on intensification factors, we can suppose that the factors recommended for the analytical calculations are to be considered suitable and acceptable even in the creep range.
S. Some considerations on verification procedures

When designing piping for high temperatures, the ANSI B 31.1 and ASME C.C. N47-17 rules are applied and, as previously remembered, the NB-3600 prescriptions of the Sect. 1177/6/. These regulations are examined by evaluating their application to the static verification for design conditions of power plant steam piping.

The application of the rules in the "Design by analysis" as laid down in article NC-3650 of the ASME Sect. III is considered. The component of the stress intensity due to pressure is \( S_{LP} = \frac{(P \cdot d^2)}{(D_e - d)^2} \). If \( M_A \) is the resulting moment due to weight and to the constraint reactions, by describing as \( S_{MA} = (0.75 \cdot i \cdot M_A) / 2 \) the relative stress, and by applying the 0.75 and 1.0 coefficient, it is possible to obtain the stress superposition through the formula \( S_{SL} = S_{LP} + S_{MA} + S_h \). Considering the relations \( S_E = \frac{i \cdot M_c}{2} \leq S_A \) and \( S_L \leq S_s + S \), where \( S_{c_y} = f(1.25 \cdot S + 0.25 \cdot S_e) \), we can obtain the ratios \( S_{SL} / S_E \) and \( S / S_A \). The maximum values of these are for section 182 respectively 0.33, 0.29, 0.30.

Moreover, as regards the \( S_{NA} \) stress calculation, it is necessary to determine the appropriate value of \( i \) relating to each type of section \( i = 0.9 \cdot h^{2/3} \) with \( h = t \cdot R / t^2 \).

The simplified analysis of art. NB-3650 of ASME Sect. III and, more exactly, of article NB-3652/3 recommends to verify the relations (9) and (10), which permit to respect in all sections the acceptable limits.

While verifying the conformity with the requirements of Code Case N 47, reference is made to art. 3651. In this case it should be necessary to respect the limits established by article 3200, but if the creep effects are neglectable, we can use the same criteria of ASME NB-3600.

In view of reducing the impact on the piping behaviour of the elastic follow-up, primary stresses in the sections which are critical as to the structure stability should be limited; in order to get to this purpose it is first of all advisable to describe the stresses due to thermal expansion as primary stresses (\( P_m \) or \( P_b \)).

As is well-known, in the case of the design conditions it is necessary to satisfy the usual relations suggested by 'C.C. N 47. We would have to consider the contribution of term \( N/A \), but it is negligible. The verification of the second equation fails as regards four bends. In particular, as to the bends in the A-B length which are made of a ferritic alloy \( (2 \frac{1}{4} \text{Cr 1Mo}) \) the non-conformity also concerns the primary membrane stresses. In the case of A/B service level verifications the margin is further reduced when compared to the acceptable values.

In this respect, the ASME Section III NB-3685.4 rules suggest to classify the membranes stresses concerning the "design by analysis" as \( P_L \) and to subdivide the bending stress into \( P_b \) in the proportion of 75 % and into \( Q \) in the proportion of 25 %. The stresses calculated in
a flexibility condition caused by imposed displacements, are classed as Q. On the other hand, the Code Case N. 47, as already pointed out, recommends to classify the thermal expansion shocks as primary, prior to an analysis of the influence exerted by elastic follow up on the section. Even if we use the Sect. III procedure the allowable limits are not respected in some bend.

6. Conclusions

From the preceding analysis it emerges that the caution degree is not very high in ANSI B 31.1 as it is in the other rules. The range of the stresses relations of ANSI B 31.1 is not very wide; this fact leads to an underestimation of the most stressed sections and components (that is bends) and to an overevaluation of the less stressed ones.

It does not seem that the recourse to a detailed analysis through indices can significantly help to solve the problem caused by the exceeding of the acceptable limits if these indices do not consider the phenomena involved in high temperature. On the other hand, the more precise analysis with finite elements required in creep situations, as stated by C.C. N. 47 becomes very difficult, too costly and so heavy to push the designer attention on the direction of usual detailed analysis by means of intensifications factors adopted to cover complex phenomena, like fatigue, creep, etc.

The Code Case N. 47 leads to the evaluation of very high stress states. This largely depends on two factors: the description of the stationary thermal flexibility shocks as primary, while the Sect. III classes them in the P₁ category, the necessity to take defence against the phenomena of progressive deformation due to elastic follow up.

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Fig. 1 - Steam line axionometric lay-out.

Fig. 2 - Total plastic strain for fatigue and creep-fatigue with different preloads (element 180).

Fig. 3 - Strain increment for cycle for five cycles (element 180).
Fig. 4 - Plastic strain distribution along the outside conference for five cycles (element 180).

Fig. 5 - Plastic and creep strain distribution along the outside surface of element 180 for 5 cycles with hold time.

Fig. 6 - Strain intensification factors of the bend from theoretical (TRICO) and experimental analysis.
Fig. 7 - Stress intensification factors of the bend from ASME III NB tab. NB 3685.1-2 and experimental data.

Fig. 8 - Stress intensification factors along the bend (outer surface), considering geometric non-linearity and creep. (θ = 0)