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An assessment of thermo-mechanically induced fatigue damage of a steam turbine shaft

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Abstract

The increasing demands on the flexibility of steam turbines due to the use of renewable energy sources substantially alters the fatigue strength requirements of components of these facilities. The work summarized hereafter was initiated by the effort to develop the methodology of prediction of thermo-mechanical fatigue of steam turbine rotors. A significant effort was put into local thermo-mechanical stress-strain response modelling in the shaft material. An FE model of the structure assuming 2D axisymmetry idealisation was developed and verified. In-house codes based on a variety of approaches to assess critical location and fatigue damage, including the Manson-McKnight and the Nagode methods, were created. The experimental programme aimed to investigate the material fatigue behaviour under the thermo-mechanical conditions was initiated in order to provide data for calibrating and verifying the fatigue prediction procedures. A preliminary study on thermo-mechanical fatigue behaviour was conducted and the results are summarized in the paper.

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Keywords: fatigue of materials; steam turbine shaft; thermo-mechanical fatigue

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1. Introduction

Fatigue life (or fatigue damage) of steam turbine components is mainly determined by service conditions that are closely related to the current loading of the electric generator, which is due to the demand for electricity and at the same time it is given by the environmental conditions. Present trends in energy industry are mainly influenced by the EU and local government energy strategies that result in a significant support for constructing and operating power plants that use renewable energy sources, such as wind-turbine and solar plants. Unstable power supply by these sources, which is caused by unsteady environmental conditions, sets new challenges for the fossil plants. These traditional energy sources play an important role in stabilizing the electrical grids by supplying extra energy during the frequent power cuts caused by the renewable sources. Significantly increased frequency of the turbine start-ups, if compared to the service conditions from the previous years, is becoming to be the direct consequence of this state. Moreover, the grid operators set higher requirements on faster start-up to compensate for the supply of electricity. This substantially changes parameters that need to be considered in the design of steam turbines.

Another example of the increasing requirements on the steam turbine flexibility are direct steam generation solar power plants. Due to the fluctuating nature of the solar energy, multiple start-ups within a 24h period must be endured by solar steam turbines (Birnbaum et al. (2011)).

Regarding the fatigue-life design of the turbines, the following two basic service scenarios determining the fatigue load cycles have to be considered:

- *Cold-start cycle* (50-250 cycles within the turbine life assumed), i.e. start from almost zero speed and cooled state, which is due to long-term operating shutdowns caused, for instance, by inspections and repairs.
- *Hot-start cycle* (6000-8000 cycles within the turbine life assumed), i.e. starts from a pre-warmed state. These cycles are mainly due to the power supplies levelling as mentioned above. Cycling of stresses and deformations is mainly the consequence of mechanical load changes. Temperature fluctuations are, if compared to the previous scenario, quite moderate.

It is the current standard to apply the finite element method (FEM) to the design phase of mechanical structures, especially when dealing with analysis of the cyclic mechanical material response. The obtained local response is then analysed by some of the fatigue prediction technologies in order to estimate fatigue damage and lifetime.

Assessing the life of components under thermo-mechanical loading conditions is still a challenging task. The reason for this is that such conditions trigger a combination of material damaging processes, where mechanical fatigue, creep and oxidation are the most pronounced ones (Neu and Sehitoglu (1989)). Depending on time distribution of loads and environmental conditions, any of these mechanisms may be suppressed to a certain extent. Based on complex material research performed on Mar-M247 nickel-based superalloy, Neu and Sehitoglu (1989) proposed a prediction model, which handles the three mentioned mechanisms. However, identification of material parameters for this prediction procedure requires an extensive experimental programme.

Relatively frequently used in the energy industry is the Manson-McKnight model, which has several modifications (Papuga et al. (2012)). However, any of the Manson-McKnight model variants is rather suitable for predicting fatigue under isothermal fatigue conditions. The advantage of the model is that finding the material parameters requires only standard uniaxial fatigue tests.

Recently, Nagode et al. (2009) have proposed a computational framework for estimating the fatigue damage under variable mechanical and thermal loading in high and low cycle fatigue domain. It employs quite elaborate procedure for analysing the instantaneous load means and amplitudes, which are inputs to the mean stress correction and further process of the fatigue damage estimation based on a set of isothermal fatigue curves. The advantage of the model is the capability to predict fatigue under variable thermal conditions at relatively small costs for the experimental program.

The aim of the paper is to introduce the work and some of the results obtained within the initial period of the FLEXTURBINE project, namely the part dealing with the development of a fatigue damage prediction methodology applicable to steam turbine shafts. The main goal of the work was to propose an accelerated computational framework for evaluating the fatigue damage. The ANSYS FE-code was utilized to simulate thermo-mechanical material response of the selected steam turbine shaft by the assumed load scenario. The axisymmetric model of the shaft for uncoupled thermal and mechanical analyses was developed and 3D submodels for detailed modelling of the most exposed localities were created. Low-cycle fatigue tests under various temperatures were performed to identify the shaft material cyclic behaviour and to obtain material constants of constitutive model governing the material elastic-plastic stress-strain response.

The first part of the paper is dedicated to the description of the experimental work. Next, the FE-model of the turbine shaft is introduced. Finally, the methods applied to fatigue prediction of the shaft are described and the obtained results are discussed. The fatigue prediction was focused on the assessment of selected locations in the area of the blades grooves and the internal seals of the turbine. An FE model loaded by both mechanical and thermal loads was processed by the selected fatigue criteria.

2. Experiments

Steam turbine components are exposed to elevated temperatures during operation, which influences the material mechanical properties significantly. If accurate material response calculation and fatigue prediction are to be performed, the temperature dependence of the respective material model parameters must be known. The temperature range considered in the experimental program must correspond to the intended load scenario.

Static and low-cycle fatigue tests at room and elevated temperatures were performed in order to identify the necessary values of the material parameters. Static tensile tests in the temperature range of 20 to 600 °C were used to determine the Young's modulus E, while the cyclic stress-strain curves (CSSC) and the Manson-Coffin and the Basquin fatigue curves were derived from the low-cycle fatigue tests. The CSSC constitutes the material stress-strain response under cyclic loading and has the following mathematical form, known as the Ramberg-Osgood relation:

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'}, \tag{1}$$

where ε_a and σ_a are the strain and stress amplitudes, respectively. K' is the cyclic hardening coefficient and n' is the cyclic strain hardening exponent. Temperature dependent parameters of back stress function of the Chaboche kinematic hardening rule (3) may be identified from the known CSSCs for the range of temperatures.

Fatigue damage and lifetime prediction under the low-cycle fatigue relies on the Manson-Coffin and Basquin curves, which are written in the common mathematical form as follows:

$$\varepsilon_a = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f'(2N)^c, \tag{2}$$

where N is the number of cycles to specimen failure, $\sigma_f{}'$ and b are the fatigue strength coefficient and exponent, respectively. $\varepsilon_f{}'$ is the fatigue ductility coefficient and c is the fatigue ductility exponent. These four parameters, as well as the Young's modulus E, are temperature dependent.

The low-cycle fatigue tests were performed on the servo-hydraulic MTS 810 machine. High-temperature conditions were induced by the split furnace Mellen and the deformation control was by the high-temperature extensometer Epsilon. Fully reversed sine wave load cycle with frequencies up to 0.5 Hz was applied to specimens with circular cross-section.

3. Finite element analysis of thermo-mechanically loaded steam-turbine shaft

The overall objective of the work on the finite element analyses (FEA) was to suggest a reliable and effective way how to perform simulations of the elastic-plastic material behaviour in the critical domains of turbine shafts with respect to complex operating modes. A sample case of the turbine shaft was selected and all calculations as part of the development of the methodology were made on this component.

In the preparation of the FE model, the assumption of axisymmetry of the shaft geometry and loads was adopted. The following types of loads were considered as dominant and therefore applied in the model:

- Thermal loads due to the constrained thermal expansion
- Inertia loads due to rotating mass of the shaft and blades
- Loads due to steam flow impact

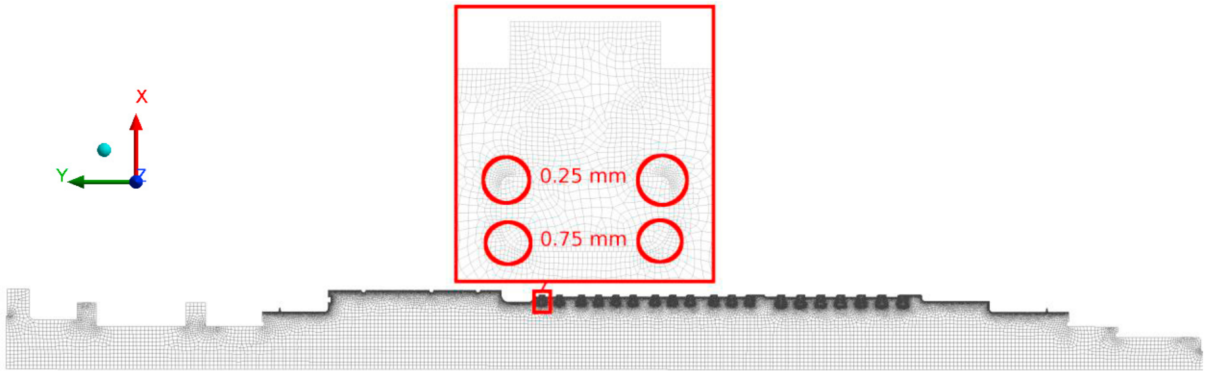


Fig. 1. View of the model mesh. The element size in the blade grooves is indicated.

In this study, the time distribution of the loads representing the cold-start process was assumed. The steam turbine cold-start procedure consists of several phases. During the pre-warming phase the turbine is rotated by a turning gear while being heated by warming steam. The acceleration phase consists of controlled increase of the speed of rotation to its nominal value in vacuum conditions. Loading phase is then a sequence of several controlled steps, during which the steam mass flow, temperature and pressure reach their nominal characteristics.

After this initial set of load regimes, the turbine is operated in approximately steady inlet and outlet conditions and the rotor temperature field reaches its steady state.

The shutdown procedure is divided into three phases: unloading to 50% and run-out, during which the speed of rotation goes from maximum to zero, and cooling as the final stage. Due to the casing insulation, it may take several weeks to cool down the turbine to the initial state.

The thermal response of the shaft material to the above mentioned procedure was simulated by a sequence of ten separate transient thermal analyses defined in the ANSYS Mechanical FE code. The simulation complexity may be illustrated by the number of thermal boundary conditions that are more than one hundred. In general, convective heat transfer conditions were defined as couples of the heat transfer coefficient values and steam temperatures. In addition to the turbine shaft, blade roots were also considered in the model for accurate determination of the temperature field in the vicinity of the blade grooves (Fig. 1).

Mechanical response of the material was analysed by taking the calculated temperature fields within the ten individual load regimes into account. Frictional contacts were set between the blade roots and grooves and the inertial forces due to rotating blade aerofoils were replaced by concentrated forces in the aerofoil centroids. The steam flow effect was replaced by the horizontal force component acting in the centroids as well.

The material cyclic elastic-plastic material behaviour was modelled by using the Chaboche nonlinear kinematic hardening model with three back stress terms. The evolution of each back stress is given by the kinematic hardening rule, which may be expressed as

$$d\boldsymbol{\alpha}_i = \frac{2}{3} C_i d\boldsymbol{\varepsilon_p} - \gamma_i \boldsymbol{\alpha}_i \lambda, \quad i = 1,2,3 \tag{3}$$

where C_i and γ_i are material parameters, $\boldsymbol{\alpha}_i$ is the i-th back stress tensor, $d\boldsymbol{\varepsilon_p}$ is the plastic strain rate and λ is the accumulated plastic strain. In this particular case, temperature dependence of the material constants has to be considered, thus $C_i = C_i(T)$ and $\gamma_i = \gamma_i(T)$. These constants were identified from a set of the isothermal low-cycle fatigue tests. The parameter γ_3 was set equal to zero to reach shakedown.

To obtain the saturated stress-strain response, three cold-start cycles were analysed consecutively. The dominant stress component in the potentially critical localities, as may be seen from Fig. 2, is the normal stress in the radial

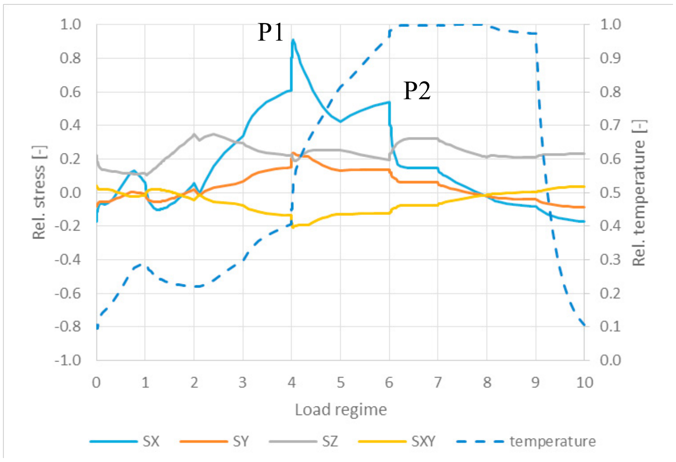


Fig. 2. Sample stress and temperature history in potentially critical localities of the turbine shaft.

direction. It occurs in a particular time instant during the start-up when the maximum speed of rotation is reached while the material is not yet fully warmed up.

4. Fatigue prediction

For the purpose of this study, the fatigue prediction was focused on critical site detection and assessment of fatigue thermo-mechanically induced fatigue damage. The model loaded by the complete set of loads, as mentioned in the previous section 3, was analysed. Fatigue analysis was done by using the Manson-McKnight criterion, the criterion of the total equivalent mechanical strain range and also by using the Nagode approach.

4.1. The Manson-McKnight criterion

The stress-based version of this method was utilized and coded in ANSYS APDL script (see the description below in the section 4.3). It computes the amplitudes and means of the stress components from the maximum and minimum values in time:

$$\sigma_{ij,a} = \frac{\max\limits_t(\sigma_{ij}) - \min\limits_t(\sigma_{ij})}{2}, \qquad \sigma_{ij,m} = \frac{\max\limits_t(\sigma_{ij}) + \min\limits_t(\sigma_{ij})}{2}. \tag{4}$$

The equivalent stress amplitude and mean are computed by using the von Mises norm:

$$\sigma_a = \frac{\sqrt{2}}{2}\sqrt{\left(\sigma_{xx,a} - \sigma_{yy,a}\right)^2 + \left(\sigma_{yy,a} - \sigma_{zz,a}\right)^2 + \left(\sigma_{xx,a} - \sigma_{zz,a}\right)^2 + 6\left(\sigma_{xy,a}^2 + \sigma_{xz,a}^2 + \sigma_{yz,a}^2\right)},$$
$$\sigma_m = \frac{\sqrt{2}}{2}\sqrt{\left(\sigma_{xx,m} - \sigma_{yy,m}\right)^2 + \left(\sigma_{yy,m} - \sigma_{zz,m}\right)^2 + \left(\sigma_{xx,m} - \sigma_{zz,m}\right)^2 + 6\left(\sigma_{xy,m}^2 + \sigma_{xz,m}^2 + \sigma_{yz,m}^2\right)}. \tag{5}$$

The equivalent mean stress value σ_m is signed according to the sign of the maximum first stress invariant over the entire analysed time history. The Walker correction may then be used to compute the resulting equivalent stress amplitude:

$$\sigma_{a.eq} = \sigma_a^{\gamma}(\sigma_m + \sigma_a)^{1-\gamma}, \tag{6}$$

where the γ exponent can be estimated by using the following empiric equation (Papuga et al. (2012)):

$$\gamma = 1 - \frac{log\left(2\frac{f_{-1}}{f_0}\right)}{\log(2)}. \quad (7)$$

f_{-1} and f_0 are the fatigue limit strength in fully reversed and repeated tension, respectively.

4.2. The Nagode approach

The Nagode approach to thermo-mechanical fatigue (TMF) (Nagode (2014), Nagode et al. (2009)) is intended to analyse the variable amplitude stress, strain and temperature signals. It allows for continuous damage parameter calculation, thus avoiding a cycle closure problem that may appear due to variable temperature.

The procedure requires as inputs time history of signed local equivalent stress and strain and temperature obtained by elastic-plastic FEA. Particular attention must be paid to signing so that physically correct inputs are used for prediction. Regarding the material inputs, a set of isothermal Manson-Coffin and Basquin curves for a range of temperatures spanning the values within the analysed time history need to be provided. The fatigue curves for intermediate temperatures were interpolated with 1 °C increment.

The method is based on the Smith-Watson-Topper (SWT) parameter. The Masing and the memory rules are applied for determining the instantaneous stress and strain amplitudes and means. With the amplitude signed according to the equivalent strain, the instantaneous SWT parameter is then evaluated and the value of fatigue damage using the Prandtl hysteresis operator is found.

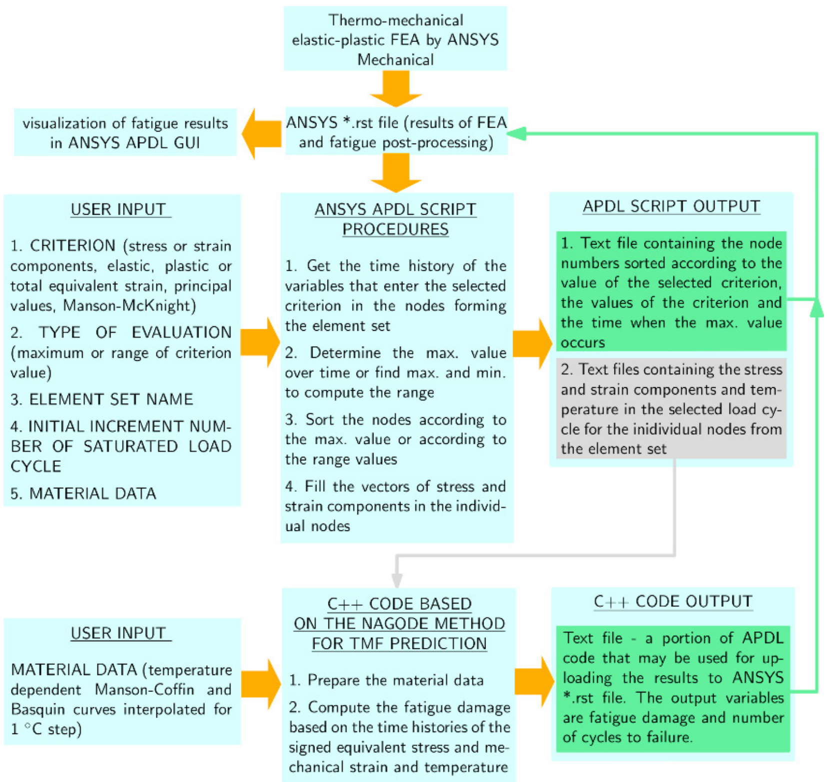


Fig. 3. The basic conception of the developed software codes for fatigue prediction of steam turbine shafts.

4.3. Program codes for fatigue prediction

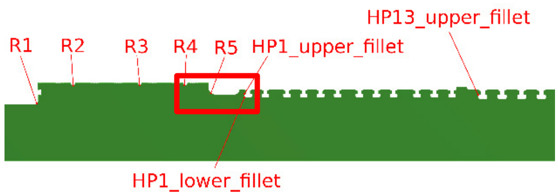
An APDL script intended especially for finding the critical locality in the turbine shaft was coded. A user can choose from a wide range of possible approaches – the maximum or range of the stress or strain tensor components, the stress or strain tensor invariants or the Manson-McKnight method. The selected criterion is evaluated in the corner nodes of the element set, which needs to be predefined in the turbine shaft FE model in ANSYS.

The script creates several kinds of outputs. Firstly, the text file with the node numbers that are sorted according to the value of the criterion is written. The criterion value and time when maximum and minimum occur are also recorded. A separate APDL script may then be applied to upload the obtained results into the original *.rst file. Secondly, for the individual nodes from the selected element set, separate data files containing time histories of the stress and strain components and temperature are written. These files may then be used for fatigue analysis by the Nagode approach, which is coded in C++. The results expressed as the local damage and lifetime are stored in a separate text file, which may be used for uploading the data back into the source *.rst. As well as the data obtained by the APDL script, these results can be mapped on the FE model of the turbine shaft and visualised, for instance, as contour plots.

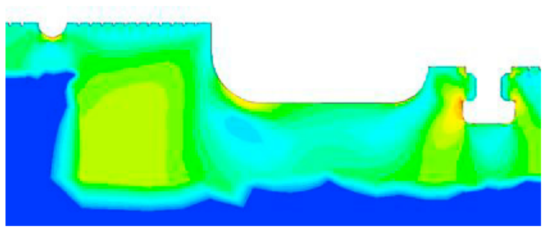
The above mentioned conception of the program codes for fatigue prediction of the turbine shaft is illustrated by the flowchart in Fig. 3.

5. Results

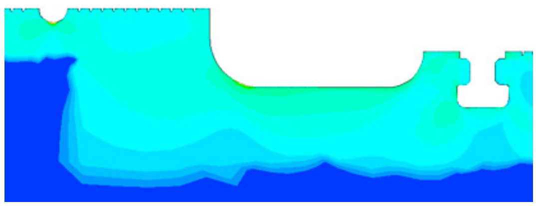
Based on the results of the FE simulations and the overall expertise, potentially critical localities were defined (Fig. 4a). These locations are primarily the regions of the blade grooves and the main internal seals. The element set spanning these locations was defined for the purpose of performing fatigue analysis using the in-house codes. The Manson-McKnight and the total mechanical equivalent strain range criteria as well as the Nagode approach were employed. Fig. 4b to Fig. 4d show the contours of the resulting variables evaluated by these criteria in the locality, which is framed in red in Fig. 4a.



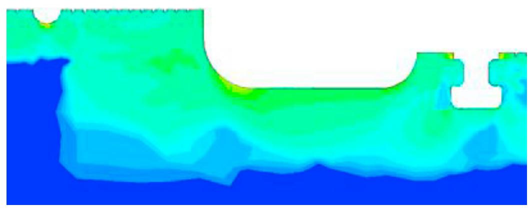
(a) Designation of localities on the steam turbine shaft.



(b) Contour plot of the equivalent amplitude computed by the Manson-McKnight method.



(c) Contour plot of the total mechanical equivalent strain range.



(d) Distribution of fatigue damage computed by the Nagode approach.

Fig. 4. Sample results of the methods applied to detection of the critical locality and the assessment of TMF damage.

Table 1. Results of fatigue analysis in the selected localities of the turbine shaft.

	R1	R2	R3	R4	R5	HP1_upper_fillet	HP1_lower_fillet	HP13_upper_fillet
MMK[a)] [MPa]	440.6	428.9	416.9	421.2	423.0	546.5	368.3	493.9
$\Delta\varepsilon_{t,mech}$[b)] [-]	4.4E-03	3.4E-03	5.4E-03	4.2E-03	3.3E-03	4.5E-03	2.2E-03	2.1E-03
D by Nagode[c)] [-]	9.3E-04	7.5E-04	2.2E-03	1.2E-03	1.2E-03	1.8E-04	4.5E-04	1.3E-05
N by Nagode[d)] [-]	1074	1327	451	847	835	5636	2222	78985

a) Equivalent amplitude by the Manson-McKnight method
b) Equivalent total mechanical strain range
c) Damage by the Nagode approach
d) Number of cycles by the Nagode approach

Tab. 1 provides the numerical results in terms of maximum values in the selected localities. The most critical place according to the Manson-McKnight is the "HP1_upper_fillet" locality, which is also a place with the maximum value of the first principal stress. Based on the total mechanical equivalent strain range, the most probable site of the primary failure is the "R3" locality. The same critical place was found by the Nagode method, which predicts 451 cycles to crack initiation under the assumed cold-start load regime.

An interesting observation can be made if we assess the damaging effect of the stress peak P2 from Fig. 2. It turns out that using the Nagode method is the damage due to this peak equal to more than 20% of the damage due to the cycle as a whole. This finding must be taken into account, for instance, if an experimental test is to be proposed to verify the prediction capabilities of the fatigue prediction methods.

It should be noted that the presented results are preliminary and will be further refined based on the progress of experimental programme conducted to measure the cyclic stress-strain curves and fatigue curves.

6. Conclusions

The work done within the FLEXTUBINE project was introduced and some preliminary results concerning the fatigue prediction methodology applicable to steam turbine rotors were presented. The strategy for TMF prediction of this structure is based on 2D axisymmetric FE model for simulating the time variable thermo-mechanical stress-strain response. The in-house codes for fatigue analysis that are capable of processing the ANSYS *.rst files are based on a number of criteria, including the Manson-McKnight and the Nagode methods. It is possible to determine the critical location including the extent of the damage or the number of cycles to initiation. The obtained results can be mapped to the original FE model to obtain an overview of the distribution of the resulting values.

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