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IMPLEMENTATION OF INTERACTING CREEP AND FATIGUE UNDER THERMO-MECHANICAL LOADING

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Abstract: *Presented work is dealt with thermo-mechanical fatigue analysis. Only elastic stress and temperature field are taken from FEM analysis. Strain components are calculated using nonlinear Maxwell model to cover both elastoplasticity and viscoplasticity. For stepwise stress history elastoplastic and viscoplastic strain component are gain independently solving one after another. For every point in loading history is consequently found closed hysteresis loop and damage increment corresponding to actual hysteresis loop is evaluated. Current damage is calculated by Prandtl-Ishlinskii model of hysteresis using iso-thermal fatigue curves.*

Keywords: Thermo-mechanical fatigue, Hysteresis modeling, Viscoplasticity, Damage prediction.

1. Introduction

During the service of an engine, a multitude of material damage such as foreign object damage, erosion, high cycle fatigue, low cycle fatigue, fretting, hot corrosion/oxidation, creep, and thermo-mechanical fatigue is induced in these parts. The mechanical loading and effects based on the temperature gradient were stated as the most important factors.

Changing temperature during the loading cycles has influence on stress-strain state and therefore it causes closure problem of stress-strain hysteresis loop. Temperature dependent fatigue properties brings additional aspects to deal with. An approach for solving hysteresis loops closure problem as well as modeling of damage can be found in Nagode (2010).

Moreover real engine can operate in long-term conditions. Besides, loading spectra can contains specific loading type, dwell for instance, and they cannot be covered by traditional way of analysis. In additional, due to high temperature field time-dependent degradation mechanism has to be taken into consideration and its interaction with pure fatigue (ϵ_{pl} induced mechanism).The way how creep and fatigue can be considered and interacted is described in further paragraphs.

2. Framework of coupling elastoplasticity and viscoplasticity

It is known that the fatigue and creep damages depend on elastoplastic strain and stress respectively. If the life prediction is based on the instantaneous values, both fatigue and creep damages should be overestimated for positive mean stress due to relaxation. For this purpose viscoplastic strain component must be evaluated and affected final elastoplastic strain and stress respectively. In order to cover viscoplasticity spring-slider model was extended to the nonlinear Maxwell model by adding nonlinear damper in series according to Nagode (2007), see Fig. 1.

Stress tensor and temperature field serve as inputs into fatigue analysis procedure. For this purpose elastic FEM analysis was performed and all necessary inputs for fatigue analysis are calculated from elastic stress tensor and temperature field. In fatigue analysis elastoplastic stress $\sigma_{el-pl}(t_i)$ is calculated with Neuber's approximation from FEM elastic input. From calculated elastoplastic stress, total strain $\epsilon_{total}(t_i)$ can be solved. For strain approximation stress-controlled Prandtl-Ishlinskii model can be used to cover elastoplasticity according to equation (1) and (2). Description of approximation of cyclic

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deformation curve and calculation of parameters of spring-slider model $\mathrm{C_r}$ and $\mathrm{r_r}$ can be seen in Nagode (2010) and Grzesikiewicz (2012).

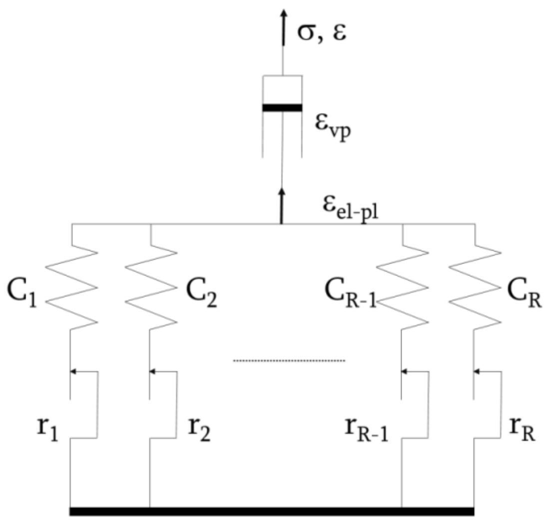

Fig. 1: Maxwell model of viscoplasticity.

$$\epsilon_{\mathrm{total}}(\mathrm{t_i}) = \sum_{\mathrm{r}=1}^{\mathrm{R}} \mathrm{C_r}(\mathrm{T_i}) * \left(\sigma_{\mathrm{el-pl}}(\mathrm{t_i}) - \sigma_{\mathrm{r}}^{\mathrm{pl}}(\mathrm{t_i})\right) \tag{1}$$

$$\sigma_{\mathrm{r}}^{\mathrm{pl}}(\mathrm{t_i}) = \max\left\{\begin{matrix} \sigma_{\mathrm{el-pl}}(\mathrm{t_i}) - \mathrm{r_r} \\ \min\left\{\begin{matrix} \sigma_{\mathrm{el-pl}}(\mathrm{t_i}) + \mathrm{r_r} \\ \sigma_{\mathrm{r}}^{\mathrm{pl}}(\mathrm{t_{i-1}}) \end{matrix}\right\} \end{matrix}\right\} \tag{2}$$

Total strain $\epsilon_{\mathrm{total}}$ can be divided into elastoplastic and viscoplastic part according to (3).

$$\epsilon_{\mathrm{total}}(\mathrm{t_i}) = \epsilon_{\mathrm{pl}}(\mathrm{t_i}) + \epsilon_{\mathrm{vp}}(\mathrm{t_i}) \tag{3}$$

For stepwise stress history elastoplastic ϵ_{pl} and viscoplastic ϵ_{vp} strain component are gain independently solving one after another. Viscoplasctic strain component is approximately calculated from eq. (4).

$$\epsilon_{\mathrm{vp}}(\mathrm{t_i}) \approx \mathrm{sgn}(\sigma_{\mathrm{el-pl}}(\mathrm{t_{i-1}}))\dot{\epsilon}_{\mathrm{vp}}(\mathrm{t_{i-1}})(\mathrm{t_i} - \mathrm{t_{i-1}}) + \epsilon_{\mathrm{vp}}(\mathrm{t_{i-1}}) \tag{4}$$

Visoplastic strain rate $\dot{\epsilon}_{\mathrm{vp}}$ in (4) is calculated from model proposed in Bina (1997) in the following form (5).

$$\log \dot{\epsilon}_{\mathrm{vp}} = \mathrm{A_1} + \mathrm{A_2}\log\left|\frac{1}{\mathrm{T}} - \frac{1}{\mathrm{A_5}}\right| + \mathrm{A_3}\log\left|\frac{1}{\mathrm{T}} - \frac{1}{\mathrm{A_5}}\right| [\sinh(\mathrm{A_6}\sigma\mathrm{T})] + \mathrm{A_4}\log[\sinh(\mathrm{A_6}\sigma\mathrm{T})] \tag{5}$$

Unknown elastoplastic strain ϵ_{pl} is then easily calculated from known total strain (1) and viscoplastic strain (4) from equation (3). Finally, stress $\sigma_{el-pl}(t_i)$ can be solved from plastic strain controlled Prandtl-Ishlinskii model, see (6) and (7).

$$\sigma_{el-pl}(t_i) = \sum_{r=1}^{R} S_r(T_i) * \left(\epsilon_{pl}(t_i) - \epsilon_r(t_i)\right) \tag{6}$$

$$\epsilon_r(t_i) = max\left\{\begin{matrix} \epsilon_{pl}(t_i)(t_i) - q_r \\ min\left\{\begin{matrix} \epsilon_{pl}(t_i)(t_i) + q_r \\ \epsilon_r(t_{i-1}) \end{matrix}\right\} \end{matrix}\right\} \tag{7}$$

According presented procedure, plastic strain component and corresponding stress are calculated in every time step from whole loading history. Because every stress and strain variable are dependent on previous state, whole loading history should be repeated several times. In the case of presented coupled viscoplasticity and elastoplasticity several repetitions are recommendable. Into every repetition comes variables from previous run. Strain component and corresponding stress were calculated to contribute to pure fatigue damage. For that reason extrapolated stabilized cyclic deformation curve for strain rate $\dot{\epsilon} \rightarrow \infty$ is used in hysteresis model. Example of simulation of two loading histories with five repetition is on following figures, see Fig. 2.

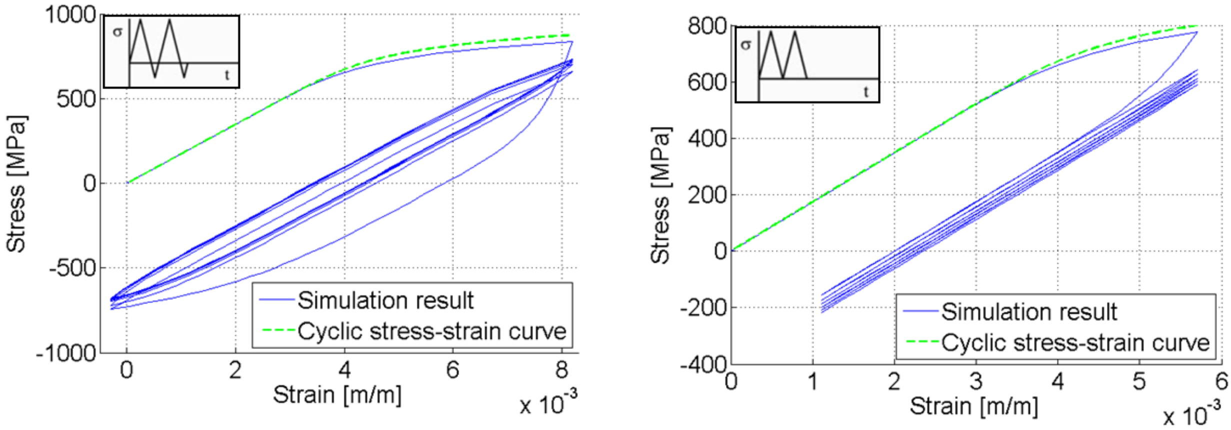

Fig. 2: Example of stress-strain simulation.

3. Damage prediction

Every step of loading history is analyzed sequentially and therefore growing damage is calculated starting from t = 0 to the end of loading spectrum. Theoretical background of damage calculation is proposed in paper Nagode (2010). In every time step hysteresis loop is formed between current analyzed time step and certain point from previous loading. Actual stress amplitude and mean stress is calculated from this loop. Actual fatigue damage is evaluated with SWT damage operator. Prandtl-Ishlinskii model of hysteresis is applied on interpolated iso-thermal fatigue curves for current temperature. Actual fatigue damage is get as the sum of elemental contributions from each individual spring-slider sub-models of fatigue curve.

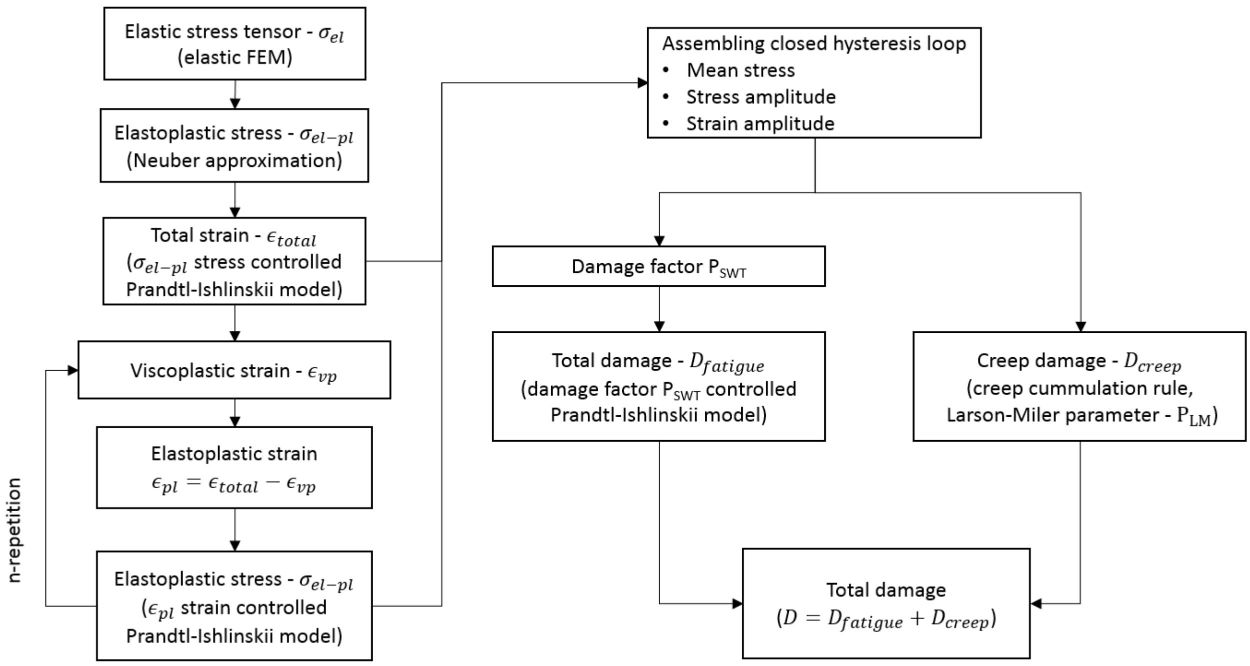

Fig. 3: Block scheme of consideration of both fatigue and creep damage mechanisms.

Creep damage is calculated according to (8).

$$D_c(t_i) = \sum \frac{t_i}{t_c} \tag{8}$$

Corresponding time to rapture t_c is calculated from creep master curve. For life time prediction where creep doesn't contribute to major part of life, Larson-Miler parameter is used to get time to rapture, see (9).

$$\log\sigma = A_1 + A_2 P_{LM} + A_3 P_{LM}^2$$
$$P_{LM} = T(\log(t_{cr}) + A_4) \tag{9}$$

Total damage is then supposed as the summation of fatigue and creep damage. Sequential block scheme of described approach is depicted in Fig. 3.

4. Conclusions

Presented paper briefly described promising approach for continuous damage calculation during the non-isothermal loading. This concept is computational cheap and very effective using only widely available material data from isothermal tests. Coupling elastoplasticity and viscoplasticity mechanisms enables calculation both fatigue and creep damage. Whole analysis framework is suitable for those cases: low level of plastic strain, crucial point is localized inside of small area and stress-strain redistribution occurs only at small scale during the loading history.

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