Abstract

The historic and everlasting aim to increase the steam temperature and pressure in steam turbines, to maximize efficiency, results in increased rate of creep/fatigue induced damage. To reduce the carbon footprint and meet the energy requirements at the same time, combination of conventional and renewable energy sources, with the predominant contribution of solar energy, is necessary. This requires flexible operation of conventional fossil fuel based power plants to compensate for the natural variation of the renewable energy availability leading to further enhancement in fatigue/creep damage. The non-linear interaction of creep and fatigue accelerates the total damage progression. The widely used uncoupled analysis using linear damage accumulation rules, wherein the damage due to creep and fatigue are considered separately and added in a linear manner, leads to conservative estimates of damage. To enable the flexible operation, advanced life assessment techniques are necessary for steam turbine rotors. Over the past two decades, studies using damage coupled unified constitutive models for the creep-fatigue interaction analysis of steam turbine components under complex loading cycles have attracted the attention of researchers/designers.

The constitutive model chosen in the present study involves the modified Chaboche non-linear kinematic and Chaboche and Rousselier isotropic hardening models with evolving damage, Norton type visco-plastic flow model, Lemaitre's damage potential function and modified form of Kachanov-Rabotnov's creep damage law. However, high computational time involved in the unified constitutive model based finite element analysis using iterative techniques hinder their widespread applications. In the present work, a non-iterative Asymptotic Numerical Method (ANM) for cyclic elasto-/visco- plasticity problems including damage evolution capable of handling multiple complex loading cycles is proposed and its application for steam turbine rotors is explored. To apply the polynomial expansion based ANM, several new regularizations of the governing equations/variables are proposed for multi-cycle elasto-/visco- plasticity. The methodology is implemented in ABAQUS through user material subroutine (UMAT). The accuracy and computational efficiency of the proposed method are tested considering results available in literature and comparison with the iterative Newton Raphson (NR) predictions for elasto- and visco- plastic analyses of steam turbine rotors under thermomechanical loading.

However, the expected computational time for the analysis of the complete rotor life is of the order of years even using the proposed ANM. To reduce the computational time to acceptable limits, a novel Representative Input Cycle (RIC) concept based local ANM is proposed for the complete life cycle analysis of steam turbine rotors. A long-term progressive damage analysis using the proposed RIC based ANM of a rotor under normal and normal followed by flexible operating regime is carried out. Reprofiling of the TSRG of the in-service rotor is investigated for enhancing the rotor life by a priori damage analysis.

Based on the analyses, it is found that ANM predictions are in excellent agreement with the Newton Raphson method. RIC based local ANM predicts normalized number of cycles to reach damage equal to unity in close agreement with the full finite element predictions and significantly smaller computational time requirement. The progressive damage analysis of a steam turbine rotor at a critical location employing the proposed RIC based ANM leads to computational time of ~5 days (including time for FE analysis for the initial loading period to construct the RIC based strain history) for 30 years of loading duration. Finally, the re-profiling of the thermal stress relief groove (TSRG) of the rotor decided through the RIC based progressive damage analysis predicted a life enhancement of ~31 years.