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Creep Fatigue Damage Assessment of an In-service Superheater Outlet Header

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Abstract

Superheater outlet header is one of the high temperature and high pressure critical component of a power boiler. The header during its service operates under process transients consisting of load ramps during start-ups and shut-downs and steady loads during its sustained load operation. Such service condition induces creep and fatigue damages on the component which on accumulation causes life consumption. One such header of a 210 MW coal fired unit is being assessed by an on-line finite element technique. The stresses and temperatures of the component are calculated from the steam parameters. The creep and fatigue damages are computed using Robinson rule and Miner rule respectively. The linear damage summation of the creep-fatigue damages is accumulated to define the life being consumed on real-time basis. The damage rate on extrapolation over the previous service period before the installation of the real time creep fatigue monitoring system is yielding the usage factor of the component. The real time monitoring system has identified shell-nozzle location from the damage contour of the header volume which has exceeded its design life. The damage assessment of the identified location was carried out by in-situ metallographic evaluation. The finite element analysis supplemented with metallographic assessment on an in-service high temperature component was implemented for remaining life assessment and the results were in conformity with each other.

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Introduction

High temperature components of thermal power plants are subjected to creep, fatigue and creep-fatigue interactions during their operating conditions. These components during the process loadings of base load operations, start-up and shut-down transients and cyclic loads undergo synergistic creep-fatigue interaction damages and thus consequently have limited life. Thus to maintain these high temperature critical components in a reliable and cost-effective manner it becomes pertinent to assess these irreversible damages and thereby estimate the remaining lives in these component. High temperature superheater and reheater headers of the fossil-fired boiler operating in the creep domain are subjected to high stresses at localized sections such as shell nozzle junctions, girth welds, etc. Superheater outlet header of the boiler is one of the most critical components in the superheater circuit operating in the creep regime. The main steam from this final superheater header exits the boiler and enters the high pressure turbine through main-steam piping for electric power generation. These headers and other such structures in service at elevated temperatures are in focus for integrity assessment and life management programme for the electric utilities globally [1-2]. They are subjected to thermal and pressure stresses which can lead to cracking and failure. The behavioral study of defect free structures and the structures containing defect at elevated temperatures is being done through various analytical techniques [3-4]. A comprehensive remaining life assessment programme for the component essentially requires the prediction for accumulation of damage due to creep and fatigue throughout their useful service. R5 code, which provides design and construction rules for components operating at elevated temperature, is used for high temperature life assessment. It enables in postulating a crack in the component and predicting its behavior during the service life time. To predict the damage in the components operating at elevated temperature due to creep and fatigue synergistic interactions, detailed methodology is given in API 579 code [5]. The high temperature pressurized components of power plants are subjected to creep and fatigue damage mechanisms and have a limited life [6-7].

The remaining lives of such components are assessed by their actual material degradation due to creep after the exhaustion of their designed lives as per applicable codes. These components aged beyond their designed life require statutory remaining life assessment by various site tests as per Indian Boiler Regulations (IBR) Act 391A of 1998. The creep damage involves detection of creep cavities and their estimation requires high quality in-situ metallography. It has been found that the manifestation of such creep cavities occur on outer surface of thick pressure parts. In principle, the creep damage of the components is obtained through reliable quality microstructures at the highly stressed zones of thick walled components like high energy piping, headers etc. which in service condition have exceeded their design life [8-19].To ensure the integrity of the high temperature critical component and prevent it from any unforeseen failures, it is necessary to monitor its critical locations on a real-time basis. A case study on real-time finite element based creep-fatigue damage assessment of in-service superheater outlet header of a 210 MW unit has been discussed in this paper.

Experimental

Creep fatigue damage assessment of superheater outlet header

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The candidate component under discussion for creep-fatigue damage assessment is a super-heater outlet header of a 210 MW boiler, which is being assessed by real-time finite element based damage monitoring system. The superheater outlet header is a thick cylinder with outer diameter of 406.4 mm, 75 mm thickness and 13.259 m length. It is a three-dimensional structure resting on two hangers horizontally with an array of nozzles along its length which perforates its bottom cylindrical half. The high temperature critical component is operating in the creep regime with a hydraulic pressure of 155 kg/ cm2 and 540°C. It is made of 2.25Cr-1Mo low alloy ferritic steel material (ASME specification SA 335 grade P22). The main steam on exit from superheater outlet header of the boiler is transported to the high pressure turbine of turbo-generator system of power plant.

The predominant damage in the material is due to creep and is manifested with time-dependent microstructural changes involving carbide precipitation at grain boundaries followed by cavitation. A typical high temperature header with locations susceptible to cracking during its service is depicted in Fig. 1.

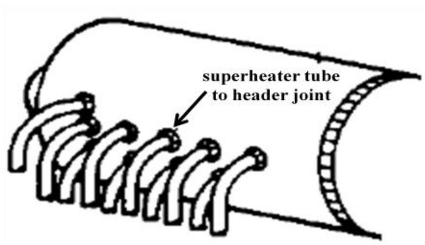


Figure 1: Superheater header with tube to header weld joint susceptible to cracking

Real-time finite element based damage computations

All the plant transients consisting of fluctuating loads, steady loads and load ramps due to start-ups and shut-downs act synergistically on the component material and thereby cause irreversible creep-fatigue damages. To assess real-time creep-fatigue damages in the operating superheater header, thermal hydraulic process parameters, viz., steam temperature, steam pressure and steam flow are acquired through plant information server in defined intervals of time. The conversion of plant transients to the temperature/ stress responses in the component is one of the most important tasks. To compute the temperature, stress intensities etc., the finite element technique is used for thermal and stress analysis of the components. The finite element model uses 3-D solid 20-noded brick elements. The details of the model are discussed in Ref. [20-26].

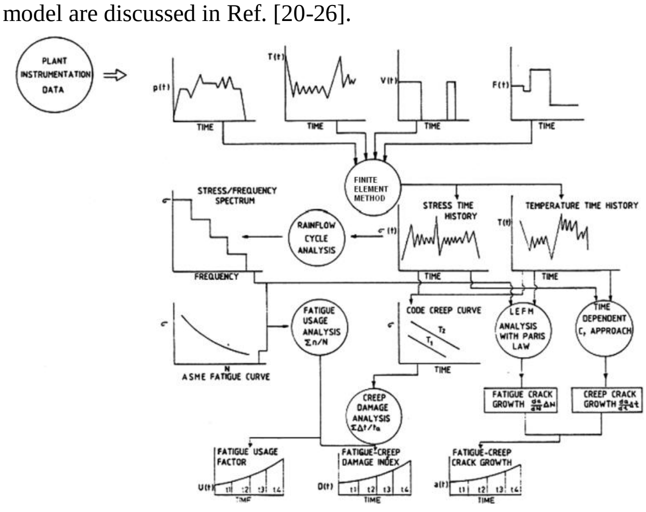
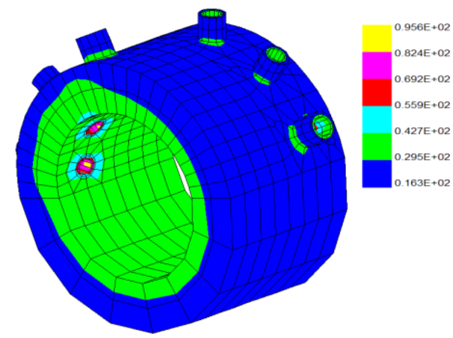
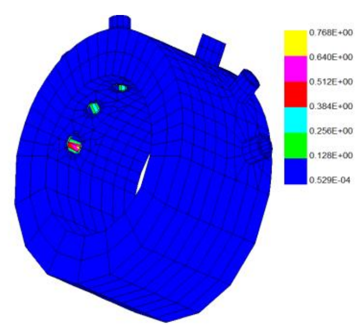


Figure 2: Various Stages of on-line Creep-fatigue Damage Assessment System

The system computes the heat transfer coefficients for the boundary of the component being analyzed. The thermal transient analysis is performed for obtaining the temperature distribution in the whole volume of the model. The stress analysis module computes thermal stresses in the component using the temperature profile obtained from the transient thermal analysis and calculates the stress distribution in the component volume under the action of fluid internal pressure, temperature gradient and the piping loads at each time interval. The stress-time history is converted to stress frequency spectrum using rainflow cycle counting algorithm. The Miner's life fraction rule is used in calculation of fatigue damage from computed cycles and material fatigue data. Robinson's life fraction rule is adopted for evaluating creep damage using computed temperature, stress histories and material creep curve as per API 579 code.



a) Contour of Stress intensity (MPa)



b) Contour of creep and fatigue usage factor

Figure 3: Stress intensity, creep and fatigue usage factor contours of superheater outlet header at an instant of time during operation

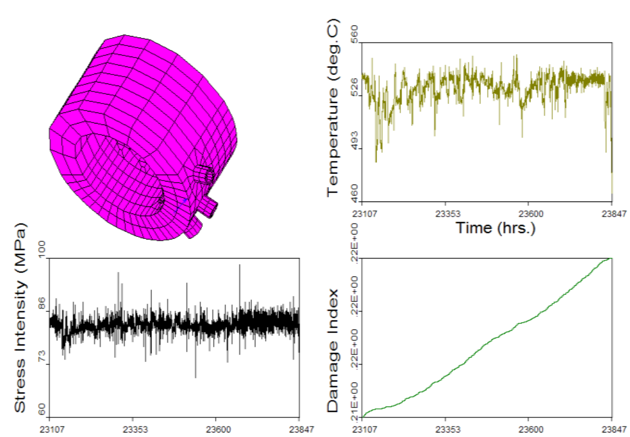


Figure 4: Computed material stress intensity, temperature, usage factor history at a shell-nozzle junction of superheater outlet header

The complete schematic of the real time creep fatigue damage monitoring system deployed for high temperature critical components of power plant is depicted in Fig. 2 [19-25]. The system is developed and being maintained by Bhabha Atomic Research Centre, Mumbai.

The contours of the stress intensity and usage factor due to creep and fatigue obtained from finite element analysis of superheater outlet header under assessment are depicted in Fig. 3. The whole-field information on stress and damage in the header is known at any instant of time. The finite element based analysis followed by creep-fatigue damage assessment has identified one set of stub-tube to header weld joints of in-service header in higher heat flux zones of the boiler the possibility of onset of crack as per ASME design code calculations on extrapolation of the usage factor after 1,12,447 hours of operation. The computed values of material temperature, maximum stress intensity and damage history at the shell-nozzle junction of the superheater outlet header are shown in Fig. 4.

This also necessitates extrapolating the logged in data to compute the damage of the entire service life of the components. Such extrapolation is based on the assumption that the logged in plant thermal-hydraulic parameters can be considered to be representative of past plant history. Under such assumption, the damage data for fatigue and creep data are extrapolated for entire service life of the components by the code during on-line calculations. The assessment of creep-fatigue damage and subsequent remaining life computations after extrapolations of monitored damage data over the service period is the basic methodology of the real-time monitoring system for components operating in the creep domain.

The system has been installed after some period of operation instead of implementing during commissioning of the new plant. The logged-in data is extrapolated to compute the usage factor for the service life of the components on an assumption that the logged-in plant thermal-hydraulic parameters are representative of past plant history. The computed creep-fatigue usage factor data are extrapolated for the service life of the components by the monitoring system using on-line acquisition of process data.

In-situ metallurgical assessment of damage

To evaluate the extent of life exhaustion, the in-situ replicated micrographs were quantified for accrued creep damages. Neubauer and Wedel model for analysis of creep damage is widely accepted for predicting the remaining life and setting inspection interval. If no creep cavities are found, but only spheroidised carbides are observed, then creep damage is considered as insignificant and the next inspection is needed after 5 to 6 years. Creep cavities nucleate and grow predominantly on grain boundaries oriented normal to the maximum principal stress. The density of cavities in ferritic steels used in boilers is dependent on the grain boundary chemistry, strain and stress. Numerous controlling mechanisms are propounded for creep cavitation, namely vacancy flow, continuum or power-law growth and constrained cavity growth. Highly stressed zones are identified based on finite element analysis of the components when subjected to fluctuating plant transients [2-3]. The creep damage occurs by spheroidization of carbides and is followed by nucleation of creep cavities and their growth along grain boundaries.

The plant transient data acquired through plant information server for super-heater outlet header were used by the on-line damage monitoring system to compute the accrued damages. The system had identified a set of shell-nozzle junctions which have exceeded its ASME designed life. The header was taken up for surveillance programme as per the statutory requirement of IBR Act 391A of 1998 for design life exhaustion. The qualitative assessment using high resolution microscopy indicated that the creep cavities correspond to stage-II of Neubauer's classification diagram.

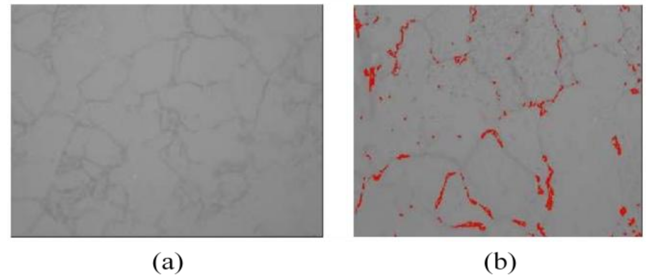


Figure 5: Micrographs obtained from super-heater shell-nozzle junction using replicas. (a) Location with relatively undamaged boundaries Location with extensive creep cavitations

Results and Discussion

The life management programme for high temperature superheater and reheater headers involves condition assessment and life extension initiatives and forms the plant's preventive predictive maintenance strategy. Superheater outlet header experiences significant creep damage operating at 540ºC which is in the creep regime for 2.25Cr-1Mo steel (ASME specification SA 335 grade P22) material. The alloy experiences inelastic strain which is dependent on sustained stress at such high temperatures.

The high temperature headers have a finite life due to accumulation of creep damage when subjected to its rated temperature and stresses during its base load operation. The creep damage accelerates during the load transients as per the grid requirements and the load ramps during start-ups and shut-downs. The cyclic operation of the boiler induces cyclic stresses and strains and may lead to fatigue related damages. The start-ups and shut downs of the boiler causes transient thermal stresses due to steam temperature changes in the thick walled headers. The header cracking is caused due to such accelerated creep damage at high stress locations such as ligament area between tube bore holes, welds etc. Thus identifying and assessing these damages is vital for reliable and safe operation of the boiler.

The prevailing approach/ practice of the utilities to estimate the need for inspection is on the basis of offline inspection and their past O&M experience. These result in frequent inspections of problem-free equipment by the utilities and also often cause unexpected failures. The application of the present real-time creep fatigue damage assessment system would help in making on-line damage assessments of different critical components and take realistic decisions in many operating plants simultaneously. The scope of monitoring of this system can be easily expanded to many other critical components. The system can be merged with existing O&M planning and scheduling activities for efficient plant management and thus provide a cost effective solution.

Conclusions

The finite element analysis based creep-fatigue damage assessment along with in-situ quantitative metallographic evaluation has established a reliable methodology to address the remaining life assessment of critical high temperature components, which is essential for operational safety, reliability and economic plant operation. This will substitute the approach of the utilities performing inspection on the basis of past operation and maintenance experience which often cause unexpected failures. The present approach of monitoring critical components would be applied along with regular operation and maintenance planning and scheduling activities to provide a cost effective plant management and thereby reducing uneconomical decisions of arbitrary inspections. The evaluation procedure for creep and fatigue usage factor is according to relevant API and ASME codes. The predicted usage factors may be improved by the use of specific material data (mechanical, creep and fatigue properties) for the component under consideration along with the provision to account for the service-related degradations. It is being planned to extend the present damage monitoring system to all ageing critical components with updated material and component specific database.

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