Introduction

Thermal and nuclear power plants are highly capital intensive and hence it is necessary to ensure not only their safe operation, but also their economic viability in the long run. Integrity of important components is essential for operational safety, reliability and low cost operation. Normally, a power plant is designed with a life expectancy of 30 to 40 years to produce continuous power economically. However, because of conservatism in the design, the actual lives of these plants are expected to be much more than the estimated value. The sustained interest in the area of remaining life prediction arises from the need to avoid costly outages and to ensure safe operations, and the necessity to extend the component operation life beyond the original design life. In power generation systems, many structural components, such as steam pipes, superheater headers, and turbine rotors operate at elevated temperatures. At the same time, they are also subjected to cyclic loading due to fluctuation of process parameters. Hence, these components are exposed to a damage mechanism caused by fatigue, creep and creep-fatigue interaction. Thus, there is a need for the development of a life prediction methodology which can account for this combined damage mechanism.

Utility Benefits

The benefits of such fatigue-creep monitoring system (FCMS) are as follows:

(i) Generating data base for the designers about the actual plant transients.
(ii) Guiding plant operators to adjust operating procedures and in-service inspection programs based on actual damage.
(iii) Assessing the structural integrity of the pressure boundaries after an event in which operating pressure and temperature exceed the limits.
(iv) Recording of material degradation due to fatigue, creep and fatigue-creep interaction.
(v) Supporting in life estimation and life extension programs of plants.

Plant Locations Susceptible to Fatigue-Creep Damage

It is neither possible nor necessary to monitor the degradation effects for all the components of a plant. An in-depth understanding of the possible damage mechanism and the plant process dynamics is essential for the selection of an optimum number of components. Some typical components of nuclear and thermal power plants which require damage monitoring, are detailed below.

In boiling water reactor (BWR), pressurised water reactor (PWR) and pressurised heavy water reactor (PHWR) type nuclear power plants, fatigue is the most important aging effect which causes failure. Here creep is not very important as operating temperature is not very high. For PWR, the components generally selected are charging nozzles, surge lines, steam generator feed water nozzles, safety injection nozzles, etc. Feed water nozzles, CRD return nozzles, etc. are selected for BWR plants for fatigue monitoring. In the case of PHWR, end fitting, pressuriser, steam generator tube sheet, etc. are the components which will be most severely affected due to the plant transients. In fast breeder reactor, the temperature is much higher and creep plays a vital role in failure mechanism.

In thermal power plants, the combination of thermal and pressure cycles cause creep and fatigue damage, particularly in heavy section components such as boiler headers, steamlines, turbine
casings, superheater and reheater tubes, nozzle blocks and valves. The accumulated creep-fatigue damage causes the component to crack, leak and in some cases fail in a catastrophic manner. Secondary superheater outlet headers are particularly prone to ligament cracking as a result of creep-fatigue interaction. By monitoring the temperatures and the difference in temperature at the tube legs and header body, the degree of damage can be assessed and possibly controlled if the differences can be minimised through operational changes. Economiser inlet headers are also known to crack in the ligament area as a result of thermal shock. During shutdown of the boiler, the drum level drops and slugs of cold water are fed into the system via the inlet header. The frequent changes of temperature lead to fatigue damage. Turbine casings and blades usually crack due to thermal fatigue. The combination of thick walls, rapid transients due to blade grooves and changes in section size promote the susceptibility of crack initiation. The steampipes are subjected to thermal and pressure transients as well as changes in global stresses due to hanger/support system. These components require a system to monitor the effects of creep, fatigue, creep-fatigue interaction and crack growth due to fatigue and creep. In chemical process industries, fatigue or both creep and fatigue based on the operating temperature of the plant are the crucial damage factors which cause structural degradation or failure of the component.

BARC Fatigue-Creep Monitoring System

In BARC, a fatigue-creep monitoring system (FCMS) has been developed. The system converts the plant transients to temperature/stress responses using finite element method (FEM) and transfer function approach. This computes the fatigue usage factor using rainflow cycle counting algorithm. The creep damage index is evaluated from the computed temperature and stress histories and the material creep curve. The damage accumulation approach is adopted to account for the combined damage mechanism.

The code is capable of handling fluctuating pressure, thermal load and piping loads. From the recorded process transients (temperature and flow rate), the temperature responses at the selected component are computed using a transient thermal finite element analysis. The thermal stresses are calculated from the temperature field. The stresses due to internal pressure and piping loads are evaluated using a stress data base which is again generated using finite element method. The stresses due to thermal load, internal pressure and piping loads are superimposed. The fatigue, creep and creep-fatigue interaction effects are estimated at several nodal points of the structure. The code is written in C language. Some special features of the various modules of this system are listed below.

Temperature Transient Module

- The formation of element coefficient matrices is done every time to avoid their storage.
- The solution of transient equations is obtained by using Galerkin's method.
- The active column solver is used to solve the set of equations.
- The temperatures and the thermal load vector at the end of previous day's calculations is stored in a restart file for the computation to proceed for the next day.

Stress/Deformation Module

- The decomposed assembled stiffness matrix, after forward elimination, is stored as a data base to be used at the beginning of every day's processing.
- For the subsequent solutions, only back substitution is required for a new load vector corresponding to every record.
• The solution scheme is again the active column solver.

Integration of System Induced Loads

Structural degradation may be attributed to parameters such as variation in the internal pressure, temperature and flow. Generally, such monitoring systems take care of fluctuations in the process parameters. Apart from these process parameters, the additional system induced external loads may also contribute to degradation of components. These external loads usually arise from the piping system. The external loads and bending moments acting on the selected component are computed by carrying out the flexibility analysis of the piping system. The resultant stresses are computed using a 3-D finite element analysis. Through this analysis, a data base is generated for the selected components for unit change of process temperature and pressure. This data base is used in the present system and these stresses are superimposed with the stresses due to process parameter fluctuations.

Fatigue, Creep and Creep-Fatigue Interaction Module

The recorded plant transients are converted to structural stress and temperature responses using finite element method. In the present system, elastic stress analysis is performed. Effects of inelasticity is not considered. As per the ASME Boiler and Pressure Vessel (Section III, Code Case N-47) guidelines for calculation of fatigue and creep damage, elastic stress analysis is acceptable. The cycles are counted based on the rainflow cycle counting algorithm and the fatigue usage factor is evaluated from the material fatigue curve. The creep damage index is evaluated from the computed elastic stress intensity and the material creep curve (ASME Boiler and Pressure Vessel Code). The combined creep-fatigue interaction is computed using combined damage mechanism rule.

Screening of Transients and Data Storing

The plant transients are generally recorded by a data recording system at a particular time interval. This time interval may be as small as, for example, 0.1 sec., or as large as 5 sec. This depends on the nature of the plant transients and the recording system. In some particular situations, when the transients are insignificant, the processing of these records are not necessary. In the present system, there is a provision of screening the input data recorded from the plant instrumentation. This helps in reducing the number of records to be processed. The transients are screened based on the severity of the fluctuations and only relevant records are further processed.

In the present system, the whole field information for temperature, stresses and fatigue usage factor are stored. The damage index is updated after the computation of each day and stored as a record. The time history variations of recorded process flow, computed structural temperature, stresses and damage parameters are also stored. The variations of structural responses (e.g., structural temperature, stresses, etc.) are stored at few selected points on the structure.

Graphics Display Module

A user friendly graphics module is incorporated for display of relevant results. When initiated, this module displays the components selected for fatigue monitoring at the plant site. For a particular component, this shows the geometry, the material properties used and the finite element mesh adopted. The recorded fluid transients are displayed giving quantitative information of the operating conditions of the plant. The computed stress and temperature histories are also available for display. The calculated rainflow cycles are plotted as a stress frequency spectrum. The fatigue usage factor, creep damage index and the combined fatigue-creep damage index histories can be seen on screen or plotted on the paper. The whole field
information for structural temperature, stresses and damage index are also displayed.

**Data Compression Algorithm and Safety Features**

The number of records of temperature and stress histories are accumulated as the system runs for a long period. A data compression algorithm has been incorporated to restrict the number of history records. The principle of rainflow cycle counting method is adapted in this compression algorithm. Once the number of records exceeds the specified storage capacity, the smaller stress or temperature excursions are eliminated from the data base.

The system has built-in safety features against some unforeseen conditions caused by power failure or human error while the computation is on. These features protect the system from malfunctioning under these situations. A backup directory is created and all the files are stored in the backup directory. When the system is installed, all the relevant files from the backup directory are copied to the working directory. After each day of computation, the results are checked, and if all the computations are performed satisfactorily, the updated results are copied to the backup directory. In case of an erroneous computation (due to some error in input signals, etc.), power failure or arbitrary interruptions to the system, the files from the backup directory would be recopied to the working directory. The operation of the system would not be affected although the data for that particular day would be lost.

**Implementation and Experience of FCMS**

The FCMS was installed at Heavy Water Plant (HWP), Kota, in mid 1996 (Fig.1). In HWP Kota, the process temperature is much below the temperature range of creep; hence the creep module is not actuated. Three nozzles are selected for fatigue monitoring: gas outlet nozzle connected to the spherical head of the waste stripper column (N01), gas inlet nozzle connected to the cylindrical column tower (N02), and inlet recirculation nozzle to the column tower (N13).

![Fig. 1 BARC on-line fatigue monitoring system implemented at Heavy Water Plant, Kota](image)

The system is combined with a disturbance recording system (DRS) developed by Reactor Control Division. The DRS continuously acquires process parameters associated with the selected components. Every night at zero hours, the fatigue monitoring module is triggered. The recorded process data are screened and only significant transients are selected for further computation. Typical process transients recorded after screening the insignificant fluctuations for the gas inlet to column tower (N02) are shown in Fig.2.
Fig. 2 Recorded process pressure, temperature and flow for gas inlet to column tower

Fig. 3 Computed temperature and stresses at a critical point of gas inlet to column tower
Figure 2 shows the recorded process transients in this plant over a period of time. The variation of the computed temperature and stresses at a selected point of this nozzle is shown in Fig.3. The fatigue usage information of the same
point is shown in Fig.4. In this figure, the calculated stress frequency spectrum from stress histories is shown in the form of a bar chart. The final fatigue usage factor is displayed on a logarithmic scale. The fatigue usage factor history is also displayed in Fig.4. The usage factor contour of the gas inlet to column tower is shown in Fig.5. The computation is repeated for all the nozzles in sequence.

A similar system will be implemented at HWP, Tuticorin. In HWP Tuticorin also, three components are selected for fatigue monitoring. These components are shell nozzle junctions connected with the ammonia drier. The necessary finite element based data base, software and hardware are ready for installation.

Discussion

The present fatigue-creep monitoring system is a dedicated software for on-line monitoring of fatigue, creep and creep-fatigue interaction of components in a plant. The system can be easily integrated with a data recording system to access plant data. This can convert plant transients to temperature/stress responses of the structure using finite element method. The fatigue usage factor is calculated using rainflow cycle counting algorithm. The creep and creep-fatigue interaction is accounted as per the guidelines of ASME Boiler and Pressure Vessel Code. A user friendly menu driven display of various information related to plant transients, computed stress and temperature responses, damage parameter, etc., is another feature of the present system. The computation is fast enough to monitor the damage of several components of a plant using a single personal computer. The present system will be very useful in life estimation and life extension program of components of a plant.

The experience of the installation and performance of the system at HWP Kota is significant. The creep and the creep-fatigue interaction modules will be of significance in the case of thermal power plants, fast breeder nuclear power plants and chemical process industries.

Availability at Web Site

Recently, a worldwide technical information network FAMONET (FAtigue MOonitoring system NETwork) has been established. The aim of this network is to set-up a framework to facilitate the exchange of information between research organisations and industries dealing with the development of fatigue monitoring systems for integrity assessment and maintenance of power plant components. Within this network, the various organisations developing fatigue monitoring systems are able to exchange technical information on the existing systems and their experience feedback, make benchmarking exercises and use the same sets of data to auto-check their systems and enhance their quality. The members of this network are BARC, India; Electricite de France (EDF) and Framatome, France; Structural Integrity Associates (SI) and Westinghouse, USA; GKN, AMTEC and MPA Stuttgart, Germany; Tractebel, Belgium; Tokyo Electric Power Corporation, Mitsubishi and Toshiba, Japan; etc. A world wide web site has been created for this purpose. The related technical information of BARC Fatigue-Creep Monitoring System is available at http://www.structint.com/famonet/.