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On line fatigue life monitoring methodology for power plant components

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Fatigue is one of the most important aging effects of power plant components. Information about fatigue helps in assessing structural degradation of the components and so assists in planning in-service inspection and maintenance. It may also support the future life extension programme of a power plant. In the present paper, the development of a methodology for on line fatigue life monitoring using available plant instrumentation is presented. The Green's function technique is used to convert plant data to stress–time data. Using a rainflow cycle counting method, stress–time data are analysed and the fatigue usage factor is computed from the material fatigue curve. Various codes are developed to generate Green's functions, to convert plant data to stress–time data, to find the fatigue usage factor and to display fatigue information. Using the developed codes, information about the fatigue life of various components of a power plant can be updated, stored and displayed interactively by plant operators.

Three different case studies are reported in the present paper. These are the fatigue analyses of a thick pipe, of a nozzle connected to a pressure vessel and of a reducer connecting a heat exchanger to its piping system.

1 INTRODUCTION

The degradation effect of power plant components is an important consideration for the safety of the plant. Among the various such aging effects, fatigue is one of the most important. This affects plant life especially when a plant approaches the end of its design life. Major factors affecting the fatigue life of a power plant components are the fluctuation of temperature, pressure and flow rate. Information about accumulation of fatigue helps in assessing structural degradation of the components. This assists one to define the in-service inspection and maintenance schedule and may also support a future life extension programme of a power plant based on the actual observation.

The effects of fatigue are estimated and restricted during the design as per the rules given in the ASME boiler and pressure vessel code. End-of-life fatigue usage factors are determined in accordance with these rules. These are calculated assuming a set of conservative design transients to ensure that plant components do not exceed a fatigue usage factor of unity throughout their design life. Many actual plant operating cycles, however, are quite different from the transients assumed in the design. Plant operation is conservatively restricted by the design transients in most of the cases. However there is currently no practical means by which one can take the credit for this implicit margin to extend the useful life of plant components. This can only be achieved by implementing a methodology to monitor and record continuously the actual loading conditions seen by a component during its operation. Subsequent sections show the development of such a methodology.

2 ON LINE FATIGUE LIFE MONITORING METHODOLOGY

It is neither possible nor necessary to monitor the fatigue life of all the components of a power plant. Fatigue life depends on the magnitude of the stress range and the number of cycles experienced by a component which in turn depend on the process transients seen by that component. A number of critical components which experience the maximum fluctuation of fluid parameters are to be selected for fatigue life monitoring. The plant parameters are measured on line and the fatigue usage factor is continuously updated for the selected components.

A transfer function approach is used to convert plant data to stress versus time data. The stresses are divided into two parts: (i) thermal stresses and stresses due to internal pressure, (ii) external loads including piping loads. Thermal stresses are calculated by a time integration of plant thermal hydraulic parameters through the use of a predetermined set of Green's functions. Stresses due to internal pressure and external loading are superimposed to obtain peak stress versus time history. The peak stress versus time history data developed in this manner are generally irregular in nature. This stress versus time history is to be converted into stress versus frequency spectra to compute the fatigue usage factor.

A 'rainflow cycle counting' method is used to analyse this irregular loading history. The number of cycles experienced by the component is counted and the fatigue usage factor is computed from material fatigue data. This information is to be continuously updated at the monitored highly stressed locations.

Several components of a fossil power plant and a fast breeder nuclear reactor operate at such an elevated temperature that creep behaviour and crack growth due to fatigue–creep interaction are also to be considered in a damage assessment model. On line fatigue monitoring methodology can also be extended to monitor the aging effects due to creep and crack growth owing to the fatigue–creep interaction. Creep damage is estimated from stress-time history using material creep data. The independent damage due to fatigue and creep is considered separately, summed and compared against the limit of damage index which the material can withstand. The accumulated crack growth is estimated by computing both the effects of fatigue and creep separately and then by adding them together. Fatigue crack growth rates are calculated using a linear elastic fracture mechanics technique. Creep crack growth rates are calculated using a time dependent C_t approach.[1] The different steps in on line age monitoring methodology are shown in Fig. 1.

3 GREEN'S FUNCTION TECHNIQUE

The Green's function technique provides a very powerful tool in on line fatigue life monitoring. This technique is used to convert plant data to peak stress–time data as the computation time is much less than the time taken by the finite element method. Closed form solutions of Green's function for certain well defined geometries are presented by Carslaw and Jaeger[2] and Boley and Weiner.[3] However, closed form solutions of Green's function are difficult to derive for the complex geometries generally used in power plants. Hence, for such complex geometries, Green's functions are derived using a finite element method for the unit change of the associated parameter.[4]

3.1 Development of a code for derivation of Green's functions

A computer code GREFIN (GREen's function evaluation by FINite element) has been developed. It has two modules, WELTEM[5] and VENUS.[6] The first module is capable of computing the Green's functions for temperature by a finite element techique for 2-D plane stress, plane strain and axisymmetric geometries. This is capable of considering surface heat transfer through forced or natural convection, volumetric heat generation and isothermal boundary conditions. Depending upon the user's choice, it can consider different types of transient solution algorithms, such as forward difference, backward difference, Galerkin, Crank Nicholson, etc. The second module of the code is a 2-D finite element code to solve plane stress–strain and axisymmetric structures. This module is capable of considering different types of loads such as pressure, concentrated load, gravity load, thermal load, etc. The elements available are four to eight noded isoparametric elements. This module is modified to generate Green's functions for stress by making it compatible with the first module.

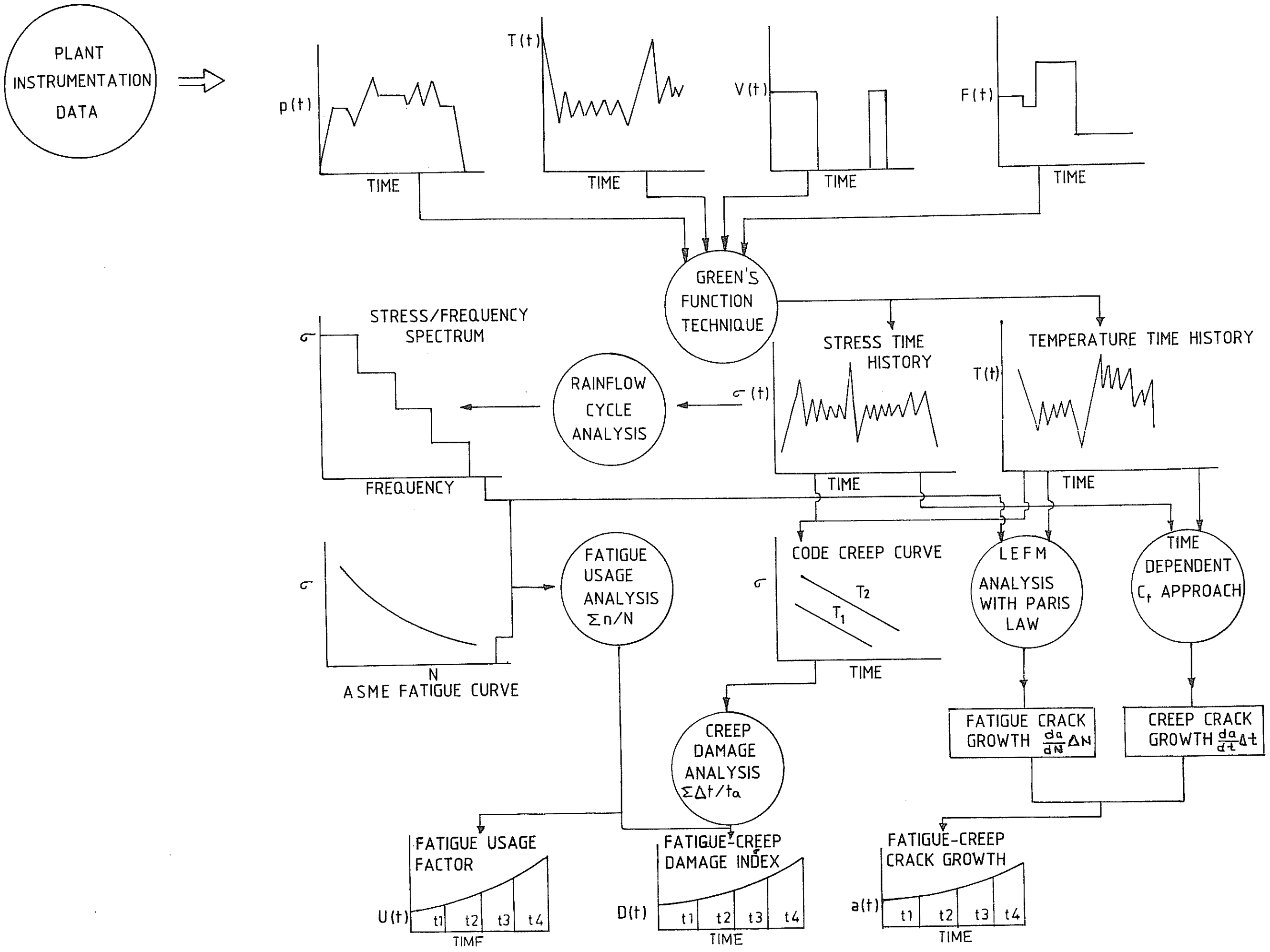


Fig. 1. Different steps in on line age monitoring methodology.

3.2 Development of a code to convert plant data to stress–time history using a Green's function technique

The Green's function technique converts plant transients into temperature–stress responses at a point in the component experiencing the transients. Generally the power plant components are subjected to multiple site (places where fluid parameters are varying) loading. A multiple site (m) problem is decomposed into two single site problems. Each single site problem is solved independently and then superimposed to compute the total effect.

For a multiple site (m) loading problem with the thermal system in a steady state condition with temperature $T_o(x_i)$, stresses $\sigma_0(x_i)$ and fluid temperatures ϕ_0^n (where $n = 1, m$), and subjected to fluid temperature disturbances $\Delta\phi^n(t)$ (where $n = 1, m$), the fluid temperature and stress of the structure can be expressed by the following equations:

$$T(x_i, t) = T_o(x_i) + \sum \Delta T^n(x_i, t) \qquad (1)$$

$$\sigma(x_i, t) = \sigma_0(x_i) + \sum \Delta\sigma^n(x_i, t) \qquad (2)$$

Here ΔT^n and $\Delta\sigma^n$ are temperature and stress distributions of the nth single site problem respectively, x_i represents the coordinates and the t is time.

A formulation for computing temperature–stress responses using a single site superimposed Green's function technique has been developed by Chen and Kuo.[7] The temperature and stress responses are expressed by the following equations:

$$T(x_i, t) = T_o(x_i) + \sum \left[\overline{G_T^n}(x_i)\, \Delta\phi^n(t) + \int_{t-t_d}^{t} G_T^{n'}(x_i, t-\tau)\, \mathrm{d}\Delta\phi^n(\tau) \right] \qquad (3)$$

$$\sigma(x_i, t) = \sigma_0(x_i) + \sum \left[\overline{G_\sigma^n}(x_i)\, \Delta\phi^n(t) + \int_{t-t_d}^{t} G_\sigma^{n'}(x_i, t-\tau)\, \mathrm{d}\Delta\phi^n(\tau) \right] \qquad (4)$$

where

$$G_{\mathrm{T}}^{n'}(x_{\mathrm{i}}, t) = G_{\mathrm{T}}^{n}(x_{\mathrm{i}}, t) - \overline{G_{\mathrm{T}}^{n}}(x_{\mathrm{i}}) \tag{5}$$

$$G_{\sigma}^{n'}(x_{\mathrm{i}}, t) = G_{\sigma}^{n}(x_{\mathrm{i}}, t) - \overline{G_{\sigma}^{n}}(x_{\mathrm{i}}) \tag{6}$$

Here $G_{\mathrm{T}}^{n}(x_{\mathrm{i}}, t)$ and $G_{\sigma}^{n}(x_{\mathrm{i}}, t)$ are the temperature and stress Green's functions of the nth single site problem. $\overline{G_{\mathrm{T}}}(x_{\mathrm{i}})$ and $\overline{G_{\sigma}}(x_{\mathrm{i}})$ are steady state values of the temperature and stress Green's functions and t_{d} denotes the decay time.

Using eqns (3) and (4) a post processor has been developed. This post processor SREGRE (Structural REsponse by GREen's functions) computes the total temperature and stress responses taking into consideration the actual change in fluid temperature and flow histories. Simpson's one-third integration rule has been adopted to compute the transient effect. This post processor is capable of handling very long fluid parameter variation histories. Very often the entire fluid parameter history cannot be read into the computer because of limitation in computer memory. The present post processor computes the temperature–stress responses while reading the input data. This makes even a Personal Computer (PC) capable of analysing power plant data for several years.

4 RAINFLOW CYCLE COUNTING METHOD

The rainflow cycle counting method has been proved to be superior to other cycle counting methods for analysing an irregular stress history. In this method the cycle is counted such that small stress excursions are considered as temporary interruptions of larger stress excursions.[8] It matches the highest peak and deepest valley, then the next largest and smallest together, etc., until all peaks and valleys are paired.

4.1 Algorithm of rainflow cycle counting method

Due to the great importance of the rainflow cycle counting method many different algorithms have been proposed in the literature.[9–12] The algorithm presented by Socie[9] requires the entire load history to be known before the counting process starts. As a result, it is not suitable for on line data processing since the entire load history is not known until the end of the test. The one-pass rainflow cycle counting algorithm presented by Downing and Socie[11] overcomes this limitation. This can operate in on line data processing. A rainflow cycle counting algorithm suitable for very long stress histories even with a small computer for on line data processing is described by Glinka and Kam.[12]

The fundamental characteristic of the rainflow cycle counting method is its simplicity in the algorithm. It is also compatible with the corresponding stress–strain relation when it is applied to a strain–time history. It is a wave analysing procedure which takes into account the sequential order of peaks and valleys while ignoring the time duration between the successive peaks and valleys. A means of collecting long term data, using microcomputer devices and interpreting the data in a manner useful to the engineer for fatigue analysis is reported in the literature.[13] A hard-wired logic for the rainflow cycle counting algorithm is described and simulated by Anzai and Endo.[14]

4.2 Development of code to compute the fatigue usage factor using the rainflow cycle counting method

A post processor FRAIN (Fatigue usage factor by RAINflow counting) has been developed. From the peak and valley stresses, this post processor finds out the number of complete cycles experienced by the component using the rainflow cycle counting method. From the appropriate material fatigue data this code also computes the accumulated fatigue usage factor. This post processor is capable of performing rainflow counting without prior knowledge of the whole stress history. Very often the entire stress history which is to be analysed cannot be read at once because of the limitation of the computer memory. Here, the stress history can be read and analysed block by block by computer without reading the whole history at once. This enables personal computers to analyse very long stress histories.

5 DEVELOPMENT OF GRAPHICS CODE

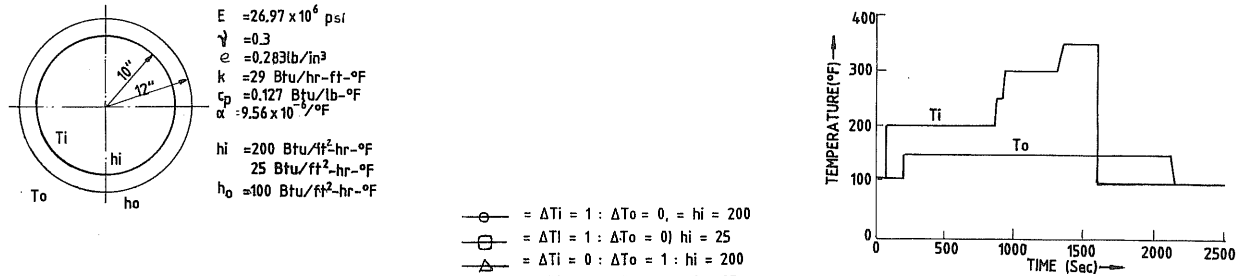
Information on fatigue degradation is to be continuously recorded and updated from the plant transients. In a power plant this is done by an operator. A graphics code IGOLFM (Interactive Graphics On Line Fatigue Monitoring) has been developed to make the methodology user friendly. This code is written in Turbo 'C' and this enables the user to interface among the earlier developed codes. The whole methodology is made menu driven and fatigue analysis can be done componentwise according to the operator's choice. Using this code the monitored transients can be analysed and information can be updated, stored and displayed when necessary. An efficient file management has been done to optimise the number of files. On line transients for a number of components of a power plant can be simultaneously processed, recorded and stored using a personal computer 386.

6 CASE STUDIES

6.1 Analysis of a thick pipe subjected to multiple site loading

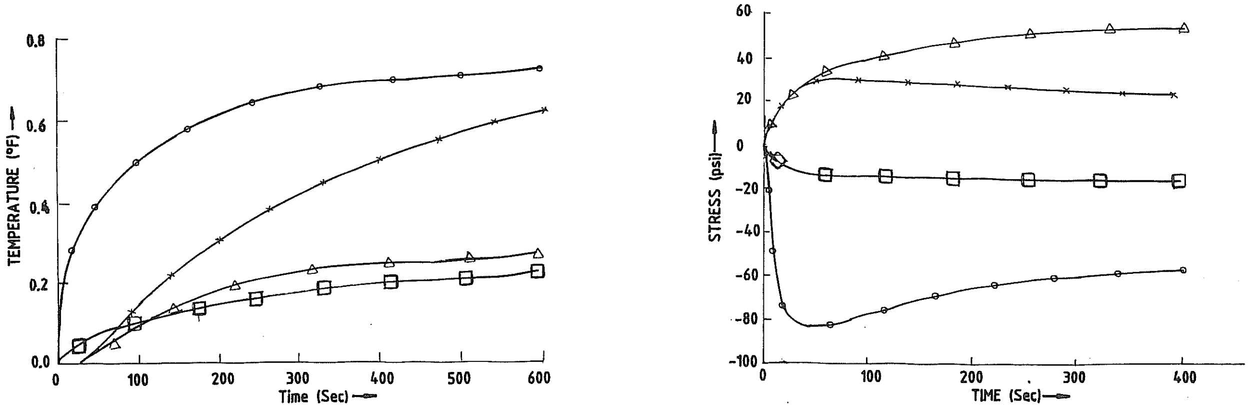
The first case study deals with the analysis of a thick pipe in a power plant having temperature and flow variation on both inside and outside surfaces. Figure 2(a) shows the geometrical dimensions, material properties and heat transfer coefficients used in this problem. The fluid temperature variations at the inner and outer surfaces are assumed to vary in a manner as shown in Fig. 2(b). A finite element discretisation has been done using axisymmetric eight noded elements. The flow rate is assumed to vary between a range such that h_i (inside heat transfer coefficient) varies between 141·85 and 1134·8 W/m^2 K (25 and 200 Btu/ft^2 h °F). Using the developed code GREFIN the temperature and stress Green's functions were computed for both inside and outside temperature variations with two different h_i values. These temperature and stress Green's functions are shown in Figs 2(c) and 2(d) respectively.

A single site problem was solved considering only the inside fluid temperature variation with a constant h_i value of 1134·8 W/m^2 K (200 Btu/ft^2 h °F). The temperature and stress responses at the inner surface were computed using the corresponding temperature and stress Green's functions. These results are shown in Fig. 3 as curve 1. For the next case, the fluid temperatures at the inner and outer surfaces were assumed to vary simultaneously. This multiple site loading



(a) GEOMETRICAL DETAILS AND RELEVANT PROPERTIES.

(b) FLUID TEMPERATURE HISTORIES



(c) TEMPERATURE GREEN'S FUNCTIONS AT INNER SURFACE

(d) STRESS GREEN'S FUNCTIONS AT INNER SURFACE

Fig. 2. Problem definition and Green's functions for case study-1.

problem was decomposed into two single site loading problems and the response for each loading was computed and superimposed to obtain the actual response. The temperature and stress responses are computed and shown in Fig. 3 as curve 2. A detailed finite element calculation was also performed for both cases. These results are also plotted in Fig. 3.

The third case in this example considers variation of fluid temperature and h_i simultaneously. A typical variation is shown in Fig. 4(a). A new set of temperature and stress Green's functions were computed for a change in h_i from 141·85 to 1134·8 W/m^2 K (25 to 200 Btu/ft^2 h °F) after a time of 800 s.

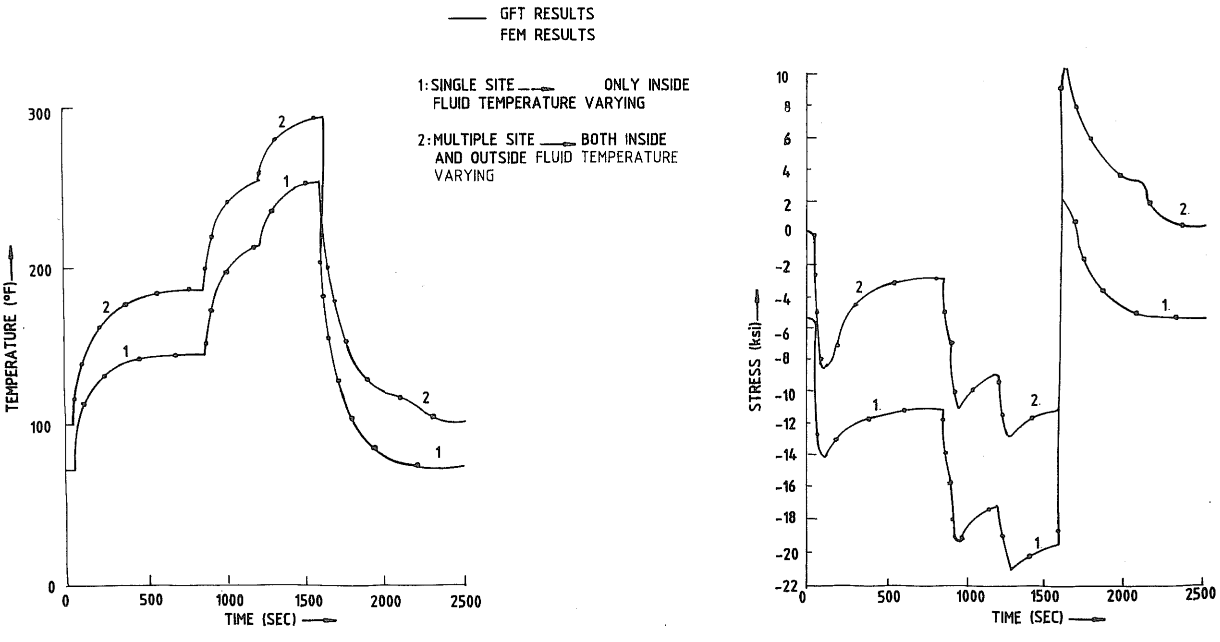
These are shown in Fig. 4(b). The temperature and stress responses using Green's functions are shown in Fig. 4(c). To verify the results finite element solutions are also obtained, which are shown in Fig. 4(c).

6.2 Analysis of a nozzle connected to a spherical head of a pressure vessle

This case study deals with a nozzle connected to a spherical head of a cylindrical pressure vessel. It is exposed to fluid temperature fluctuations. Figure 5(a) shows the geometrical dimensions, material properties and heat transfer coefficients of the problem. A typical fluid temperature variation is assumed on the vessel and nozzle surfaces as shown in Fig. 5(b). A finite element discretisation has been done using axisymmetric four noded elements to generate Green's functions. This discretisation is shown in Fig. 5(c). Temperature and stress Green's functions due to a unit rise in temperature of the nozzle side fluid and vessel side fluid were computed separately. The temperature Green's function was computed for point 'A' (Fig. 5(a)), whereas the stress Green's function was computed for the centre of the element surrounding point 'A'. These Green's functions are shown in Fig. 6(a). These Green's functions were then used to compute temperature and stress responses for the given fluid temperature transients (Fig. 5b)). These are shown in Fig. 6(b).

6.3 Analysis of a reducer joining a heat exchanger to an outlet pipe of a nuclear plant

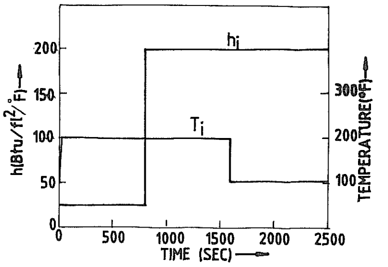
A heat exchanger connected to its piping system through a reducer used in a nuclear plant is studied. The temperature of the fluid is continuously monitored as it comes out of the heat exchanger. This temperature was observed



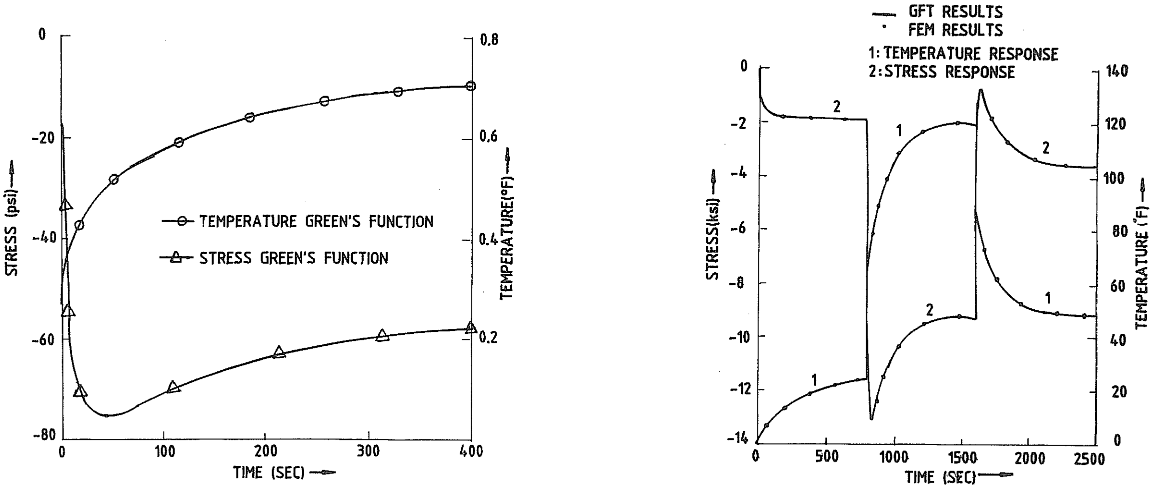
(a) TEMPERATURE RESPONSE AT INSIDE SURFACE

(b) STRESS RESPONSE AT INSIDE SURFACE

Fig. 3. Temperature and stress responses of case study-1 due to fluid temperature fluctuations.



(a) INSIDE TEMPERATURE & HEAT TRANSFER COEFFICIENT VARIATION.



(b) TEMPERATURE & STRESS GREEN'S FUNCTIONS FOR HEAT TRANSFER COEFFICIENT VARIATION

(c) TEMPERATURE & STRESS RESPONSE AT INNER SURFACE

Fig. 4. Analysis of effects of heat transfer coefficient variation in case study-1 and comparison of results with FEM.

to be varying with time. Stresses were found to be moderately high in the reducer due to discontinuity in the geometry. The geometrical details, material properties and fluid heat transfer coefficient are shown in Fig. 7(a). The reducer is insulated at its outer surface, hence the problem is a single site thermal loading problem. The fluid temperature is recorded by gas thermometer; nearly 27 days fluid temperature data have been studied here. The fluid temperature variation is shown in Fig. 7(b).

A finite element discretisation has been done using axisymmetric four noded elements. The stress Green's function was derived for the point 'A' which is found to be the critical location. This stress Green's function is shown in Fig. 7(c). The stress response at 'A' due to the fluid temperature fluctuations was determined. The peak and valley stresses are shown in Fig. 7(d). The stress range and mean stress of the cycles experienced by the component were determined by a rainflow cycle counting method. For each cycle the fatigue usage factor was computed from the material fatigue data[15] and these were added to compute the accumulated fatigue usage factors for all cycles counted. The cycles counted as derived by the rainflow cycle method are grouped into several bands of stress ranges and are shown in Fig. 7(e).

7 CONCLUSIONS

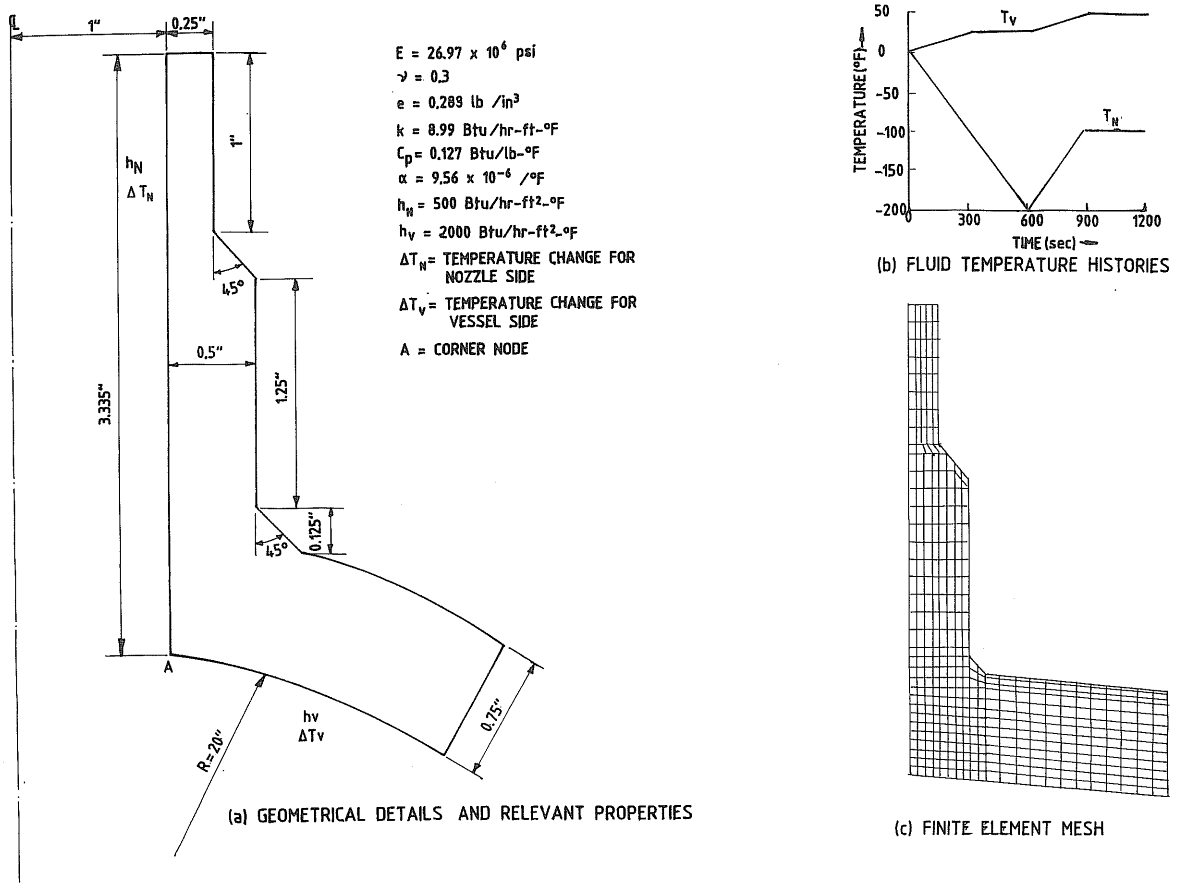
The following conclusions are drawn from the above analysis:

—Development of a methodology has been shown which can be efficiently used for on line monitoring of the fatigue usage factor of different components of a power plant.

—The fast computation of stress transients is required for on line monitoring methodology. This can be achieved by using the Green's function techique.

—The Green's function technique is found to be as accurate as any other numerical method such as the finite element technique (Case study 1).

—The excellent agreement of the results computed using Green's function with the results of finite element analysis prove that the multiple site loading problem can be very

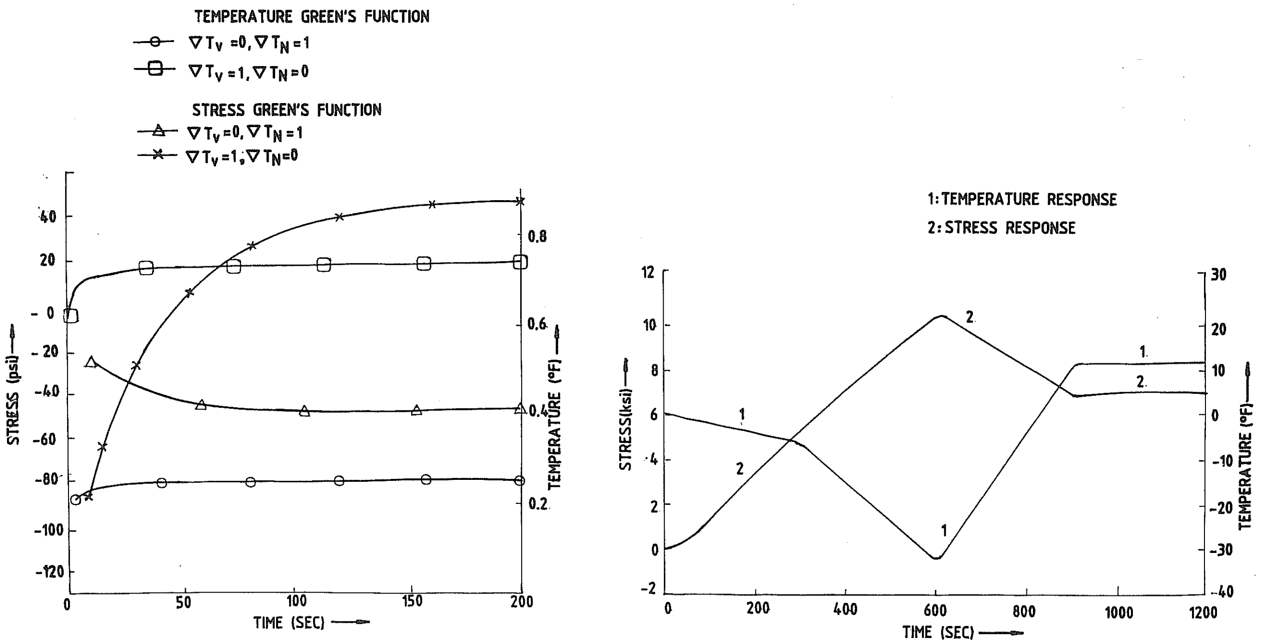


(a) GEOMETRICAL DETAILS AND RELEVANT PROPERTIES

(b) FLUID TEMPERATURE HISTORIES

(c) FINITE ELEMENT MESH

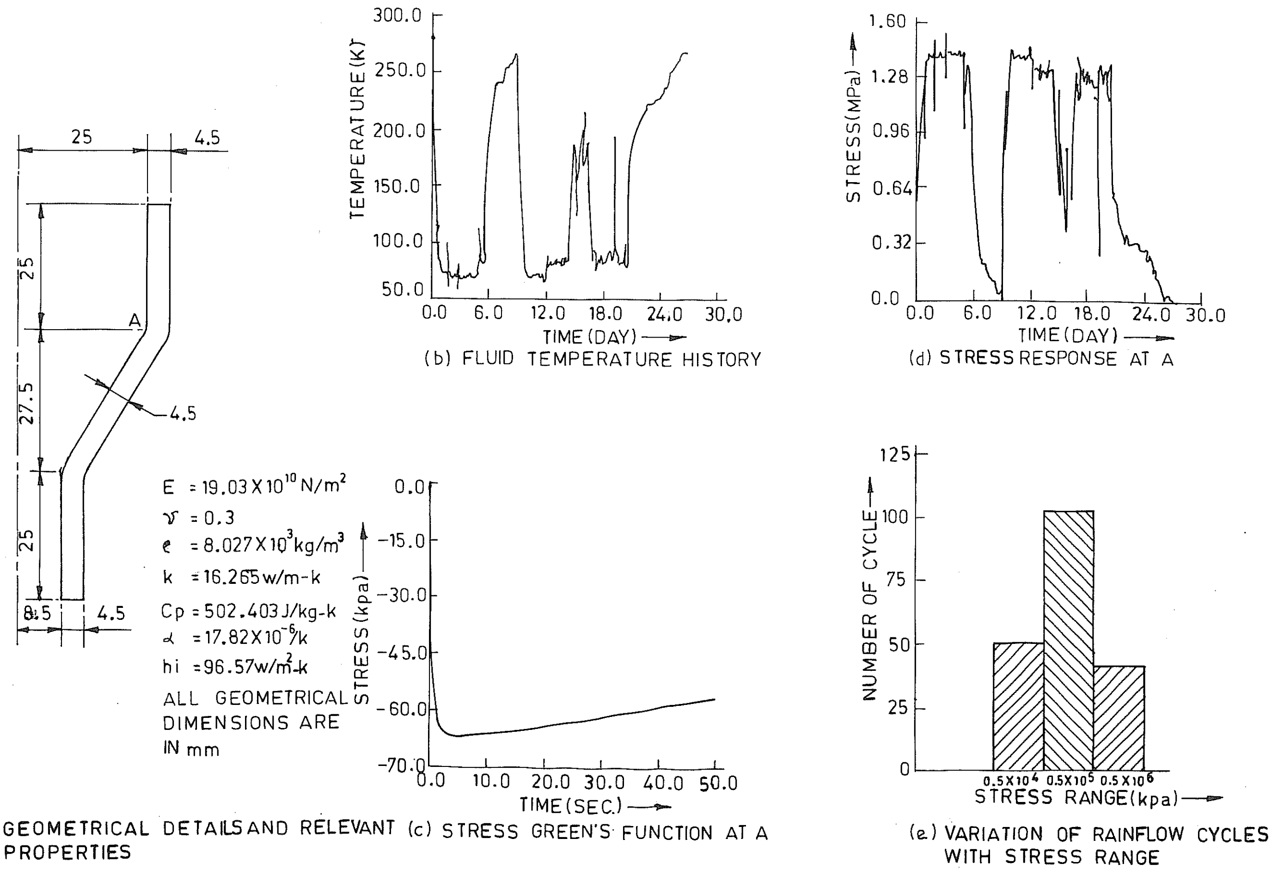
Fig. 5. Problem definition and finite element mesh for Green's function evaluation for case study-2.



(a) TEMPERATURE AND STRESS GREEN'S FUNCTIONS

(b) TEMPERATURE AND STRESS RESPONSE AT A

Fig. 6. Green's functions, temperature and stress response for case study-2.



(a) GEOMETRICAL DETAILS AND RELEVANT PROPERTIES (b) FLUID TEMPERATURE HISTORY (c) STRESS GREEN'S FUNCTION AT A (d) STRESS RESPONSE AT A (e) VARIATION OF RAINFLOW CYCLES WITH STRESS RANGE

Fig. 7. Fatigue cycle evaluation for reducer of a heat exchanger subjected to fluid temperature variation.

efficiently solved using a single site superimposed Green's function technique.

—However the Green's function technique can not be used in the cases where nonlinearities are involved such as material properties changing with temperature, yielding of material at geometrical discontinuity, rapid variation of heat transfer coefficients. However, through the present study, it is found that the variation of heat transfer coefficients can be considered in the case of discrete variations. This is done by generating Green's functions for different values of heat transfer coefficient separately.

—Development of the present methodology has proved that the Green's function technique and rainflow cycle counting method can be efficiently used for on line monitoring of fatigue usage factors from process transients.

—On line transients of a large number of components of a power plant can be processed, stored and displayed when necessary as the computation time taken in this methodology is low.

—This fatigue monitoring methodology can be further extended to provide information about the creep and crack growth rate of the components operating at an elevated temperature.

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