Structural integrity assessment of FBR components using a distributed computing environment

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ABSTRACT In this work, the structural integrity of the critical components of the fast breeder reactor (FBR) that are subjected thermal striping is assessed using a fracture mechanics approach based on linear elastic fracture mechanics (LEFM). The structural integrity is assessed in terms of the actual life of the component for a particular difference between the hot and cold liquid temperatures at the critical mixing velocities. A generalized procedure is attempted for the computation of fatigue life. It is demonstrated in this work that the analysis procedure adopted is computationally very efficient. Green's function method is used for transient mode I crack propagation analysis. An inherent parallelism in the method is exploited for computational efficiency. A distributed computing environment is, therefore, used to demonstrate the effectiveness of Green's function method for crack propagation analysis for the kind of problem solved in this work. A simple idealization in the form of flat plate geometry is used in a numerical example to show the computational efficiency. The method shows a good scale-up justifying the benefit of using a distributed computing environment given a large amount of input data for the thermal striping problem.

Keywords distributed computing; functional decomposition; Green's function; structural integrity; thermal striping.

NOMENCLATURE

a = crack depth
$a_i b_i c_i$ = constants used in Buckner's weight function method
C = paris law constant
E = Young's modulus
$f(x)$ = initial temperature distribution function
$G(x, t)$ = response to unit impulse or unit heavy side function
$G_k(x, t)$, $G_\sigma(x, t)$ = modified $G(x, t)$ for evaluation of stress intensity factor and stress
$\bar{G}$ = array of change in $G(x, t)$ with x for various t_d values
$H(t)$ = temperature response function
h = plate thickness
$K(a, t)$ = stress intensity factor
L = plate semi height or width
$M(a, x)$ = weight function
m_i = polynomial used in Buckner's weight function method
Ni = number of temperature distribution units of size ΔK_i
N = number of elements to be analyzed in rain flow counting
N_s, N_E, N_R = starting, ending elements, elements considered
$R(x, t)$ = response at time t to input temperature distribution

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t = time
t_q = time at which response is desired
t_d = decay time
T = temperature variable
$T(x, t)$ = temperature distribution function
$T_s(x)$ = steady-state temperature response
$T_t(x, t)$ = transient state temperature response
$X(x), \beta(t)$ = functions of x, t in the solution for $T(x, t)$
x = thickness coordinate from front $x = x_0$ at $t = t_q$
α = coefficient of linear expansion
δt = duration of temperature pulse
Δa = increment in crack depth
ΔK_i = size of the ith cycle in histogram
ΔK_{th} = threshold value of SIF
$\delta(x - t) = f(\xi)$ = Dirac delta function
$\theta_i(t)$ = magnitude of temperature signal at time t
$\theta_s(x, t)$ = temperature response function
$\sigma(x, t)$ = stress response function
γ = Poisson's ratio

INTRODUCTION

The design of Liquid Metal Fast Breeder Reactor (LMFBR) involves fulfilling highly stringent safety norms. This requires in-depth analysis of the failure processes that the reactor may undergo including the events of low probability which are usually neglected in the design practices of other common industrial plants. In the fast breeder reactor (FBR), sodium is used as a heat-transferring fluid. From the structural mechanics viewpoint, there are a few problems due to the random temperature fluctuations (thermal stripping) that occur due to mixing of sodium at different temperatures.

The random fluctuations that occur in the fluid due to mixing of sodium at different temperatures are transferred to the surface of the structure adjacent to the mixing zone. This random temperature fluctuation on the structure for prolonged duration causes crack initiation and propagation of cracks, formed and pre-existing. Such loads are inevitable, and hence there is a need to come up with a limit on temperature difference of mixing fluids. This limit is known as the thermal striping limit. Considering the design life and structural integrity of the component the thermal stripping limit is obtained. There are two aspects of the thermal stripping problem. One is the thermo-hydraulic aspect and the other is the mechanics aspect. In the present work, the mechanics aspect of thermal stripping, which deals with the damage caused due to the thermal striping load on the surface of the structure is studied. Efficient computational analysis for fatigue failure due to thermal striping is the primary focus of this work.

In the present study, an integrity assessment is made for a fully constrained flat plate model of material SS316L (N). A crack is assumed to exist in the component. A transient domain approach is adopted in the analysis. The integrity assessment involves major tasks like identification of critical loading, thermomechanical analysis to obtain stresses, and evaluation of stress intensity factors in the structure and crack propagation analysis. It is demonstrated that this method can be computationally very effective if parallelized using the message passing interface (MPI) library functions. An inherent parallelism in some critical steps of the procedure accounts for the computational efficiency.

Functional decomposition of a program is governed by its granularity. The effect of functional decomposition of a problem depends on communication overheads in passing data between processes and synchronizing processes, a trade-off of grain size against efficiency and execution time. Transient analysis such as heat conduction provides a good platform for studying the granularity of the problem owing to the large amount of data involved and the methodology adopted for analysis.

Many studies have reported the life assessment of components subjected to thermal stripping and the use of Green's function for transient analysis. Jones *et al.*[1] have studied thermal fatigue damage under thermal striping conditions based on the impulse response method. Jones *et al.*[2,3,4] have also carried out an analysis based on the frequency response approach. Lee *et al.*[5] have used a stress analysis approach called Green's function method to study the thermal stripping damage on the tee junction. The results produced by this method showed good agreement with practical observations. It is important to note that this method is quite powerful in that the computational time involved to find the results for a randomly fluctuating temperature is very small compared to the FEM fatigue analysis procedure. Muralidharan *et al.*[6] implemented this method to perform a transient analysis for a unit input function. Studies by Miller,[7,8] Clayton *et al.*,[9] and Galvin *et al.*[10] throw some more light on the problem.

The present work focusses on the implementation of Green's function method as a time domain approach for thermal striping analysis. This was done for a unit impulse function and for a unit heavy side function. A simple model of an LMFBR component is considered and analyzed for crack propagation. The present work also demonstrates that this method can be effectively parallelized using Message passing Interface (MPI) library functions.[11]

Green's function for non-homogeneous boundary conditions is derived in the following section. Subsequently, the paper outlines the various steps involved in the integrity assessment and life estimation of LMFBR under thermal striping. Parallelization of Green's function and the results from a numerical study are in the last sections of the paper.

GREEN'S FUNCTION TRANSIENT ANALYSIS WITH NON-HOMOGENEOUS BOUNDARY CONDITIONS

The important step in solving the thermal striping problem is to obtain a solution for a transient heat-conduction problem with non-homogeneous boundary conditions. In this section, the methodology of solving such a problem using Green's function is presented.

Green's function is defined as the response to a unit input or stimulus (Fig. 1).[5] It is an integrating kernel, which can be used to solve a non-homogeneous differential equation with boundary conditions. Green's function is determined either by using the separation of the variable method or by the finite element approach. In the following, we solve the heat conduction equation to obtain the required Green's function.

The heat conduction equation to be solved for is of the form

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad 0 < x < L \quad t > 0, \tag{1}$$

with the homogeneous boundary conditions

$$T(0, t) = T(l, t) = 0; \quad t > 0, \tag{2}$$

and the initial condition,

$$T(x, 0) = f(x); \quad 0 < x < L. \tag{3}$$

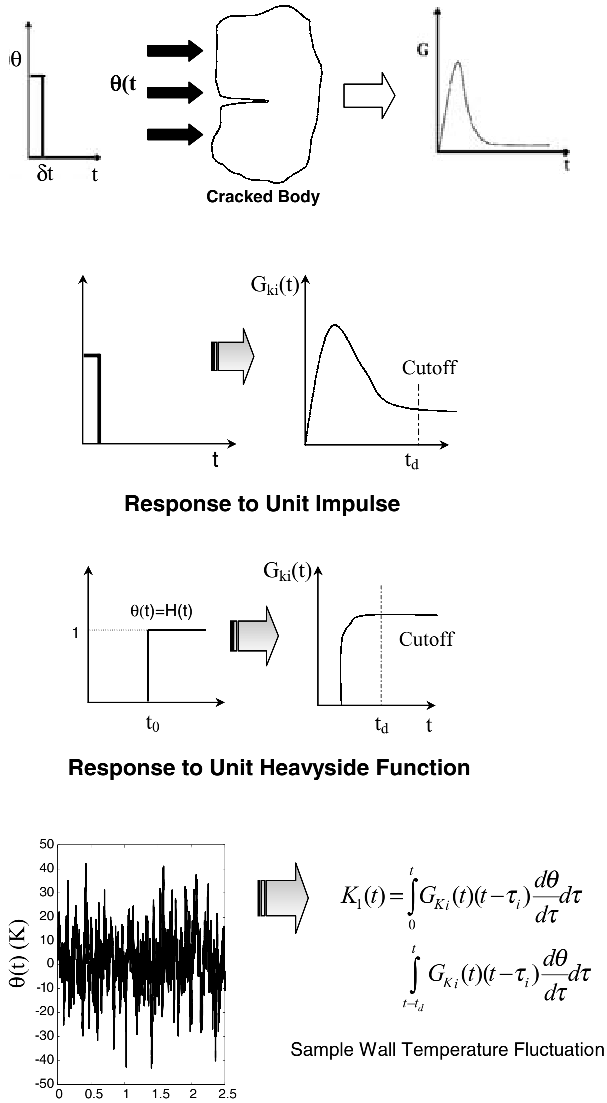


Fig. 1 Concept of Green's function approach for calculation of SIF (Lee *et al.*)

The solution is obtained by the variable separable method and is of the form

$$T(x, t) = X(x)\beta(t). \tag{4}$$

The solution exists when the roots are real and distinct. The solution takes the form

$$T(x, t) = (C_1 \cos \lambda x + C_2 \sin \lambda x)\left(C_3 e^{-\alpha\lambda^2 t}\right). \tag{5}$$

The above solution is defined for a static or steady-state response with homogeneous boundary conditions and modifications are required for incorporating the non-homogeneous boundary conditions for static and transient response. The transient response may be obtained either for a unit impulse function input or a unit step function

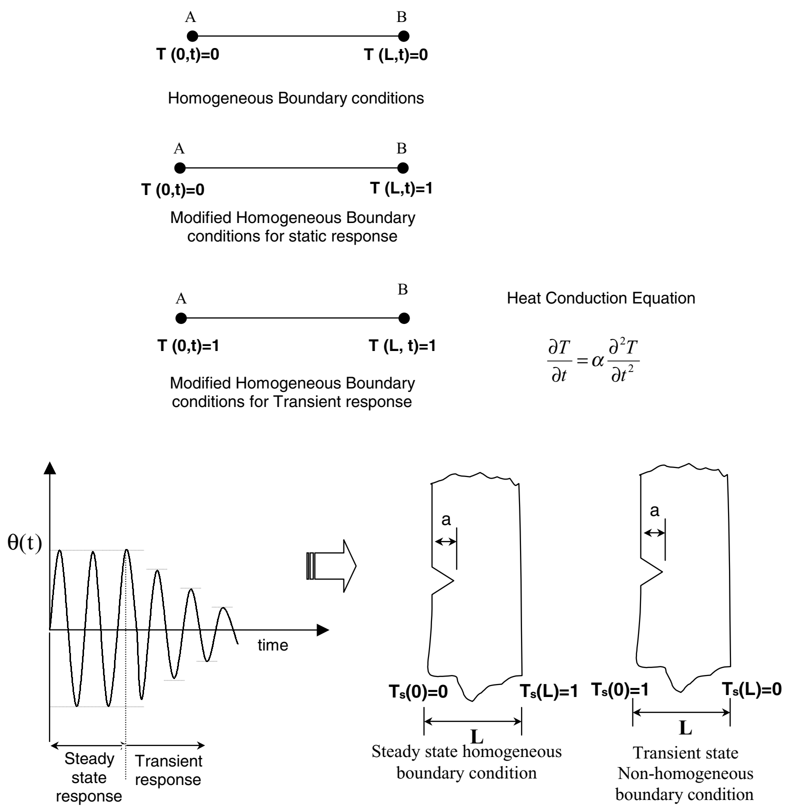


Fig. 2 Steady state and transient response with respective modified boundary conditions.

input (Fig. 1). The change in the boundary conditions from steady state to transient state is indicated in Fig. 2.

The equation for heat flow is independent of time during the steady-state condition and is given by

$$\frac{\partial^2 T}{\partial x^2} = 0, \tag{6}$$

the solution of which is given by,

$$T = C_1 x + C_2, \tag{7}$$

where $C_1$and C_2 are constants with respect to x.

Satisfying the boundary conditions as given in Fig. 2 for static response we can write the initial condition as

$$T(x, 0) = x/L. \tag{8}$$

The solution satisfying the two different states is of the form (Fig. 2).

$$T(x, t) = T_s(s) + T_t(x, t). \tag{9}$$

Thus, the static solution which satisfies the boundary condition (Fig. 2) is obtained as

$$T_s(x) = 1 - x/L. \tag{10}$$

The solution to the transient part satisfying the nonhomogenous boundary conditions is obtained as

$$T_t(x, t) = \sum_{m=1,2,3,..}^{\infty} -\frac{2}{n\pi}(\cos n\pi + 1)\sin\frac{m\pi x}{L} e^{-\frac{\alpha m^2 \pi^2 t}{L^2}}. \tag{11}$$

Thus, the overall solution is of the form

$$T(x, t) = 1 - \frac{x}{L} - \frac{2}{\pi} \sum_{m=1,2,3,}^{\infty} \frac{1}{n} \sin\frac{m\pi x}{L} e^{-\alpha m^2 \pi^2 t/L^2}. \tag{12}$$

The relation between Green's function and the above solution in (12) can be written as

$$T(x, t) = \int G(x, \xi, t) f(\xi)\, \mathrm{d}\xi, \tag{13}$$

or in terms of the Dirac delta functions we can write the solution in (13) as

$$T(x, t) = \int G(x, \xi, t)\delta(x - \xi)\, \mathrm{d}\xi, \tag{14}$$

where $f(\xi)$ is Dirac delta function, for a one-dimensional situation

$$T(x, t) = G(x, t) \int_{-\infty}^{+\infty} \delta(x - \xi)\, \mathrm{d}\xi. \tag{15}$$

Therefore, Green's function itself represents the solution and is given by

$$G(x,t) = 1 - \frac{x}{L} - \frac{2}{\pi}\sum_{m=1,2,3}^{\infty}\frac{1}{n}\sin\frac{m\pi x}{L}e^{-\alpha m^2\pi^2 t/L^2}. \quad (16)$$

In order to analyze a general input loading, consider that the stripped face is subjected to a general temperature history of the form shown in Fig. 3. The input boundary load

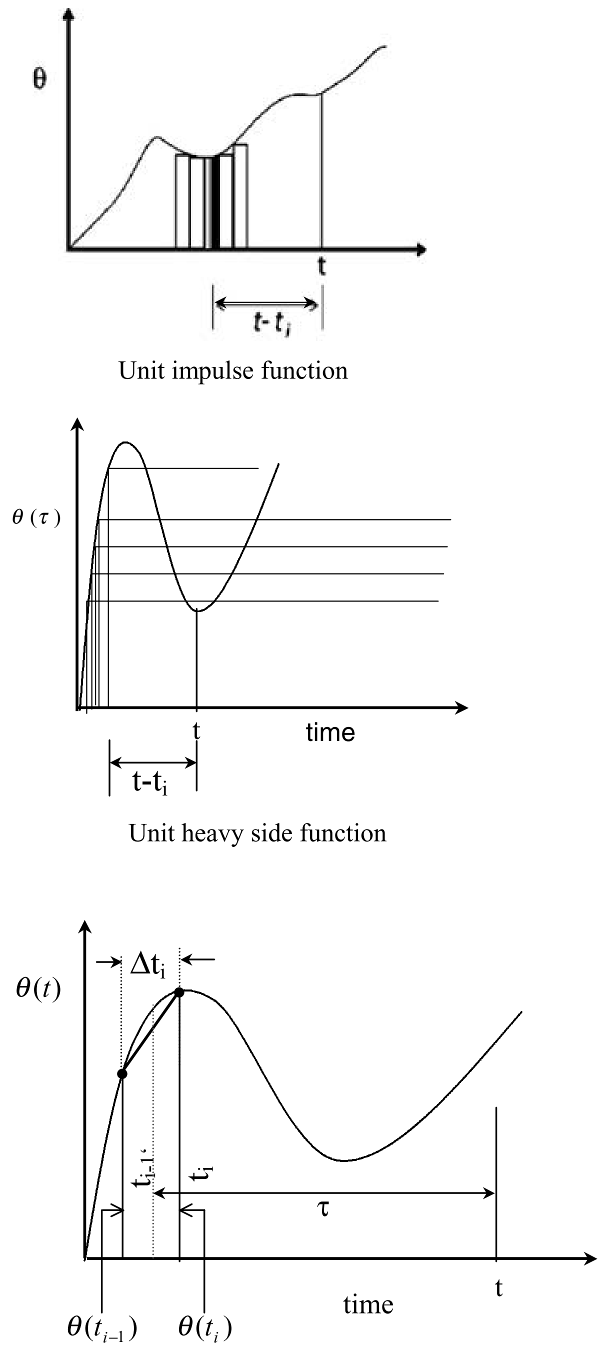


Fig. 3 Wall temperature as an integration of small changes.

$\theta_i(t_i)$ at time $t_i = i*\Delta t$ is discretized into a number of heavy side unit step functions (Fig. 3). The temperature response $R(x, t)$ at any time is the cumulative effect of the associated Green's function. The input load is approximated as a piecewise linear fit as given below:

$$\theta(\tau) = \theta_{(i-1)} + \left(\theta_{(i-1)} - \theta_i\right)/(\Delta t)(\tau - t_i) + \cdots\cdots$$
$$\frac{\mathrm{d}\theta}{\mathrm{d}\tau} = \theta(\tau) = \Delta\theta_\tau = \frac{\theta_i - \theta_{i-1}}{\Delta t_i}. \quad (17)$$

For each of the temperature difference values between times t_i and t_{i-1} the response up to any arbitary time t_q is expressed as given below by using convolution integral

$$R(x,t) = \int_0^{t_q} G(x, t_q - \tau)\frac{\mathrm{d}\theta(\tau)}{\mathrm{d}\tau}\,\mathrm{d}\tau \text{ or}$$
$$R(x,t) = \int_0^{t_q} G(x,\tau)\frac{\mathrm{d}\theta(t_q - \tau)}{\mathrm{d}\tau}\,\mathrm{d}\tau. \quad (18)$$

The above integration of the temperature response is carried out in two regions. In the first region Green's function varies with respect to time till it reaches a constant amplitude at decay time t_d.

$$R(x,t_q) = \frac{1}{\Delta t}\int_0^{t_q} G(x,\tau)(\Delta\theta(t_q - \tau))\,\mathrm{d}\tau, \quad (19)$$

$$R(x,t_q) = \frac{1}{\Delta t}\int_0^{t_d} G(x,\tau)(\Delta\theta(t_q - \tau))\,\mathrm{d}\tau + \int_{t_d}^{t_q} G(x,\tau)(\Delta\theta(t_q - \tau))\,\mathrm{d}\tau. \quad (20)$$

The decay time is determined from the response of the system for a unit step input. Thus, response to the input function, $\theta(t)$ at the surface ($x = 0$) can be written as

$$R(x,t) = \int_0^{t-t_d} G(x, t-\tau)\frac{\mathrm{d}\theta(\tau)}{\mathrm{d}\tau}\,\mathrm{d}\tau. \quad (21)$$

On integrating by parts we get

$$R(x,t) = G(x,t-\tau)\theta(\tau)_0^t - \int_0^t \theta(\tau)\frac{\mathrm{d}G(x,t-\tau)}{\mathrm{d}\tau}\,\mathrm{d}\tau. \quad (22)$$

Rewriting we get

$$R(x,t) = (1 - x/L)\theta(0) - \int_0^t \theta(\tau)\frac{\mathrm{d}G(x,t-\tau)}{\mathrm{d}\tau}\,\mathrm{d}\tau. \quad (23)$$

For various values of x from the second term of Eq. (23) we can get an array of values corresponding to $x = 0$, $x = x_1, \ldots, x = x_m$ as,

$$\bar{G} = \left[\bar{G}_m, \bar{G}_{m-1}, \ldots., \bar{G}_1\right] \quad (24)$$

from which the variation of the decay time t_d for various values of x can be obtained.

METHODOLOGY FOR LIFE ASSESSMENT OF COMPONENT: TIME DOMAIN APPROACH

Using the linear fracture mechanics approach assuming an initial crack the integrity of the component is assessed. It is also assumed that LEFM can be used for the range of crack lengths dealt with in this study. Integrity assessment involves the following major tasks: thermomechanical analysis to obtain stresses in the structure, evaluation of stress intensity factor (SIF) and finally crack propagation analysis.

Thermomechanical analysis to obtain stresses in the structure: The analysis of stresses involves finding the temperature distribution in the structure (heat transfer analysis) and evaluation of strains and stresses due to temperature gradients (stress analysis). Green's function approach has been implemented for the stress determination. The input can be a unit impulse input or a unit heavy side function (Figs 1 and 3). The wall temperature is described as the integration of small changes of the wall temperature and therefore the superposition principle can be used to compute the stress at a point at a given time as the following integral

$$\sigma(x,t) = \int_0^t G_\sigma(x, t-\tau)\frac{\mathrm{d}\theta}{\mathrm{d}\tau}\,\mathrm{d}\tau, \tag{25}$$

where θ is the wall temperature as a function of time. In terms of the temperature response we can write

$$\sigma(x,t) = \beta R(x,t) \text{ where } \beta = \left(\frac{\alpha E}{1-\gamma}\right) \tag{26}$$

and α is the coefficient of thermal expansion, E is Young's Modulus of the material, γ is Poissons ratio.

Green's function decays fast to a constant value with time (decay time t_d). This constant value is taken to be a fraction of the peak amplitude. The above integration for a particular time, thus, needs only to be evaluated within decay time before the current time of evaluation. This reduces the computation time considerably. Integration by parts is done to derive a response (Eqs (21)–(23)), which involves the evaluation of the derivative of Green's function and wall temperature function.

Stress intensity factor calculation: Stress intensity factor was computed for mode I fracture only. The other modes of crack are assumed to be less conservative than the mode I crack. The weight function method proposed by Bueckner[12] is used in this study. The stress intensity factor according to the Buckner weight function approach at a time t for an edge crack length a is given by

$$K(a,t) = \int_0^a \sigma(x,t)M(a,x)\,\mathrm{d}x. \tag{27}$$

In the above integral, $M(a, x)$ is the weight function and is given by

$$M(a,x) = \left(\sqrt{\frac{2}{\pi a}}\right)\sum_{i=0}^{2} m_i(1-x/a)^{(i-1/2)} \tag{28}$$

where $m_i = a_i + b_i(a/h)^2 + c_i(a/h)^6$, $i = 0, 1, 2$. m_i are polynomials independent of x, and a_i, b_i *and* c_i are constants unique to the Buckener weight function method. These expressions are valid only in the range of $0 \le a \le h/2$.

Inserting an expression for stress in terms of Green's function (Eq. (25)), we can obtain a fresh Green's function G_k such that the stress intensity factor $K(a, t)$ can be written as

$$K(a,t) = \int_0^t G_k(a, t-\tau)\frac{\mathrm{d}\theta}{\mathrm{d}\tau}\,\mathrm{d}\tau \text{ and}$$
$$G_k(x,t) = \int_0^a G_\sigma(x,t)M(a,x)\,\mathrm{d}x. \tag{29}$$

Crack propagation analysis: In this analysis, linear elastic fracture mechanics is assumed to apply. Only positive stress intensity factor values are assumed effective in crack propagation analysis. For the random temperature fluctuation load on the structure, the SIF history at intermediate crack lengths is obtained using Eq. (29). In order to obtain the amplitude and mean of the cycles of SIF history for a particular crack length a, a standard rainflow counting procedure is adopted.

The Paris law for crack propagation is used to find the increment in crack length for a given crack length. Using the Paris law, the total crack growth per block for a given crack length is computed. The stress intensity factor history obtained at intermediate crack lengths a for the random load is analyzed by the rainflow counting technique and crack growth, Δa, is obtained at each crack length. Having obtained crack growth (Δa) for intermediate crack length a, a piecewise fit is obtained and integrated from initial crack length to final crack length to estimate life. Thus, for a given random input load, initial crack length and final crack length, the crack growth and hence life of the component can be estimated.

Rainflow analysis: Rainflow counting procedure is used to decompose the complex irregular history into a series of simple events equivalent to individual cycles in a constant amplitude history. There are several algorithms available to perform the counting but most of them require that the entire load or stress history be known before the counting process starts and in addition, require rearrangement of the history before counting. In the present study an algorithm proposed by Glinka *et al.*[13] has been implemented. The main feature of the algorithm (Fig. 4a and b) is counting the history in segments called blocks. Thus, only one relatively short block is required to be read to computer memory each time. The size of one block depends on the computer capability and requires no rearrangement of history. The whole history only needs to be analyzed

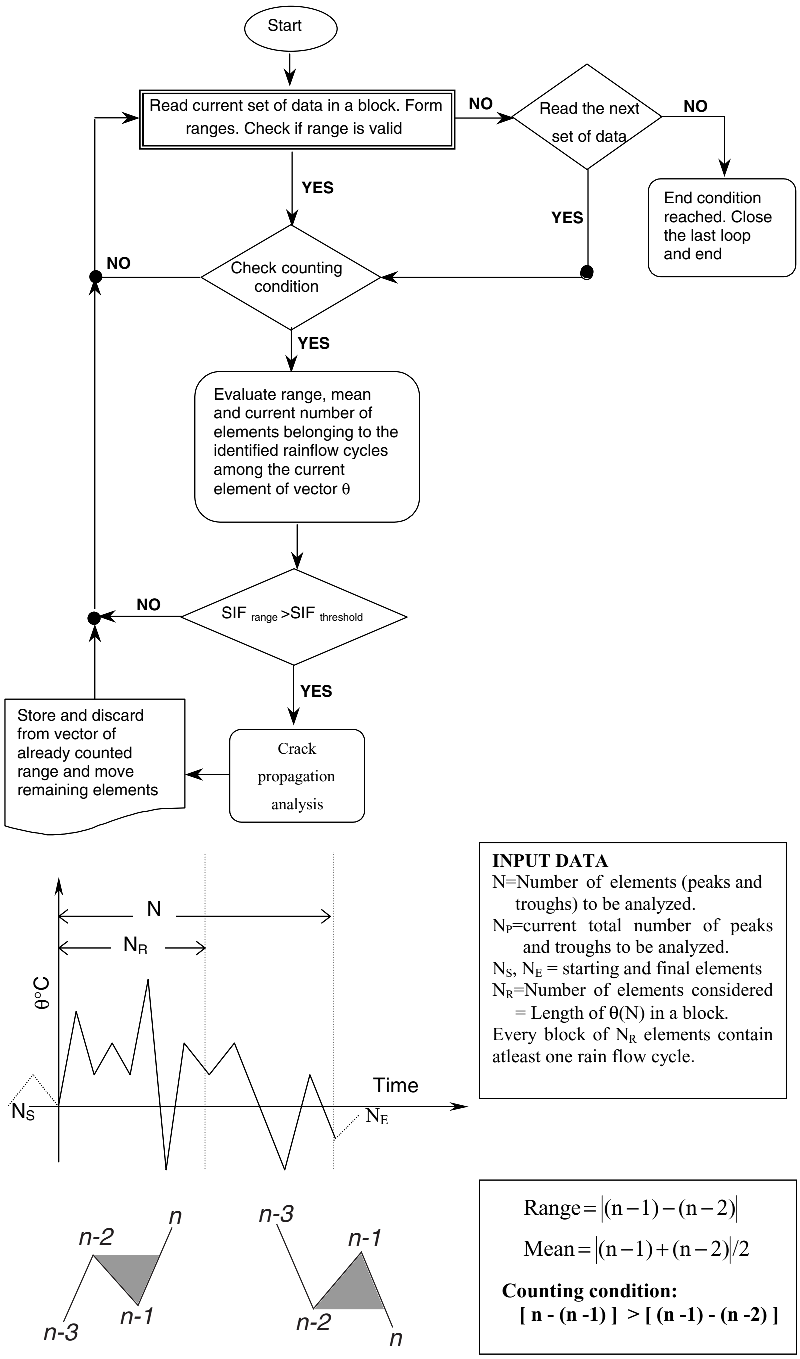


Fig. 4 (a) Flow chart for rainflow technique. (b) Illustration for rain flow technique.

once without any changes in the remaining part of the history. This saves computing time in comparison with other algorithms.[13]

For a block of SIF time history for a particular crack length a, N_i cycles of size ΔK_i are obtained from the

$$\Delta a = \int_a^{a+\Delta a} \mathrm{d}a = \int_N C(\Delta K)^n \,\mathrm{d}N \approx \sum_{i=1}^{N} N_i C(\Delta K_i)^n \tag{30}$$

rainflow counting procedure. The above increase in crack length occurs over a time interval Δt, where Δt is the time length of the given loading block. Only ΔK_i above the threshold value, ΔK_{th}, is taken into consideration in the above crack propagation determination. An average crack growth rate $\Delta a/\Delta t$ can be obtained over the loading time interval leading to (a, $\Delta a/\Delta t$) pairs available for finding the total time period taken for crack to propagate to a particular crack length. Reasonably close (a, $\Delta a/\Delta t$) pairs will give rise to a smooth plot of time elapsed to crack propagated plot (a vs t). Two possibilities could occur. There could be crack arrest, which means that there is no propagation of crack for an increase in time or there could be progressive crack propagation beyond a particular time. The critical crack length for the first case cannot be determined from a failure point of view but the designer could enforce a limit on the amount of crack length allowed. In the second case, clearly the crack length at which a progressive crack growth starts to occur is the critical crack length.

METHODOLOGY AND JUSTIFICATION FOR FUNCTIONAL DECOMPOSITION

As stated earlier, Green's function method for the determination of SIF values for a discretized input using a unit heavy side function has been implemented in a distributed computing environment. This was implemented on Param 10000. This section justifies the implementation of Green's function method on a distributed computing environment.

Because Green's function quickly reached a constant value asymptotically within the decay time t_d, the convolution integral for a particular time needs to be evaluated only within the length of time equal to the decay time just before the current time of evaluation. This reduces the computation time considerably.

The response is obtained using Green's function for a piecewise linear fit of the input loading (Fig. 2):

$$R(x,t) = \frac{1}{\Delta t}\int_0^{t_d} G(x,\tau)\Delta\theta(t_q-\tau)\,\mathrm{d}\tau + \left(1-\frac{x}{L}\right)\int_{t_d}^{t_q}\Delta\theta(t_q-\tau)\,\mathrm{d}\tau, \quad (31)$$

where t_d, N and m are the decay time, total number of time steps, and number of time steps up to decay time respectively.

The above response can be rewritten as

$$R(x,t) = \left(1-\frac{x_0}{L}\right)\Delta t\left(\sum_{t_d}^{t_r}\Delta\theta\right) + \frac{1}{\Delta t}\left[\Delta\theta_k\bar{G}_1+\cdots+\Delta\theta_{k-m-1}\bar{G}_m\right]. \quad (32)$$

If we consider another time $t_r > t_q$ and let k be the number of divisions up to t_r, i.e. $k > N$, we can rewrite the above response as

$$R(x,t) = \frac{1}{\Delta t}\left[\Delta\theta_N\bar{G}_1+\Delta\theta_{N-1}\bar{G}_2+\cdots+\Delta\theta_{N-m-1}\bar{G}_m\right] + \left(1-\frac{x_0}{L}\right)\int_{i_d}^{t_q}\Delta\theta(t_q-\tau)\,\mathrm{d}\tau, \quad (33)$$

where

$$\bar{G} = \left[\bar{G}_m, \bar{G}_{m-1}, \ldots, \bar{G}_1\right]. \quad (34)$$

Thus, for any new time t_i it is seen that the operation requires shifting and multiplying the G matrix with the input θ values. Because of variation of G up to t_d there is a reduction in θ values. Beyond t_d, G is a constant. This requires a shift in θ values and multiplication by G for the evaluation of new response. Instead, to account for this the values are taken for a length of t_d prior to the actual first term as zeros and we shift the G matrix by one term of θ value. This being a repeated process of vector multiplication, parallelization drastically reduces the computational

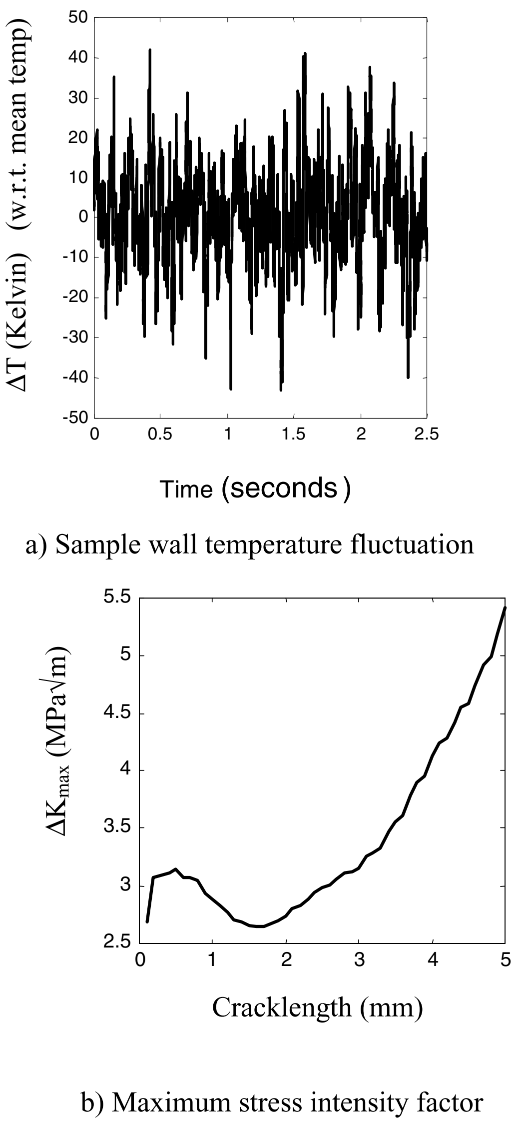


Fig. 5 (a) Wall temperature input considered in the present problem. (b) Variation of maximum stress intensity factor for various crack lengths.

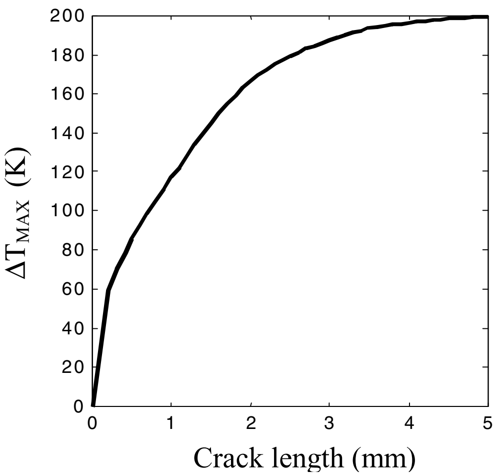
time given that a large amount of input data is involved in the analysis, thereby rendering efficiency in the computation of fatigue life. Appendix I gives the details of the algorithm adopted for parallel computation. The computations were carried out on a platform called Param. The details of Param are also given in Appendix I.

NUMERICAL STUDIES

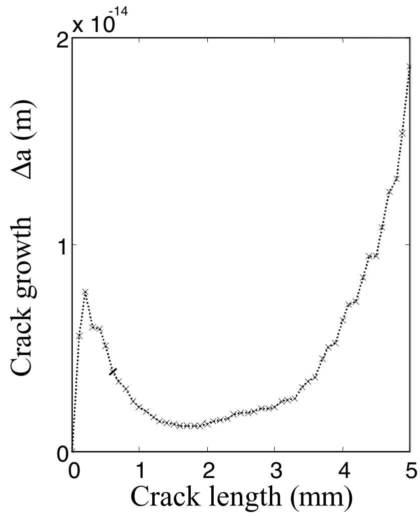
Input data: The geometry of LMFBR components can be idealized to be a flat plate. The flat plate geometry is assumed to be fully restrained to obtain conservative results.[2] The flat plate is assumed to have an edge crack or flaw of length a. It is stressed again that only thermal striping loading is considered in the analysis.

Relevant data are given below:

Material: SS316LN
Plate thickness: 10 mm
Maximum wall temp: 820 K
Thermal conductivity: 21.54 W/m-K;
Thermal expansion coefficient = 20.4×10^{-6}/K
Elastic modulus = 149 Gpa
Specific heat = 58.2 J/kg-K
Density = 7739 kg/m^3
Paris law constant $C = 7.5e\text{-}13$; $n = 4$

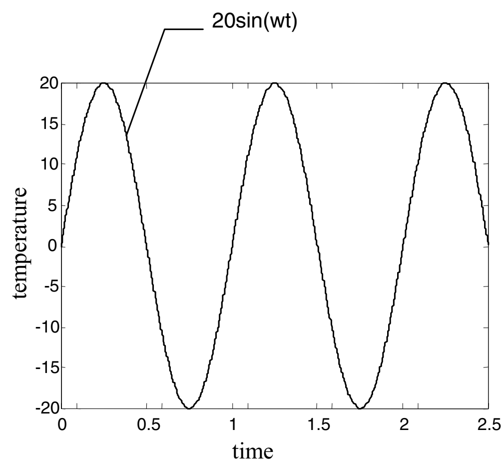


a) ΔT_{MAX} vs. crack length for a life of 1 year

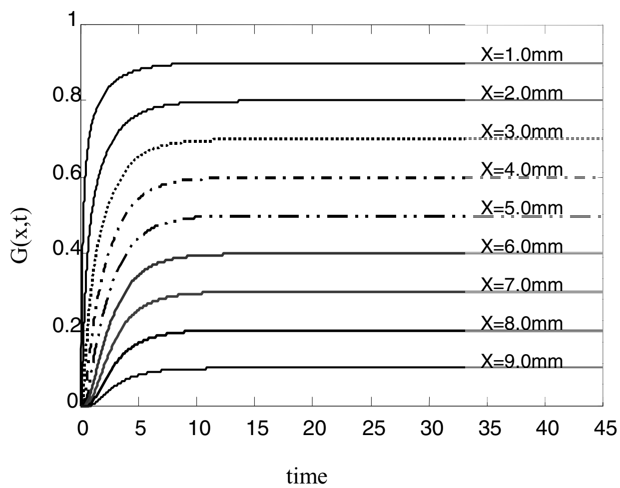


b) Crack Growth Δa vs. crack length

Fig. 6 (a) Variation of maximum temperature difference allowed for various crack lengths for an allowable period of 1 year. (b) Variation of crack growth Δa for various crack lengths. Obtained using unit impulse response.



(a)



(b)

Fig. 7 (a) Input load function considered. (b) Variation of Green's function with respect to time for various plate thicknesses.

Geometry: Flat plate geometry fully restrained to obtain conservative results

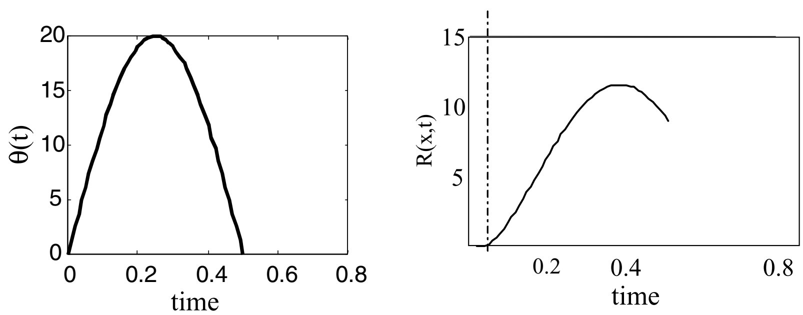
Response studies: In studying the response for a unit impulse function the allowable temperature difference evaluated for 45 years of a component life by the impulse response method for a random fluctuating load as shown in Fig. 5a is found to be 128 K. The variation of the maximum SIF for various crack lengths shows an increase in maximum SIF with crack length shown in Fig. 5b. Crack growth at various crack lengths is shown in Fig. 6a. For a life period of one year, the variation of maximum temperature difference for various crack lengths is obtained as in Fig. 6b.

The response to unit heavy side function is studied. Figure 7a shows a plot of sinusoidal temperature fluctuation considered as input. Green's function derived for the non-homogeneous boundary condition is obtained for various lengths of plate and is plotted in Fig. 7b. The response obtained for the input shown in Fig. 7a is plotted as shown in Fig. 8a. There is a clear shift in the response over a period, of time. For a particular crack length, a typical plot of the decay time is obtained for various thicknesses of the plate as shown in Fig. 8b. A plot of Green's function versus time, obtained for various crack lengths is shown in Fig. 8c.

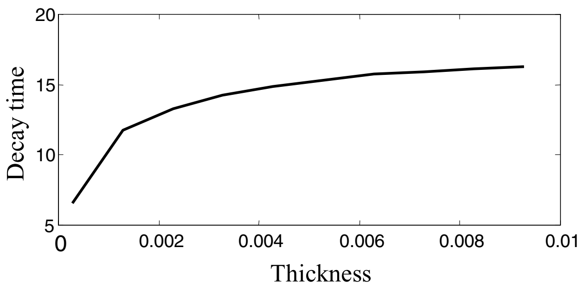
Computational time, speed-up and efficiency are computed in parallelization of Green's function method on a distributed computing environment by using functional decomposition and are reported. The computation of response after the decay time was done in parallel on Param. Figure 9a and b, gives a plot of the computational time as against the number of processors showing that a good speed-up is achieved.

CONCLUSIONS

A method of structural integrity assessment of LMBFR components subjected to thermal striping is presented in this paper. The variation of maximum SIF for various crack lengths shows an increase in maximum SIF with crack length. For a life period of 1 year, the variation of the maximum temperature difference for various crack lengths was found to increase. The response for a unit heavy side function shows an increase in decay time with an increase in thickness or crack lengths for SIF values changing with time. It is demonstrated that the procedure using Green's function approach for crack propagation analysis is computationally quite efficient. The procedure is found to have an inherent parallelism. This characteristic of the procedure is efficiently used in functional decomposition for implementation in a distributed computing environment. The distributed code developed is used to numerically solve a typical linear transient problem. Results show good scale-up justifying the implementation.

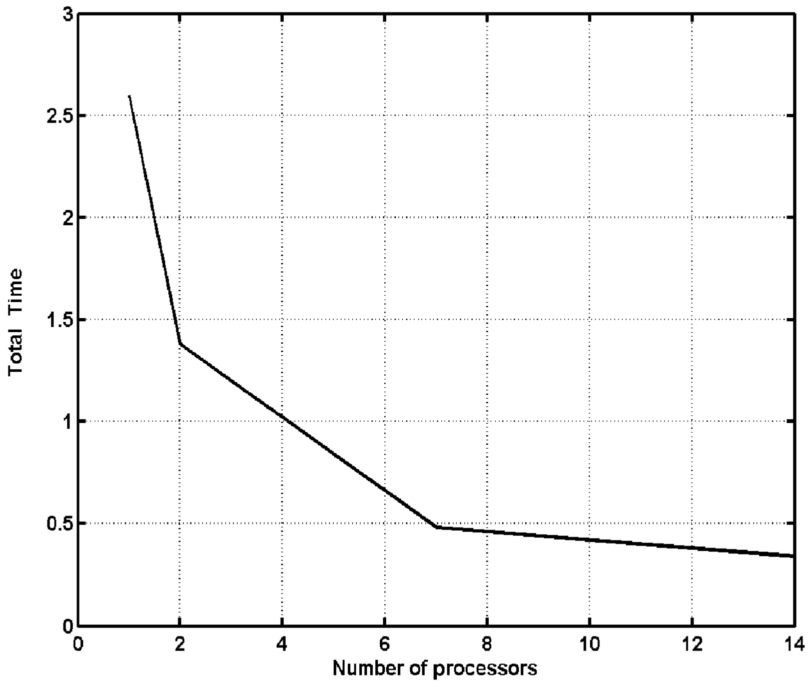


a) Shifted response

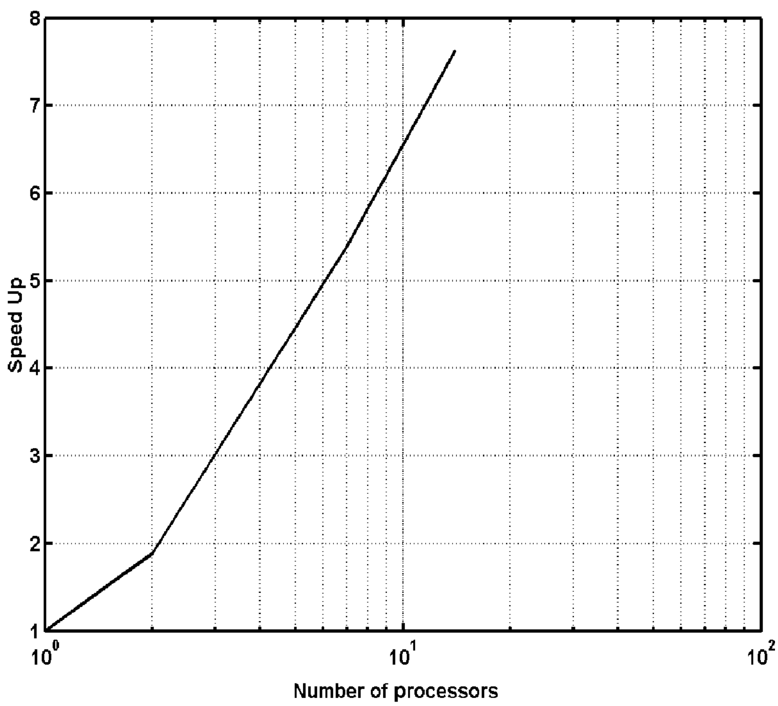


b) Decay time Vs thickness

Fig. 8 (a) Plot of the shifted response. (b) Plot of the decay time t_d for various thickness. (c) Plot of stress intensity factor for various times.



(a)



(b)

Fig. 9 (a) Plot of the computational time versus number of processors. (b) Speed-up versus the number of processors.

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APPENDIX I

Algorithm for integrity assessment based on SIF computation

- Input parameters read. Assumed initial crack length, thickness of plate, time increment, material properties (Young's modulus, thermal conductivity, coefficient of thermal expansion, thermal diffusivity, Poissons ratio, mass density, specific heat.
- Generating random input temperature load. For a given total number of terms for time increment the temperature values at various times and the incremental temperature between times is computed.
- Computation of decay time. For the crack length input Green's function and the decay time is found as the point at which Green's function no longer varies with respect to time.
- Loop on time up to and beyond decay time.
- Computation of SIF. Numerical integration procedure is adopted.
- Parallel processing.
- Computing Green's function matrix up to decay time. Made available on all processors by master.
- Computing number of terms up to decay time, say ($N1$). N1 locations ahead of the first temperature value are made zero.
- Temperature data distributed to P processors. (N/P) computation on each processor in computing the response. N = number of terms taken for time increment.
- Determination of response up to and beyond decay time (N–$N1$) terms this is done on P processors. Computing the life in the master or the processor with task id zero.

Details of PARAM architecture

Param 10000—Distributed Memory architecture with two interconnection networks ARAMNet and Fast Ethernet. It has basically one file server node and three-compute node with details as given below.

FILE SERVER NODE	COMPUTE NODES
Two UltraSparc II 64-bit RISC CPUs of 400 MHz each, with 2 MB external cache per CPU · 512 MB main memory expandable to 2 GB · Two Ultra SCSI HDD of 9.1 GB each. One PARAMNet CCP2 Card · One 10/100 Fast Ethernet Card	Two UltraSparc II 64-bit RISC CPUs of 400 MHz each, with 2 MB external cache per CPU · 1 GB main memory expandable to 2 GB · Four Ultra SCSI HDD of 9.1 GB each · One PARAMNet CCP2 Card · One 10/100 Fast Ethernet card