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GENERATION OF DATA BASE FOR ON-LINE FATIGUE LIFE MONITORING OF INDIAN NUCLEAR POWER PLANT COMPONENTS: PART I – GENERATION OF GREEN'S FUNCTIONS FOR END FITTING

by

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60 Abstract :Green's function technique is the heart of the on line fatigue monitoring methodology. The plant transients are converted to stress and temperature response using this technique. To implement this methodology in a nuclear power plant, Green's functions are to be generated in advance. For structures of complex geometries, Green's functions are generated using finite element method. The Green's functions are to be stored in a data base to convert on-line, the plant data to temperature/stress response, using a Personal Computer. End fitting, end shield, pressurizer, steam generator tube sheet are few such components of PHWR where fatigue monitoring is needed. In the present paper, Green's functions are generated for end fitting of a 235 MWe Indian PHWR using finite element method. End fitting has been analysed using both 3-D and 2-D (axisymmetric) finite element models. Temperature and stress Green's functions are generated at few critical locations using the code ABAQUS.

70 Keywords/Descriptors : PHWR TYPE REACTORS; NUCLEAR POWER PLANTS; REACTOR COMPONENTS; FATIGUE; AGING; REACTOR MONITORING SYSTEMS; ON-LINE SYSTEMS; GREEN FUNCTION; STRESSES; TRANSIENTS; FINITE ELEMENT METHOD; A CODES; MATHEMATICAL MODELS; JOINTS; HEAT TRANSFER; TWO-DIMENSIONAL CALCULATIONS; THREE-DIMENSIONAL CALCULATIONS; THICKNESS

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ABSTRACT

A major concern in the continued, cost effective operation of nuclear power plants is the accumulation of various aging effects in the critical components and systems. Such systems are typically exposed to severe thermal transients and other repetatitive loading operations like operating cycles, testing cycles etc. These can cause metal aging at points of high stress concentration due to fatigue. On-line fatigue life monitoring methodology is a well established remaining life prediction methodology. This methodology helps in avoiding costly forced outages, guides maintenance and inspection schedule, provides valuable data for future design and extends plant life beyond design life.

Green's function technique is the heart of the on line fatigue monitoring methodology. The plant transients are converted to stress and temperature response using this technique. To implement this methodology in a nuclear power plant, Green's functions are to be generated in advance. For structures of complex geometries, Green's functions are generated using finite element method. The Green's functions are to be stored in a data base to convert on-line, the plant data to

temperature/ stress response, using a Personal Computer. End fitting, end shield, pressurizer, steam generator tube sheet are few such components of PHWR where fatigue monitoring is needed. In the present paper, Green's functions are generated for end fitting of a 235 MWe Indian PHWR using finite element method. End fitting has been analysed using both 3-D and 2-D (axisymmetric) finite element models. Temperature and stress Green's functions are generated at few critical locations using the code ABAQUS.

1. INTRODUCTION:

A realistic method is proposed for on line fatigue life monitoring of nuclear power plant components using available plant instrumentation in literature [1-4]. In on-line fatigue life monitoring methodology, the plant transients are monitored on-line. These data are converted to temperature/ stress response using Green's function technique. Green's function technique converts plant data to temperature/ stress response most efficiently. Multiple site thermal loading problem is solved using superimposed single site Green's function technique [1]. The stress time history is reduced to peak stress versus time history. Rainflow cycle counting algorithm is used to count the actual number of complete cycles experienced by the component for a specified stress range. This technique converts peak stress time history to stress frequency spectrum [2,4]. Fatigue usage factor is computed from stress frequency spectrum using material fatigue data.

In order to implement on-line fatigue life monitoring methodology in a nuclear power plant, Green's functions are to be generated in advance for the selected critical components. Close form solution of Green's functions are available for few well defined geometries [5]. However, for structures of complex geometry, as generally used in nuclear power plant, Green's functions are to be generated using finite element method. The Green's functions are to be stored in a data base to convert on-line the plant data to temperature/ stress response using a Personal Computer. The subsequent sections of this paper describe the generation of a data base for a component of Indian PHWR.

2. SELECTION OF CRITICAL COMPONENTS:

It is neither possible nor necessary to monitor the degradation effects for all the components of a nuclear power plant. Structural degradation depends mainly on the stress cycles experienced by a component which in turn depends on the transients seen by that component in the operative time period. A number of critical components which will experience the maximum fluctuation of fluid parameters, are to be selected for on line fatigue monitoring. The degradation and remaining life of the entire plant can be assessed by estimating the consumed fatigue life of these components.

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 the maximum failures. On line fatigue life monitoring methodology is already in use in many advanced countries like U.S.A., France, Germany etc. [3] as a life prediction and life extension programme. The components selected for fatigue monitoring are charging nozzles, surge line, steam generator feedwater nozzles, safety injection nozzles etc. for PWR plants. For BWR plants feedwater nozzles, CRD return nozzles etc. are selected for fatigue monitoring. In PHWR end fitting, end shield, steam generator tube sheet, pressuriser are the few components which will be most severely affected by the plant transients.

3. GENERATION OF TEMPERATURE AND STRESS GREEN'S FUNCTIONS FOR END FITTING OF INDIAN PHWR:

End fitting is a very important component of PHWR. The inlet and outlet ends of coolant tubes of PHWR are connected to rest of the PHT system through end fitting. The other end of end fitting is connected to reactor refuelling system during refuelling operation. This component is made up of martensitic stainless steel grade 403. This is subjected to internal pressure and thermal load due to hot pressurised heavy water coolant flowing through this. There are also thermal shocks caused by different reactor transients. Another kind of thermal shock is caused by room temperature heavy water injection during refuelling operation. This heavy water from refuelling system is at higher pressure ($\simeq$10.6 MPa) than coolant pressure to stop back flow of coolant during refuelling.

Fatigue behaviour of end fitting of RAPS-I was analysed for the cold injection of heavy water during refuelling operation [6]. Analysis was carried out for the internal pressure and transient thermal load. In this analysis, three types of thermal transients were considered. Phase I transient corresponds to the natural convection cooling of hot end fitting body near B-5 bore by the heavy water from refuelling machine once fuelling machine is connected to the endfitting body. Phase II transient is caused during retraction back of the seal plug and also during normal refuelling operation. The Phase III transients corresponds to the mounting back of the seal plug on the end fitting body and slowly lower the pressure to atmospheric condition before disconnecting the fuelling machine It was shown in this analysis that the most of the increment in fatigue usage factor occurs during the phase II transients Hence, in the present study Green's functions are generated for that particular transient condition.

3.1.GEOMETRICAL DETAILS, MATERIAL PROPERTIES AND LOADING CONDITIONS:

The geometrical details of an end fitting of NAPP is shown in Fig.1. One end of the end fitting is rolled to the coolant tubes and the other end is connected to the F/M during the refuelling operation. The end fitting is connected to the PHT system through a feeder nozzle. The various mechanical properties are provided in ASME handbook of material properties [7].

End fitting is subjected to a internal pressure of 10 MPa. The outside of end fitting is surrounded by air at atmospheric pressure and at slightly higher temperature than ambient (≃70°C). Heavy water at 10 MPa and 249°C temperature flows through the end fitting to the coolant tubes from feedwater nozzles. The end fitting which is at down the stream, heavy water at 293°C flows to the PHT system through the feedwater nozzle. During refuelling period heavy water at ambient temperature and slightly higher pressure (≃10.6 MPa) is injected to the end fitting as described above.

3.2. FINITE ELEMENT MODELLING:

There are few structural discontinuities in the end fitting. This may cause stress concentration which is important from fatigue point of view. The most important structural discontinuity occurs where feed water nozzle is connected to the end fitting. Another great important structural discontinuity is at the groove where seal plate makes contact. Two different finite element models have been generated to study the effects of these structural discontinuities on stresses.

In the first case, end fitting is modelled using 3-D shell elements. This model considers the discontinuity due to the feeder nozzle connection with end fitting. This model is shown in Fig.2. Eight noded coupled temperature displacement shell elements have been used for this analysis [8]. The geometry considered for analysis includes portion of end fitting from fuelling machine side to the portion considerably away from the feedwater nozzle. This also includes the nozzle. Half of the end fitting with the feedwater nozzle is modelled using 492 elements with 1583 nodes utilising the plane of symmetry. Five sections have been specified along the thickness direction where temperature and stress are to be integrated. Symmetric boundary condition is specified. The computer code ABAQUS is used for this analysis.

The second finite element model uses eight noded coupled temperature displacement axisymmetric elements [8]. This uses 336 elements with 1155 nodes. The finite element mesh is shown in

Fig.3. The geometry considered for the analysis includes portion of the end fitting from fuelling machine to the portion considerably away from the feeder nozzle. This geometry includes B-5 bore and detail contours of the seat where the seal disc makes contact. The feeder nozzle could not be considered in this 2-D model.

3.3 GENERATION OF TEMPERATURE AND STRESS GREEN'S FUNCTIONS:

The end fitting is surrounded by air at atmospheric pressure and 70°C temperature at outside. This temperature does not undergo severe transients. The possible effect of change of outside air temperature on the end fitting is very small as heat transfer coefficient of air is much less compared to that of inside heavy water. So Green's functions are generated considering only the change of inside heavy water temperature. The calculation of various heat transfer coefficients used in the analysis is presented in Appendix-I.

During refuelling operation, the end fitting experiences a thermal transient due to flow of cold heavy water from fuelling machine. The high temperature feed water mixes with this water which causes a drop in the temperature. This drop in temperature is found to be nearly 284°C and is very small. Also this mixing occurs far away from the points of structural discontinuity inside the linear tube. Hence thermal transients is mainly governed by cooling of the end fitting due to the flow of cold F/M heavy water before it mixes with the hot PHT water. In the present analysis, Green's functions have been generated for unit rise of inside heavy water temperature surrounding the surface, keeping all other fluid temperatures zero as per the definition of Green's function.

In the first analysis using shell elements, firstly temperature response is computed. Using the temperature for all the nodes, the stress response is also computed for each time step. The stresses are found to be high at two locations. These locations are shown in Fig.1 as 'A' and 'B'. The temperature and stress Green's functions at 'A' are shown in Fig.4(a) and Fig.4(b) respectively. The Green's functions at 'B' are shown in Fig.5(a) and Fig.5(b).

The analysis is also repeated for the second 2-D model using axisymmetric elements. The responses are found out to be high at two locations. These locations are shown in Fig.1 as 'B' and 'C'. The temperature and stress Green's functions for these two locations are shown in Fig.6 and Fig.7 respectively.

4.DISCUSSION AND CONCLUSION:

In the 3-D analysis the stresses are high at locations 'A' and 'B'. 'A' is the location where thickness of end fitting is maximum and suffers a sharp reduction in thickness. 'B' is the location where seal disc seats and this is also near to the feeder nozzle connection. In the 2-D analysis, which considers the deatil configuration of seal disc seat, locations 'B' and 'C' show higher stresses. Stresses at 'C' cannot be obtained from 3-D analysis. The stress responses at 'B' and 'C' in 2-D analysis match well.

The 3-D shell element model provides slightly higher values than 2-D axisymmetric results. From the above results, locations

'A' and 'B' are identified as locations where stresses are to be monitored for fatigue analysis. To be in the conservative side, the temperature and stress Green's functions at 'A' and at 'B' using 3-D shell element model, are considered as Green's function data base for on-line fatigue monitoring computation. Finally as fatigue in end fitting is caused by the thermal transients due to the flow of heavy water during refuelling operation, fatigue life can be analysed considering it essentially a single site thermal loading problem.

In Hall No. 7 of B.A.R.C. Trombay, a test facility of an end fitting is in operation. The geometrical details and the loading conditions of this end fitting resemble that of an end fitting of Indian PHWR. A project is undertaken with Reactor Control Division of B.A.R.C. to implement on-line fatigue monitoring methodology in this test facility. The generated Green's function data base can be used for fatigue computation of end fitting in this fatigue monitoring system.

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APPENDIX-I

In this present appendix calculations of various heat transfer coefficients used in the analysis is presented. The empirical correlation has been taken from literature [9]. The various properties of air and heavy water at different temperature and pressure conditions have been provided in references [9-10].

1.CALCULATION OF HEAT TRANSFER COEFFICIENT FROM END FITTING TO SURROUNDING AIR:

1.1 OUTSIDE SURFACE OF END FITTING:

Outside of the end fitting is cooled by air at atmospheric pressure at 70°C temperature.

Air temperature $T\alpha$= 70°C

Outside surface temperature T_o= 264.44°C

Film temperature T_f =($T\alpha$ + T_o)/2 = 167.22°C

Effective diameter of end fitting d_e= 134.69 mm

Air properties at film temperature T_f = 167.22°C

Density ρ= 0.80316 Kg/m^3

Specific heat C_p= 1.01936 E+03 J/Kg-K

Viscosity μ = 2.3333 E-05 Pa-sec

Thermal conductivity k= 0.0364 W/m-K

Prandtl Number Pr= 0.6842

Kinematic viscosity ν =28.268 E+06 m^2/sec

Grashop Number Gr= $(\beta\ g\ \Delta T\ d_o^3)/\ \nu^2$

Here β = 2.27159 E-03 /°C

ΔT= 194.44 °C

Therefore, Gr= 13.25 E+06

Nusselt Number $Nu = 0.53\ (Gr.\ Pr)^{0.25}$

$= 29.08$

heat transfer coefficient $h = (Nu * k)/d_o$

$= 7.86\ W/(m^2 - K)$

1.2 OUTSIDE SURFACE OF FEEDWATER NOZZLE:

Here film temperature $T_f = 167.22\ ^\circ C$

Diameter of feedwater nozzle $d_o = 72$ mm

Now $Gr = 1.012\ E+06$

$Nu = 0.548 (Gr.Pr)^{0.25}$

$= 15.865$

Heat transfer coefficient $h = 8.018\ W/(m^2 - K)$

2. CALCULATION OF HEAT TRANSFER COEFFICIENT FROM END FITTING TO INSIDE HEAVY WATER:

2.1 INSIDE SURFACE OF FEEDWATER NOZZLE:

In one side of end fitting heavy water at 293°C and at 10 MPa pressure flows from the coolant channel to the PHT system through the end fitting and feedwater nozzle. In the other side heavy water at 249°C and at 10 MPa pressure flows to the coolant tubes from the PHT system through the feedwater nozzle and end fitting. Heat transfer characeristics are calculated with heavy water at temperarure 293°C.

The inside pressure $p_i = 10$ MPa

Density $\rho = 0.805\ E+03\ Kg/m^3$

Thermal conductivity $k = 0.486\ W/m-K$

Specific heat $C_p = 5.22\ E+03\ J/Kg-K$

Viscosity $\mu = 0.977\ E-04$ Pa-sec

$Pr = 1.047$

Mass flow rate of heavy water m_f= 12.6 Kg/sec

Internal diameter d_i= 49.2 mm

Velocity in the annulus v= 8.233 m/sec

Reynold's Number Re= $(\rho \ v \ d_i)/ \mu$

=33.37 E+05

Nu= 0.023 $(Re)^{0.8}$ $(Pr)^{0.4}$

= 3876.53

Heat transfer coefficient h= 38.29 E+03 W/m^2-K

2.2 INSIDE SURFACE OF END FITTING TOWARDS FUELLING MACHINE SIDE:

During refuelling operation end fitting is cooled with heavywater at ambient temperature at 10.6 MPa.

Temperature of heavy water $T\alpha$= 30°C

Temperature of end fitting surface T_s= 288°C (assumed)

Film temperature T_f= 159°C

Density ρ= 1.013 E+03 Kg/m^3

Viscosity μ= 1.984 E-04 Pa-sec

Specific heat C_p= 4.16 E+03 J/Kg-K

Thermal conductivity k= 0.6257 W/m-K

Pr=1.3189

Inside diameter d_i= 101.65 mm

Flow rate of refuelling heavy water Q= 1.135 E-03 m^3/sec

Velocity of refuelling heavy water v= 0.1399 m/sec

Re= 7.26 E+04

Nu= 0.023 $(Re)^{0.8}$ $(Pr)^{0.33}$

=195.03

Heat transfer coefficient h= 1200 W/ m^2-K

2.3 INSIDE SURFACE OF END FITTING TOWARDS CALENDRIA SIDE:

In the portion between the feedwater nozzle and end fitting heavy water at 293°C flows in the annulus between end fitting body and liner tube.

Temperature of heavy water $T\alpha$= 293°C

Mass flow rate of heavy water from feedwater nozzle m_f= 12.6 Kg/sec

Inside pressure p_i= 10 Mpa

Density ρ=0.805 E+03 Kg/m^3

Viscosity μ= 0.977 E-04 Pa-sec

Thermal conductivity k= 0.486 W/m-K

Specific heat C_p= 5.22 E+03 J/Kg-K

Pr=1.047

Inside diameter d_i= 91.02 mm

Outside diameter d_o= 109.22 mm

Velocity in annulus v= 5.468 m/sec

Equivalent diameter D_e= 4* Area / Wetted Perimeter

= 18.2 mm

Re= 8.2 E+05

$Nu = 0.023\ (Re)^{0.8}\ (Pr)^{0.33}$

= 1261.12

Heat transfer coefficient h=33.67 E+03 W/ m^2-K

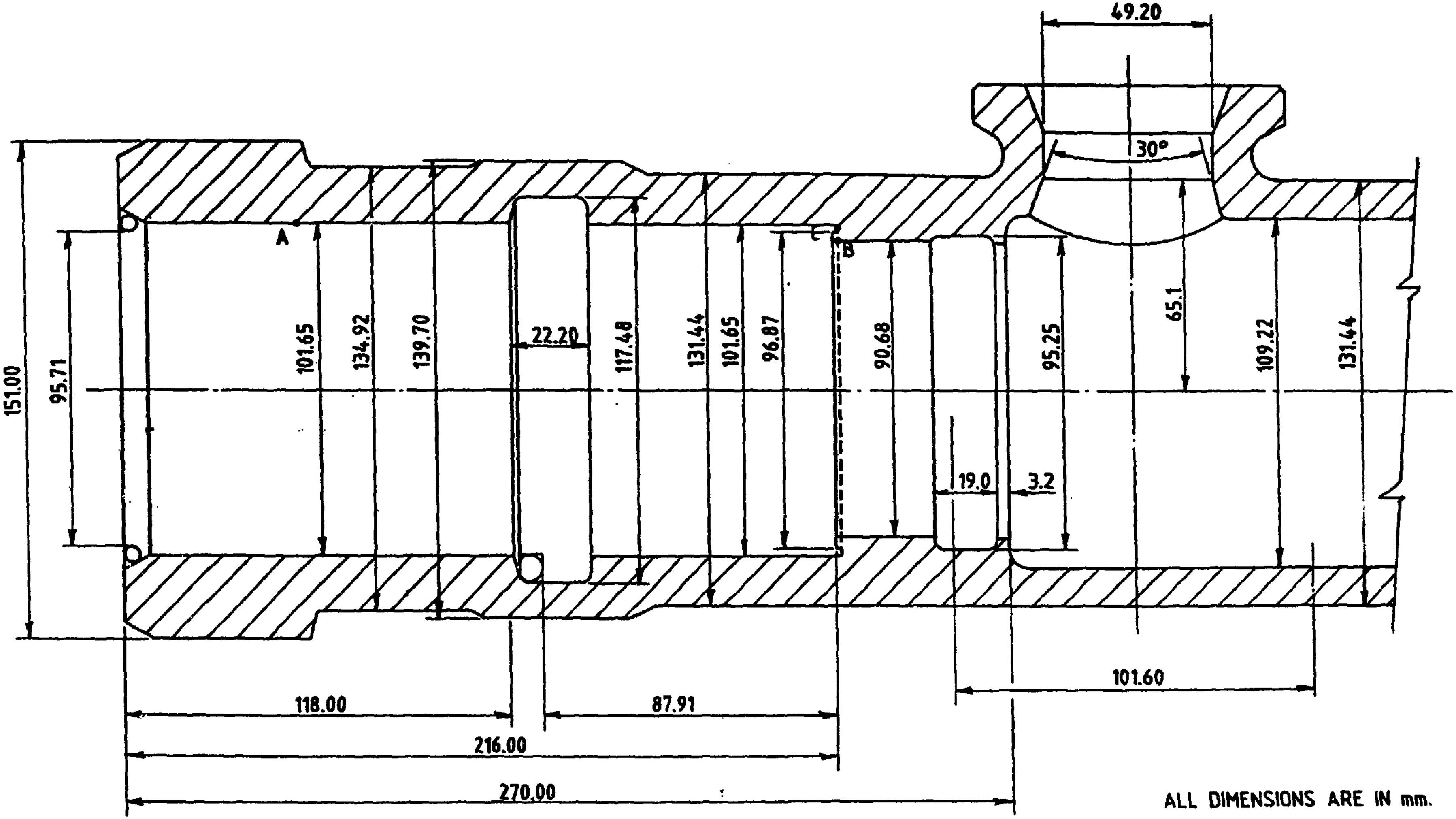

FIG. 1. GEOMETRICAL DETAILS OF ENDFITTING

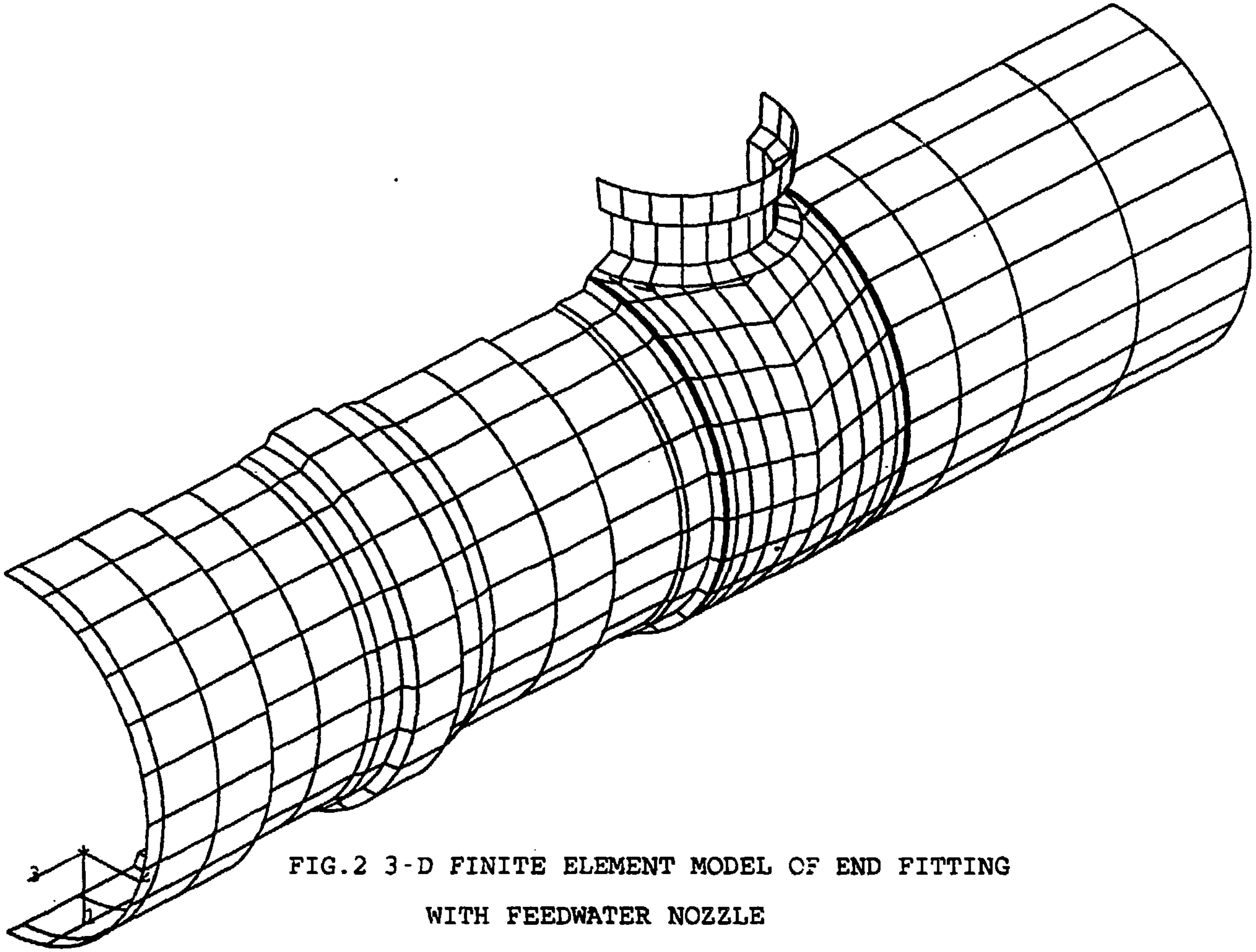

FIG.2 3-D FINITE ELEMENT MODEL OF END FITTING
WITH FEEDWATER NOZZLE

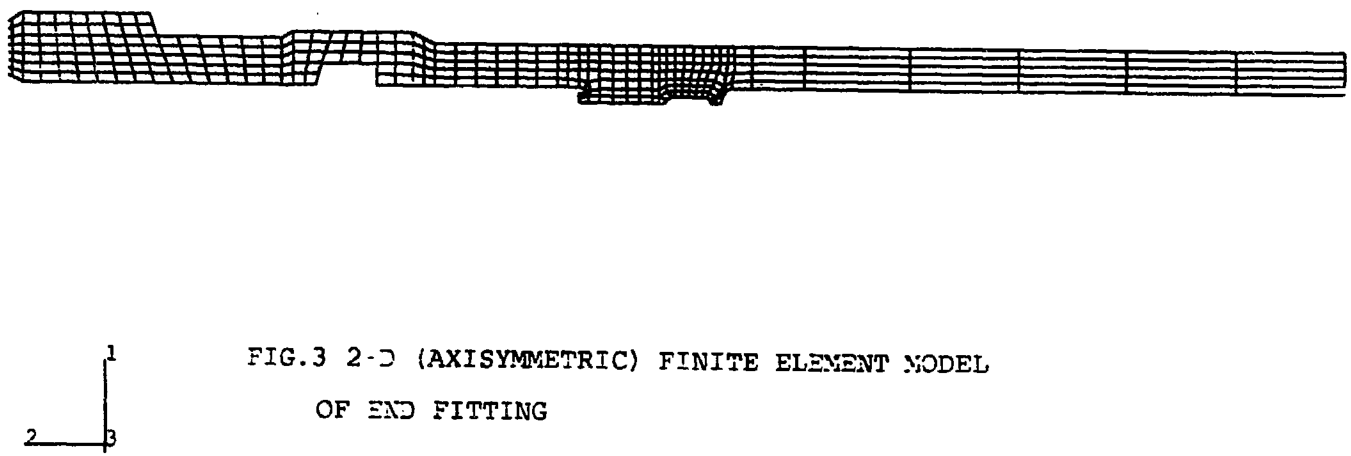

FIG.3 2-D (AXISYMMETRIC) FINITE ELEMENT MODEL
OF END FITTING

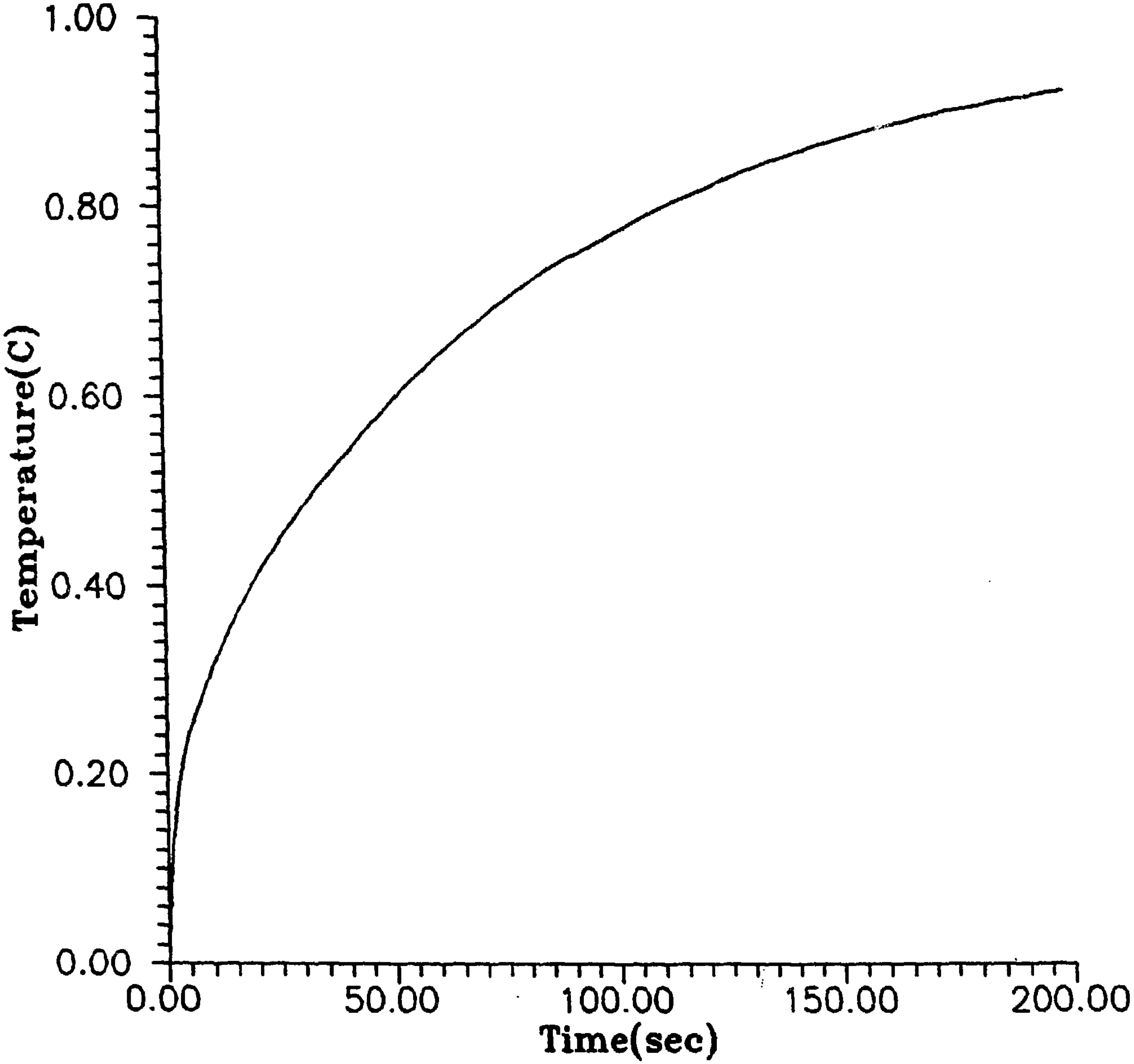

Fig.4(a) Temperature Green's function at 'A' using 3-D modelling

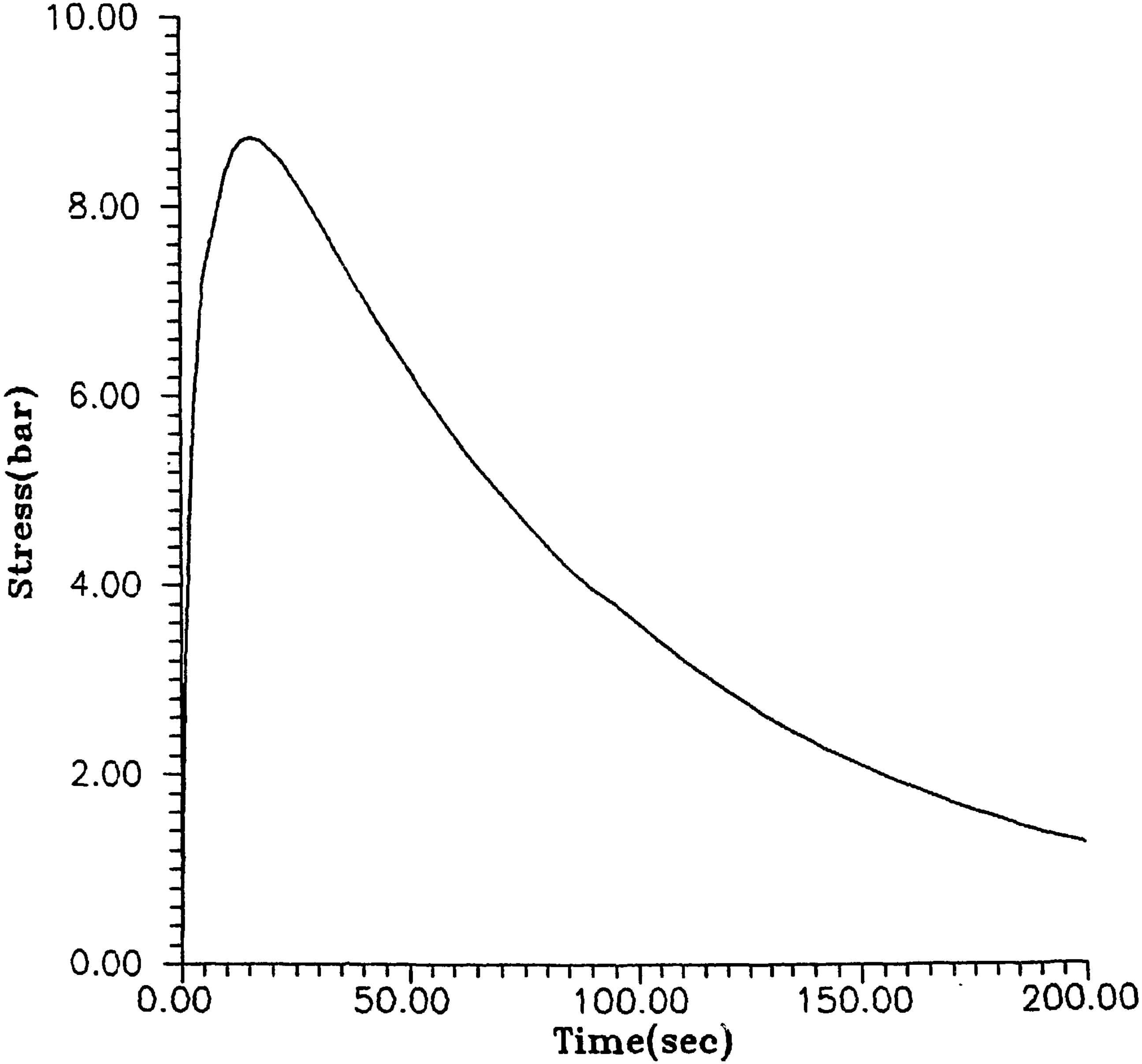

Fig.4(b) Stress Green's function at 'A' using 3-D modelling

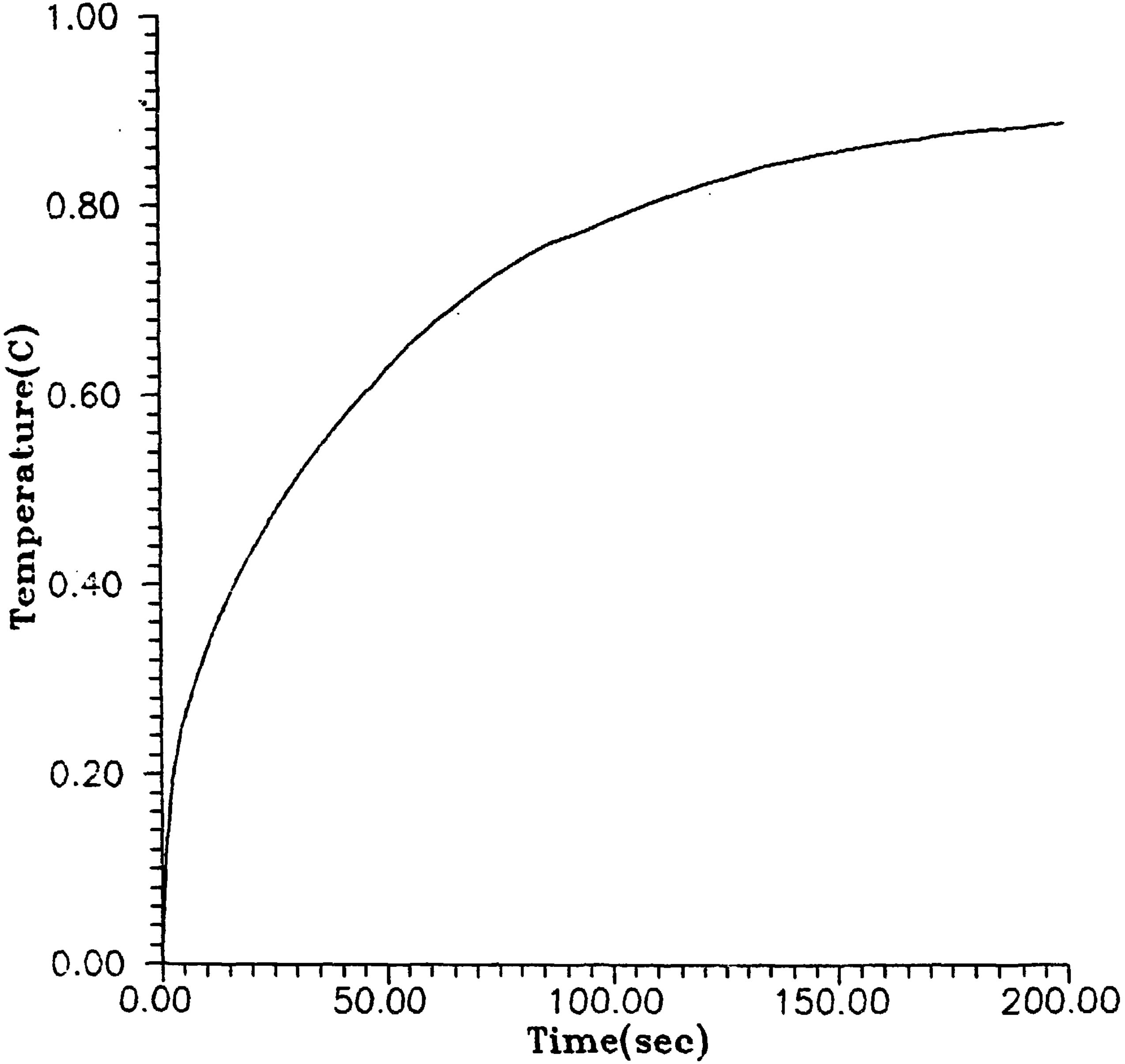

Fig.5(a) Temperature Green's function at 'B' using 3-D modelling

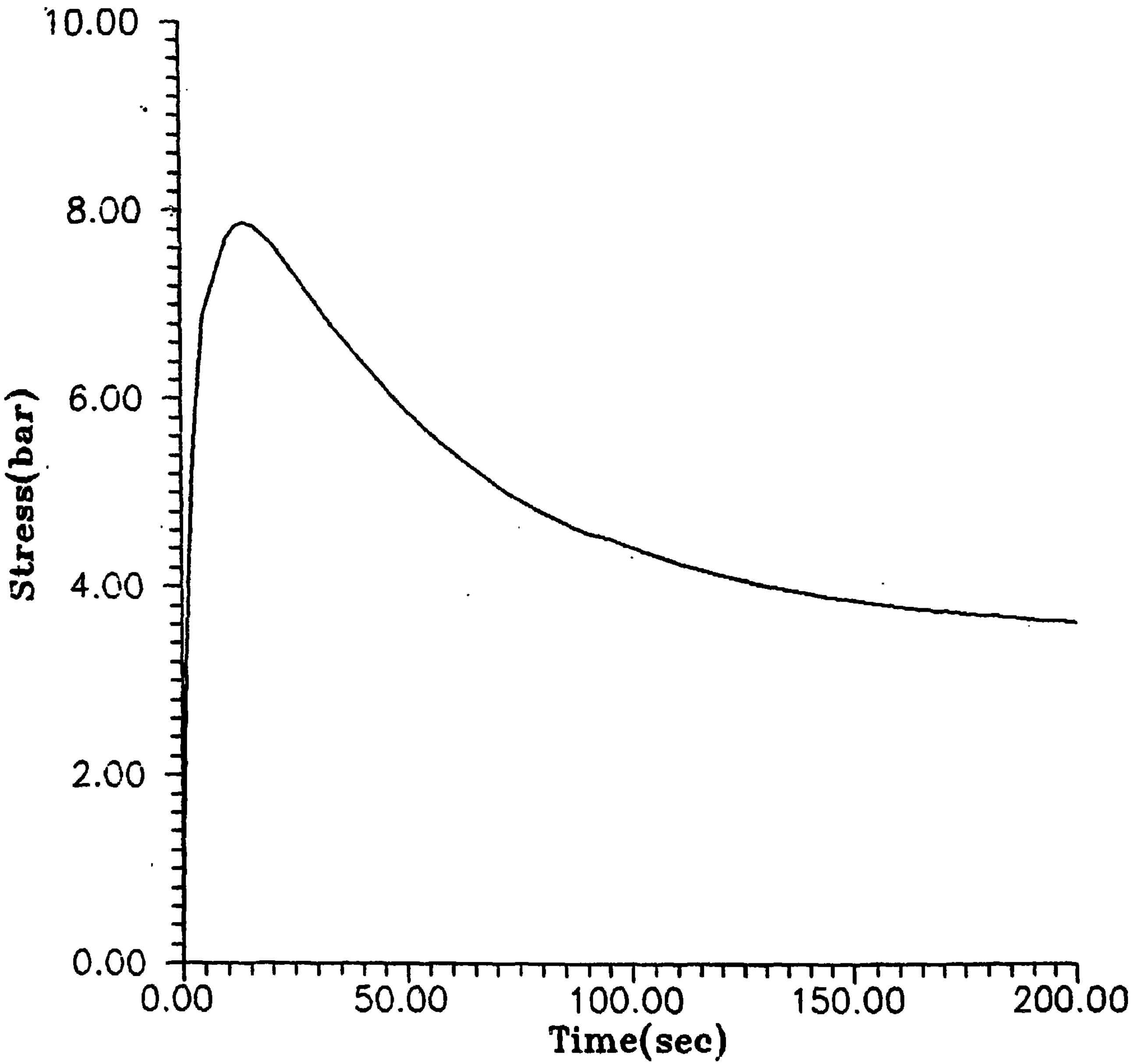

Fig.5(b) Stress Green's function at 'B' using 3-D modelling

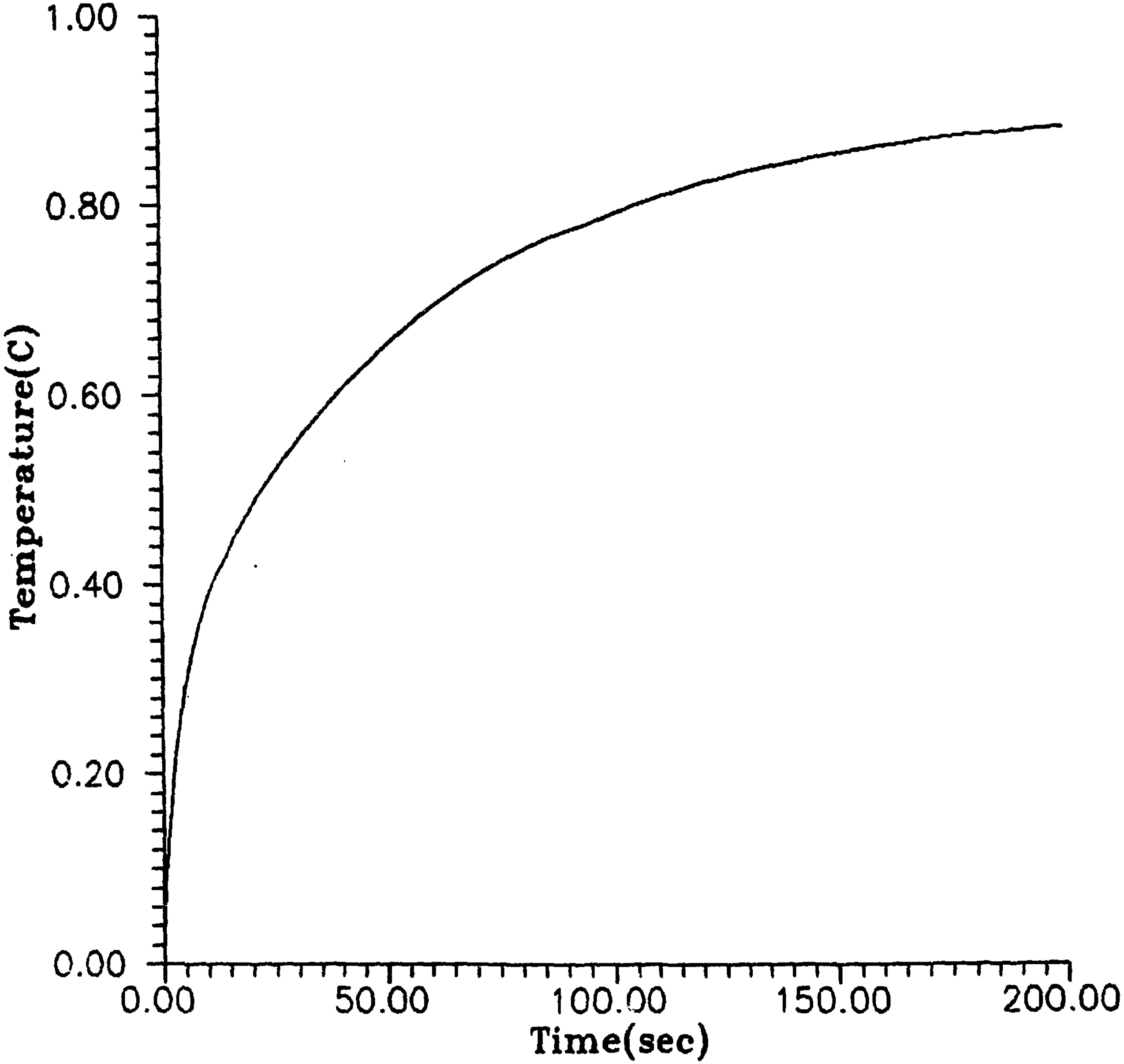

Fig.6(a) Temperature Green's function at 'B' using 2-D (axisymmetric) modelling

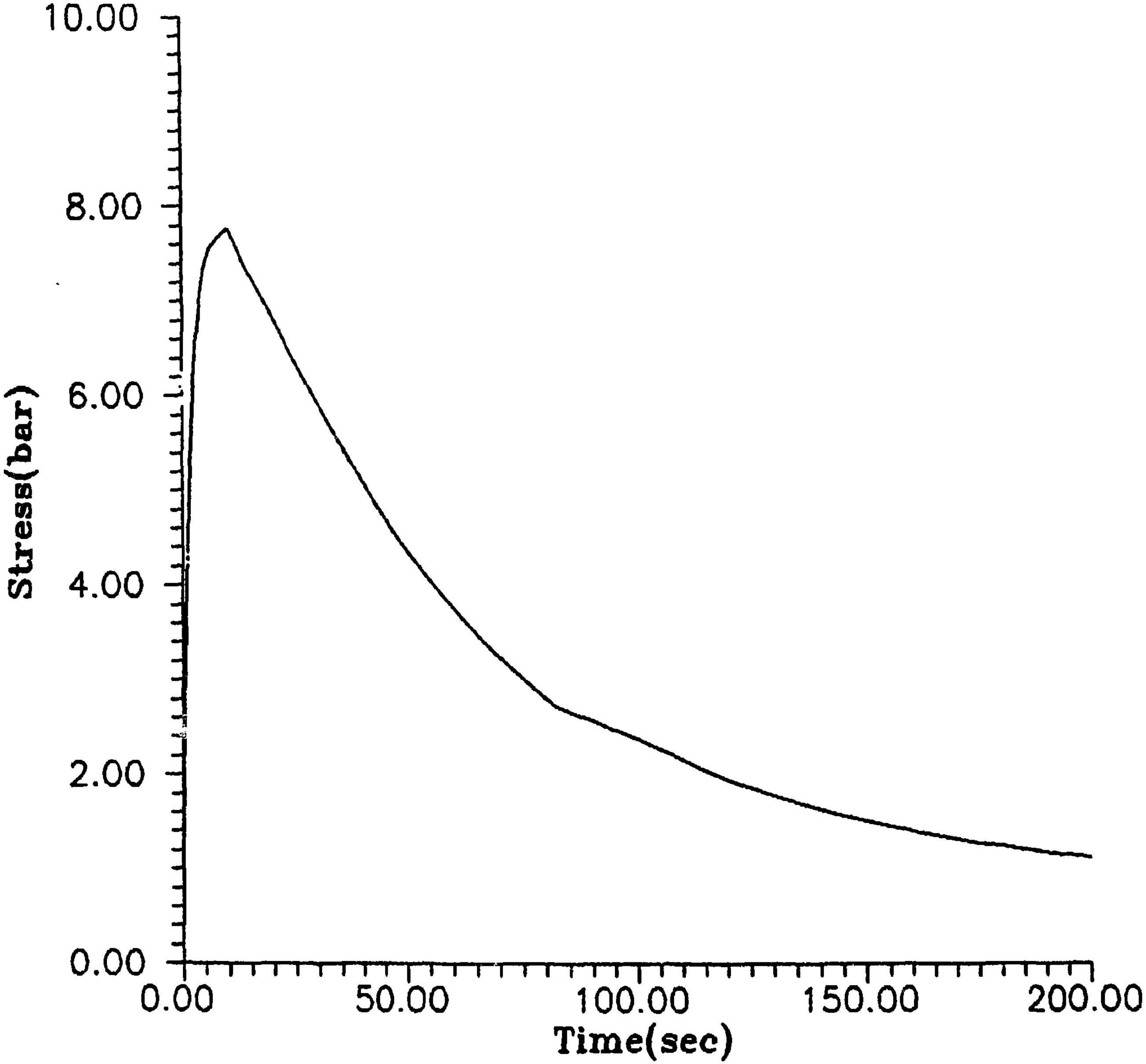

Fig.6(b) Stress Green's function at 'B' using 2-D (axisymmetric) modelling

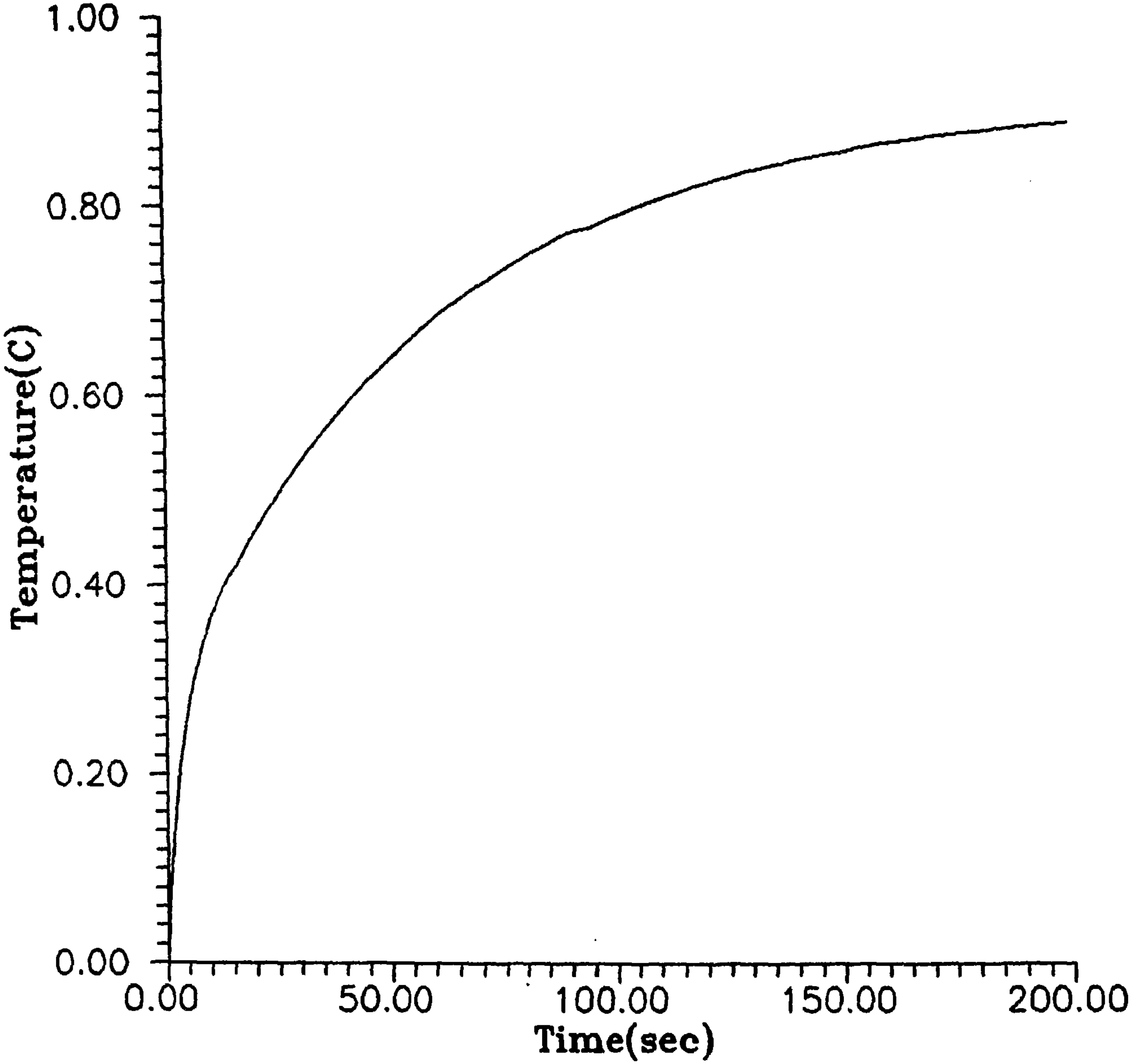

Fig.7(a) Temperature Green's function at 'C' using
2-D (axisymmetric) modelling

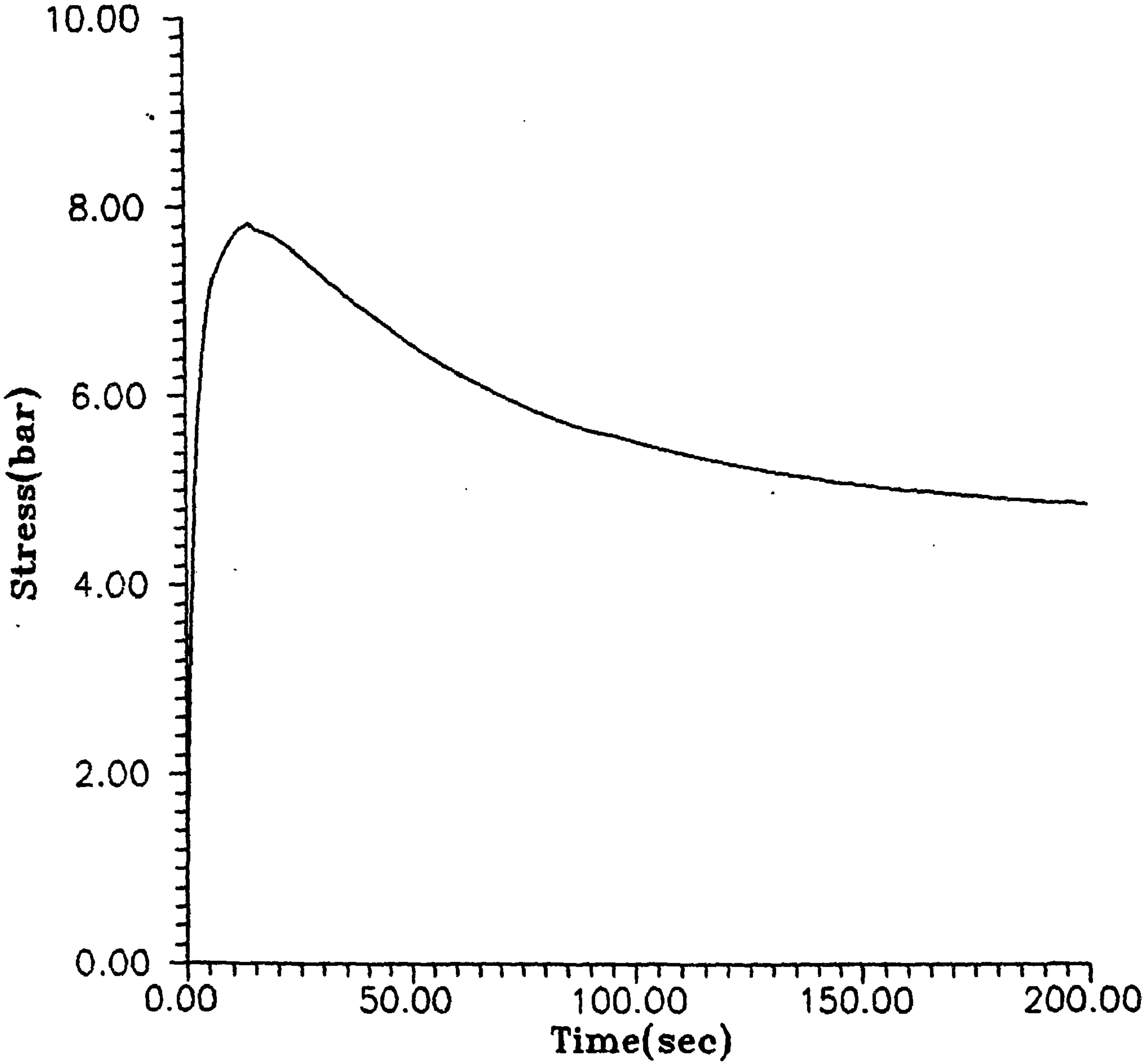

Fig.7(b) Stress Green's function at 'C' using 2–D (axisymmetric) modelling

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