Localized Thermostructural Analysis of LMFBR-Core Components Through the FEM-Code IAFETIN

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Summary:

Striving for high burn-up and high reliability the structural design of the core components of a LMFBR requires the detailed evaluation of all the factors limiting the service life through impairment of the structural integrity or of the functional adequacy.

In addition to a sufficient knowledge of the material behavior and to the structural design criteria, necessary design tools include advanced techniques to calculate deformations, stresses and strains, on which the evaluation parameters depend. Computational methods must be available not only for the prediction of the global response of the components, such as e.g. fuel pin-codes or core restraint codes, but also for investigation of localized critical regions for a proper definition of operating conditions, which has to compromise between high fuel usage and reliable component behavior. In the latter case a modelling of the geometry, of the loading history and of the complex material behavior in great detail is indispensable and in practice can be performed only on the basis of numerical techniques, such as the finite element method and the increment-iterative procedure.

This paper gives at first a brief description of the salient capabilities of IAFETIN, a finite element code developed at INTERATOM for transient temperature distribution, swelling, irradiation and thermal creep and cyclic plasticity analysis of two dimensional structures.

An application is then presented as sample analysis to show some IAFETIN capabilities. The selected structure is one critical location of a double walled fuel pin used for an irradiation test of a heterogeneous pin, namely the region at the fuel blanket transition where the cladding was supposed to experience the most severe thermal loading.

The results presented in this paper are however limited to the steady state loading conditions and illustrate the differences in the temperature and stress predictions with and without temperature displacement interaction.

1. Introduction

Among the factors conditioning the service life of the core components of a LMFBR the structural requirements on material integrity and on functional adequacy play a primary role.

Striving for high burn-up and high reliability the structural designer has to evaluate the components for all failure modes through accurate calculation of the corresponding damage parameters. These evaluation parameters relate generally to the deformations, strains and stresses and in particular to their peak values which normally arise in restricted locations of the components. Typical example is the pin cladding regions at the fuel blanket transition. The peak quantities and their time distribution can only roughly be calculated with the methods usually applied for prediction of the global response of the components, such as e.g. fuel pin codes or core restraint codes.

In addition to a sufficient knowledge of the material behavior, to adequate structural design criteria and to global analysis methods, structural design tools must therefore include also advanced techniques for the investigation of localized critical regions, allowing in great detail the modelling of the geometry, of the loading history and above all of the complex material behavior in the core environment.

In practice such a sophisticated analysis can be performed only on the basis of numerical techniques, such as the finite element method and the increment-iterative procedure. The computer code IAFETIN, which is briefly described in the next chapter finds in these cases suitable application.

2. The IAFETIN+)-Code

IAFETIN is a special purpose finite element program for steady state or transient thermal analysis and for static mechanical analysis of two dimensional structures with material nonlinearities. It has been developed at INTERATOM in the frame of the fast breeder R&D activities to set up structural design tools for core components and for high temperature plant components [1]. The main features of IAFETIN are summarized in Table 1. Typical capabilities, so far implemented for use in core structure analysis are internal heat generation, neutron irradiation induced behavior (swelling and creep) of the core materials DIN-grade 1.4981 cw, 1.4970 cw and 1.4970 cw-a and the interaction of the temperature and displacement fields. The latter finds application in the prediction of the thermostructural response of the pin cladding, where the changes of the pellet-clad gap have a strong influence on the temperature distribution and consequently on the radial displacements. For steady state situations this thermomechanical interdependency is

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+) INTERATOM-Finite Element program for temperature and inelastic structural analysis

Table I - Main features of the IAFETIN code

1. Capabilities

- Geometry	:	- 2 -dimensional (axisymmetrical, plane stress and plane strain), - limited automatic mesh generation
- Loading and boundary conditions	:	- time dependent thermal loading (internal heat generation, *) surface film heat transfer, inside or boundary temperatures) - static, time dependent mechanical loading (pressure, concentrated forces, initial displacements) - time dependent neutron flux loading - identity of displacement components and/or temperatures at two or more modal points
- Material behaviour	:	- Thermoelasticity - cyclic plasticity - swelling *) - thermal and irradiation creep *) - Temperature dependent material properties

2. Output

- Nodal point values of

  Temperature,
  neutron fluence, *)
  displacement components,
  stress components,
  swelling, thermal and irradiation creep strain components, *)
  plastic strain components,
  total strain components.

- Plots of initial and deformed geometry.

3. Analysis Method

- Finite Element Method (displacement method), 6 Node isoparametric triangular element,
- Time increment iterative approach and initial strain method for inelastic analysis,
- Restart capability,
- Time increment automatic halved, if necessary,
- option for Temperature-displacement interaction (*).

(*) typical of core components.

taken into account in IAFETIN through iterations of thermal and mechanical calculations up to a prefixed temperature error, whereas in the time dependent analysis the geometry is updated according to the actual displacements at selected time points before the temperatures are calculated.

One of the most useful capabilities is the possibility to specify identity of displacement components and/or of the temperature at two or more points. That enables e.g. the schematisation of generalized plane strain in a disk cut out of a long cylinder through the condition for the surface nodal points to have the same axial displacement.

The thermal and elastic analysis methods are based on the classical finite element displacement formulation [2] with the six node isoparametric triangular element. The assemblage of the stiffness matrices and of the nodal force vectors, using a compacted storage scheme, as well as the out of core solver for the solution of the equilibrium equation global systems originate from the general purpose program ADINA [3].

The inelastic analysis is performed following a linearization of the problem with a time increment iterative approach and the initial strain method for both plasticity and creep. Swelling not dependent on stress, is treated in a manner similar to thermal strains, whereas the stress dependent irradiation creep is handled as the thermal creep.

Cyclic plasticity and plant material thermal creep are treated according to the mathematical model suggested by ORNL for high temperature applications [4], regarding e.g. the bilinear σ-ε-curve, primary creep strain hardening and auxiliary hardening rules to account for stress reversals. The time increments in the inelastic calculations are normally specified by the user; however an increment is automatically halved if any of the read-in limits on the iteration number, on the ratio of creep strain increment to elastic strain or on the change of the stress in the step is reached. In each time increment the creep strains are calculated on a subincrement basis to better account for the variability of the stresses during the time increment.

IAFETIN is limited to small displacements and small strains, whereas there is no problem size limitation other that of the core storage available thanks to the implemented variable dimensioning.

The IAFETIN capabilities for steady state and transient temperature and thermoelastic analysis are largely verified and have found several applications in design analysis. The inelastic analysis part has not yet been used in real design applications to be submitted in the licensing procedure.

3. Sample analysis

To show some IAFETIN capabilities a sample application on a FBR heterogeneous fuel pin is now presented. However the results presented here, available at the time of writing this paper, are limited to those of the stationary loading condition.

This analysis is actually the first step of a complete study including transient loadings and inelastic material behavior as necessary to demonstrate compliance with thermal and structural design limit.

The component (fig. 1a) is a double walled fuel pin used for an irradiation test of a heterogeneous pin in the central core position of the german experimental LMFBR KNK II. The critical location selected for detailed study is the region at the fuel blanket transition where the pin linear power peaks and the inner cladding was supposed to experience the most severe thermal loading.

Fig. 1 (b and c) shows the model, the finite element idealisation and the boundary conditions. The axial length is enough to include the whole transition zone with an acceptable computer cost associated with the 745 nodal points and 343 six node triangular elements. The lower points are free to move only radially whereas the condition of same axial displacement is specified for the 3 groups of nodal points at the upper end of the blanket, of the inner cladding and of the outer cladding respectively.

Eight distinct materials were considered; the 2 claddings are separated by sodium and are of austenitic steel, DIN-grade 1.4970 cw,a inside and 1.4981 outside. Three different materials for the dishing space, for the blanket-cladding interface and the fuel-cladding interface were considered with the aim of parametric study of the influence of various heat transfer conditions at the gaps. In this first analysis however only the thermal properties of Helium were assigned to the 3 gaps.

In the mechanical calculation the sodium- and gap-elements (material n. 2,6,7,8) were eliminated. The stationary loadings included internal heat generation in the fuel and blanket, corresponding to a linear pin power of 326 W/cm and 70 W/cm respectively, and heat transfer to the sodium flowing outside at the constant temperature of 420 ^{o}C.

The iterations of temperature and displacement calculations were repeated until a temperature difference in 2 consecutive iterations at every nodal point less than 5 ^{o}C resulted. On the basis of the final temperature distribution the stresses were then calculated.

Some results are plotted in Fig. 2 and compared with those of the analysis without temperature-displacement interaction, i.e. practically with constant gaps. Fig. 2b shows the radial temperature distribution at 3 cross sections. Relatively to a portion of the considered region (detail A of fig. 1) the fig. 2 c,d,e show the axial temperature distribution at the pin axis, at the pellet surface, at the inside of the inner and outer claddings, and the axial distribution of the axial stresses (σ_z) at the inside of the inner cladding. It will be observed that quite different temperatures and stresses already under stationary conditions are predicted with and without accounting for gap changes.

These differences are emphasized under transient conditions where following gap closure still higher thermal gradients and above all possible pellet cladding contacts are to be expected. For the cladding behavior under the cyclic thermal loadings associated with the upset and emergency reactor operation to be realistically investigated the contact problem (gap closure and opening) has therefore to be solved.

Work on implementation in IAFETIN of such solution methods is in hand.

References

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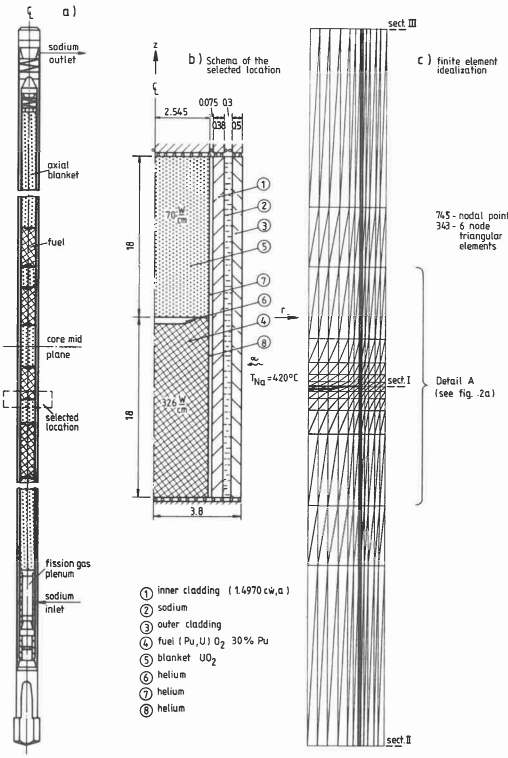

Fig. 1 Geometry, materials, loading and boundary conditions of the IAFETIN sample problem.

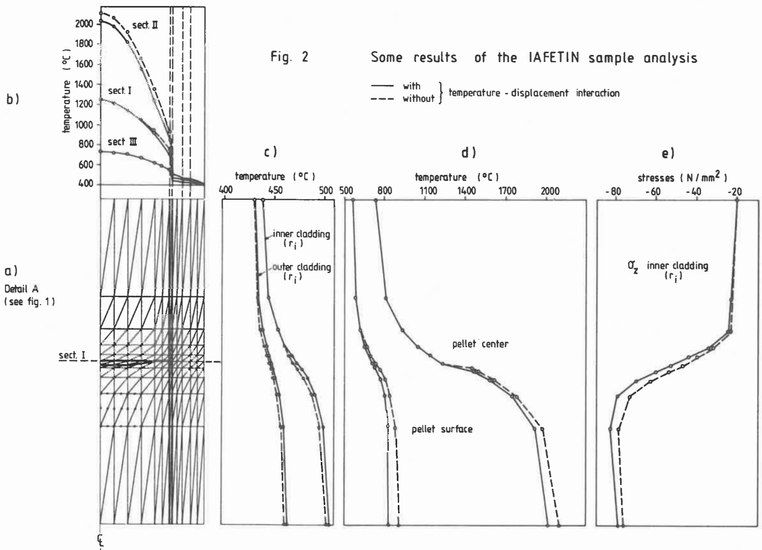

Fig. 2 Some results of the IAFETIN sample analysis