RULES FOR THE ANALYSIS OF MECHANICAL STRUCTURES AT ELEVATED TEMPERATURES

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ABSTRACT

This paper describes how the experience gained by the CEA (French Atomic Energy Commission) in design, construction and operation of pool type LMFBRs, as well as in research an development is used to establish rules for the analysis of mechanical structures at elevated temperatures.

These rules are written by different working groups and approved by a committee named RAMSES. The working methods of the RAMSES committee are described. Some of the approved recommandations are presented. The ongoing work and futur topics are also described.

1. INTRODUCTION

Two liquid metal fast breeder reactors are now in operation in FRANCE. The Rapsodie experimental reactor and the 250 MWe Phenix power plant. A third one, the 1200 MWe Super Phenix power plant, is under construction. All of these reactors are of the pool type and have been developped by the CEA. In fact the first two reactors were constructed under the CEA supervision and are its property. The third one is now in erection under CEA licensing.

A wide experience has been gained by the CEA through these projects and by more than 20 years of research and development in LMFBRs technology. This experience had to codified and since a few years the CEA launched a wide project to collect, through its different departments, what could represent the state of the art in design for elevated temperature applications.

A committee was set up to write recommandations on design rules based on this background experience. These recommandations deal mainly with structural analysis design rules. The committee called RAMSES (for Règles d'Analyses Mécaniques des Structures aux Températures Élevées) joins together many working groups [1]. These working groups are composed of participants involved in many different technical fields such as : material behavior, testing of components in sodium environment, structural mechanics, computer codes development, etc ...

The work of the committee is aiming at three objectives : to write formal rules reflecting the state of the art in elevated temperature design, to give a detailed analysis and criteria justifying them, and to develop pratical methods to apply the proposed rules.

2. THE RAMSES COMMITTEE

A large number of research and development laboratories disseminated in several research centers are providing their experimental data and theoretical publications to specialised working groups. These working groups are attached to four divisions. The projects approved by the divisions committee are passed to the RAMSES committee for final approval and publication.

The different divisions and their working groups are :

A. Materials division
- Material behavior WG
- Mechanical properties of materials WG
- Irradiated material WG
- Fatigue and creep - Fatigue WG

B. Components division
- Component testing in sodium WG
- Phenix components behavior WG
- Failure analysis of components WG

C. Computer codes division
- Computer codes development WG
- Constitutive equations in computer codes WG
- Benchmarking of computer codes WG

D. Structural Analysis division
- Design rules below creep range WG (not yet active)
- Design rules above creep range WG
- Assesment and reviewing of other codes and standards WG

When recommandations are approved by the RAMSES committee they are submitted for reviewing to the other parties interested in the development of LMFBRs in France. This reviewing is necessary to reach a wide consensus in the mechanical engineening community on the validity and conservativness of the recommanded rules. The consultants are until now :

- The CEA research and development divisions
- The safety bodies
- The french nuclear power plant contactors
- The utilities
- The authorities

Some foreign Research Centers are also consulted when they have an agreement with the CEA for exchanges on Research and Development. After receiving the consultants' opinions the RAMSES committee transmits them to the appropriate working groups for further action.

3. THE RAMSES RECOMMANDATIONS

It must be firstly emphasized that the RAMSES recommandations are developped for the french pool type reactors. These reactors are not of the pressure retaining boundaries type which are generally considered in existing design codes. This feature gives greater importance to secondary loads and caracterises the priorities of the RAMSES committee.

A second observation is that as a first step these recommandations are written with large safety factors and are over conservative. They will probably evolve with time when more and more of the available experimental data are taken in account.

The **characteristics** and **stress limits** for five materials are considered and two recommandations are already printed. One for the main Phenix material [2] (a 304 type steel) and one for the main Super Phenix [3] (a 316 type steel). For each material these recommandations describe the chemical and mechanical specifications, the physical properties, the minimal mechanical properties in simple tension and in creep, the allowable stresses and also the data necessary for the elastoplastic computations which are required by some RAMSES recommandations.

A recommandation is given on the **design based on elastic calculations** [4]. This recommandation can be compared to the ASME code case N47 elastic analysis [5]. The main departure being the introduction of a creep redistribution factor on membrane primary stresses. Ratchetting in the creep range and creep-fatigue interaction are not included in this text. This is due to the importance of these questions, so they are (or will be) treated in separate recommandations.

To avoid overwork for the designer when he has to deal with short duration excusion in the creep range cycles, a **creep range cross over curve** [6] is defined for each material. This recommandation gives the conditions for which creep effects can be neglected (and thus apply low temperature rules). It is given in the form of a time-temperature curve [figure 1]. If the characteristics of a cycle are under this curve it is not necessary to do a creep analysis, nor a creep-ratchetting analysis nor a creep-fatigue analysis for this cycle. For different cycles a linear cumulative damage rule is given.

The **ratchetting** problem is considered separately below and above the creep range. The usual elastic rules below the creep range ratchetting were found adequate and recommanded. But to help the designer to overcome the conservativness of these rules a method based on **elastic-plastic calculations** was developped [7]. For each type of cycles a few cyclic loads are computed in plasticity. A rule is given to **extrapolate** the strain results to the number of cycles of this type. Then a rule is given to conservatively **cumulate** the total strains obtained for each type of cycle. This gives an upper approximation of the expects strains for the components' life. (Figure 2 gives the equations required for such an analysis).

For **creep-ratchetting** a recommandation is given based on elastic calculations [8]. The total components' life is divided in time periods. Each period is caracterised by the maximal values of primary stresses, range and temperature. These values are used to obtain an effective primary stress for each period. This effective stress is entered in the creep or rupture curve (depending the criteria level) to obtain allowable times. The total damage is obtained by linear cumulation.

As **elasto plastic calculations** are required by somes rules, one of the RAMSES recommandations is devoted to the constitutive equations to be used in the computer codes [9]. For monotonic loads isotropic hardening is recommanded. For cyclic loads a multilayer kinematic hardening model without cyclic hardening is recommanded.This model is very conservative and an experimental program was launched to assess new cyclic loads constitutive equations in plasticity which are hoped to be more accurate [10].

Elasto-plastic buckling was thoroughly explored for dished heads [11]. Experiments and calculations were conducted [12]. Based on this work the RAMSES committee has recommanded a simplified method which needs only the stress-strain characteristics of the material to compute elasticaly an approximation of the buckling load. But it is felt that some improvements can be made to lower the safety coefficients on secondary loads. This task is delayed until the results of the many experiments conducted presently at CEA on this subject are analysed.

Simplified methods for **piping analysis** are proposed within the framework of modern elastic-plastic-creep-dynamic computer analysis. The simplification resulting from beam type methods applied to piping components. This work is based on the results obtained by Spence [13] and R. Roche et all. [14].

4. FUTURE WORK

The most important ongoing works are on creep-fatigue analysis by elastic methods and buckling analysis.

The recommanded creep-fatigue analysis is for an interim period, to use the elastic analysis of code case N47 of ASME. This method is very conservative especially in the operating range of the considered reactors and a RAMSES recommandation more appropriate to the materials and the design procedure used here is prepared.

As for the buckling analysis two problems are considered by experimental and analytical means, it is the primary load-secondary load buckling interaction and the effect of geometrical imperfections.

Of great concern are the environmental effects. This subject is now in an early stage due to the amount of experimental data gathered through the CEA Laboratories which has to be taken in account.

The elastic-follow up problem has received great attention and a recommandation [15] was printed. But this recommandation has to be developped with new simplified methods available for specific components.

Recommandations for specific components are also scheduled by the committee and the most advanced one is a project for rules on bellows.

In developping these recommandations for the structural design of the French LMFBR it became clear that the proposed rules could be greatly improved and benefit by further experiments and computer simulation. This promoted new development programs on materials caracterisation, constitutive equations development and improvement of computer codes and simplified analysis.

REFERENCES

[1] K. Schaller et all. — Development of rules for design at elevated temperature (The RAMSES group) IWGFR specialist's meeting on properties of primary circuit materials Bensberg october 1977

[2] RAMSES 40.701 — Caracteristiques et Valeurs admissibles pour les aciers VIRGO 14SSB CEA april 1977

[3] RAMSES 40.702 — Caractéristiques et Valeurs admissibles pour les aciers Z4 CND 18 - 12 CN (316 CN) CEA april 1978

[4] RAMSES 30.015 — Application de l'élasticité linéaire aux structures fonctionnant aux températures élevées CEA march 1978

[5] Code Case N47 — ASME Boilier and Pressure Vessel Code, Code Cases, 1977 edition, the ASME New York

[6] RAMSES 30.211 — Conditions définissant l'absence de fluage significatif CEA, april 1977

[7] RAMSES 30.414 — Estimation et Cumul de la déformation progressive à partir de calculs tenant compte de la déformation plastique. CEA, march 1978

[8] RAMSES 30.417 — (To be published)

[9] RAMSES 30.106 — Modèle mathématique du comportement des matériaux pour l'analyse élasto-plastique CEA, april 1977

[10] J. Boulais et all. — Essais de déformation progressive de l'acier inoxidable 304 L à température ambiante Note CEA N 2058 septembre 1978

[11] M. Alix, R. Roche — Essais expérimentaux sur le flambage de fonds elliptiques soumis à la pression interne. 1978 Note CEA N 2079

[12] B. Troclet et all. — Système CEASEMT, validation des modules flambage plastique. Fonds en anse de panier. Comparaison avec les résultats expérimentaux de KIRK et GILL 1975 Note CEA N 1893

[13] S. Spence, J.T. Boyle — ASME paper PVP-PB-029 (Montreal 1978)

[14] R.L. Roche, A. Hoffmann, A. Millard — Inelastic analysis of piping systems. A beam type method for creep and plasticity SMIRT5 Berlin 1979 paper L4/7

[15] RAMSES 30.308 — Prévention des conséquences de l'effet de ressort CEA, april 1977

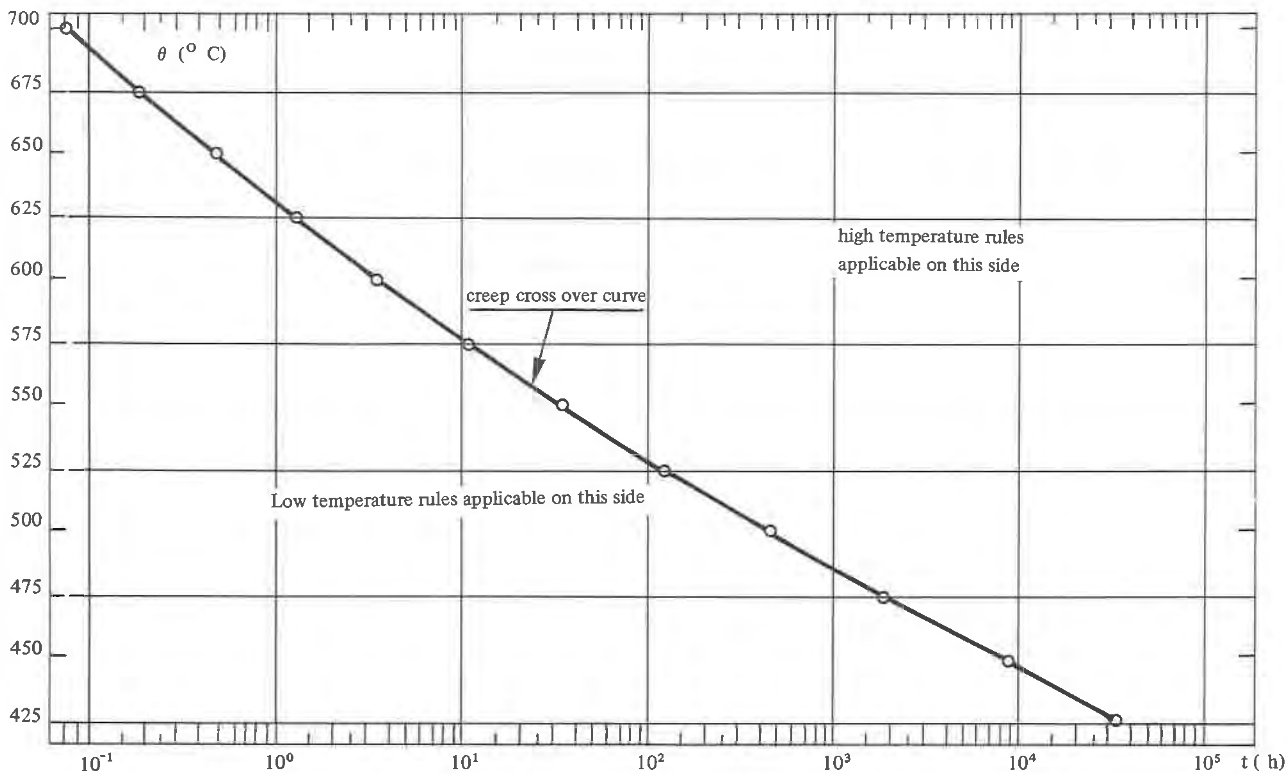

FIG. 1 Z4 CND 18-12 CN Steel Time-Temperature creep cross over curve

1. The strains at a point are considered for four consecutive cycles

   $\epsilon_n, \epsilon_{n-1}, \epsilon_{n-2}, \epsilon_{n-3} \quad (n \geqslant 4)$

2. Increments are computed

   $\Delta\epsilon_n = \epsilon_n - \epsilon_{n-1} \quad \Delta\epsilon_{n-1} = \epsilon_{n-1} - \epsilon_{n-2} \quad \Delta\epsilon_{n-2} = \epsilon_{n-2} - \epsilon_{n-3};$

3. $m = 0{,}9 \min \left(-\frac{\log(\Delta\epsilon_n/\Delta\epsilon_{n-1})}{\log(n/n-1)}, -\frac{\log(\Delta\epsilon_n/\Delta\epsilon_{n-2})}{\log(n/n-1)}, -\frac{\log(\Delta\epsilon_{n-1}/\Delta\epsilon_{n-2})}{\log(n-1/n-2)} \right)$

4. For N cycles the total strain is given by the extrapolation

$$\epsilon_N = \begin{cases} \epsilon_n + \frac{n\Delta\epsilon_n}{m-1} \left(1 - \left(\frac{n}{N}\right)^{m-1}\right) & \text{if } N \leqslant 4n \\ \epsilon_n + \frac{n\Delta\epsilon_n}{(m-1)4^m}(4^m - 4) + \frac{\Delta\epsilon_n}{4^m}(N - 4n) & \text{if } N > 4n \end{cases}$$

5. For different cycles (a, b, c, ...) the m_a, m_b, m_c ... are computed as in 1,2 and 3 above.

6. The m_a, m_b, m_c, ... values are sorted the lowest value being the first and the largest being the last. The cumulation is made in this order

7. For each cycle the initial ϵ_n value is taken as the extrapolated value of the preceding cycle. The final value of ϵ_N thus is obtained the cumulated value of the extrapolation for the a, b, c, ... cycles.

Fig : 2 Extrapolation and cumulation of elasto-plastic ratchetting calculations