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Improved design-by-analysis procedures for LWR design codes

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ABSTRACT

The European Fast Reactor (EFR) collaboration with the EFR Associates Design and Construction Rules Committee, and the R&D Agreement (AGT 9B) produced significant developments in design-by-analysis procedures for high temperature plant. Many of these developments are judged to be relevant to the non-creep conditions of LWR plant, and for this reason, the CEC DGXI Working Group Codes and Standards funded this study contract to review and make recommendations on their potential application for improving LWR design code procedures.

1. INTRODUCTION

Design procedures have been developed within the European Fast Reactor (EFR) collaboration which are relevant to the non-creep conditions of light water reactors (LWR). The EFR developments within the EFR Associates' Design and Construction Rules Committee (DCRC) and the R&D Agreement (AGT9B) provided significant enhancements to the current fast reactor (FR) design-by-analysis procedures in RCC-MR [1] and ASME CC N47 [2].

For these reasons, the CEC DGXI Working Group Codes and Standards (WGCS), initiated a study contract (COSU-CT94-0064UK) within the 1994 programme, to review the FR developed design procedures and make recommendations on their applicability and potential benefit to LWR design codes, in terms of enabling more efficient structural design whilst maintaining safety levels.

The topics considered in the review are judged to be those where the most significant and relevant developments have been made and the list, although not exhaustive, is as follows:

- Negligible creep criteria
- Design-by-analysis procedures for weldments
- Shakedown design rules
- Design-by-analysis methods for tubeplates
- Buckling rules
- Interaction diagrams for assessing ratcheting
- Rules for the prevention of elastic follow-up in piping

- Strain range enhancement
- Constitutive equations for inelastic analysis
- Margins on Level D criteria
- Zarka method

For each of the above fast reactor (FR) developments, a detailed review of the background and potential application to LWR design codes was first performed, and then this was followed by a corresponding review of the current LWR method and consideration of the potential benefit to LWR design code procedures.

Because it is not possible to describe the FR developments in detail within the confines of this paper, a summary of the conclusions to this work for each topic is provided in the following sections.

2. NEGLIGIBLE CREEP CRITERIA

Negligible creep curves have been introduced into high temperature design codes to preclude the need for time-dependent analysis for short term excursions into the creep regime. It was perceived that this may be of potential benefit for increasing the operating envelope for LWR components beyond the current limits (ie 375°C - ferritics; 427°C - austenitics).

However, negligible creep criteria are deemed not to be necessary for LWR applications since transients in the design basis do not exceed the temperature limits in LWR design code. Nevertheless, negligible creep curves for LWR materials may be useful for the exclusion of creep effects in consideration of beyond-design-basis accident conditions. Therefore, no recommendations are made for the introduction of such criteria into LWR design codes.

3. DESIGN-BY-ANALYSIS RULES FOR WELDMENTS

The UK FR procedures provides an alternative approach to introducing fatigue strength reduction factors (FSRF) based on tests of actual weldments. This has particular advantage in dealing with as-welded weldments with indeterminate surface geometries and partial penetration weldments with sharp crevice-type features.

Essentially for as-welded weldments, the FSRF incorporates the geometric stress concentration and the material mis-match effects and is applied to the range of linearised primary plus secondary stresses derived from the nominal weldment geometry. For dressed or profiled weldments, in which the geometry is specified by the designer, the peak geometric stress concentration can be determined analytically (eg finite elememt analysis) and, therefore, the FSRF only needs to take account of the material mis-match effect which can be determined from tests on flush-ground butt weldments.

Currently, LWR design codes take account of more realistic plant conditions, such as weldments, by the factors of 2 and 20 incorporated in the fatigue design curves. Geometrical effects are incorporated by use of stress concentration factors, such as stress indices for piping. However, a detailed review of the methods for assessing the fatigue life of weldments, and the adequacy of the design margins of 2 and 20 in the design fatigue curve, will be included in CEC DGXI contract C2/ETU/1154 'Re-evaluation of Fatigue Analysis Criteria'; therefore, no specific recommendations are made within the present study.

4. SHAKEDOWN DESIGN RULES

The Shakedown Method provides an alternative approach to establishing freedom from ratcheting in structures. It has general applicability to all types of structures and makes use of elastic analysis results to establish an elastic core, thus avoiding the complexities and uncertainties of inelastic analysis.

In detail, the Shakedown Method requires the establishment of a constant residual stress field (ie a set of 'locked-in' and self-balancing stresses remaining when the structure is unloaded) which when the cyclic operational stresses are superimposed, the structure remains within the effective yield locus. 'Strict' shakedown is defined as when every point in the structure meets this criterion but, in fact, this is not absolutely necessary to ensure structural shakedown. 'Overall' shakedown is defined as when 80% of the structural section meets the shakedown criteria, and it is considered that the establishment of an elastic core to this extent, is sufficient to prevent ratcheting. For those regions outside strict shakedown, the material may be allowed to undergo reversed plastic straining (which needs to be taken into account in the fatigue analysis) due to the restraint of the material in the elastic core.

Current LWR procedures are well established and, perhaps, more straightforward to use, making use of the 3 Sm limit in conjunction with the Bree diagram. It is concluded that the Shakedown Method provides a useful more detailed approach to establishing shakedown. It is, therefore, recommended that the method be evaluated for improvement of current LWR design code procedures by application on LWR components and comparison with experimental results.

5. DESIGN-BY-ANALYSIS METHODS FOR TUBEPLATES

Current design procedures such as ASME Section III [3] provide methodologies for analysis of flat thick perforated tubeplates with a triangular pitch. However, no guidance is given on the treatment of anisotropy in the out-of-plane direction or for circular penetration patterns, both of which have been considered in the FR developed methods. In addition, a method of analysis for a thick dished tubeplate is provided which applies to an equilateral triangular hole pitch of a specific ligament efficiency (minimum ligament width divided by hole pitch) of 0.657.

The equivalent solid plate elastic constants developed for the triangular penetration pattern are considered to be an improvement on ASME values, and can be used to evaluate existing margins in current LWR design codes. Improved guidance for the analysis of the transition between the perforated region and outer rim are also of interest for LWR application. The development of methods for circular patterns and dished tubeplates are not relevant to current PWR designs but should be referred to if this type of feature is considered in future designs.

Evaluation and updating of methods applicable to square penetration patterns, and the development of equivalent elastic constants for holes with other than round geometries (eg steam generator tube support plate) has been identified as additional requirements for LWR design codes.

6. BUCKLING RULES

The fast reactor rules for buckling analysis incorporate significant developments which may enhance existing LWR codes although buckling is not generally a big issue for relatively thick structures of LWR's. For example, it may be possible to reduce the design safety factors with respect to the ASME code values reducing from 3, 2.5 and 1.5 to 2.5, 2, 1.3 respectively for service Levels A/B, C, and D. Also, for the design of structures having service conditions including superposition of static and dynamic loads (eg seismic analysis) it may be possible to avoid unnecessary conservatism by reducing the dynamic loading (ie. by a knock-down factor) before combination with the static value.

The FR developed methods offer the potential of reducing design margins for Levels A/B, C and D, plus a less onerous procedure for combining static and dynamic (eg seismic) loadings. Also, the concept for continuous variation of geometric imperfection instead of the 1% ovality criteria could be of benefit. It is recommended that specific application and verification against typical LWR components should be performed in order to evaluate the potential benefits of the FR developed criteria. An additional requirement identified for LWR design codes is the applicability to beam-like structures.

7. INTERACTION DIAGRAMS FOR THE ASSESSMENT OF RATCHETING

Interaction Diagrams are analogous to the Bree type approach in current LWR design codes but have been extended to allow a more generalised treatment, particularly to cases involving an axial temperature gradient or moving temperature front. In particular, there are two simplified diagrams covering axisymetric cylindrical shells loaded by internal pressure combined with radial and axial temperature gradients either static or moving. On the basis of these Interaction Diagrams, the designer is able to perform a simple assessment to evaluate whether the structure is free from ratcheting, or whether a more detailed analysis is required, or whether a re-design is needed.

Alternative procedures are used in LWR applications for severe transients that do not meet current criteria, in order to avoid inelastic analysis, and Interaction Diagrams should be considered in this context. It is recommended that applications to typical LWR components subjected to severe thermal loadings should be performed with the objective of evaluating the potential for improving current LWR design code procedures. In this context, reference should be made to the applicationsions performed under the FR programme which may, also, be relevant to LWR components.

8. RULES FOR THE PREVENTION OF ELASTIC FOLLOW-UP (EFU) IN PIPING

Methods of treating EFU in piping have been examined in detail for FR applications and the effects of EFU on the plastic collapse load and cyclic plastic strain range enhancement, also using discrete parameters for local and global effects, may be applicable to LWR piping.

Currently, elastic follow-up is prevented in LWR applications through design (sizing) provisions and limitation of primary stresses, and primary plus secondary stress range (eg Pe). It is recommended that FR developed methods be evaluated by application to typical LWR piping configurations. Also, the significance and definition of stress indices for piping should be studied in the context of elastic follow-up due to differences in interpretation between various experts.

9. STRAIN RANGE ENHANCEMENT

The FR developed strain enhancement factors are more precise evaluations of different effects compared to the current LWR method based on Ke which is known to have some shortcomings. In particular, the FR developed methods take account of the Neuber effect at notches, the change in Poisson's Ratio with plasticity and the effects of geometry and loading conditions. Nevertheless, the FR method may be difficult to apply in practice and may compound conservatisms resulting in a more pessimistic overall result. Simplifications should be proposed, for example a unique Neuber-type correction may seem appropriate in most cases and easier to apply.

A review of the current Ke factor in LWR design codes will be included in CEC DGXI contract C2/ETU/1154 'Re-evaluation of Fatigue Analysis Criteria'. Proposals for future developments and comparison of various rules on practical examples should be performed to evaluate and further improve LWR codes.

10. CONSTITUTIVE EQUATIONS FOR INELASTIC ANALYSIS

The FR review covered the main constitutive models: ORNL, Chaboche, Interatom, Robinson and FR state variable model. Apart from describing time-dependent effects, the FR constitutive models are capable of describing complicated features such as hardening due to non-proportional loading paths and various phenomena of ratcheting (eg temperature history effects and mean stress effects) which are certainly important for LWR. At least for calculating accumulated strains, the non-linearity of kinematic and the isotropic hardening is essential. Also, expertise developed during the FR project for identifying material parameters from experimental data and implementing constitutive equations in finite element codes are also of potential value of LWR design codes.

In conclusion the FR review provides useful guidance when performing inelastic analysis. However, experience shows that evaluations of progressive deformation requires sophisticated constitutive models and that the results obtained have a limited accuracy. For fatigue evaluations, elastic-plastic results are more accurate and it is envisaged to introduce into LWR design codes cyclic stress-strain curves for this evaluation. Nevertheless, it is not recommended to introduce detailed inelastic analysis methods into LWR design codes.

11. MARGINS ON LEVEL D CRITERIA

FR calculations have established that the margin between Level D elastic analysis allowable stress limits and elastic-plastic collapse load is not uniform with a minimum occurring for combined high membrane and bending loads. However, current methods in LWR design codes are considered to be sufficiently conservative to compensate for this effect and, therefore, no recommendations are made.

Large displacement inelastic FE analysis was also performed to establish the ultimate load bearing capacity of a FR Intermediate Heat Exchanger. However, this type of analysis is only used on an exceptional basis and does not justify code revisions. Nevertheless, the guidance provided on establishing ductility based criteria at structural discontinuities, and in determining the Plastic Instability Load with this type of analysis is noted and may be referred to if required for LWR applications.

12. ZARKA METHOD

The benefit of this simplified method is to evaluate the inelastic behaviour without resort to a detailed step-by-step inelastic analysis. The method can be used to estimate:

- elastic/plastic strain range (fatigue assessment)
- strain accumulation (ratcheting assessment)
- plastic limit load

The Zarka method requires a number of (modified) elastic analyses and additional calculations to predict the above parameters. The underlying assumptions of material behaviour ensure that the structure will attain a steady state condition after some number of cycles of loading so that either global elastic or plastic shakedown is enforced. The Zarka method predicts whether global or plastic shakedown will occur, but not after which number of cycles. Its aim is to predict the strain range and accumulated strain at each location in a structure after shakedown has been reached. A variant of this method is that it can used to extrapolate results from one half or one complete inelastic cycle to a large number of cycles, and this option is implemented in RCC-MR, Appendix 10 [1]

However, the common practice for more detailed analysis of LWR applications is to use inelastic analysis to evaluate the above parameters, rather than such calculation procedures as the Zarka method. Nevertheless, the Zarka method may be used to confirm or supplement such calculations rather than being included as a specific method in LWR design codes.

13. OVERALL CONCLUSIONS

This study has confirmed that several FR developments have the potential for making significant improvements to LWR design codes. In particular, the developments on shakedown, tubeplates, buckling, interaction diagrams, and piping elastic follow-up, are judged to be of sufficient benefit that recommendations are made for trial applications on typical LWR components, inorder to further quantify the potential improvements. Recommendations on the topics of weldment design-by-analysis methods and strain range enhancement will be further considered within the scope of a current CEC DGXI contract C2/ETU/1154 'Re-evaluation of Fatigue Analysis Criteria'. The developments on constitutive equations, Level D criteria, and the Zarka method may be used as guidance to confirm or supplement existing LWR procedures, if required.

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