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Fracture Mechanics and Structural Integrity

INDEPENDENT REVIEW OF THE FRENCH RSE-M CODE FOR APPLICATION TO THE UK EPR FRACTURE MECHANICS ASSESSMENTS

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ABSTRACT

As for many civil nuclear reactors in the UK, as part of the safety case for the EPR to be built at Hinkley Point C, it will be claimed that gross failure of certain components within the design basis can be discounted. These components are designated high integrity components. As part of one of the legs of the high integrity component safety case, it is required that a suitable margin exists between the calculated end-of-life limiting defect size, and the sum of the minimum detectable defect size and lifetime fatigue crack growth for 60 years. It is required that the ratio between these two quantities, which is termed the Defect Size Margin, has a value approaching 2.

For the EPR at Hinkley Point C, the French rules for in-service inspection of mechanical components on a PWR nuclear island, RSE-M, implemented according to a methodology developed for Hinkley Point C have been selected by the Licensee, NNB GenCo, for conducting fracture mechanics assessments.

During the generic design assessment of the UK EPR conducted by the Office for Nuclear Regulation it was noted that there was a significant difference in the end-of-life limiting defect size values obtained by the requesting parties (EDF and Areva) using RSE-M and the more familiar R6 procedure. Assessments were repeated for the EPR; pressuriser shell circumferential weld, reactor pressure vessel belt-line circumferential weld, and reactor pressure vessel closure head weld.

In order to address concerns relating to this, NNB have undertaken an independent review of the parts of the RSE-M code to be used for the fracture mechanics assessments. The review has been undertaken by a panel of independent industry and topic experts. This paper provides an overview of the arrangements and the technical areas covered by the review.

Though RSE-M can prove considerably less conservative than R6 in certain cases of combined primary and secondary loading (such as a cold thermal shock), there are no concerns regarding a potential lack of overall conservatism within RSE-M. An important point to note is that RSE-M is intended to assess situations particular to PWR plant, whereas R6 is a more general assessment procedure with a much wider scope of application. In the case covered here, the version of the R6 procedure used inherently covered cases where elastic follow-up can occur, and hence amplification of the secondary stresses interacting with primary stresses. However, this behaviour is not expected to occur in the typical cold thermal shock transients occurring in PWR plant.

INTRODUCTION

As for many civil nuclear reactors in the UK, as part of the safety case for the EPR to be built at Hinkley Point C (HPC), it will be claimed that gross failure of certain components within the design basis can be discounted. These components are designated high integrity components (HICs). As part of one of the legs of the HIC safety case, it is required that a suitable margin exists between the calculated end-of-life

limiting defect size (ELLDS), and the sum of the minimum detectable defect size (QEDS) and lifetime fatigue crack growth (LFCG) for 60 years. It is required that the ratio between these two quantities, which is termed the Defect Size Margin (DSM) (Equation 1), has a value approaching 2.

$$DSM = \frac{ELLDS}{QEDS+LFCG} \quad (1)$$

For the EPR at HPC, the French rules for in-service inspection of mechanical components on a PWR nuclear island, RSE-M (Reference 1), implemented according to a methodology developed for HPC (Reference 2) have been selected by the Licensee, NNB GenCo, for conducting fracture mechanics assessments (FMAs).

During the generic design assessment (GDA) of the UK EPR conducted by the Office for Nuclear Regulation (ONR) it was noted that there was a significant difference in the ELLDS values obtained by the requesting parties (EDF and Areva) using RSE-M and the more familiar R6 procedure (Section 4.2.3.4 of Reference 3). Assessments were repeated for the EPR; pressuriser (PZR) shell circumferential weld, reactor pressure vessel (RPV) belt-line circumferential weld, and RPV closure head weld.

In order to address concerns relating to this, NNB have undertaken an independent review of the parts of the RSE-M code to be used for the fracture mechanics assessments. The review has been undertaken by a panel of independent industry and topic experts. This paper provides an overview of the arrangements and the technical areas covered by the review.

PROJECT ARRANGEMENTS AND TECHNICAL AREAS ADDRESSED

The review was arranged by NNB but managed by a prime contractor, Rolls-Royce Power Engineering plc (hereafter referred to as Rolls-Royce) on their behalf. Rolls-Royce set up an Independent Expert Working Group (IEWG) to carry out the review and issued a technical specification (Reference 4) providing a detailed definition of the tasks required to achieve the objectives of the review, which were to:

- develop an improved understanding of RSE-M Appendix 5 fracture assessment methodology;
- provide confidence in the RSE-M methodology;
- establish the extent of validation of RSE-M by comparison of models with experiments or other available codes;
- compare the extent of validation of RSE-M and R6 (Reference 5);
- establish strengths and weaknesses by comparison with other international fracture mechanics codes, in particular R6;
- study the limits of applicability of RSE-M and R6;
- develop an understanding of the review and update process for RSE-M; and
- provide a view on the availability of independent advice on RSE-M fracture mechanics assessment and what infrastructure will be needed to support this into the future.

The work covered the following five main areas listed below taken from Reference 4, together with a short description of the sub-tasks:

- **Task Group 1: general topics**
  - Task 1.1 - General Methodology in RSE-M: *This task considered the general RSE-M approach to failure assessment and the differences with respect to R6.*

- Task 1.2 – Validation of the RSE-M Code: *This task considered the depth and suitability of the validation of the RSE-M Code.*
- Task 1.3 - Comparison between the 1997 edition of RSE-M with third Addendum 2005 and 2010 Edition of RSE-M: *The latest edition of the RSE-M code is 2010. Previous work undertaken to support the application of the RSE-M code to UK EPR components in GDA was based upon the 1997 edition of RSE-M with 3rd addendum 2005. This task covered the comparison of the two RSE-M code editions.*

- **Task Group 2: capability**
  - Task 2.1 - Process for Revision and Update of the Code: *This task considered the process for review and update of the RSE-M code.*
  - Task 2.2 - Revision and Update of the Safety Cases: *This task considered implications following revision and update to the code and the impact on safety cases in the future.*
  - Task 2.3 – Gap Analysis and Skills Required: *This task provided an understanding of the principles, skills in using and understanding of the limitations of RSE-M.*
  - Task 2.4 – Future Developments: *The independent review considered the need to provide suggestions for future developments to enhance the application of the code, as well as further develop its verification and validation.*

- **Task Group 3: elastic-plastic fracture model**
  - Task 3.1.1 – Stress Intensity Factor Solutions and Mixed Mode Loading Rules: *This task reviewed and compared the SIF solutions and mixed mode loading methods with those available in R6.*
  - Task 3.1.2. – Methodology for the Determination of the Mechanical Load Reference Stress and Associated Crack Driving Force, J_s: *The objective of this task was to understand the theoretical background and the differences between the Corrected Limit Load (CLL) and the Elastic Plastic Stress (EPS) approaches.*
  - Task 3.1.3 - Methodology for the Determination of the Constrained Plasticity Crack Driving Force Parameter, K_{cp}: *The objective of this task was to investigate and understand the use of plasticity correction parameter, K_{cp}, paying particular attention to the range of cases in RSE-M*
  - Task 3.2 - Methodology for Treatment of Interaction between Primary and Secondary Stresses: *Within RSE-M the interaction between primary and secondary load thermal stresses is provided by an elastic-plastic correction factor (k_{th}^*). The objective of this task was to investigate and understand the background of k_{th}^*, its validity and technical basis.*
  - Task 3.3.1. - Methodology for the Determination of the Plasticity Correction Term k_{th}: *When a radial temperature variation through the wall of a component results in a stress that is in excess of yield RSE-M requires a correction to be applied (via a correction factor k_{th}). The objective of this task was to identify the background to k_{th}, its validity and technical basis.*
  - Task 3.3.2. – Methodology for Treatment of Thermal Stress: *The objective of this task was to review the analytical solutions, provided in Appendix 5.4 of RSE-M, proposed for calculating thermal stresses.*
  - Task 3.3.3. – Methodology for Treatment of Weld Residual Stress (WRS): *This task considered the proposed guidelines for the inclusion of WRS in the RSE-M methodology.*

- **Task Group 4: specialist topics**
  - Task 4.1 – Methodology for Treatment of Ductile Tearing: *The objective of this task was to review the treatment of ductile tearing between RSE-M and R6 for infrequent transients.*
  - Task 4.2 – Methodology for the Characterisation and Interaction of Defects: *The objective of this task was to review and compare the relevant RSE-M appendices, characterisation and interaction rules with those available in other codes and standards including R6.*
  - Task 4.3 – Methodology for the Treatment of Imposed Displacement: *The objective of this task was to understand the theoretical background to the RCC-MRx J solution for the displacement imposed loading and establish the scope of application to the UK EPR.*
  - Task 4.4: Methodology for Treatment of Clad Components in RSE-M*: The objective of this task was to provide a review of the methods used in RSE-M to assess defects in clad components.*
  - Task 4.5: Methodology for Treatment of Fatigue Crack Growth (FCG) in RSE-M*: The objective of this task was to provide a review of the application of the RSE-M fatigue crack growth requirements, which are more prescriptive than those detailed in R6.*
  - Task 4.6 –Other Tasks: *the objective of this task was to identify topic areas within R6 that are not covered by the RSE-M.*

- **Task Group 5: coordination activities**
  - Task 5.4 Final Report on the Independent Review: *A final report will be produced, endorsed by the IEWG, which summarises the work carried out during the Independent Review.*

Individual reports were produced for each of the sub-tasks within a task group. The arrangements for the review, together with a summary of the significant findings for the sub-tasks are described in Reference 6 in support of the 3rd evolution of the HPC pre-construction safety report (PCSR), noting that at the time of writing not all of the sub-tasks were complete. A summary of the significant findings and recommendations, where appropriate, for the complete review will be contained in a final report produced by Rolls-Royce.

Although the final conclusions of the review are yet to be drawn at the time of writing this paper, the cause of the discrepancies between the values of calculated ELLDS from GDA has been explained, and in this respect the fracture mechanics methodology in RSE-M implemented according to Reference 2, is considered to be generally accurate and conservative for the typical loading anticipated on PWR plant. A description of some of the key causes of the discrepancies is provided below.

CAUSE OF SIGNIFICANT DIFFERENCES IN ASSESSMENT RESULTS

As noted earlier significant differences in the ELLDS values calculated during GDA by the requesting parties and the findings by the ONR from Step 4 of GDA was the main driver for NNB as a Licensee to conduct an independent review of the fracture mechanics methodology in Appendix 5 of RSE-M.

In addition to independently generated cases, the independent review used a reference case for comparisons of methods in many of the sub-tasks. The reference case considered an internal

circumferential semi-elliptical defect in a thick-walled pressure vessel, with moderate primary load, subject to a severe cold thermal shock. For this case, the ELLDS reported by the requesting parties in GDA was 32.5mm, and the ELLDS obtained from the ONR's repeat R6 assessment was 16.5mm.

Comparison of the RSE-M and R6 methodologies by the independent review for the determination of J under combined mechanical and thermal loads identified only two fundamental differences; the treatment of interaction of primary and secondary stresses, and the failure assessment curve. To a lesser extent, differences in assumed temperatures leading to differences in material properties were also identified as a contributing factor. The differences in approaches for interaction of primary and secondary loads and the failure assessment curve are discussed further below.

Treatment of Interaction of Primary and Secondary Loads

It is noted that RSE-M is based on the determination of an effective (elastic-plastic) crack driving force, J, whereas a typical R6 assessment is based on the failure assessment diagram (FAD) approach. However, to aid comparison of the two approaches the expressions can be rearranged to be in the same form. For combined mechanical and thermal loading J is defined in RSE-M (Section VI.2 of Appendix 5.4) as:

$$J = \left[\sqrt{J_s^{mt}} + k_{th}^{*}\sqrt{J_{el}^{th}}\right]^2 \leq J_{IC} \quad (2)$$

Making the conversion between J and K, Equation (2) can be re-written to determine the equivalent effective stress intensity factor (SIF) as:

$$K_{eq} = \frac{K_{el}^{mt}}{K_r(L_r)} + k_{th}^{*}K_{el}^{th} \leq K_{IC} \quad (3)$$

The R6 solution can be expressed in the form of a J-estimation (Section III.3.1 of R6) as:

$$J(L_r) = \frac{1}{E'}\left[\frac{K_I^p + VK_I^s}{f(L_r)}\right]^2 \quad (4)$$

Again, making the conversion between J and K, Equation 4 can be written to determine the effective SIF, K_J as:

$$K_J = \frac{K_I^p}{f(L_r)} + \frac{V}{f(L_r)}K_I^s \quad (5)$$

Comparing Equations (3) and (5) it can be seen that for the interaction of primary and secondary stresses the R6 term $V/f(L_r)$ is equivalent to the RSE-M k_{th}^{*}.

The methods for calculating k_{th}^{*} are provided in Section VI.3 of Appendix 5.4 of RSE-M. Solutions are provided for straight pipe, thickness transitions and elbows considering both surface breaking circumferential or axial defects. The specific requirements for k_{th}^{*} have not been repeated here. However in most cases where the primary loading is low, k_{th}^{*}, is equal to the plasticity correction factor for secondary loads in isolation, k_{th}, but is always in the range 0.5 to 1.0. In effect, there is no enhancement of the secondary SIF due to the interaction between primary and secondary stresses, only relaxation is considered. This precludes the presence of elastic follow-up, which is considered highly unlikely in the practical situations of thermal shock in PWR components. In contrast, values of V/f(Lr) can be significantly greater than unity.

From Section II.6.4 of R6, V is defined as:

$$\boldsymbol{V = \frac{K_J^s}{K_I^s}\xi} \quad (6)$$

The parameter ξ is determined from tabular data based on values of L_r and the ratio $\beta_J^s = K_J^s/\left(K_I^p/L_r\right)$. It is noted that for secondary loading acting in isolation ξ is set to unity and:

$$\boldsymbol{V = V_o = \frac{K_J^s}{K_I^s} \equiv k_{th}} \quad (7)$$

Expressing the interaction term, $V/f(L_r)$, in a similar form to k_{th}^* (i.e. as a function of the plasticity correction term for secondary loading acting in isolation), gives:

$$\frac{V}{f(L_r)} = V_o \frac{\xi}{f(L_r)} \quad (8)$$

Equation (8) can be further deconstructed by assuming that there is no relaxation of secondary stresses, that is $V_0 = 1.0$ (equivalent to assuming $k_{th} = 1.0$), so that the term $\xi/f(L_r)$ can be investigated. Firstly, plotting ξ (from Table II.6.3 in Amendment 10 to Revision 4 of R6) in Figure 1, enhancement of ξ for increasing values of β_J^s can be observed to L_r values of approximately 0.7 to 0.9. The enhancement is due to the thermal loading creating a plastic zone at the crack tip which at low mechanical loads causes the J value to increase more rapidly under combined loading than mechanical loading alone, in a similar manner to the elastic follow-up phenomenon.

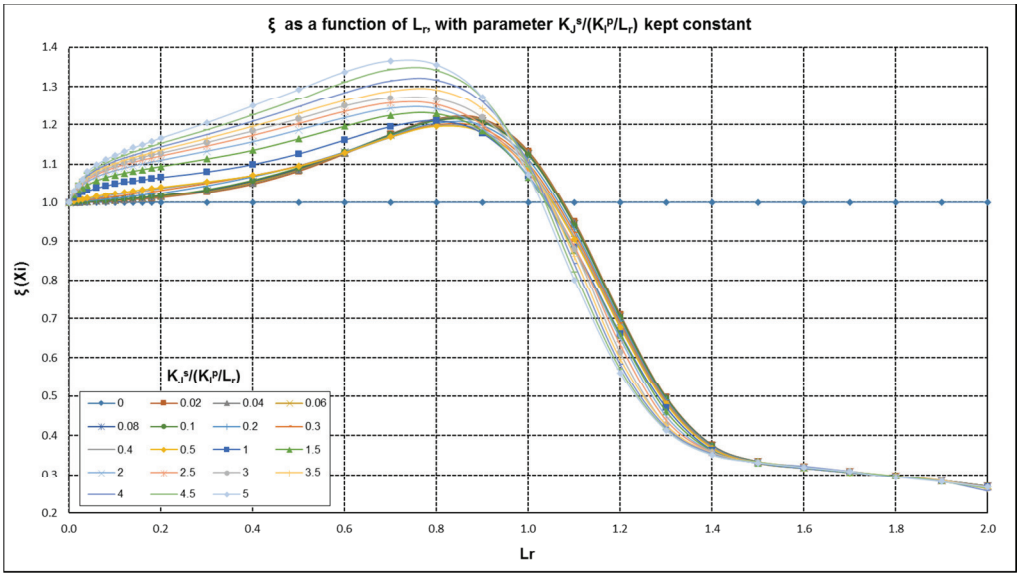

Figure 1. Variation of R6 Parameter ξ

Now, the effect of this enhancement can be investigated in the parameter $\xi/f(L_r)$. Note that the variation of $\xi/f(L_r)$ against L_r is dependent on the choice of failure assessment curve. Adopting the general Option 1 FAD, the variation of $\xi/f_1(L_r)$ against L_r for constant β_J^s is as shown in Figure 2 (taken from Reference 7, noting that this corresponds to Amendment 10 to Revision 4 of R6, current at the time of review). It can be seen from Figure 2 that $\xi/f_1(L_r)$ is always greater than unity, hence the secondary SIF is always enhanced due to interaction effects. It can be seen that above L_r values of approximately 1.1 plastic

relaxation takes effect and the level of enhancement is reduced. Noting that in this case, $k_{th} = 1.0$, and k_{th}^* is generally equal to k_{th}, no enhancement would be made in RSE-M. The further enhancement is due to the dependence on the failure assessment curve, in this case $f_1(L_r)$. This highlights the other major difference between the two methodologies, that is; from Equation (5) it can be seen that the failure assessment curve appears in both the primary and secondary terms in R6, whereas in Equation (3) for RSE-M the secondary term is not enhanced by the primary stress field. These are referred to as "strong" and "weak" interactions respectively.

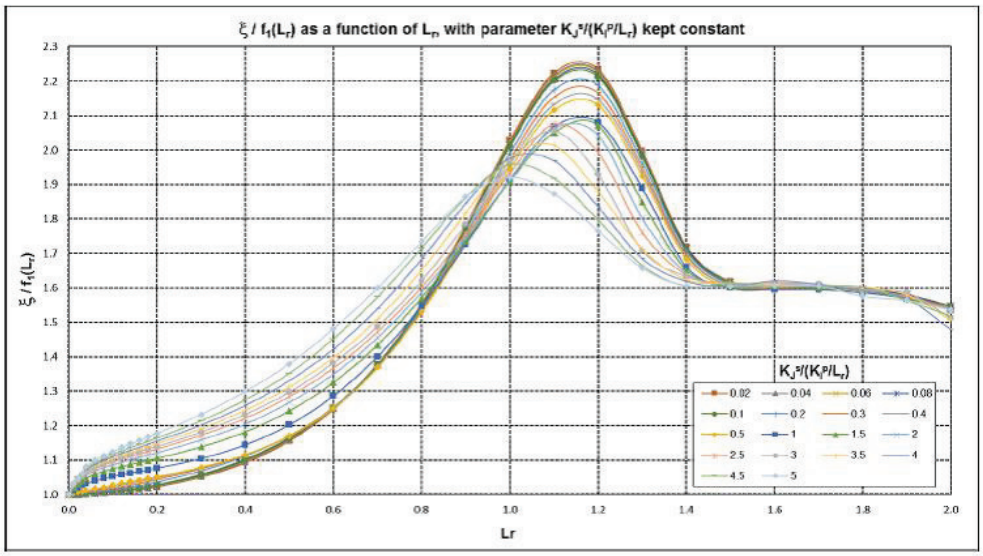

Figure 2. Variation of R6 Parameter $\xi/f_1(L_r)$

Failure Assessment Diagrams

The primary terms of Equations (3) and (5) include the failure assessment curve as the denominator. For RSE-M (Section IV.4.1.1.1 of Appendix 5.4) $K_r(Lr)$ is defined as:

$$K_r(L_r) = \left[\frac{E\varepsilon_{ref}}{L_r S_y} + 0.5\frac{L_r^2}{L_r^2+1}\right]^{-0.5} \quad (9)$$

This is similar to the Option 2 material specific FAD in R6 (Section I.6.2):

$$f_2(L_r) = \left[\frac{E\varepsilon_{ref}}{L_r S_y} + \frac{L_r^3 S_y}{2E\varepsilon_{ref}}\right]^{-0.5} \quad (10)$$

A comparison of an Option 1 and Option 2 FAD (for a low alloy ferritic steel) from R6 together with the RSE-M curve from Equation (9), referred to as an Option 2' FAD is presented in Figure 3.

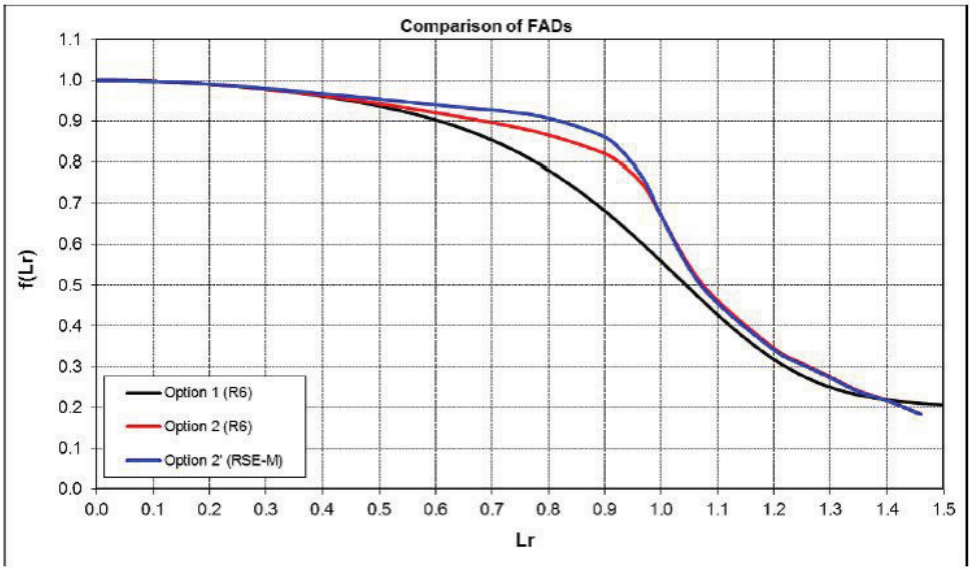

Figure 3. Comparison of FADs

It can be seen that the Option 2 and Option 2' FADs are very similar, although the Option 2' FAD is marginally less restrictive than the Option 2 FAD in the small scale yielding region of L_r between ~0.5 and 1.0. However, the difference is small, less than 5% in terms of $f(L_r)$. Furthermore, in the reference case considered by the IEWG the primary loads resulted in an L_r value of ~0.4. Thus, although a difference exists it was not a significant contributor to the discrepancies in ELLDS highlighted in GDA.

Summary

The above discussion provides an overview of two of the most significant contributions for the differences in assessment methodologies in RSE-M and R6. The most noteworthy in terms of the ELLDS values calculated in GDA is the treatment of the interaction of primary and secondary stress.

Though RSE-M can prove considerably less conservative than R6 in certain cases of combined primary and secondary loading (such as a cold thermal shock), there are no concerns regarding a potential lack of overall conservatism within RSE-M. In addition, RSE-M validation work, essentially based on comparison against a large database of finite element assessments, considers primary loading applied first. This is consistent and conservative with regards to recent work carried out in this area (Reference 8).

An important point to note is that RSE-M is intended to assess situations particular to PWR plant, whereas R6 is a more general assessment procedure with a much wider scope of application. In the case covered here, the version of the R6 procedure used inherently covered cases where elastic follow-up can occur, and hence amplification of the secondary stresses interacting with primary stresses. However, this behaviour is not expected to occur in the typical cold thermal shock transients occurring in PWR plant. When this is taken into account, R6 and RSE-M provide results with very good agreement. In addition, it is noted that the latest version of R6 (Amendment 11 to Revision 4, March 2015), now includes provision to reduce conservatism in cases where elastic follow-up is expected to not be significant.

NOMENCLATURE

E' Young's modulus: E for plane stress, and $E/(1-\nu)^2$ for plane strain
$f(L_r)$ R6 failure assessment curve

J	combined mechanical and thermal elastic-plastic crack driving force
J_s^{mt}	crack driving force from mechanical loads obtained using analytical solutions
J_{el}^{th}	crack driving force from thermal loads assuming a linear elastic material
$J(L_r)$	combined mechanical and thermal elastic-plastic crack driving force at corresponding L_r
J_{IC}	material resistance to fracture initiation
K_{IC}	material initiation fracture toughness
k_{th}^*	elastic-plastic correction for combined mechanical and thermal loading
k_{th}	elastic-plastic correction for thermal loading in isolation
K_{eq}	equivalent stress intensity factor
$K_r(L_r)$	RSE-M failure assessment curve
K_{el}^{mt}	linear elastic stress intensity factor for mechanical loads
K_{el}^{th}	linear elastic stress intensity factor for thermal loads
K_I^p	linear elastic stress intensity factor for primary loads
K_I^s	linear elastic stress intensity factor for secondary loads
K_J^s	effective stress intensity factor used to define V
L_r	measure of the proximity to plastic collapse
S_y	material yield strength
V	plasticity correction factor for combined primary and secondary loads
V_o	plasticity correction factor for secondary loads in isolation
QEDS	qualified examination defect size
ε_{ref}	reference strain
ξ	parameter used to define V

REFERENCES

1. AFCEN (2010). "In-Service Inspection Rules for Mechanical Components of PWR Nuclear Islands," *RSE-M*, Edition 2010.
2. Chapuliot, S., (2014). "Critical Crack Size Determination and Propagation Analysis Methodological Document", *NNB GenCo Report,* UKX-UK1401-AU-RCP-STU-002931, Revision C, 21st October 2014.
3. "Generic Design Assessment – New Civil Reactor Build, Step 4 Structural Integrity Assessment of the EDF and Areva UK EPR Reactor," *Office for Nuclear Regulation*, Assessment report ONR-GDA-AR-11-027 Revision 0, 14th November 2011.
4. Bell, C. D., Martin, M, Watson, C (2012). "IEWG 02 - Technical Specification for the RSE-M Independent Review", *Rolls Royce Civil Nuclear Engineering Document*, E0537-903-00002 Issue 1.
5. "Assessment of the Integrity of Structures Containing Defects", *EDF Energy Nuclear Generation Limited*, R6 Revision 4.
6. Scully, K., "RSE-M Independent Review Arrangements", *NNB GenCo Report*, HPC-NNBOSL-XX-000-REP-100050, Version 0.4 (expected to be issued in May 2015).
7. Shard, P. A., (2014). "IEWG 25 – RSE-M Independent Review Task 3.2 – Methodology for the Treatment of Interaction between Primary and Secondary Stresses", *Rolls Royce Civil Nuclear Engineering Document*, E0537-104-00011 Issue 1.
8. Kim, Y. J., et al, "Comparison of R6 and A16 J Estimation Methods under Combined Mechanical and Thermal Loads with FE Results", *International Journal of Pressure Vessels and Piping*, draft, September 2013.