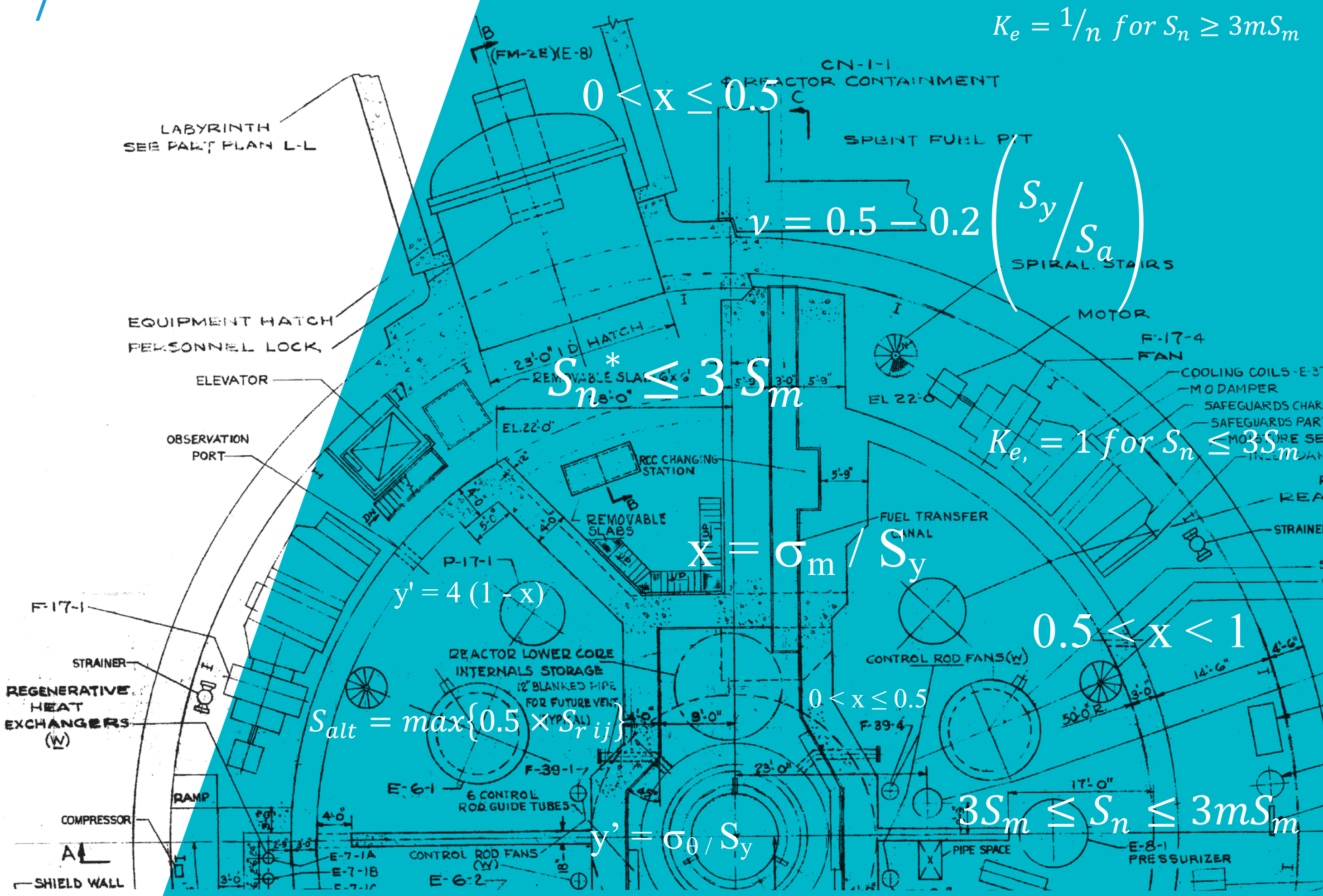
WORLD NUCLEAR ASSOCIATION



Non-Linear Analysis Design Rules

Part 1: Code Comparison

Cooperation in Reactor Design Evaluation and Licensing – Mechanical Codes and Standards Task Force

Title: Non-Linear Analysis Design Rules
Part 1: Code Comparison
Produced by: World Nuclear Association
Published: February 2017
Report No. 2017/002

Technical Coordinator		
Claude Faidy	CF Int. Engineering	France
Project Coordinator		
Andrew Wasylyk	World Nuclear Association	UK
Main Contributors		
Claude Faidy	AFCEN	France
Seiji Asada	JSME/MHI-Japan	Japan
Andrey Obushev	ENES/NIKIET	Russia
Karl Herter	KTA/MPA	Germany
Robert Ainsworth	R5/Manchester University	UK
Hoon-Seok Byun	KEPIC	Korea
Reviewers		
Robert Keating	ASME Code - Working Group Design Methodology	USA
Wolf Reinhart	ASME Code - Working Group Design Methodology	Canada
Jinhua Shi	AMEC Nuclear-UK	UK
Cecile Petesch	RCC-MRx Sub-Committee	France
Denis Pont	EDF-SEPTEN	France

Foreword

The Cooperation in Reactor Design Evaluation and Licensing Working Group (CORDEL) was established by the World Nuclear Association in 2007, with the aim of stimulating a dialogue between the nuclear industry (including reactor vendors and operators) and nuclear regulators on the benefits and means of achieving a worldwide convergence of industry standards for reactor designs.

The CORDEL Mechanical Codes and Standards Task Force (MCSTF)[1] was set up in 2011 to collaborate with the Standards Development Organizations Board (SDO Board) and the Multinational Design Evaluation Program (MDEP) Codes and Standards Working Group (CSWG)[2] on the international convergence of mechanical codes and standards related to the design of nuclear power plant components important to safety. In September 2012, the CORDEL MCSTF Pilot Project was launched to investigate divergences and to promote international convergence in two technical areas:

1) Certification of non-destructive examination (NDE) personnel

2) Non-linear analysis methodology in nuclear mechanical design codes.

The areas were chosen from a survey sent out to the World Nuclear Association CORDEL membership as well as formal discussions with the SDOs and MDEP-CSWG.

The second CORDEL-MCSTF pilot project will results in three reports:

- *Non-Linear Analysis Design Rules; Part 1: Code Comparison* reviews and compares the current code requirements in non-linear analysis for different failure modes (plastic collapse, plastic instability, local failure and buckling) and some degradation mechanisms (fatigue, plastic shakedown) in the major nuclear and non-nuclear design codes.
- *Non-Linear Analysis Design Rules; Part 2: Good Practices* presents recommendations for good industrial practices when performing non-linear analyses.
- *Non-Linear Analysis Design Rules; Part 3: Benchmarks* presents a set of benchmarks designed to provide input to support the set of good practices presented in part 2.

After extensive reviews, including via MDEP-CSWG, the harmonized good practices presented in part 2 will be proposed to each international standard development organization as a draft Code Case for their own use, in order to minimize future code divergence and facilitate areas of convergence.

---

[1] The task force was previously called the CORDEL Codes & Standards Task Force (CSTF) but was renamed in 2015 to better reflect its remit.

[2] International group of regulators which searches for ways to harmonize and converge national codes, standards, and regulatory requirements and practices in the area of nuclear mechanical design codes, while recognizing the sovereign rights and responsibilities of national regulators in carrying out their safety reviews of new reactor designs

Table of contents

Tables

Equations

Figures

1 Introduction

Major design rules in pressure vessel and piping codes, nuclear and non-nuclear, are based on the linear elastic method associated with the classification of stresses into primary stress (for load control), secondary stress (for strain control) and peak stress on the surface. This approach is only easy to develop for simple cases, such as cylindrical shell under axisymmetric quasi-static loads. For more complex geometries and load combinations, the stress classification methodologies available are complicated to implement, highly conservative and dependent on the user's approach. Such difficulties are regularly encountered when designing and assessing nuclear power plant components, such as a vessel nozzle under complex piping loads or piping systems.

Consequently, non-linear analysis at design level is an efficient alternative to the basic linear elastic approach, using real material behaviour and more accurate deformation criteria. One of the major benefits is to remove the issue of the classification into primary versus secondary stress associated with elastic analysis.

CORDEL MCSTF has developed the project on non-linear analysis design rules in order to investigate the differences in various codes and propose recommendations. This report reviews the existing non-linear rules in selected mechanical design codes (see Table 1) and compares the scope, methods, criteria and availability of material data needed to perform analysis.

This report focuses on vessels and piping systems, which are considered defect-free and operated outside of their creep regime. Furthermore, local thinning areas are not considered.

No specific code was considered as a baseline reference for this comparison. Requirements for each of the codes presented in Table 1 are considered independently.

Table 1: List of Codes Considered [1-10][3]

Nuclear design codes						**Non-nuclear design codes**	
ASME BPVC Section III	AFCEN RCC-M	KTA	JSME	KEPIC	PNAE-G7	ASME BPVC Section VIII-2	EN 13445

The requirements to protect against three major failure modes, two major degradation mechanisms and two types of loading conditions are presented in this report.

The following major failure modes are considered:

- Excessive deformation (or plastic collapse).
- Plastic instability (or ultimate load).
- Fracture-decohesion with no crack initiation (local failure).

The following major degradation mechanisms are considered:

- Fatigue: simplified elastic-plastic method using plasticity correction factors (K_e, K_v, etc.)
- Elastic and plastic shakedown (ratcheting)

Two types of loads are considered:

- Monotonic loads
- Cyclic loads

It is important to note that due to the fact that a number of nuclear design codes do not currently have English translations, the authors of this report were dependent on expert input and information available in the literature for the JSME Pressure Vessel Code, KEPIC MN code and the Russian PNAEG code.

This report is aimed at engineers with a good grasp of failure analysis and access to the codes in question, as well as experts involved in the development of nuclear design codes.

---

[3] See References at the end

2 Status of non-linear analysis in the different nuclear codes

2.1 RCC-M Code Section I – Edition 2010

2.1.1 Introduction

AFCEN[4] is an association that was founded in October 1980 by “Electricité de France” (EDF) and Framatome (now Areva). The 2007 edition with 2010 addenda of the RCC-M specification defined the Design and Construction Rules for Mechanical Components of PWR Nuclear Islands is used for this comparison.

RCC-M defines the requirements for all safety classified pressure equipment of pressurised water reactors, such as the vessel, heat exchanger, piping, pump, valve and associated support. The comparison presented in this report is limited to vessel and piping systems, excluding bolts and associated flanges. Sections B 3200, B 3600 and Appendix ZF define the requirements for Class 1 components and C 3200 and C 3600 define the requirements for Class 2 components.

2.1.2 Transient category and criteria level

Five categories of transient are considered in RCC-M: normal, upset, emergency, faulted and test; these are supplemented by a reference situation corresponding to maximum pressure and maximum temperature in normal operation. For each of them a minimum set of failure mode need to be analyzed and associated criteria are required to be fulfilled (see Table 2)

Table 2: AFCEN RCC-M Transients and Criteria

Transient	Criteria level	Damage considered
Reference (maximum design pressure and design temperature)	O	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Normal	A	Ratcheting Fatigue
Upset (no level B considered in RCC-M Class 1 components in accordance with French nuclear regulation)	B	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Emergency	C	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Faulted	D	Plastic instability Elastic and elastic-plastic instability
Test (hydrostatic test)	T	Excessive deformation

---

[4] Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières electro-nucléaires - French Association for Design, Construction and Surveillance Rules of Nuclear Power Plant Components

2.1.3 Scope of non-linear analysis

Requirements for analysis methodologies to be used are defined in sections B3212 of the RCC-M. This section refers specifically to two locations in RCC-M B3000 defining requirements for non-linear analyses:

- B 3240, which defines general rules for elastic-plastic analysis
- Appendix ZF, which defines dedicated requirements for Level D criteria.

2.1.3.1 Scope of use of non-linear analysis

Limit load analysis conducted in accordance to B 3240 can be used as an alternative to the meeting acceptance criteria defined in B 3230, specifically for the determination of the lower bound collapse load when designing against excessive deformation (B 3242) for Level O and C criteria, as well as for test conditions (Level T). It also provides an alternative for the determination of the maximum strain defined in the user's design specification when designing against plastic instability (B 3242) for Level O, C and D criteria when conducting elastic-plastic analysis.

Cyclic elastic-plastic analysis may also be used to show that the structure will undergo a shakedown response, that can be used to develop simplified elastic-plastic analysis (K_e) or detailed fatigue analysis.

No details are provided concerning to the appropriate material models to be used in these analyses.

Similar rules are proposed in C 3290 for non-linear analysis of class 2 vessels. No rules exist for class 3 vessels. Non-linear analysis is not directly proposed in RCC-M for piping systems, except for class 1 piping in level D through Appendix ZF.

2.1.3.2 Definitions of failure modes

AFCEN RCC-M defines limit analysis and lower bound approach as in section B 3141. The definitions are as follow:

Limit analysis – collapse load: The deformation of a structure made up of an elastic perfectly plastic material, increases without bound for a loading level termed collapse load. Limit analysis can be used to estimate this loading level.

Collapse load – lower bound: A given load is less than or equal to the collapse load if there is a stress distribution which everywhere satisfies equilibrium and nowhere exceeds the material yield strength.

No specific definitions for failure modes listed in B 3111 (excessive deformation, plastic instability load or elastic / elastic-plastic instability load) are provided in RCC-M B3000.

2.1.3.3 Definition of degradation mechanisms associated with cyclic loads

The degradation mechanisms that are relevant to this report, and covered by RCC-M, are plastic adaptation, plastic accommodation and global plastic adaptation. These degradation mechanisms are defined in B 3223.3 as follows:

Plastic adaptation (elastic shakedown): For cyclic loadings, a structure is practically adapted if, after a few cycles, behaviour becomes elastic at every point in the structure.

Plastic accommodation (plastic shakedown): For cyclic loadings, a structure undergoes plastic accommodation if, after a few cycles, the behaviour while remaining elastic-plastic is the same at each cycle. Plastic accommodation excludes the possibility of progressive deformation.

Global plastic adaptation (general shakedown): Global plastic adaptation is the state of a structure which undergoes plastic accommodation and in which plastic deformation only appears in deformation concentration zones whose dimensions are less than the lengths of the supporting line segments of the sections under consideration. In this state, the response of the structure is generally elastic and the development of plastic deformation is inhibited by restraint ensured by the parts which remain elastic. The deformation concentration effect depends mainly on geometry and loading and only to a lesser degree on the stress-strain relationship of the material.

2.1.4 Plastic collapse (excessive deformation)

In RCC-M, the plastic collapse load (C_L) is defined in B 3241 for Class 1 components. It is based on a lower bound limit load analysis, with a flow stress equal to S_y (minimum yield stress defined in Appendix ZI for all the RCC-M Materials) at maximum temperature of the transient.

Limiting criteria for design against plastic collapse are defined in B 3242 for each design level. Table 3 defines the applicable limiting criteria to be applied for each design level for the use of non-linear analysis methodologies when assessing against plastic collapse failure mode.

Table 3: Plastic Collapse Criteria Associated with Design Levels in RCC-M

Criteria level	Margin evaluation
level O	for low alloys and carbon steels, the applied load C_{appl} has to be less than 0.66 of the collapse load C_L for stainless steels and Nickel-based alloys: 0.9 C_L or strain level criteria defined in the design specification
level C:	$C_{appl} \leq 1.2\ C_L$
level D	Not required
level T	$C_{appl} \leq 0.8\ C_L$

2.1.5 Plastic instability requirements

In RCC-M, the plastic instability load (C_I) is defined in B 3241. It is based on an elastic plastic analysis, with the material stress-strain curve obtained at the maximum transient temperature. No details are provided regarding the non-linear analysis methodology to be used in the code, but the methodology and data to be used should be specified in the “design specification” of the component analysed. Associated criteria are defined in B 3243 (see Table 4).

Table 4: Plastic Instability Criteria Associated with Design Levels in AFCEN RCC-M

Criteria level	Margin evaluation
Level O	$C_{appl} \leq C_I / 2.5$
Level B	No level B in RCC-M class 1
Level C	$C_{appl} \leq C_I / 2$
Level D	appendix ZF
Level T	Not required

2.1.6 Local failure requirements

Specific requirements to protect from local failure are defined in chapter B 3238 of RCC-M. These requirements are specific to class 1 component; they are based on elastic analysis of the component and are applicable for all design level conditions.

B 3238.4 defines that the sum of all the elastic principal stresses should not exceed a value of four times S_m (see Equation 1).

No proposal or recommendation to use elastic-plastic analysis is given in the code.

Equation 1: RCC-M elastic local failure criteria

$$\sigma_1 + \sigma_2 + \sigma_3 < 4S_m$$

Where σ_1, σ_2, σ_3 are the elastic principal stresses in all locations in the component pressure boundary

2.1.7 Plastic shakedown requirements

The shakedown failure criterion is considered when analyzing level A conditions. In RCC-M, the elastic shakedown and plastic shakedown can be analyzed using elastic and non-linear analysis methodologies. Requirements for elastic analysis of shakedown are defined in B 3234, and elastic plastic analysis of shakedown is defined in B 3244.

2.1.7.1 Elastic analysis

Paragraph B 3234.2 defines the shakedown criteria: S_n should be less than $3\ S_m$ as shown in Equation 2.

Equation 2: RCC-M limiting criteria for shakedown using elastic analysis

$$S_n = \Delta(P_L + P_b + P_e + Q) < 3\ S_m$$

with P_L the local membrane stress, P_b the bending stress, Q the membrane and bending secondary stress and P_e[5] the secondary stress due to thermal expansion .

2.1.7.2 Simplified elastic-plastic analysis:

Paragraph B 3234.3 defines the shakedown criteria: S_n* should be less than $3\ S_m$ as shown in Equation 3.

Equation 3: RCC-M limiting criteria for shakedown using Simplified elastic-plastic analysis

$$S_n{}^* \leq 3\ S_m$$

Where $S_n^* = S_n$ – (thermal bending load) and S_m the Design stress intensity

Thermal ratcheting rules are defined in B 3234.8 and applied to $S_y / R_m \leq 0.8$ (B 3234.3) at room temperature. The rules are based on the classical Bree diagram for linear and parabolic temperature distribution through the wall. They have to be checked in areas where the membrane stress caused by pressure is classified as primary general membrane stress. For axisymmetric shell the allowable range of thermal stress has to be checked with following equations:

$$y' = \sigma_\theta / S_y \qquad \text{and} \qquad x = \sigma_m / S_y$$

With:

σ_θ = maximum allowable range of thermal stress,

σ_m= maximum general membrane stress due to pressure

S_y = yield strength for the maximum temperature reached during the cycle[6]

Specific requirements are defined depending of the through wall temperature variation.

1. If the temperature variation is linear through the wall:

$$y' = 1/x \quad \text{for} \quad 0 < x \leq 0.5$$

$$y' = 4\ (1 - x) \quad \text{for} \quad 0.5 < x < 1$$

2. If the temperature variation is parabolic through the wall:

$$y' = 5.2\ (1 - x) \qquad \text{for } 0.615 \leq x < 1$$

and: for $x < 0.615$

x =	0.3	0.4	0.5
y' =	4.65	3.55	2.7

2.1.7.3 Elastic-plastic analyses:

Paragraph B 3244 defines the general non-linear analysis methodologies and associated requirements for plastic shakedown when designing against level A conditions. Specific requirements for elastic-plastic analysis are defined in B 3234.3 and criteria for progressive deformation and fatigue are defined in B 3244.1.

---

[5] P_e does not apply in analysis of vessels

[6] (1.5 S_m may be used wherever it is greater than S_y; where the yield strength is higher than the endurance limit, the later value, S_a at 10^6 cycles, shall be used if there is to be a large number of cycles)

The RCC-M code requires that the overall behaviour of the region under consideration shall be analyzed using a cyclic elastic-plastic approach, with the actual material behaviours modelled. The elastic-plastic analysis should demonstrate that plastic accommodation occurs after a specified limited number of cycles (as opposed to progressive deformation). In addition, specific requirements regarding cumulative strains before plastic accommodation occurs should not be exceeded. The maximum value has to be defined in the user's design specification.

2.1.7.4 Plastic shakedown in piping systems

Specific requirements for the analysis of piping systems under level A conditions are defined in paragraph B3600.

Paragraph B 3653.3 defines the requirements for shakedown using elastic analysis methodologies. The requirements are the same as the defined in section B 3234.2, with the additional requirement to take the stresses due to temperature differences into account (Equation 4, Equation 5, Equation 6).

Equation 4: Elastic analysis with ΔT_1 (B 3653.3)

$$S_n = C_1\, PD_0/2t + C_2\, D_0\, M_i / 2I + ½(1-\nu)\, E\alpha\, \Delta T_1 + C_3\, |\alpha_A\, T_A - \alpha_B\, T_B| < 3\, S_m$$

Paragraph B 3653.5 defines the requirements for shakedown using simplified elastic-plastic analysis methodologies.

Equation 5: Simplified elastic-plastic analysis (B 3653.5)

$$S_e = C_2\, D_0 / 2I\, M^* < 3\, S_m$$

Where M^* = thermal expansion load + thermal anchor motion load

Equation 6: Simplified elastic-plastic analysis

$$S_q = C_1\, PD_0/2t + C_2\, D_0\, M_i / 2I + C'_3\, |\alpha_A\, T_A - \alpha_B\, T_B| < 3\, S_m$$

Where Mi = weight and inertial part of seismic load.

There are currently no recommendations for full cyclic elastic-plastic analysis in the code.

2.1.8 Fatigue analysis requirements

In RCC-M, all Class 1 and 2 components should be designed against fatigue failure. Three analysis methodologies are available for the fatigue analysis of components:

- Elastic analysis defined in paragraph B3234.5 (vessels) & B3653.5 (piping).
- Simplified elastic-plastic analysis defined in sections B3234.6 & B3653.6.
- Elastic plastic analysis defined in B3234.a.

2.1.8.1 Elastic analysis

Paragraph B 3234.5 (vessels) and B 3653.6 (piping) define the requirements for the design of components against fatigue failure using elastic analysis.

The maximum allowable number of cycles the component can experienced is related to the stress intensity S_{alt} (Equation 7). The number of allowable cycles N_{allow} associated with the S_{alt} value is defined using the corresponding material fatigue curves (S, N) of RCC-M appendix ZI.4.0 and the fatigue usage factor (UF) which is the ratio of the number of applied load cycles to the number of allowable number of cycles (Equation 8):

Equation 7: RCC-M definition of Salt for elastic fatigue analysis

$$S_{alt} = 0.5 \times E_C \times \frac{S_p}{E}$$

Equation 8: RCC-M definition of fatigue usage factor

$$UF = N_{appl} / N_{allow}$$

2.1.8.2 Simplified elastic-plastic analysis K_e

Paragraphs B 3234.6 and B 3653.6 define the requirements for the design of components against fatigue using simplified elastic-plastic analysis (Equation 9). The elastic stress intensity factor has to be corrected by a factor K_e to consider some plasticity effects and material characteristics. The specific correction factor K_e is defined in B 3234.6 on the basis of Equation 10 and
Equation 11.

Equation 9: RCC-M S_{alt} corrected equation

$$S_{alt}(1)_{pq} = 0.5\ max_{ij}\left\{\left(K_{e,mech}\right)_{pq}\left(S_{p,mech}(1)\right)_{ij} + \left(K_{e,therm}\right)_{pq}\left(S_{p,therm}(1)\right)_{ij}\right\}$$

Equation 10: RCC-M K_e factor for thermal loads

$$K_{e,therm} = max\{1; 1.86[1 - 1/(1.66 + (S_n/S_m))]\}\ \text{(RCCM eq. 7)}$$

Equation 11: RCC-M K_e factor for mechanical loads

$$K_{e,mech} = 1\ for\ S_n < 3S_m$$
$$K_{e,mech} = 1.0 + \{(1-n)(S_n/(3S_m - 1))\}\ for\ 3S_m \le S_n \le 3mS_m$$
$$K_{e,mech} = {}^{1}/_{n}\ for\ S_n > 3mS_m$$

With the m and n coefficients of the cyclic curve for different classes of materials defined in B3234.6 (Table 5)

Table 5: RCC-M Material Coefficients m, n

Materials	m	n
Carbon steel	3.0	0.2
Low alloy steel	2.0	0.2
Martensitic stainless steel	2.0	0.2
Austenitic stainless steel	1.7	0.3
Nickel-copper	1.7	0.3

2.1.8.3 Elastic-plastic analysis for fatigue analysis

No detailed requirements exist for direct elastic-plastic analysis of the strain amplitude in RCC-M. Generic guidelines are never-the-less provided in paragraph B 3244.a, allowing the direct evaluation of $\Delta\varepsilon_t/2$ by elastic-plastic analysis, without defining the methodology to be used to perform this analysis.

RCC-M has no elastic-plastic analysis rules proposed for evaluation of K_e for a set of similar cases.

2.1.9 Piping stress classification

In RCC-M, specific rules exist for the analysis of piping systems:

- Rules for the analysis of nozzle to piping transition zone are defined in paragraph B 3238.5.a, B 3238.5.b, c and d.
- Rules for piping thermal expansion in B3624 and seismic load criteria in B3652.3.
- Rules for non-linear analysis of piping system are defined for Level D criteria in Appendix ZF.

2.1.9.1 Nozzle to piping transition zone

One of the areas of interest and where stress classification methodologies associated with elastic analysis can cause issues is in the nozzle to piping transition zone.

2.1.9.1.1 *Elastic analysis:*

In RCC-M, requirements for stress classification and elastic follow up for nozzle to piping transition zones are defined in paragraph B 3238.5.The requirements in paragraph B 3238.5 are based on elastic analysis, with B 3238.5 (a) putting the responsibility on the code user to justify the stress classification principle used. Inside the reinforcement area, thermal expansion stresses (defined as the mean thermal expansion stress through the wall) have to be considered as primary stresses (B 3238.5 (b)). Outside of the reinforcement area, thermal expansion stresses should be considered as primary stresses (B 3238 (b)). Furthermore, the range of the membrane plus bending stresses resulting from thermal expansion of the connected piping shall be less than $3\ \mathrm{Sm}$ (B 3238 (c)). Outside the reinforcement area the thickness of the nozzle shall neither be less than the thickness of the piping and $[t_p\ S_{mp} / S_{mn}]$ (where t_p is the nominal thickness of the connected piping; p pipe, n nozzle)

2.1.9.1.2 *Elastic-plastic analysis:*

There are currently no requirements in RCC-M allowing the code user to apply elastic-plastic analysis or limit load analysis to investigate the nozzle to piping transition zone.

2.1.9.2 Piping analysis: thermal expansion

In B 3624, B 3653.3 and B 3672, generally thermal expansion stresses are considered secondary in RCC-M equations 10, 11, 12 and 13

Elastic-plastic analysis is not permitted for the analysis of thermal expansion in piping, despite experimental approaches being allowed as defined in RCC-M Appendix II.

2.1.10 Appendix ZF: rules associated with level D criteria

Appendix ZF defines the rules for the analysis of the behaviour of components under conditions requiring compliance with level D criteria for pressure components and their supports. The main failure modes investigated are plastic instability and buckling.

All the requirements are defined to enssure consistency between system and component analysis using elastic and plastic analysis.

Appendix ZF provides definitions for the allowable methods specific to this appendix, namely elastic-plastic analysis and limit load analysis for plastic collapse and plastic instability (ZF 1321). For methods used in the main body of the code, such as limit load analysis, the appendix references back to the main code section (e.g. RCC-M B 3241.1 for limit load). ZF 1321.1 d) defines the collapse load as the load for which permanent plastic distortion is equal to elastic distortion (double slope method)

Two levels of analysis methods are presented in this appendix, system analysis and component analysis (ZF 1322.2).

Elastic system and components analysis requirements are defined in ZF 1323, including analysis criteria (ZF 1323.1) and collapse load criteria (ZF 1323.1), with the following requirements specified:

- Specified loads should be less than 90% of the collapse load determined by limit analysis (B 3241.2), by elastic-plastic analysis (ZF 1321.1.), or by test (ZF 1321.2 a).
- If a limit analysis is employed, the yield strength value shall be 230% of the value of S_m at the appropriate temperature
- If deformation limits are stated in the equipment specification, this limit analysis method shall not be used to analyze the behaviour of the portion of the component to which these limits are applicable.

Methods for evaluating primary stresses in a component through inelastic analysis are defined in ZF 1324. The primary stress limits defined in B 3232 are satisfied both for the components and their support (Equation 12).

Equation 12: primary stress limit (B 3232)

$$S_m = \max \{0.7\ S_u, [S_y + 1/3\ (S_u - S_y)]\}$$

Methods for evaluating system and component collapse load using inelastic analysis are defined in ZF 1324.2 and should be used in combination with ZF 1323.2.

Methods for evaluating systems and components' plastic instability using inelastic analysis are defined in ZF 1324.3 and define the following limiting criteria for applied loads:

- 70 % of the plastic instability load P_I
- 100 % of the loads which would result in membrane stress intensity defined in Equation 13:

Equation 13: membrane stress intensity for inelastic instability analysis in RCC-M appendix ZF

$$[S_y + 1/3\ (S_I - S_y)]$$

Where S_I is the true effective stress associated with the plastic instability

Inelastic system analysis and strain limit load analysis for components may only be applied if the applicable loads are less than those required to satisfy Appendix ZF1324.3 and less than 100% of the load P_s associated with the specified strain limits (ZF 1324.4).

Inelastic methods defined in the ZF appendix are only applicable if the rules of ZF 1324.1 are applied (see ZF 1324.5).

2.1.11 First conclusion on RCC-M Code and open points

2.1.11.1 Elastic-plastic analysis

Elastic-plastic analysis and limit load methods are available in RCC-M as alternatives to elastic analysis. Despite the alternative approaches existing, there are very few details regarding specific elastic-plastic methods to be used, constitutive equations or detailed data and requirements for material properties. Associated criteria are generally presented for plastic collapse and plastic instability; using S_y for plastic collapse and maximum strain for plastic instability.

There are currently no methods proposed for direct elastic-plastic finite element analysis (FEA) analysis of the following failure mechanisms in the RCC-M Code:

- K_e/K_v.
- Fatigue.
- Direct strain amplitude evaluation.
- Plastic shakedown analysis.
- Local failure analysis.

Appendix ZF presents the possible analysis methods for level D criteria using elastic-plastic analysis, associated with a set of requirements for consistency of piping system and component analysis.

Instability analysis of vessels is the only calculation that requires elastic-plastic analysis.

2.1.11.2 Open points

There are still a number of open points in the use of elastic-plastic analysis when applying the RCC-M requirements, notably:

- Whilst Finite element analysis (FEA) uses Von Mises criteria, existing elastic rules are based on Tresca criteria. This can lead to confusion, and as such, the criteria has to be clearly defined in the Code in case of non-linear analysis
- the validity of the use of classical Finite Element Analysis (FEA) for lower bound limit load evaluation has to be confirmed.
- Use of limit analysis for level D criteria (possible large displacement…) and flow stress value have to be clarified .

The following recommendations for the application of finite element analysis are proposed:

- The temperature for each step of these analyses should be specified.
- The tolerances and precise geometry for performing inelastic analysis should be specified.
- More general FEA recommendations (mesh refinement, small versus large displacement, convergence criteria, etc.) should be included in the code.
- All the material properties for all these analysis (engineering/ true and cyclic stress-strain curves, material constitutive equations…) are needed in the code.
- All strain criteria for elastic-plastic analysis should be proposed in the code with possible alternative values specified in the user's design specification.
- Cyclic elastic-plastic analysis for fatigue and shakedown need to be explained in details with analysis recommendations, dedicated material properties and associated criteria in the code.
- Local failure requirements are proposed in RCC-M for level D criteria without any opening to perform elastic-plastic analysis.
- For thermal expansion load classification in piping systems, in particular in nozzle area, is completely detailed for elastic approach, an elastic-plastic analysis rules is needed in the Code
- The technical basis of some Sy / Su limitation in non-linear analysis are unclear

2.2 ASME Code Section III – Edition 2010

2.2.1 Introduction

The American Society for Mechanical Engineers (ASME) was first established in 1911 to provide construction rules in order to increase the quality and reduce accidents related to boilers. In 1956, ASME established a committee in charge of writing a new code, the “ASME Boiler and Pressure vessel Code for nuclear age”. In 1963, this committee proposed adding a new section to the ASME BPVC to cover the rules and good practices to be followed in the new-born civil nuclear industry, ASME BPVC Section III. The latest edition of ASME BPVC was published in 2015. In this report, the 2010 edition of the ASME BPVC is considered.

ASME BPVC Section III defines the requirements for the design and construction for all the nuclear safety classified components. Section III is divided into five divisions (see Table 6) and each division is divided into three major sub sections: NB for Class 1 components, NC for Class 2 components, ND for Class 3 components, and associated mandatory and non-mandatory appendices. NB, NC, ND 3200 cover vessel rules and NB, NC, ND 3600 cover piping rules.

The comparison presented in this report is limited to vessel and piping systems, excluding bolts and associated flanges. Section III division I subsection NB 3200 and non-mandatory Appendix F define the analysis methodology and associated criteria for Class 1 components in light water reactors, and are investigated in this report.

Table 6: ASME BPVC Section III Organization

ASME BPVC Section III	
Division 1	Light water reactors: vessel, heat exchanger, piping, pump, valve and associated support, metallic containment
Division 2	Concrete containment
Division 3	Containment for transportation and storage of spent fuel and high-level radioactive material and waster
Division 4	Fusion reactors
Division 5	High-temperature reactors

2.2.2 Transient category and criteria levels

ASME BPVC Section III NB does not define the service levels or damage conditions that have to be considered in the design of components, but paragraph NB 1110 refers to ASME BPVC Section III NCA requirement.

NCA specifies five categories of transient which has to be considered normal, upset, emergency, faulted and test, which should be defined in the user’s design specification. Each transient category has an associated criteria level and associated failure criteria to be accounted for in the design (see Table 7)

Table 7: ASME BPVC Section III Transient and Criteria

Transient	Criteria Level	Damage considered
Normal	A	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and Ratcheting Fatigue
Upset	B	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and Ratcheting Fatigue
Emergency	C	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Faulted	D	Plastic instability Elastic and elastic-plastic instability
Test	T	Excessive deformation

2.2.3 Scope of non-linear analysis

Definitions of the terms associated with stress analysis are defined in ASME BPVC subsection NB 3213. The scope of where non-linear analysis methodologies can be used and allowed non-linear analysis methodologies are defined in subsection NB 3228 (Application of Plastic Analysis), Appendix XIII (Design of Class 2 vessels meeting the requirements of NC 3200) and Appendix F (Rules and Service limits for Evaluating Components and Supports Subjected Level D Service Limits).

ASME BPVC Section III Subsection NB 3200 provides detailed requirements for design by analysis, allowing flexibility for the code users as to how they meet the code requirements.

2.2.3.1 Definitions, failure modes and analysis methods

ASME BPVC Section III NB 3213 defines Terms Relating to Stress Analysis defines: plasticity, plastic analysis, collapse load, plastic instability load, limit load, lower bound approach, plastic hinge, ratcheting and shakedown and NB 3228 “Applications of Plastic Analysis” defines rules related to non-linear analysis.

The following definitions are of interest for this report:

Plasticity: Plasticity is the special case of inelasticity in which the material undergoes time-independent non-recoverable deformation.

Plastic Analysis: Plastic analysis is that method which computes the structural behaviour under given loads considering the plasticity characteristics of the materials, including strain hardening and the stress redistribution occurring in the structure.

Plastic Analysis — Collapse Load: A plastic analysis may be used to determine the collapse load for a given combination of loads on a given structure. The following criterion for determination of the collapse load shall be used. A load–deflection or load–strain curve is plotted with load as the ordinate and deflection or strain as the abscissa. The angle that the linear part of the load– deflection or load–strain curve makes with the ordinate is called θ. A second straight line, hereafter called the collapse limit line, is drawn through the origin so that it makes an angle $\phi = \tan^{-1}(2 \tan\theta)$ with the ordinate. The collapse load is the load at the intersection of the load–deflection or load–strain curve and the collapse limit line. If this method is used, particular care should be given to ensure that the strains or deflections that are used are indicative of the load carrying capacity of the structure.

Plastic Instability Load: The plastic instability load for members under predominantly tensile or compressive loading is defined as that load at which unbounded plastic deformation can occur without an increase in load. At the plastic tensile instability load, the true stress in the material increases faster than strain hardening can accommodate.

Limit Analysis: Limit analysis is a special case of plastic analysis in which the material is assumed to be ideally plastic (non-strain-hardening). In limit analysis, the equilibrium and flow characteristics at the limit state are used to calculate the collapse load. The two bounding methods which are used in limit analysis are the lower bound approach, which is associated with a statically admissible stress field, and the upper bound approach, which is associated with a kinematically admissible velocity field. For beams and frames, the term "mechanism" is commonly used in lieu of "kinematically admissible velocity" field.

Limit Analysis — Collapse Load: The methods of limit analysis are used to compute the maximum load that a structure assumed to be made of ideally plastic material can carry. At this load, which is termed the collapse load, the deformations of the structure increase without bound.

Collapse Load — Lower Bound: If, for a given load, any system of stresses can be found which everywhere satisfies equilibrium, and nowhere exceeds the material yield strength, the load is at or below the collapse load. This is the lower bound theorem of limit analysis which permits calculations of a lower bound to the collapse load.

Plastic Hinge: A plastic hinge is an idealized concept used in Limit Analysis. In a beam or a frame, a plastic hinge is formed at the point where the moment, shear, and axial force lie on the yield interaction surface.

In plates and shells, a plastic hinge is formed where the generalized stresses lie on the yield surface.

2.2.3.2 Definition of degradation mechanism

The degradation mechanisms that are relevant to this report and covered by NB 3213 of ASME BPVC Section III are ratcheting and plastic shakedown.

Ratcheting: Ratcheting is a progressive incremental inelastic deformation or strain which can occur in a component that is subjected to variations of mechanical stress, thermal stress, or both.

Shakedown: Shakedown of a structure occurs if, after a few cycles of load application, ratcheting ceases. The subsequent structural response is elastic, or elastic–plastic, and progressive incremental inelastic deformation is absent. Elastic shakedown is the case in which the subsequent response is elastic.

2.2.3.3 Use of non-linear analysis

Elastic-plastic analysis may be used in ASME BPVC Section III mainly to meet the requirements for service level A as alternative to NB 3222 and for service level D in Appendix F.

Full elastic plastic analysis conducted in accordance with NB 3228 can be used as an alternative to meeting the acceptance criteria defined in NB 3222 for level A conditions. Elastic-plastic analysis can be used specifically for the determination of the limit analysis (NB 3228.1 – elastic perfectly plastic analysis), shakedown (NB 3228.4), fatigue analysis (NB 3228.4). For level D criteria, specific rules are defined in Appendix F for class 1 components and in paragraph NC 3200, using the methods described in the mandatory Appendix XIII-1150, for the plastic analysis, limit analysis and shakedown analysis of class 2 and 3 components.

2.2.4 Plastic collapse (excessive deformation)

ASME BPVC Section III NB defines three approaches to define the collapse load, through plastic analysis and a twice elastic slope (NB 3213.25), a limit analysis (NB 3213.27 & NB 3213.28) and using the lower bound theorem (NB 3213.29).

Limit analysis collapse load approach defined in NB-3213.28 should be used, with 1.5Sm used as the yield strength. (S_m: Design stress intensity values defined in Section II, Part D, Subpart 1, Table 2A for ferrous metals and Table 2B for non-ferrous materials, for nuclear application.)

In ASME BPVC, the plastic collapse load criterion (C_L) is defined in paragraph NB3228 using two distinct methodologies, limit load or twice elastic slope.

Table 8 defines the applicable limiting criteria to be applied for each design level when assessing against plastic collapse failures mode and assessing against a “lower bound limit load analysis” using non-linear analysis methodologies.

Table 8: Plastic Collapse Criteria Associated with Level A-D Criteria in ASME Section III

Criteria level	Margin evaluation
Level A:	Applied load $\leq 2/3\ C_L$ with yield stress of $1.5\ S_m$ (NB 3228)
Level B:	Not considered in the code
Level C:	Not considered in the code
Level D:	Appendix F: applied load $\leq 0.9\ C_L$ with yield stress defined in Equation 14

Equation 14: Allowable strength for level D limit analysis in ASME Section III

$$allowable\ stress = \min\{2.3S_m, 0.7\ S_u\}$$

Table 9 defines the applicable limiting criteria for each design level when assessing against plastic collapse failures defined through twice elastic slope criteria obtained geometrically from the component’s load displacement curve. The load / displacement curve can be derived from experimental tests or full elastic-plastic Finite Element Analysis of the component under the loading investigated.

Table 9: Plastic Collapse Criteria Associated with Criteria Levels in ASME Section III NB

Criteria level	Margin evaluation
Level A:	Maximum strain defined in the Design Specification
Level B:	Not considered in the Code
Level C:	Not considered in the Code
Level D	Appendix F 1341.2: C_L + additional criteria

Furthermore, when the twice elastic slope approach is used, the following additional stress criteria are defined for level D condition.

Primary membrane stress (Pm):

$$P_m \leq 0.7S_u \text{ for ferritic steels}$$

$$P_m \leq \min(0.7S_u, S_y+(1/3)(S_u-S_y)) \text{ for austenitic steels}$$

Maximum primary stress (Pm + Pl + Pb)

$$P_m + P_L + P_b \leq 0.9Su$$

Maximum primary shear (Ps) across any section loaded in pure shear

$$P_S \leq 0.42S_u$$

Where S_u is the tensile strength of the material at temperature.

Furthermore, the applied load cannot exceed the plastic collapse load obtained using the “twice elastic slope” method.

2.2.5 Plastic instability requirements

ASME BPVC Section III NB-3213.26 defines the plastic instability criterion (P_I). It can be obtained from a full elastic-plastic analysis and is defined as the load at which unbounded plastic deformation can occur without any increase in load. At the plastic instability load, the true stress in the material increases faster than strain hardening can accommodate. In ASME BPVC Section III NB, plastic instability is only calculated for level D criteria, which references Appendix F (F 1321.7). The instability load may be calculated using a plastic or experimental analysis.

The limiting criteria on plastic instability for level D are defined in F 1330 “Acceptance Criteria Using Elastic System Analysis” and F1331.1(c).2. It states that static or equivalent static loads shall not exceed 90% of the limit analysis collapse load using a yield stress which is the lesser of $2.3\ S_m$ and $0.7\ S_u$, or 100% of the plastic analysis collapse load.

2.2.6 Local failure requirements

Specific triaxiality requirements to protect from local failure have been defined in ASME BPVC Section III. These requirements are specific to class 1 & 2 components (subsections NB & NC), are based on elastic analysis of the component and are applicable for all design level A (NB 3222), B (NB 3223) and C (NB 3224.3) conditions. It is important to note that for level C, the criterion is 120% the value required for level A & B.

B 3227.4 defines that the sum of all the elastic principal stresses should not exceed a value of four times S_m for level A, B and C (see Equation 15).

Equation 15: section III NB & NC elastic local failure requirement for level C conditions

$$\sigma_1 + \sigma_2 + \sigma_3 < 4\ S_m$$

No proposal or recommendation to use elastic-plastic analysis is given in the code.

2.2.7 Plastic shakedown requirements

Shakedown failure criteria are considered when analyzing level A & B conditions in Section III. The elastic shakedown and plastic shakedown criteria can be analysed using elastic and elastic plastic methodologies. Requirements for elastic analysis of shakedown are defined in NB 3222 and simplified elastic-plastic analysis of shakedown in NB 3228.

2.2.7.1 Elastic Analysis

Paragraph NB 3222-2 states that the shakedown criteria S_n should be less than $3\ S_m$ as shown in Equation 16

Equation 16: Section III NB limiting criteria for shakedown using elastic analysis

$$S_n = \Delta(P_L + P_b + P_e + Q) < 3\ S_m$$

where P_L the Local membrane stress, P_b the bending stress, Q the membrane and bending secondary stress and P_e the secondary stress due to expansion.

2.2.7.2 Simplified elastic-plastic analysis:

Paragraph NB-3228-5 defines that the range of primary plus secondary membrane plus bending stress intensity, excluding thermal bending stress, shall be less than three times Sm as shown in Equation 17

Equation 17: Section III NB limiting criteria for shakedown simplified elastic-plastic analysis

$$S_n^* \leq 3\ S_m$$

Where $S_n{}^* = S_n$ – (thermal bending load)

Thermal ratcheting rules are defined in NB 3222.55. The rules are based on the classical Bree diagram for linear and parabolic temperature distribution through the wall. They have to be checked in areas where the membrane stress caused by pressure is classified as primary general membrane stress. For axisymmetric shell the maximum allowable range of thermal stress has to be checked using the following equations:

$$y' = \sigma_{\theta} / S_y \qquad \text{and} \qquad x = \sigma_m / S_y$$

Where:
σ_θ = maximum allowable range of thermal stress
σ_m= maximum general membrane stress due to pressure
S_y = yield strength for the maximum temperature reached during the cycle[7]

Specific requirements are defined according to the through-wall temperature variationSpecific requirements are defined depending of the through wall temperature variation in NB 3222.5.

1. If the temperature variation is linear through the wall:

$$y' = 1/x \quad \text{for} \quad 0 < x \leq 0.5$$
$$y' = 4\,(1 - x) \quad \text{for} \quad 0.5 < x < 1$$

2. If the temperature variation is parabolic through the wall:

$$y' = 5.2\,(1 - x) \quad \text{for } 0.615 \leq x < 1$$

and: for x < 0.615

x =	0.3	0.4	0.5
y' =	4.65	3.55	2.7

2.2.7.3 Elastic-Plastic Analyses:

Paragraph NB-3228 defines the general non-linear analysis methodologies and associated requirements.

ASME Section III NB requires that the accumulated local plastic strain does not exceed 5% strain. This rule only applies if the following criteria defined in Equation 18 are met.

Equation 18: Section III requirements to meet plastic shakedown conditions

$$S_y/R_m < 0.7 \text{ at room temperature}$$

No details regarding the method to be used for the elastic plastic analysis, or which material properties to be used, are defined in ASME Section III NB.

2.2.7.4 Plastic shakedown in piping systems:

Specific requirements for the analysis of piping systems under Level A conditions are defined in paragraph NB 3600.

Paragraph NB 3653.1 defines the requirements for shakedown using elastic analysis methodologies. The requirements are the same as the defined in section NB 3228.5, with the additional requirement to take the stresses due to temperature differences into account.

Equation 19: ASME BPVC Section III Simplified Shakedown analysis

$$S_e = C_2\, D_0 / 2I\, M^* < 3\, S_m$$

Where M^* = thermal expansion load + thermal anchor motion load

Equation 20: ASME BPVC Section III Shakedown analysis with temperature

$$S_q = C_1\, PD_0/2t + C_2\, D_0\, M_i / 2I + C'_3\, |\alpha_a\, T_a - \alpha_b\, T_b| < 3\, S_m$$

Where M_i = weight and inertial part of seismic load

There are currently no recommendations for full cyclic elastic-plastic analysis in the Code.

---

[7] (1.5 S_m may be used wherever it is greater than S_y; where the yield strength is higher than the endurance limit, the later value, S_a at 10^6 cycles, shall be used if there is to be a large number of cycles)

2.2.8 Fatigue analysis requirements

2.2.8.1 Elastic analysis

All class 1 components should be assessed for their suitability for cyclic operation for design levels A, B and C. If requirements defined in NB 3222.4(d) are met, no analysis for cyclic loading is required, and it may be assumed that the limits on peak stress intensity as governed by fatigue have been satisfied by compliance with the applicable requirements for material, design fabrication, examination, and testing of this subsection.

If the requirements in paragraph 3222.4(d) are not met, a cyclic analysis should be performed according to the procedure defined in NB 3222.4(e). These requirements for the assessment of fatigue life of a component undergoing cyclic loadings are based on a comparison of peak stresses with strain cycling fatigue strength curves defined in Appendix I-9.0. The fatigue design curves are derived for different type of steels used in the nuclear industry, and dependent on temperature and ultimate tensile strength (UTS).

S_{alt} is determined using the procedure defined in paragraph NB-3216.1. The principal stresses need to be derived first, at the service condition investigated. The stress differences S_{ij} should be derived from the principal stresses. The extremes of the range through which each stress difference S_{ij} fluctuates should be determined, and the absolute magnitude of this range is called S_{rij}. The S_{alt} is then determined using Equation 21:

Equation 21: Calculation of Salt in ASME Section III NB

$$S_{alt} = max\{0.5 \times S_{r\,ij}\}$$

2.2.8.2 Simplified elastic-plastic analysis K_e

Simplified elastic-plastic analysis can be used to meeting the requirements for Level A, B and C conditions. NB-3228.5 defines the requirements for simplified elastic-plastic analysis. It limits the calculations for conditions where the range of primary plus secondary membrane plus bending stress intensity (excluding thermal bending) shall be inferior or equal to $3Sm$.

The value of S_a to be used when assessing the component against fatigue should be corrected using the K_e factors defined in Equation 22. Furthermore, the temperature should not exceed pre-set temperatures defined in Table 10 for each material, should meet the thermal ratcheting rules defined in NB 3222.5 and the ratio of the minimum yield strength to specified minimum tensile strength of 0.70.

Equation 22: ASME K_e factor for ASME materials

$$K_{e,} = 1\,for\;S_n \leq 3S_m$$
$$K_e = 1.0 + \{(1-n)(S_n/(3S_m - 1))\}\,for\;3S_m \leq S_n \leq 3mS_m$$
$$K_e = {}^{1}/_{n}\;for\;S_n \geq 3mS_m$$

Table 10: Section III NB K_e Correction Factors m, n and Maximum Allowable Temperature

Materials	m	n	T max F (C)
Carbon steel	3.0	0.2	700 (370)
Low alloy steel	2.0	0.2	700 (370)
Martensitic stainless steel	2.0	0.2	700 (370)
Austenitic stainless steel	1.7	0.3	800 (425)
Nickel-chromium-iron	1.7	0.3	800 (425)
Nickel-copper	1.7	0.3	800 (425)

An alternative methodology is available when assessing components using elastic analysis beyond yield strength in NB 3227.6. This approach allows the evaluation of the local thermal stresses to be conducted using the elastic equations with a modified Poisson's ratio as defined Equation 23.

Equation 23: Poisson's ratio correction for simplified elastic plastic calculation

$$\nu = 0.5 - 0.2\left({}^{S_y}\!/_{S_a} \right)$$

With S_a the alternating stress intensity determined ion NB-3224.2(e) prior to the elastic modulus adjustment in NB-3222.4(e) (4), and S_y the yield strength of the material at the mean value of the temperature of the cycle.

Additional alternative rules are available in Code case N779. This Code Case is currently beyond the scope of the code comparison report.

2.2.8.3 Elastic-plastic analysis

Elastic-plastic cyclic analysis can be conducted when carrying out a shakedown analysis according to NB-3228.4 in Level A, B and C conditions.

For fatigue analysis, direct evaluation is possible using the NB-3228.4 approach, with the evaluation of the stresses to be compared with fatigue allowable to be conducted according to Equation 24.

Equation 24: evaluation of allowable stresses using plastic analysis in ASME BPVC Section III

$$S_a = max(\Delta\varepsilon_{total} \times (E/2))$$

where E is the elastic modulus defined in Section II, Part D, Subpart 2, tables T_m at the mean value of the temperature of the cycle and $\Delta\varepsilon_{total}$ the principal total strain range.

No details are provided on the methodology to be used to conduct the cyclic plastic calculations or the evaluation of the cyclic analysis results.

2.2.9 Piping stress classification

2.2.9.1 Nozzle to piping transition zone

NB 3227.5 presents classification of stresses in the reinforcement areas and refers to simplified elastic-plastic analysis in case the $3\ S_m$ limits on the range of primary plus secondary stresses are exceeded, through NB-3228.5. The range of membrane plus bending stress intensity in the nozzle due to the restraint of free end displacement of the attached piping is limited to $3\ S_m$.

2.2.9.2 Piping analysis

Thermal expansion stresses are considered secondary in NB 3650 and NB 3672. In case the $3\ S_m$ limit on the range of primary plus secondary stresses from all sources is exceeded, NB 3650 limits the range of membrane plus bending stress intensity due to the restraint of free end displacement of the piping to $3\ S_m$

2.2.10 Appendix F: rules associated with level D criteria

Similarly to AFCEN's RCC-M Appendix ZF, this appendix collects rules for level D:

It defines the requirements for elastic system analysis (F 1341.1), plastic system analysis (F 1341.2), collapse load analysis (F 1341.3) and plastic instability analysis (F 1341.4).

For elastic analysis, it requires that the static or equivalent static loads shall not exceed 90% of the limit analysis collapse load using a yield stress which is the lesser of 2.3 Sm and 0.7 Su, or 100% of the plastic analysis collapse load or test collapse load.

For plastic analysis, the following stress limits shall be applied:

- The general primary membrane stress intensity Pm shall not exceed $0.7Su$ for ferritic steel materials included in Section II and the greater of $0.7Su$ and $Sy + 1/3\ (Su - Sy)$ for austenitic steel, high-nickel alloy, and copper-nickel alloy materials included in Section II
- The maximum primary stress intensity at any location shall not exceed 0.90 S_u

F-1341.3 Collapse Load. Static or equivalent static loads shall not exceed 90% of the limit analysis collapse load using a yield stress which is the lesser of $2.3S_m$ and $0.7S_u$, or 100% of the plastic analysis collapse load or test collapse load.

F-1341.4 Plastic Instability Load. The plastic instability load is designated P_I and may be determined by one of the following methods:

(a) plastic analysis

(b) experimental analysis

The applied load shall not exceed $0.7P_I$.

2.2.11 Appendix II: Experimental stress analysis

The "double-slope" criterion is defined in this Appendix II. Collapse is defined when the plastic part of the deformation has the same magnitude as the elastic part (see II 1430 and associated figure)

Figure II-1430-1
Construction for II-1430

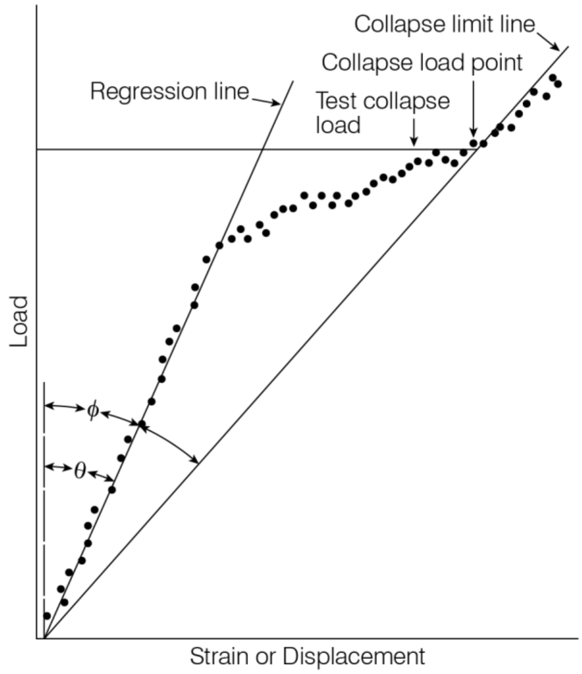


Figure 1: ASME Appendix 2 – Double slope collapse load

2.2.12 Appendix XIII: design based on stress analysis

2.2.12.1 Elastic analysis

This appendix is mainly dedicated to class 2 vessels designed in according to NC 3200, the elastic design rules (XIII 1140) are based on $k.S_m$ with k value of 1 for design and level A, 1.1 for level B, 1.2 for level C and 2 for level D.

2.2.12.2 Plastic analysis, limit analysis and shakedown analysis

Plastic analysis, limit analysis and shakedown analysis are proposed and presented in Appendix XIII-1150; they are similar to NB 3228 Class 1 rules.

2.2.12.2.1 *Plastic analysis*

The following subparagraphs provide guidance in the application of plastic analysis and some relaxation of the basic stress limits which are allowed if plastic analysis is used.

1. Poisson ratio (XIII 1151.1):
   (a) In evaluating stresses for comparison with any stress limits other than fatigue allowable stresses shall be calculated on an elastic basis using the elastic value of Poisson's ratio.
   (b) In evaluating stresses for comparison with fatigue allowable, the elastic equations shall be used, except that the numerical value substituted for Poisson's ratio shall be determined from the expression:

$$\nu = 0.5 - 0.2\ (S_y / S_a),\ \text{but not less than } 0.3$$

where:

S_a = alternating stress intensity

S_y = the yield strength of the material at the mean value of the temperature of the cycle

2. Plastic analysis procedures (XIII 1151.2)
   The limits on local membrane stress intensity, primary plus secondary stress intensity, thermal stress ratchet in shell, and thermal stress in non-integral connections need not be satisfied at a specific location if at that location the procedures of the following (a), (b) and (c) are used.
   (a) In evaluating stresses for comparison with the stress limits of general primary membrane plus primary bending stress intensity only, the stresses are calculated on an elastic basis.
   (b) In lieu of satisfying the specific requirements at a specific location, the structural action is calculated on a plastic basis and the design shall be considered to be acceptable if shakedown occurs, as opposed to continuing deformation, and if the deformations which occur prior to shakedown do not exceed specified limits.
   (c) In evaluating stresses for comparison with fatigue allowable, the numerically maximum principal total strain range which occurs after shakedown shall be multiplied by one-half of the modulus of elasticity of the material at the mean value of the temperature of the cycle.

2.2.12.2.2 *Limit Analysis (XIII 1152)*

The limits on local membrane stress intensity and primary membrane plus primary bending stress intensity need not be satisfied at a specific location if it can be shown by means of limit analysis or by tests that the specified mechanical and thermal loadings do not exceed two- thirds the lower bound collapse load.

2.2.12.2.3 *Plastic shakedown (XIII 1153)*

The $3S_m$ stress intensity limit on the range of primary plus secondary stress intensity (XIII-1145) may be exceeded provided that the range of primary plus secondary membrane plus bending stress intensity, excluding thermal bending stresses (S_n* in RCC-M), shall be $\leq 3Sm$ and that the following requirements of (a) through (e) are met.

(a) The value of S_a used for entering the design fatigue curve is multiplied by the factor K_e

(b) The rest of the fatigue evaluation stays the same as required in Mandatory Appendix XIV, except that the procedure of XIII-1151.1 need not be used.

(c) The component meets the thermal ratcheting requirement of Appendix XIV-1400.

(d) The temperature does not exceed those listed in Table XIII-1153(a)-1 for the various classes of permitted materials.

(e) The material shall have a specified minimum yield strength to specified minimum tensile strength ratio of less than 0.80.

2.2.13 Code Case N-779: Alternative rules for simplified elastic-plastic fatigue analysis

Alternative rule for K_e value for Class 1 vessel and piping is presented in the Code Case considering K_e, K_v and K_n with a set of formulae connected to material strain hardening n coefficient.

2.2.13.1 Vessel Rules

1. The total stress intensity range, excluding both thermal bending stresses caused by linear through-wall thermal gradients and local thermal stresses, shall be multiplied by the factor K_e given in NB-3228.5(b).
2. The local thermal stress range [NB-3213.13(b)] is multiplied by a factor K_v for Poisson's ratio effects:

$K_\nu=1.4$ for $S_p > 3S_m$ and $S_{p\text{-}tb\text{-}lt} \geq 3S_m$
$K_\nu=1.0+0.4(S_p-3S_m)/(S_{tb+lt})$ for $S_p > 3S_m$ and $S_{p\text{-}tb\text{-}lt} < 3S_m$
$K_\nu=1.0$ for $S_p \leq 3S_m$

with:
S_p = total stress intensity range
S_{tb+lt} = thermal bending plus local thermal stress intensity range
$S_{p\text{-}tb\text{-}lt}$ = total stress intensity range excluding thermal bending and local thermal stresses

The thermal bending stress range caused by linear through-wall thermal gradients is multiplied by a factor K_v as defined above for Poisson's ratio effects, and a factor K_n as defined below for plastic strain redistribution at local discontinuities (such as notches):

$$K_n = 1.0 + \left[\left(\frac{S_{p-lt}}{S_n}\right)^{\frac{1-n}{1+n}} - 1\right]\left[\frac{S_{p-lt}-3S_m}{S_{p-lt}}\right] \quad \text{for} \quad S_{p\text{-}lt} > 3S_m$$

$$K_n = 1.0 \quad \text{for} \quad S_{p\text{-}lt} \leq 3S_m$$

$$\text{and} \quad K_n . K_v \leq K_e$$

$S_{p\text{-}lt}$ = total stress intensity range excluding local thermal stresses
S_n = primary plus secondary stress intensity range. For piping, the linear radial thermal gradient stress intensity, classified as a peak stress, is added to Sn in this procedure to determine Kn.
n = strain hardening exponent (Table NB-3228.5 (b)-1)

2.2.13.2 Piping Rules

Alternative equations are provided in Code Case N779 for the analysis of piping systems.

$$S_{alt} = 0.5\left[K_e\left(K_1 C_1 \frac{PD_0}{2t} + K_2 C_2 \frac{D_0}{2\,I}\right) M_i + K_3 C_3 E_{ab}\,|\alpha_a T_a - \alpha_b T_b| + K_\nu K_n\left(\frac{1}{2(1-\nu)} K_3\, E\alpha\,|\varDelta T_1|\right) + K_\nu \frac{1}{1-\nu}\, E\alpha\,|\varDelta T_2|\right]$$

where K_v = the lesser of 1.4 and K_e
and $K_n\ K_v \leq K_e$

$$K_n = 1.0 + \left[\left(\frac{S_p - \frac{1}{1-\nu}\,E\alpha\,|\Delta T_2|}{S_n + \frac{1}{2(1-\nu)}\,E\alpha\,|\Delta T_1|}\right)^{\left[\frac{1-n}{1+n}\right]} - 1\right]\left(\frac{S_p - \frac{1}{1-\nu}\,E\alpha\,\Delta T_2 - 3S_m}{S_p - \frac{1}{1-\nu}\,E\alpha\,|\Delta T_2|}\right)$$

2.2.14 First conclusion on ASME Section III (BPVC) and open points

2.2.14.1 Elastic-plastic analysis

Elastic plastic analysis and limit load methods are available in ASME BPVC Section III as an alternative to elastic analysis. Despite the alternative approaches existing, there are very little details with regards to specific elastic-plastic methods to be used, constitutive equations or detailed data and requirements for material properties. Associated criteria are generally presented for plastic collapse (and plastic instability in connection with Sm definition) for level A load criteria, using $1.5\ S_m$ flow stress and associated with a criteria of $0.66\ C_L$, not for level C.

There are currently no methods proposed for direct FEA analysis of the following failure mechanisms in the ASME BPVC Section III Code:

- K_e/K_v elastic-plastic evaluation,
- fatigue direct strain amplitude evaluation or
- plastic shakedown analysis,
- local failure analysis.

It is interesting to note that a specific Code Case is dedicated to the evaluation of K_e for vessels and piping components.

A particular Appendix (App. F) presents the possible analysis methods for level D criteria using elastic or plastic piping system analysis to assure consistency of piping system and component analysis. Another Appendix (App. XIII) presents possible plastic analysis methods for class 2 vessels.

Instability analysis of vessels is the only failure mechanism that requires elastic-plastic analysis.

2.2.14.2 Open points

There are still a number of open issues in the use of elastic-plastic analysis when applying the ASME BPVC Section III requirements:

- Finite Element Analysis use Von Mises criteria, existing elastic rules are based on Tresca criteria; NB-3212 states “the theory of failure used in the rules of this Subsection for combining stresses is the maximum shear stress theory”. It is not clear whether this statement applies to elastic-plastic analysis results.
- Use of classical Finite Element Analysis (FEA) for lower bound limit load evaluation has to be reviewed and validated
- Use of limit analysis for level D criteria (possible large displacement…) and flow stress value have to be defined and validated,

Detailed recommendations for analysis are required, as:

- Temperature to use for each step of these analyses
- Tolerances and precise geometry to perform inelastic analysis
- More general FEA recommendations (mesh refinement, small versus large displacement, convergence criteria…) have to be included in the Code
- Cyclic elastic-plastic analyses for fatigue and shakedown need to be explained in details with analysis recommendations, dedicated material properties, associated criteria and corresponding validation
- K_v, K_e and K_n factors: optimization and associated justification of simplified elastic-plastic analysis is needed
- All the strain criteria for elastic-plastic analysis have to be proposed in the Code with possible alternative value in the user’s design specification
- Local failure requirements: not required in level D and opening to elastic-plastic analysis with associated criteria has to be added in the Code.

- All the material properties for all these analysis (engineering, true and cyclic stress-strain curves, material constitutive equations…) have to be proposed in the Code.
- Thermal expansion load classification in piping systems and nozzle needs background information and benchmarking for final validation
- The background of some Sy / Su limitation in case of non-linear analysis need background information.
- Appendix XIII is dedicated to class 2 NC-3200 vessels: criteria consistency with class 1 and possibilities to enlarge the scope of this Appendix needs to be checked and the Appendix supplemented.
- The different objectives of NB-NC, Appendix XIII and Appendix F, Code case N 779 have to be reviewed in order to limit part duplication
- The background of the requirement on systematic satisfaction of the wall thickness criteria is required for different materials.

2.3 RCC-MRx Code Section I – Edition 2012

2.3.1 Introduction

AFCEN is an association that was founded in October 1980 by Electicité de France (EDF) and Framatome (now Areva). The RCC-MRx specifications define the design and construction rules for mechanical components used in high temperature, experimental and fusion reactor technology.

RCC-MRx defines the requirements for all components considered important to safety and operability of the power plant. This includes components playing a role in ensuring leak-tightness, partitioning, guiding, box structures, heat exchanges and their support and drive mechanisms.

To apply this code, the list of components and supports subject to RCC-MRx must specify entrance keys described in this code to determine the applicable rules.

RCC-MRx can be applied for non-creep (e.g. research reactors), or creep regimes (e.g. HTRs). Some of the rules can be used on a case by case basis for light water reactors.

Only non-creep rules are presented in this report.

2.3.2 Transient category and criteria level

Three category levels are considered in RCC-MRx, SF1$_{\&}$2, SF3 and SF4 (RB 3160). For each of them a minimum set of failure modes need to be analyzed and associated criteria to be fulfilled. Table 11 presents the transients, criteria levels and damage considered.

Due to French nuclear regulatory requirements, no level B criteria are considered for class 1 components.

Table 11: RCC-MRx Operating Conditions and Associated Damage Analyses

Transient	Criteria level	Damage considered
SF1$_{\&}$2 Normal operations (including normal operating incidents); start-up and shut-down	A	P-type S-type
SF$_3$ Emergency conditions	C	P-type
SF$_4$ Highly improbable conditions but whose consequences are of safety relevance	D	P-type

SF: category of operation conditions.
P-type: primary stress failure modes.
S-type: secondary stress degradation mechanisms generally attached to cyclic loads.

The following definitions for the different damage considered are provided in RCC-MRx:

P-type damage: Damage resulting from constant or monotonic loadings including excessive deformation (immediate or time dependent), plastic collapse (immediate or time-dependent) and time dependent fracture (creep rupture).

S-type damage: Damage resulting from cyclic loadings including progressive deformation (ratcheting), progressive deformation (ratcheting) + creep, fatigue and fatigue creep (creep-fatigue interaction).

Buckling: damage resulting from elastic or elastoplastic instability, (load controlled buckling, strain-controlled buckling and time dependent buckling).

Fast fracture: Fracture occurring without appreciable global deformations.

The following transient levels are provided in RCC-MRx:

Level A: aims at protecting the equipment against P-type and S-type damage. It guarantees the highest level of safety margins against both P-type and S-type damage throughout the entire life of the component.

Level C: aims at protecting the equipment against P-type and buckling damage. It guarantees a relaxed level of safety compared to level A (no fatigue analysis). Small overall deformations can occur if some loading (although satisfying level C) exceeds level A criteria. In this case, it could be necessary to inspect the component before re-using it. The number of stress cycles is limited to 10.

Level D: aims at protecting the equipment against the same damage of level C but with lower safety margins. It is not always possible to put again in service the components subjected to loadings limited only by level D criteria.

2.3.3 Scope of non-linear analysis

AFCEN RCC-MRx defines the requirements for limit analysis and lower bound approach in paragraphs RB 3228-1 and RB 3228-2. The definitions associated with non-linear analysis are as defined in section 2.3.3.1.

2.3.3.1 Definitions and failure modes

Limit Analysis: The deformation of a structure made of a perfectly plastic rigid material increases without bound for a loading level called the collapse load. The limit analysis methods enable this loading to be calculated.

A given load is less than or equal to the collapse load if there is a stress distribution which satisfies at all points the laws of equilibrium and such that the material plasticity criteria is at no point exceeded. This theorem allows a lower bound to be calculated for the collapse load.

Collapse load: is the load for which the overall offset deformation of the structure reaches the deformation which would occur in purely elastic behavior.

Elastic-plastic analysis and experimental analysis: in elastic-plastic analysis and experimental analysis, the collapse load by convention designates the load for which the overall offset deformation of the structure reaches the deformation which would occur in purely elastic behaviour.

Excessive deformation: is when the overall permanent deformation begins to increase rapidly and to a point that it is said to be excessive. The following convention is recommended: excessive deformation is attained when the overall permanent deformation exceeds the deformation which would occur with purely elastic behaviour.

Limit analysis and elastic-plastic analysis are defined in RB 3228-1 and -2.
Appendix A10.2000 provides detailed descriptions of the general principles for modelling including material plasticity models and constitutive equations.

RCC-MRx allows the use of a number of analysis methodologies including elastic, elastic-plastic with monotonic loading, elastic-plastic with cyclic loading and elastic-viscous-plastic. The latter one is not covered in this report.

RB 3241, 3242 and 3243 provide detailed requirements for the methodologies to be applied for elastic analysis, elastic-plastic analysis of a structure subjected to monotonic loading and elastic-plastic analysis of a structure subjected to cyclic loading.

Paragraph RB 3241 states that for elastic analysis, the following assumptions should be made:

- The behaviour of the material is elastic and linear.
- The material is isotropic.
- The displacements and strains are small.
- The initial stresses are nil.

The material behaviour law depends on Young's modulus E and Poisson's ratio ν; the transverse modulus G is equal to $E/[2(1+\nu)]$. The values of Young's modulus as a function of temperature are given in A3.22. Poisson's ratio is in general equal to 0.3 but can be modified in certain cases (A3.23).

Paragraph RB 3242 states that for elastic-plastic analysis under monotonic loadings, the following assumptions should be made:

- No unloading ever occurs in any part of the structure which undergoes plastic strain
- At all points of the structure, the stress tensor components calculated elastically vary simultaneously and proportionally to a single parameter
- The material is subjected to a monotonic increasing or decreasing loading
- The Von Mises plasticity criterion is applied
- The associated normality law for plastic strain: plastic flow rule is used,
- An isotropic strain hardening rule is used.

Detailed requirements for the use of tensile curves obtained experimentally are defined in RB 3242.1 and definitions of the von Mises plasticity criterion are defined in RB 3242.2,.

The flow rules that should be followed to carry out the strain calculations are defined in RB 3242.3 and the associated hardening rules are defined in RB 3242.4.

Elastic-plastic under cyclic loading requirements are defined RB 3243.

2.3.4 Plastic collapse (excessive deformation)

In RCC-MRx, limit analysis requirements are defined in paragraph RB 3251.11 for level A criteria, paragraph RB 3251.12 for level C criteria and paragraph RB 3251.13 for level D criteria.

When performing a limit analysis under RCC-MRx RB 3222.9, the absence of potential risk of elastic follow-up in the structures must be checked first. The structure will be protected from P-type damage if the characteristic stress S_0 does not exceed $S_m(\theta_{max})$. RCC-MRx defines the characteristic stress S_0 (Equation 25) and Table 12 defines the applicable limiting criteria for each design level.

Equation 25: RCC-MRx limit load definition

$$S_0 = (C/C_L)R_L$$

Where:
C_L = limit load for flow stress R_L,
R_L = elastic-perfectly plastic material yield strength
C = the applied load considered

The limit load C_L can be obtained either from a lower bound theorem or by an elastic-plastic analysis performed with an elastic, perfectly plastic material with a yield strength R_L.

Table 12: RCC-MRx Plastic Collapse Criteria Associated with Design Levels

Criteria level	Margin evaluation
level A	$S_0 \leq S_m$ (RB 3251.11)
level C	$S_0 \leq \min(1.35\,S_m;\,R_{p0.2\%})$ (RB 3251.12)
level D	$S_0 \leq \min(2.4\,S_m;\,0.7\,R_m)$ (RB 3251.13)

When elastic-plastic analysis is performed in accordance with RB3232, P-type damage should assessed by multiplying the load C by the multiplication coefficients as defined in Table 13.

Table 13: RCC-MRx Plastic Collapse Criteria Associated with Design Criteria Levels

Criteria level	Margin evaluation
Level A	$C_{app} \leq 1.5\ C_L$ (with S_y)
Level C	$C_{app} \leq 1.2\ C_L$ (with S_y)

No excessive deformation analysis is required for level D conditions when an elastic-plastic analysis is performed.

2.3.5 Plastic instability

The concept of plastic instability in RCC-MRx is defined in paragraph RB 3121.2 where the weakening of the structure due to deformation is no longer counteracted by the increase in strength of the material through strain hardening.

In order to assess for plastic instability, a full elastic-plastic analysis must be performed in accordance with RB3232, and the limiting condition for each level is defined in Table 14.

Table 14: RCC-MRx Plastic Instability Criteria Associated with Design Levels

Criteria level	Margin evaluation
Level A	$2.5\ S_0 \leq S_m$
Level C	$2.0\ S_0 \leq \min(1.35\ S_m;\ R_{p0.2\%})$
Level D	$1.35\ S_0 \leq \min(2.4\ S_m;\ 0.7\ R_m)$

2.3.6 Local failure requirements

No requirements are defined in RCC-MRx to protect the structure from local failure by triaxiality limitation.

2.3.7 Plastic shakedown requirements

2.3.7.1 Elastic analysis

For a given operating period, the progressive deformation evaluation method uses the notion of effective primary stress intensity. This effective primary stress intensity is compared with the allowable stress S_m. The following two methods can be used to prevent the appearance of progressive deformation.

Method 1: "efficacity diagram"

$SR_1 = \Delta Q / \max(\sigma_m)$ and $SR_2 = \Delta Q / \max(\sigma_L + \sigma_b)$

$SR \leq 0.46$; $v = 1$
$0.46 < SR < 4$; $v = 1.093 - 0.926\ SR^2 / (1 + SR)^2$
$SR \geq 4$; $v = 1 / SR^{0.5}$

Criteria: $P_1 \leq 1.3\ S_m$ and $P_2 \leq 1.3 \times 1.5\ S_m$

Method 2: Level A criteria alternative rule

For a period covering all loadings for which compliance with level A criteria is required, the following limit must be checked at all points of the structure: the sum of the maximum stress value Max $\overline{(P_L + P_b)}$ and the secondary stress range value ΔQ must be less than 3 Sm (see equation

Equation 26: Elastic analysis method 2 approach

$$\text{Max}\ \overline{(P_L + P_b)} + \overline{\Delta Q} \leq 3\ S_m$$

2.3.7.2 Elastic-plastic analysis

Progressive deformation analysis using simplified elastic-plastic methods is defined in Appendix A10.9000 of RCC-MRx. A progressive deformation analysis method for use in elastic analysis is given in RB 3261.111. A special procedure exists for dealing with the case where the loading induces significant secondary membrane stresses, particularly in the case of axial thermal gradient.

If, where such loadings exist, the elastic analysis rules for progressive deformation are not satisfied, one of the two simplified elastic-plastic methods described below may be used:

Method 1: This method is similar to the one described in RB 3261.111 except that stresses, max (σ_m) and max ($\sigma_L+\sigma_b$), are evaluated from the plastic calculation for the first loading cycle. The rule is then applied in the same manner as in RB 3261.1112 to RB 3261.1115.

Method 2: This method is derived from elastic analysis methods using an efficiency diagram. It has been put forward as a way of improving forecasts obtained with efficiency diagrams, particularly where there is significant elastic follow-up and significant secondary membrane stresses

This enables the stress intensity to be evaluated at all points of the structure (Equation 27)

Equation 27: Stress Intensity

$$\bar{\sigma}_{max} = \left(\frac{E\vartheta}{\bar{P}}\right)^{\frac{1}{2}\ln(1+\,\alpha.\beta.\gamma)} .\bar{P}$$

where :

ϑ = Max$\{\varepsilon_1,\Delta\varepsilon\}$

ε_1: maximum elastic + plastic strain intensity obtained at the point considered using an elastoplastic calculation for the first loading cycle. This calculation is performed under all mechanical and thermal loadings using one of the models described in A10.4000 to A10.6000, with minimum monotonic material behaviour curves for materials subject to cyclic hardening and reduced cyclic curves for materials subject to cyclic softening. This should be considered when we use the term "material tensile curve".

$\Delta\varepsilon$: variation in elastoplastic strain intensity for the cycle

E: Young's modulus corresponding to the temperature θ_{max} of the point considered at the moment in time when the value of ε_1 is reached.

$\bar{P}$: primary stress intensity given by Equation 28:

Equation 28: Primary stress intensity calculation

$$\bar{P} = \{\overline{\sigma_p} \text{ If } \overline{\sigma_p} \neq 0 \ ; \ (\text{E}.\vartheta - \overline{Q_{max}}) \text{ if } \bar{\sigma}_p = 0\}$$

σ_p: total stress intensity obtained at the point studied during an elastic analysis, under the effect of the imposed forces

Q_{max}: maximum membrane + bending stress intensity due to loads of imposed displacement type obtained at the point studied during elastic analysis.

α, β and γ are correction terms which depend upon the material and the loading. They are given below for materials covered by Properties Groups 1S, 2S, 3S, 4S and 18S of RCC-MRx Appendix A3 (Equation 29):

Equation 29: Correction factors for material and loading conditions

$$\alpha = ln\left(1.75 + 2.8\frac{R_{p0.2}}{E\bar{\epsilon}_1}\right) \ \beta = \ln\left(0.25 + 2.3\frac{R_{p0.2}}{\bar{P}}\right) \ \gamma = ln\left(2.10 + 4.5\frac{\sigma_{1\%}-R_{p0.2}}{R_{p0.2}}\right)$$

2.3.8 Fatigue analysis requirements

2.3.8.1 Elastic analysis

With regard to the application of RCC-MRx rules, the damage resulting from the effects of fatigue must be estimated for all loading cycles requiring compliance with level A criteria.

At each point of the structure, this set of cycles shall be characterized by the fatigue usage fraction $\mathrm{V_A}\ (\overline{\Delta\varepsilon})$ calculated in accordance with RB 3261.1123.

The cumulative fatigue usage fraction at a given point of the structure is calculated using equation Equation 30.

Equation 30: Cumulative Fatigue usage fraction

$$V = \sum_j \frac{n_j}{N_j}$$

The strain cycles corresponding to the operating period concerned are classified into different types of cycles. For each type of cycle j:

- The number $\mathrm{n_j}$ of associated cycles is given in the Design Specification.
- The strain range $\overline{\Delta\epsilon_j}$ associated with is determined.
- The maximum number $\mathrm{N_j}$ of strain cycles allowable for the type of strain cycle j is determined with the specified fatigue curves given in RCC-MRx Appendix A3.
- The fatigue usage fraction for the type of strain cycle j is equal to the ratio of the number of strain cycles $\mathrm{n_j}$ to the maximum allowable number $\mathrm{N_j}$ for this type of cycle.

2.3.8.2 Simplified elastic-plastic analysis K_e, K_v

RCC-MRx requirements for the calculation of the fatigue usage factor $\boldsymbol{V_A}\ (\overline{\varDelta\boldsymbol{\epsilon}})$ in order to assess the components for S-type damage are defined in Paragraph RB 3261.1123 for the simplified elastic-plastic analysis (Equation 31):

Equation 31: calculation of total strain range using simplified elastic-plastic analysis

$$\overline{\Delta\boldsymbol{\epsilon}} = \overline{\Delta\boldsymbol{\epsilon}_1} + \overline{\Delta\boldsymbol{\epsilon}_2} + \overline{\Delta\boldsymbol{\epsilon}_3} + \overline{\Delta\boldsymbol{\epsilon}_4} \text{ from elastic stress range } \overline{\Delta\sigma_{tot}}$$

For each of the cycles under analysis, the range of the total stress calculated elastically at the point under examination $\overline{\varDelta\sigma_{tot}} = \overline{\varDelta(P+Q+F)}$ must be known.

This range can be obtained either by a sufficiently detailed calculation of the region concerned or by using the stress concentration factor.

These four strain terms are determined using the cyclic curve corresponding to the highest temperature at the point examined during the cycle concerned (maxθ) using the following equations

Equation 32: Strain range component calculations for fatigue usage factor using simplified elastic-plastic analysis

$$\overline{\Delta\boldsymbol{\epsilon}_1} = \frac{2}{3}\,(1+\nu)\,\overline{\Delta\sigma_{tot}}\,/\,\mathrm{E}$$

$$\overline{\Delta\boldsymbol{\epsilon}_2} = \overline{\Delta[\,P_m + 0.67\,(P_b + P_L - P_m)]}$$

$\overline{\varDelta\boldsymbol{\epsilon}_3}$, the "plastic" increase in strains, intersection point of the cyclic curve and the hyperbola $\overline{\varDelta\boldsymbol{\sigma}}.\overline{\varDelta\epsilon}$ = constant passing through point (c), with coordinates $[\overline{\varDelta\epsilon_1} + \overline{\varDelta\epsilon_2}\ ;\overline{\varDelta\sigma_{tot}}\,]$

$\overline{\varDelta\boldsymbol{\epsilon}_4} = (K_\nu - 1)\,\overline{\varDelta\boldsymbol{\epsilon}_1}$ represents the plastic increase in strain due to triaxiality.

Table 15: Calculation of the Strain ranges for RCC-MRx Fatigue Analyses

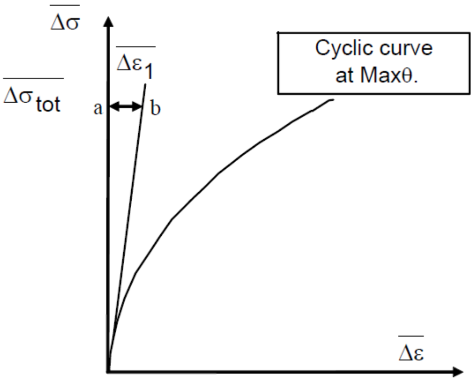


Diagram 1: Determination of $\Delta\varepsilon 1$
$\Delta\varepsilon_1$ represents the strain range given by elastic analysis $\Delta\varepsilon 1$ is calculated on the basis of elastic analysis

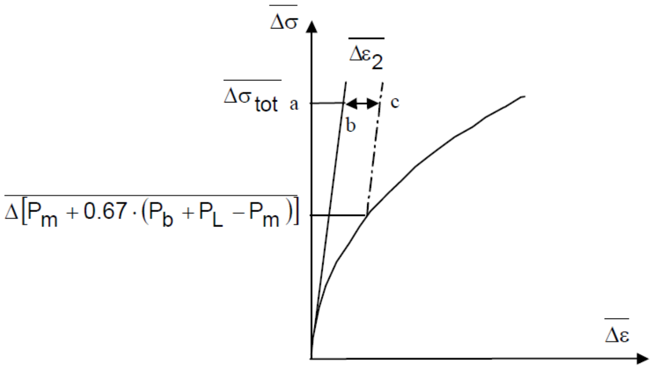


Diagram 2: Determination of $\Delta\varepsilon 2$
$\Delta\varepsilon_2$ represents the plastic increase in strain due to the primary stress range at the point examined, equal to $\Delta\ [P_m{+}0.67(P_b{+}P_L{-}P_m)]$

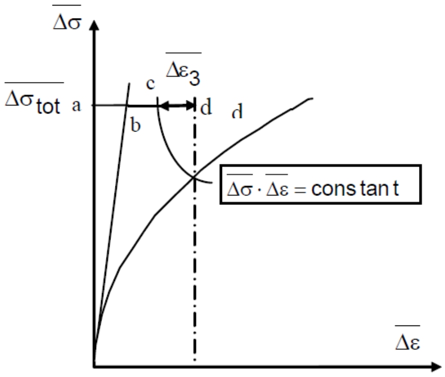


Diagram 3: Determination of $\Delta\varepsilon_3$
$\Delta\varepsilon_3$ represents the plastic increase in strains along path (cd);
(d) is the intersection point of the cyclic curve and the hyperbola $\Delta\sigma \cdot \Delta\varepsilon$ = constant passing through point (c) with coordinates
$(\Delta\varepsilon_1 + \Delta\varepsilon_2\ ;\ \Delta\sigma_{tot})$

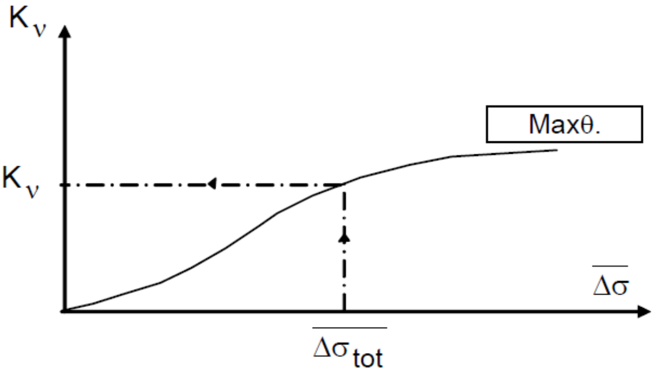


Diagram 4: Determination of $\Delta\varepsilon_4$
$\Delta\varepsilon_4$ represents the plastic increase in strain due to triaxiality.

2.3.8.3 Elastic-plastic analysis

No elastic-plastic analysis procedure is available to derive K_e. Nevertheless, a procedure for direct evaluation of the total strain range is available in RCC-MRx Appendix 10. The code requires the user to perform cyclic elastic-plastic analysis for all the sub-cycles experienced by the component. For each sub-cycle, the ratio of peak to minimum equivalent strain needs to be determined, and the fatigue usage factor $V_A\,(\overline{\Delta\varepsilon_{eq}})$ should then be determined from each sub-cycle.

RCC-MRx Appendix A10 does not provide a detailed description of all the phenomena induced by the non-linear behaviour of materials. Instead, it sets out to describe the laws that are available today for producing the best possible models for some of them.

A10.2000 to 6000give the equations used to describe the behaviour of the material:

- General Principles for medialization (A10.2000)
    - Von Mises plasticity criteria.
    - Plastic flow rule.
    - Strain hardening law.

- Perfectly Plastic Material (A10.3000).
- Isotropic Strain Hardening (A10.4000).
- Kinematic Strain Hardening (A10.5000).
- Combined Strain Hardening (A10.6000).
- A10.7000 is a user guide to the various material behaviour mathematical models,
- A10.8000 deals with problems relating to extrapolation methods. Various acceleration and extrapolation methods are proposed in order to reduce the number of cycles to be calculated.

2.3.9 Piping stress classification

2.3.9.1 Introduction

For complex geometries and loading, stress classification is needed to apply elastic methods and associated criteria. Never the less, in RCC-MRx, it is possible to use non-linear analysis methods to support the stress classification or justify some complex classification rules in piping systems.

2.3.9.2 Nozzle to piping transition zone

Different rules are proposed for vessels, piping, pumps and valves for reinforcement areas and stress classification in different part of the nozzle. All these rules are based on elastic approaches, with no possibility to use dedicated non-linear analysis.

2.3.9.3 Piping analysis

It is possible that a small part of a mechanical structure will undergo inelastic deformation whereas the rest of the structure undergoes predominantly elastic deformations. The majority of the structure thus acts as a spring with regard to a small part of the structure. Even if the loading only causes relaxable stresses, the flexibility of the spring part can induce large deformations of the small inelastic part, without stress relaxation being effective. This is due to the fact that the large local deformations of the inelastic part do not result in sufficient distortion of the entire structure. The inelastic zones can be the areas where strain concentrations are likely to damage the structure despite the fact that the major part of the stresses is considered as relaxable. The elastic follow-up mostly has harmful effects (local damage or even fracture) when the design of the structure is inadequate.

It should be pointed out that unless the design is really clumsy, the harmful effects are infrequent if there is no creep. It is in fact when the strain is highly dependent on the stress applied that the accumulation of local strain easily occurs.

RCC-MRx limit analysis or elastic-plastic analysis can be used to prevent this local effect.

2.3.9.4 Seismic piping criteria

RCC-MRx Appendix A1 is dedicated to seismic load criteria with possible use of non-linear analysis, without detailed procedure, data and associated criteria.

2.3.10 First conclusion on RCC-MRx code and open points

2.3.10.1 Elastic-plastic analysis requirements

The RCC-MRx code allows the user to apply elastic-plastic analysis as an alternative to elastic analysis. Notably, limit load analysis can be used for collapse load analysis and instability load for vessel design using S_y flow stress. For all the other cases, only very general methods are proposed in the code. Whilst many advanced non-linear analysis methods are described in the code book, the application of these methodologies to meet the code requirements is not very well defined.

Many material properties for elastic-plastic analysis are defined in RCC-MRx Appendix A3 and A9 for conventional base metals and welds. This includes monotonic and cyclic stress-strain curves versus temperature.

No detailed methods are available in RCC-MRx for K_e evaluation, fatigue direct strain amplitude evaluation and plastic shakedown analysis.

Two innovative rules are included in the code:

- A K_v formula proposed to correct elastic fatigue analysis, part of the correction factor for K_e,
- A plastic shakedown analysis with "efficacity diagram"

No requirements or proposals for local failure are suggested in the RCC-MRx code.

2.3.10.2 Open points

There are still a number of open issues in the use of elastic-plastic analysis when applying the AFCEN RCC-MRx requirements:

- Detailed requirements for the transferability of collapse analysis results based on Tresca or von Mises analysis.
- Guidelines for the use of classical finite element analysis (FEA) for limit load evaluation would be a useful addition to the code.
- Use of limit analysis for level D criteria (possible large displacement) and flow stress value should be defined in the code.

Detailed recommendations for finite element analysis should be in the code, such as:

- Temperature to use for each step of these analyses.
- Tolerances and precise geometry to perform inelastic analysis.
- More general FEA recommendations (mesh refinement, small versus large displacement, convergence criteria, etc.).
- Guidelines to perform cyclic elastic-plastic analysis for fatigue and shakedown analysis should be included in the code with associated validation, material properties and criteria.
- Strain criteria for different elastic-plastic, with possible modification in the user's design specification.
- Local failure requirements for levels A, B and C should be added through elastic and elastic-plastic analysis with associated validated criteria.

2.4 KTA German Nuclear Code

2.4.1 Introduction

In Germany, the Nuclear Safety Standards Commission[8] (KTA) has the task of issuing nuclear safety standards. The KTA standards are issued when a consensus has been reached between experts from the national manufacturers, nuclear power plant operators, authorized experts and state officials. The KTA Standards are published by the German government, and are therefore required by federal law.

The KTA design rules were originally derived from ASME Section III rules. The code has evolved with time to incorporate specific German industrial experience in pressure equipment. KTA has a smaller scope than ASME BPVC, and is limited to pressure retaining components and LWR technology.

KTA 3201.2: *Components of the Reactor Coolant Pressure Boundary of Light Water Reactors, Part 2: Design and Analysis* is investigated in this report. It specifies detailed requirements for:

- The classification into code classes, load case classes and level loadings.
- The design and analysis of components.
- The calculation procedures and design principles for obtaining and maintaining the required quality of the components.
- The documents for the certificates and demonstrations to be submitted.

2.4.2 Transient category and criteria level

Five categories of transient are considered in RCC-M: normal, upset, emergency, faulted and test. These are supplanted by a reference situation corresponding to maximum pressure and temperature in normal operation. For each of them a minimum set of failure modes should be analyzed and associated criteria are required to be fulfilled (Table 16)

Table 16: KTA Transient and Criteria Level

Transient	Criteria Level	Damage considered
Normal	A	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and ratcheting Fatigue
Upset	B	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and ratcheting Fatigue
Emergency	C	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Faulted	D	Plastic instability Elastic and elastic-plastic instability
Test	T	Excessive deformation

2.4.3 Scope of non-linear analysis

General requirements are considered for the use of non-linear analysis in KTA 3201.2 paragraph 7.4.

---

[8] Kerntechnischer Ausschuss

2.4.4 Plastic collapse (excessive deformation)

Elastic-plastic analysis for plastic collapse is possible in KTA 3201, but no detailed rules are proposed; in particular no recommendations are proposed for limit load analysis.

2.4.5 Plastic instability

Elastic-plastic analysis for plastic instability is possible in KTA 3201, but no detailed rule is proposed; in particular no recommendations are proposed for limit load analysis or elastic-plastic analysis nor associated criteria.

2.4.6 Local failure requirements

A local failure analysis is not considered in KTA 3201.

2.4.7 Plastic shakedown requirements

Elastic-plastic shakedown analysis is not considered in KTA 3201.

2.4.8 Fatigue analysis requirements

2.4.8.1 Elastic analysis

KTA 3201 proposes similar rules as ASME Section III NB.

2.4.8.2 Simplified elastic-plastic analysis K_e

KTA 3201 proposes similar rules as ASME Section III NB

2.4.8.3 Elastic-plastic analysis

KTA 3201 does not propose elastic-plastic analysis rules for K_e evaluation or direct strain range amplitude evaluation in order to perform fatigue analysis.

2.4.9 Piping stress classification

No specific rule proposed in KTA 3201.

2.4.10 First conclusion on KTA code

2.4.10.1 Elastic-plastic analysis requirements

KTA accepts non-linear design rules by computation of the structural behaviour under given loads considering the plastic characteristics of the materials, including strain hardening and the stress redistribution occurring in the structure. In KTA 3201.2, Chapter 7.4: Stress/Strain Loadings, KTA mentions that in the case of elastic-plastic analysis the effective stress-strain relationship shall be taken into account. In KTA 3201.2, Chapter 7.7 mentions that, by means of a stress analysis that no inadmissible distortions and especially only limited plastic deformations occur shall be proved in conjunction with the material properties.

2.4.10.2 Conclusion on KTA 3201-2

Non-linear analysis based on elastic-plastic material behaviour is possible in KTA 3201-2, but no detailed rules, data and criteria are proposed in KTA for monotonic and cyclic non-linear analysis.

2.5 JSME EPD Code Case

2.5.1 Introduction

In Japan, the Design by Analysis concept was incorporated into the MITI Notification 501 of a Japanese regulatory code and also the JSME Design & Construction Code. The JSME Design & Construction Code allows partial use of plastic analysis but does not have a rule on shakedown plastic-analysis nor a detailed procedure. Never the less, the JSME EPD Code Case provides alternative rules for primary stress evaluation, primary + secondary stress evaluation, thermal ratcheting evaluation and fatigue evaluation.

In this report, both the JSME Design & Construction Code and the JSME EPD Code Case are considered. It is important to note that no English version of the code was available in the drafting of this report. As such, supporting papers and reports were used to compile the list of JSME requirements for non-linear analysis requirements.

2.5.2 Background to JSME EPD Code Case:

In order to develop a plastic analysis design methodology, an alternative stress evaluation criterion suitable for inelastic FEA was developed by the Committee on Three Dimensional Finite Element Stress Evaluation (C-TDF) of the Japan Pressure Vessel Research Council. The Committee on Elastic-Plastic Analysis Design Guideline (C-EPD), as a research committee of the Thermal and Nuclear Power Engineering Society, studied and revised the alternative criteria to apply to class 1 components of nuclear power plants. A proposed code implementing the alternative criteria was discussed by the committees on Codes for Nuclear Power Generation Facilities – Rules on Design and Construction for Nuclear Power Plants of JSME. A Code Case on alternative design methodology, using elastic-plastic FEA for class 1 vessels, was introduced in JSME rules on design and construction (JSME EPD Code Case).

2.5.3 Transient category and criteria level

Five categories of transient which have to be considered are specified in the JSME code: normal, upset, emergency, faulted and test. Each transient category has an associated criteria level and associated failure criteria to be met (Table 17).

Table 17: JSME Transient and Damage Considered

Transient	Criteria level	Damage considered
Normal	A	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and ratcheting Fatigue
Upset	B	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and ratcheting Fatigue
Emergency	C	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Faulted	D	Plastic instability Elastic and elastic-plastic instability
Test	T	Excessive deformation

2.5.4 Scope of non-linear analysis

The JSME Design & Construction Code is supplemented by the JSME EPD Code Case. The JSME EPD Code Case provides alternative rules for the JSME Design & Construction Code for Primary Stress Evaluation, Primary + Secondary Stress Evaluation, Thermal Ratcheting Evaluation, and Fatigue Evaluation.

The JSME EPD Code Case was developed to protect against ductile failure/plastic collapse, excessive plastic distortion/ratcheting and fatigue failure. Furthermore, the JSME EPD Code Case aims to eliminate stress linearization and classification. It is has been developed to accurately evaluate the failure modes identified above by using elastic-plastic finite element analysis (FEA).

The current JSME Design & Construction Code uses Tresca equivalent stress for stress intensities, but the JSME EPD Code Case uses von Mises equivalent stress in order to be consistent with conventional elastic-plastic FEA which use the von Mises yield criterion.

On the other hand, the current JSME Design & Construction Code requires pure shear evaluation but does not exclude the von Mises yield criterion. The von Mises yield criterion is more accurate than the Tresca yield criterion, but the Tresca yield criterion was chosen because it is a little more conservative, is easier to apply, and offers advantages in some applications such as fatigue analysis.

Here, Tresca equivalent stress can be positive or negative and the difference between the two is the stress intensity range. The evaluation of range of von Mises equivalent stress requires another method. ASME BPVC Section III specifies two kinds of methods in NB 3216 *Derivation of Stress Differences*. One is NB 3216.1 *Constant Principal Stress Direction* and the other is NB 3216.2 V*arying Principal Stress Direction*. The latter method is used for any case in which the directions of the principal stresses at the point being considered change during the stress cycle and also for calculating stress intensities by subtracting each of the stress components of an extreme from the corresponding stress components of the other extreme. This method is a more general procedure and the von Mises equivalent stress range also can be obtained by using this method. The JSME EPD Code Case has employed this method to calculate the von Mises equivalent stress range in the same way as the ASME B&PV Code Section VIII, Division 2.

2.5.5 Plastic collapse (excessive deformation)

JSME PVB 3160 specifies limit analysis as the primary stress evaluation method. Three approaches are available in JSME for the derivation of the collapse load (C_L): limit load analysis, elastic compensation method and twice elastic slope method.

The limit load analysis methodology is based on the lower bound theorem. It can be derived from compendia of limit load solutions, or from elastic-perfectly-plastic analysis, with the limit load defined as the maximum load.

The elastic compensation method is based on the lower bound theorem. The Young's modulus is modified at each position in the structure by an iterative elastic FEA in accordance Equation 33:

Equation 33: Collapse load analysis using the elastic compensation method

$$E^{(i+1)} = E^{(i)}.\ S / \sigma^{(i)}$$

This procedure reduces the stiffness at the higher stress regions and increases it at the lower stress regions. The maximum von Mises equivalent stress at each iteration step is calculated and $\overline{\sigma_{eqb}}$ is set to the minimum von Mises equivalent stress in all steps. $\overline{\sigma_{eqb}}$ is compared with the allowable stress for each service level. Nishiguchi *et al.* applied the elastic compensation method to complex three-dimensional models and dissimilar cylinder models, and obtained accurate and conservative predictions of the limit loads. Hence, the elastic compensation method has been incorporated into JSME EPD Code Case.

The twice elastic slope approach is the same approach as the one defined in ASME BPVC Section III Appendix II-1430.

JSME requires the use of S_m for the yield strength of limit analysis to analyze the allowable limit load on design conditions, similar to ASME Code Sections III and VIII Division 2, which require the fulfilment of the thickness equation before limit load analysis.

JSME requires the use of $1.5\ S_m$ flow stress for level A loading. No supplementary details are provided for level C. For level D requirements, two analysis methods are available, limit-load analysis and elastic compensation method.

Two methods are available to determine a collapse load from a load-deflection curve:

- The lower bound approach. This method determines the maximum load as the final load at which convergence was achieved in the finite element analysis.
- The twice elastic slope method, using the same definition as ASME Section III, Appendix II, II-1430.

2.5.6 Plastic instability

The analysis of plastic instability in JSME is based on a limit analysis, using of $1.5S_m$ as the flow stress.

2.5.7 Local failure requirements

The local failure requirements in the JSME Code are same as in ASME Section III NB.

2.5.8 Plastic shakedown requirements

Plastic shakedown is not considered in the JSME Code, but is covered by the JSME EPD Code Case.
The JSME EPD Code Case conservatively uses the elastic-perfectly-plastic model, so as to comply with the Miller's Diagram. In order to do this, two criteria have been developed:

- Equivalent plastic strain criterion.
- Elastic region width criterion.

Further details are presented in: *"Overview of Code Case on Alternative Design Methodology by Using Elastic-Plastic Finite Element Analysis for Class 1 Vessels in JSME Rules on Design and Construction", PVP2010-25525.*

2.5.9 Fatigue analysis requirements

The JSME EPD Code Case specifies two methods to calculate K_e-factors, by formula of by elastic-plastic analysis.

2.5.9.1 Elastic analysis

The JSME code proposes the same rules as ASME Section III NB rules for elastic fatigue analysis.

2.5.9.2 Simplified elastic-plastic analysis K_e,

The current JSME Design & Construction Code has the K_e-factor formula expressed by Sn. This K_e-factor formula was developed by the Committee on Stress Compensated (K_e) Factor for Simplified Elastic-Plastic Analysis, similar to ASME Code Section III.

This committee also developed the K_e-factor formula expressed by S_p as follows:

$$K_e'' = \frac{\overline{\varepsilon_{ep}}}{\overline{\varepsilon_e}} = 1 + (q_p - 1)\left(1 - \frac{3S_m}{S_p}\right)$$

Where: $q_p = (q_1 - q_0)\left(1 - \frac{3S_m}{S_p}\right) + q_0$

With: $q_0 = 1.5$ and $q_1 = 4.0$

2.5.9.3 Elastic-plastic analysis

Elastic-plastic analysis is possible in the JSME code, but no detailed rules are included in the code.

2.5.10 Piping stress classification

2.5.10.1 Nozzle to piping transition zone

The nozzle to piping transition zone is not considered in the reference JSME code.

2.5.10.2 Piping analysis

The non-linear analysis like elastic follow-up in piping systems is not considered in JSME code.

2.5.11 First conclusion on the JSME code and open points

2.5.11.1 Elastic-plastic analysis

JSME Code:

- Limit load analysis can be used for collapse load analysis and instability load for vessel design using 1.5 S_m flow stress for Level A loading, and S_m for design analysis and thickness evaluation.
- Elastic-plastic analysis is only possible through the twice elastic slope method, used to define plastic collapse loads. The JSME EPD Code Case provides detailed alternative rules for elastic-plastic analysis, with the aim of eliminate the need to categorize and linearize stresses.
- For all the other cases, the use non-linear analysis is not generally forbidden in the code. However, there is very limited scope for the use of non-linear analysis for piping systems, in particular for level D specific criteria.
- For the evaluation of K_e or fatigue direct strain amplitude, non-linear analysis methods are not forbidden, but no detailed methods are proposed in the code.
- Two alternative rules for K_e formulae are available in the code, one based on S_p and one based on the compensation method for simplified elastic-plastic analysis of fatigue.
- Only elastic analysis is available for for level A to C loads, with no requirements for level D.

JSME EPD Code Case:

The JSME EPD Code case consists of *Protection Against Collapse, Evaluation for Cyclic Loading and Fatigue Assessment.* Evaluation for protection against collapse no longer needs stress linearization and classification and the limit load for a component is directly analyzed by using elastic-plastic FEA or Elastic Compensation Method.

Evaluation for cyclic loading also no longer needs stress linearization and classification and consists of two steps.

The first step requires elastic FEA for thermal transients in the same way as the conventional method using stress linearization and classification, but the JSME EPD Code Case directly evaluates shakedown from FEA results without the stress linearization/classification process. If the requirement for shakedown is not satisfied, ratcheting assessment (the second step evaluation) is performed by using elastic-plastic FEA.

Fatigue assessment needs elastic FEA for thermal transients in the same as the conventional method but does not need stress linearization/classification process. The stresses on the surface are used for fatigue analysis and elastic-plastic FEA is performed if the shakedown requirement is not satisfied.

For cyclic loadings, the JSME EPD Code Case provides original alternative methods using elastic-perfectly-plastic material behaviour for shakedown analysis and two criteria, equivalent plastic strain criterion or elastic region width criterion

2.5.11.2 Open points

There are still a number of open issues in the use of elastic-plastic analysis when applying the JSME requirements and the EPD Code Case:

- The transferability between the Tresca and von Mises analyses should be validated.
- Validation of the use of finite element analysis (FEA) for lower bound limit load evaluation has to be developed.
- Use of limit analysis for level D criteria (possible large displacement) and flow stress values need to be validated and a specific procedure should be proposed in the code.

Detailed recommendations for finite element analysis should be in the code, such as:

- Temperature to use for each step of these analyses.
- Tolerances and precise geometry to perform inelastic analysis.
- More general FEA recommendations (mesh refinement, small versus large displacement, convergence criteria, etc.).
- Cyclic elastic-plastic analyses for fatigue and shakedown.
- The strain criteria for elastic-plastic analysis should be proposed in the code with possible modification by the user's design specification.
- Local failure requirements through elastic and elastic-plastic analysis should be added to the code with associated criteria.
- All the material properties for these analyses (engineering/ true and cyclic stress-strain curves, material constitutive equations, etc.) should be included in the code.

2.6 Korean Nuclear Code

2.6.1 Introduction

Korea Electric Power Industry Code (KEPIC) MN *Rules for Construction of Nuclear Facility Components* is developed by KEA (Korea Electric Association).

The 2010 edition was used for this comparison. It is important to note that no English translation was available at the time and input from KEPIC was used to draft the comparison. The last published edition or addenda in Korean and English is 2013 addenda.

The KEPIC MN code was developed based on ASME BPVC and its structure is therefore similar to the ASME Code (see Table 18).

Table 18: KEPIC MN Nuclear Code Content

KEPIC MN Title		ASME BPVC Sec. III
MNA	General Requirements	NCA & Div. 3 WA
MNB	Class 1 Component	Div. 1 Subsection NB
MNC	Class 2 Component	Div. 1 Subsection NB
MND	Class 3 Component	Div. 1 Subsection ND
MNE	Metallic Containment	Div. 1 Subsection NE
MNF	Support	Div. 1 Subsection NF
MNG	Core Support Structure	Div. 1 Subsection NG
MNS	Class TC Transportation Containment	Div. 3 Subsection WC
MNT	Class SC Storage Containment	Div. 3 Subsection WB
MNZ	Appendices	Div. 1 Appendices

2.6.2 Transient categories and criteria levels

Five categories of transients are considered in the KEPIC MN Code: normal, upset, emergency faulted and test. Each transient category has an associate criteria level and associated failure criteria to be designed against (see Table 19)

Table 19: KECPIC MN Transient and Damage Considered

Transient	Criteria Level	Damage considered
Normal	A	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and ratcheting Fatigue
Upset	B	Excessive deformation Plastic instability Elastic and elastic-plastic instability Plastic shakedown and ratcheting Fatigue
Emergency	C	Excessive deformation Plastic instability Elastic and elastic-plastic instability
Faulted	D	Plastic instability Elastic and elastic-plastic instability
Test	T	Excessive deformation

2.6.3 Scope of non-linear analysis

The KEPIC MN Code has a similar structure and similar rules to ASME BPVC Section III. In KEPIC MN, non-linear analysis considering elastic-plastic behaviour of materials is defined in MNB 3228 *Application of Plastic Analysis*, which is similar to ASME Section III NB 3228.

2.6.3.1 Definitions and non-linear analysis rules

KEPIC MNB-3213 defines the terms associated with design by analysis for class 1 Vessels. The scope of the terms defined as well as their definitions are the same as in ASME BPVC III NB 3213, namely: plasticity, plastic analysis, collapse load, plastic instability load, limit analysis, limit load, lower bound approach, plastic hinge, ratcheting and shakedown.

Plastic analysis can be conducted when defining the stress limits of components other than bolts using the requirements defined in MNB-3220. The basic analysis methodology allows the user to apply elastic analysis for stresses beyond the yield strength (MNB 3227.6):

- In evaluating local thermal stresses, the elastic equation can be used with ν modification: $\nu = 0.5 - 0.2\,(S_y / S_a)$.
- With Sa alternating stress intensity from MNZ Figure I-9.0 of MNB-3222.4.

Basic limits of stress intensity can also be relaxed using limit analysis as defined in MNB 3228.1, or by using collapse load determined by test as defined in MNB 3228.2. Full plastic analysis using the actual material stress-strain curve is defined in MNB 3228.3.

Full elastic-plastic analysis approach is available for cyclic loading, but no detailed approach or criteria are defined for plastic shakedown (MNB 3228.4) or for fatigue analysis (MNB 3228.5(2).

The $3S_m$ limit on the range of primary plus secondary stress intensity may be exceeded in cases defined in MNB 3228.5(1)

2.6.3.1.1 *MNB 3600: class 1 piping design by analysis rules*

Elastic rules are defined in MNB 3611.2. MNB 3656 refers to dedicated non-mandatory Appendix F for level D criteria with possible use of non-linear analysis.

2.6.3.1.2 *MNC 3000-MND 3000: class 2-3 components design by analysis rules*

No approach for non-linear elastic-plastic analysis is proposed in KEPIC MN code.

2.6.4 Plastic collapse (excessive deformation)

Similarly to ASME BPVC Section III NB, the KEPIC MN Code defines in MNB 3213.25 theplastic collapse load as the load determined with $\phi = \tan^{-1}(2 \tan \theta)$ (see Figure 2)

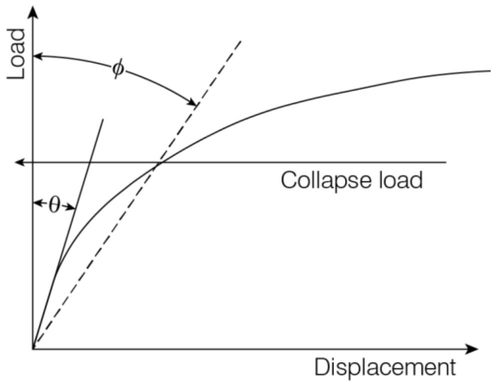


Figure 2: Collapse load definition

2.6.5 Plastic instability

Plastic instability is defined in MNB 3213.26 as the point at which unbounded plastic deformation occurs without an increase in the load.

As in ASME III Code, limit load using $1.5\ S_m$ is considered as covering plastic instability load.

2.6.6 Local failure requirements

In MNB 3227.4, the algebraic sum of the three elastic primary principal stresses ($\sigma_1 + \sigma_2 + \sigma_3$) shall not exceed 4 times the tabulated value of S_m, except for Service Level D:

$$\sigma_1 + \sigma_2 + \sigma_3 < 4\ Sm$$

No alternative rules using non-linear analysis are proposed.

2.6.7 Plastic shakedown requirements

Elastic analysis is proposed in MNB 3222.2 and 3227.6, where the limit on primary plus secondary stress intensity of $3Sm$ has been placed at a level which ensures shakedown to elastic action.

Non-linear analysis possibilities for shakedown analysis are mentioned in MNB-3228.4, but no recommendation to use cyclic elastic-plastic analysis is developed in trhe KEPIC MN code.

2.6.8 Fatigue analysis requirements

2.6.8.1 Elastic analysis

Cumulative usage factor U is determined by elastic analysis for cyclic loading in MNB 3222.4. For all the major class 1 and 2 components, elastic analysis is required based on S_{alt} and considering (S,N) design fatigue curves defined in MNZ I-9.0:

$$S_{alt}=0.5 \cdot S_{range} \cdot \beta \cdot K_e$$

Where β= correction factor for elastic modulus, K_e: elastic-plastic stress concentration factor

2.6.8.2 Simplified elastic-plastic analysis K_e

A similar rule to ASME Section III NB is proposed in KEPIC MN Code, where S_{alt} is multiplied by a K_e greater than 1 when the linearized stress S_n is greater than $3\ S_m$:

$K_e = 1$ for $S_n \leq 3\ S_m$
$K_e = 1.0 + \{(1-n)(S_n / 3\ S_m - 1) / [n\ (m-1)]\}$ for $3\ S_m < Sn < 3m\ S_m$
$K_e = 1/n$ for $S_n \geq 3m\ S_m$

Table 20: m and n Values for Different Materials

Materials	m	n
Carbon steel	3.0	0.2
Low alloy steel	2.0	0.2
Martensitic stainless steel	2.0	0.2
Austenitic stainless steel	1.7	0.3
Nickel-chromium iron	1.7	0.3
Nickel-copper	1.7	0.3

2.6.8.3 Elastic-plastic analysis

No direct proposals to derive K_e or evaluate direct strain amplitude using non-linear material properties are included in KEPIC MN code.

2.6.9 Piping stress classification

No detailed information is provided in KEPIC MN for the piping stress classification

2.6.10 First conclusion on the KEPIC code and non-linear analysis rules

Only plastic limit load and elastic-plastic analysis can be performed with KEPIC MN Code, using similar rules as ASME BPVC Section III (paragraph 2.2 of this report). As in the ASME BPVC III Code, non-linear analyses based on elastic-plastic material behaviour are possible, but no detailed rules are proposed for monotonic and cyclic non-linear analysis.

2.7 Russian Nuclear Code

2.7.1 Introduction

To date only PNAE G-7-002-86 (1989) [7] is legally recognized by Russian regulatory body *Rostechnadzor*. The document should be used as a basis for Nuclear Power Plant design in Russia. Division RPP of SPiR-BN-2011 Code *Rules for NPP Components of Sodium Cooled Reactor* has been finished in 2012. Division RPP of SPiR-VVER-2013 *Code of Rules for NPP Components of VVER-type reactor* is in project and is expected to replace PNAE G-7-002-86 as the code defining the requirements for the design of VVER-type reactors.

PNAE G-7-002-86 prescribes to use of one type of elastic-plastic analysis: the simplified elastic-plastic correction of local stress for fatigue damage calculation. Other types of elastic-plastic analysis are out of scope of PNAE G-7-002-86. PNAEG7-002-86 from 1989 is not available in English. As such input provide by NIKIET is used in this report.

2.7.2 Summary of non-linear analysis in PNAEG

In PNAE G, only K_e formulae can be derived from elastoplastic analysis. PNAE G 7 defines the material cyclic behaviour from the monotonic stress-strain properties: E^T, $R_{p0.2}{}^T$; $R_m{}^T$; Z^T versus temperature T.

Molski and Glinka found that Neuber's rule may overestimate the local plastic strains, leading to significant errors in fatigue life predictions. Therefore they proposed the new method of elastic-plastic stress and strain calculation based on an energy approach (figures 3 and 4)

Final comparison of K_e PNAEG formulae with ASME III-NB (figure 6) confirms the conservatism of ASME for $S_n/3S_m > 2$ and a K_e greater than 1 for $S_n/3S_m < 1$; the PNAEG proposed a K_e formulae function of the stress concentration factor K_σ

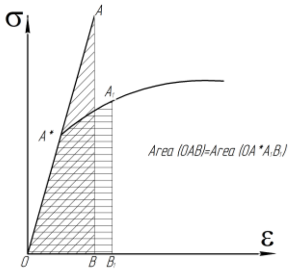


Figure 3 Graphical interpretation of Molski's and Glinka's rule

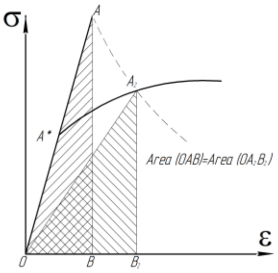


Figure 4: Graphical interpretation of Neuber's rule

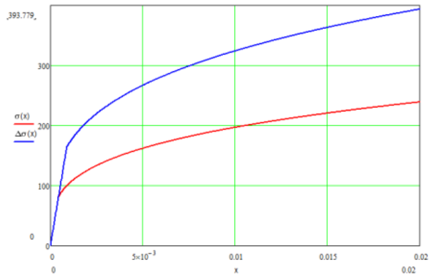


Figure 5: Static and cyclic stress-strain curves for austenitic stainless steel

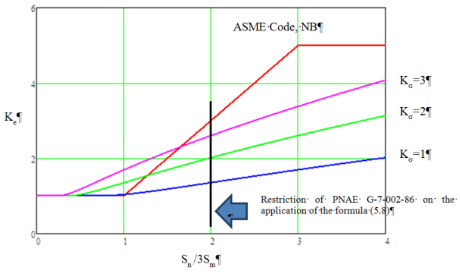


Figure 6: ASME III NB - PNAE G-7 comparison of Ke for carbon steel

2.7.3 First conclusion on PNAEG and open points

2.7.3.1 Elastic-plastic analysis requirements

Only a specific K_e formula is proposed in PNAEG Code. This approach is based on the stress concentration K_σ and generally less conservative than the ASME III–NB proposal.

2.7.3.2 Open points

Two open points were identified:

- What is the validity limits of the Ke proposal in PNAE G7.
- An enlargement of the scope of the code to include non-linear design rules for plastic collapse, plastic instability, plastic shakedown, fatigue direct strain range evaluation, local failure and buckling is required.

2.8 UK R5 Rule

2.8.1 Introduction

R5, is owned and maintained by EDF Energy for application on UK AGR. It is not a Code, but a set of rules developed in accordance with the R6 procedure for cracked component under creep regime, and enlarged case by case to some non-crack component rules.

One important aim for AGR application is to guarantee plastic shakedown in some component locations.

The R5 procedures provide an assessment of the continuing integrity of a component, where the operating lifetime might be limited by one of the following mechanisms:

- Excessive plastic deformation due to a single application of a loading system
- Creep rupture (outside the scope of this report).
- Ratcheting or incremental plastic collapse due to a loading sequence.
- Creep deformation enhanced by cyclic load (outside of this report).
- Initiation of cracks in initially defect-free material by creep and creep-fatigue mechanisms (outside the scope of this report).
- Flaw growth by creep and creep-fatigue mechanisms (outside the scope of this report).

The R5 methodology is written as a series of step-by-step instructions in a number of volumes, each addressing one or more of the above mechanisms affecting structural integrity at high temperature. The R5 volumes concerned by our report are as follows: Volume 1: *The Overview* and Volume 2/3: *Creep-fatigue Initiation Procedure for Defect-free Structures*.

2.8.2 Summary of non-linear analysis in R5

R5 mainly proposes methods for creep-fatigue shakedown, which can be used for negligible creep conditions. This report considers the non-linear analysis methodologies as well as cyclic requirements defined in R5, but does not review the creep regime requirements.

R5 step by step instructions:
Step 1. Resolve load history into cycle types.
Step 2. Perform elastic stress analysis.
Step 3. Demonstrate sufficient margins against plastic collapse
Step 4. Determine whether creep is significant.
Step 5. Demonstrate that creep rupture endurance is satisfactory.
Step 6. Perform a simple test for shakedown and check for insignificant cyclic loading.
Step 7. Perform a global shakedown check and calculate the cyclic plastic zone size.
Step 8. Calculate the shakedown reference stress, reference temperature and start-of-dwell stress.
Step 9. Estimate the elastic follow-up factor and associated stress drop during the creep dwell.
Step 10. Calculate the total strain range.
Step 11. Check limits on cyclically enhanced creep and calculate creep usage factor.
Step 12. Summarize the assessment parameters.
Step 13. Treatment of weldments
Step 14. Calculate the fatigue damage per cycle.
Step 15. Calculate the creep damage per cycle.
Step 16. Calculate the total damage.
Step 17. Assess significance of results and perform a sensitivity analysis.
Step 18. Report results.

Furthermore, R5 proposes screening criteria for non-significant cyclic load: $\bar{\sigma}_{el,lin}(x,t) \leq K_s S_y$.

R5 allows for non-linear analysis in Step 7, stating that if global shakedown cannot be demonstrated, then the procedure for the assessment of creep-fatigue and strain limits cannot be applied directly and it may be necessary to consider detailed inelastic analysis in order to substantiate the component.

2.8.3 Detailed R5 rules step-by-step

Step 1. Resolve load history into cycle types.
The complete load history of a component is required to define the cyclic conditions in the region under investigation. The history needs to be broken down into well-defined cyclic events or service cycles. Each different service cycle has an associated cyclic load, a steady state load which operates during a dwell or hold period and a characteristic temperature. This simplifies the actual loading history so that it is reduced to a well-defined number of different service cycles.

Step 2. Perform elastic stress analysis.
Elastic stress analyses are performed, assuming a homogeneous body of parent material, to determine the variation, with position x and time t, of the multiaxial stress field $\tilde{\sigma}_{el}(x,t)$ throughout the component, for each different service cycle. For each type of cycle, the von Mises equivalent elastic stress and strain, $\bar{\sigma}_{el}(t)$ and $\bar{\varepsilon}_{el}(t)$, and equivalent elastic stress and strain ranges, $\Delta\bar{\sigma}_{el}$ and $\Delta\bar{\varepsilon}_{el}$, at the chosen locations (x), are calculated from the history of the multi-axial stress field $\tilde{\sigma}_{el}(x,t)$.

Step 3. Demonstrate sufficient margins against plastic collapse.
These tests are standard and are specified in R5 to ensure that the component does not suffer plastic collapse on the first application of load, that excessive plastic deformation is not accumulated before the steady cyclic state is reached and that it is possible for the steady cyclic state to be within global shakedown (see Step 7 below).

Step 4. Determine whether creep is significant.

Step 5. Demonstrate that creep rupture endurance is satisfactory.

Step 6. Perform a simple test for shakedown and check for insignificant cyclic loading.
The demonstration of shakedown ensures the avoidance of ratcheting or incremental collapse. R5 first provides a simple test which may be used to obviate the need for a detailed shakedown analysis. If it is further possible to demonstrate insignificant cyclic loading, the need to complete Steps 7 to 14 of the procedures is removed and the assessment continues at Step 15.

In many cases, with the satisfaction of the primary stress limit of Step 3, the elastic stress history determined in Step 2 for the most severe cycle is within global shakedown (i.e. linearized stresses within the shakedown criterion). For these cases, a simple test for shakedown is provided by assuming that the residual stress field, Step 7, is null, and demonstrating that the equivalent elastic stresses determined from linearized stresses, at all the points x on the structural section for all times t, denoted $\bar{\sigma}_{el,lin}(x,t)$ are within a modified yield limit:

Equation 34: equivalent elastic stresses limits

$$\sigma_{el,lin}(x,t) \le K_s S_y$$

Here, the product $K_s S_y$ is a measure of the ability of the material to develop a steady cyclic behaviour, S_y is the minimum 0.2% proof stress for the material for the temperature at point x and time t. The values of K_s are obtained from figures in R5 for the same material and temperature, based on stress-controlled cyclic tests.

Stress linearization methods follow those in other codes and ensure membrane and bending equilibrium. In addition to the application of the linearized stresses in Equation 34, the extent of the length of the stress classification line, at the inner and outer surfaces, $(r_p)_i$ and $(r_p)_o$ respectively, over which the total equivalent stresses $\bar{\sigma}_{el}(x,t)$ exceed $K_s S_y$ is identified, and it should be demonstrated that $(r_p)_i + (r_p)_o \le 20\%$ of the section thickness

Then, a detailed shakedown analysis, Step 7, to find a residual stress field and a steady cyclic stress history is not required and the cyclic plastic zone size, r_p, is taken as $(r_p)_i$ or $(r_p)_o$ as appropriate.

At this stage, if inequality (Equation 34) has been satisfied, it may also be possible to demonstrate that the section under assessment is within strict shakedown (i.e. peak stresses are within the shakedown criterion), fatigue is insignificant and creep behaviour is unperturbed by cyclic loading. Demonstration of insignificant cyclic loading removes the requirement to perform Steps 7 to 14 inclusive. The necessary criteria for insignificant cyclic loading are as follows.

The most severe cycle is within the elastic range of the material are calculated using Equation 35.

Equation 35: Most sever cycle within the elastic range requirements

$$\Delta\bar{\sigma}_{el,max} \leq \left(K_s S_y\right)_c + (K_s S_y)_{nc}$$

Where subscripts c and nc refer to values during the creep dwell and at the non-creep end of the cycle, respectively.

The total fatigue damage for all cycles, is less than 0.05,

$$D_f \leq 0.05$$

Where the fatigue damage, $\mathrm{D_f}$, is calculated using the maximum elastic strain range, $\Delta\bar{\epsilon}_{el,max}$ for each cycle,

$$D_f = \sum_j \frac{n_j}{N_{0j}}$$

Where $\mathrm{N_0}$ is the fatigue endurance at strain range, $\Delta\bar{\varepsilon}_{el,\mathrm{max}}$

Creep behaviour is unperturbed by cyclic loading. If the creep dwell is at the tensile peak stress, this criterion is satisfied by demonstrating,

$$\Delta\bar{\sigma}_{el,max} \leq \sigma_{ss} + \left(K_s S_y\right)_{nc}$$

Where σ_{ss}, the steady state creep stress, is equal to the rupture reference stress, σ_{ref}^{R}, defined under Step 5. Satisfaction of the above three criteria ensures that the steady state for all cycles is within strict shakedown; fatigue is insignificant and does not perturb creep behaviour.

Step 7. Perform a global shakedown check and calculate the cyclic plastic zone size.
R5 assesses the ability of the structure to attain global shakedown (i.e. linearized stresses within the shakedown criterion) to nearly elastic behaviour after the first few cycles of loading, so that avoidance of plastic ratcheting or incremental collapse is ensured. The state of shakedown is brought about by the action of residual stresses due to the manufacturing process or plasticity in the early cycles of load and an estimate of the residual stress field is needed. The elastically calculated stress σ_{el} exceeds the yield stress σ_{y} and therefore plasticity occurs on first loading to give a residual stress $\sigma_{\mathrm{y}} - \sigma_{\mathrm{el}}$. With creep, a different residual stress is likely and the residual stress, ρ, is depicted as that which leads to compressive yielding when the loading is removed. Any number of estimates of residual stress fields may be generated, but only one field, $\tilde{\rho}$ (x), which is constant with respect to time throughout all loading cycles is used for the assessment of shakedown. It is necessary to obtain equivalent stresses $\bar{\sigma}_{\mathrm{s}}(\mathrm{x,t})$ applying during the steady cyclic state for each type of loading cycle, at least for the extremes of stress occurring during the cycle at the locations of maximum cyclic stress range. This is done by first forming the steady cyclic stresses $\tilde{\sigma}_{\mathrm{s}}(\mathrm{x,t})$ by the addition of the elastically calculated stress $\tilde{\sigma}_{\mathrm{el}}(\mathrm{x,t})$ to the residual stress field $\tilde{\rho}$ (x):

$$\tilde{\sigma}_s(x,t) = \tilde{\sigma}_{el}\ (\mathrm{x,t}) + \tilde{\rho}(x)$$

The steady cyclic history of equivalent stress, $\bar{\sigma}_{\mathrm{s}}(\mathrm{x,\ t})$, is determined from $\tilde{\sigma}_{\mathrm{s}}(\mathrm{x,\ t})$. If the elastically calculated stresses have been linearized, all values of $\bar{\sigma}_{\mathrm{s}}(\mathrm{x,\ t})$ should be shown to satisfy the short-term shakedown criterion

$$\bar{\sigma}_s\ (x,t) \leq K_s S_y$$

If elastic stress distributions have not been linearized, the extent of the regions, at the inner and outer surfaces, $(r_p)_i$ and $(r_p)_o$ respectively, over which inequality is violated should be identified.

Limited regions of the structure may be exempted from the strict shakedown requirement if at least 80% of the thickness of every section consists of a ligament over which the criterion is continuously satisfied. If this requirement is satisfied for all types of load cycle for all points in the structure apart from the stated exemptions and for all instants of time during each cycle, then the structure is within global shakedown. In this event, no further tests are necessary for plastic ratcheting or incremental collapse. If global shakedown cannot be demonstrated, then the procedure given here for the assessment of creep-fatigue and strain limits cannot be applied directly *and it may be necessary to consider detailed inelastic analysis in order to substantiate the component.*

Step 8. Calculate the shakedown reference stress, reference temperature and start-of-dwell stress
R5 characterizes the creep dwell period in each cycle in two different ways. First a shakedown reference stress, and associated reference temperature, is calculated to give a measure of the overall creep deformation and creep rupture life of the component. Secondly, a start-of-dwell stress is defined to give a measure of the local creep damage which contributes to local creep-fatigue crack initiation in the component.

This step also involves determining the combination of shakedown reference stress and temperature which results in the shortest rupture life. For the period of each type of cycle during which loadings are constant with time, the value of $\overline{\sigma}_s$ (x,t) calculated in Step 7 using linearized stresses, is selected which, in combination with the temperature T at the same point during the same period, gives the shortest rupture time read from minimum stress/time-to-rupture curves. This value of $\overline{\sigma}_s$ (x, t) is then defined as the shakedown reference stress σ^s_{ref} for the structure during this period and the corresponding temperature T is the shakedown reference temperature T^s_{ref}. The residual stress field may be chosen to minimize the shakedown reference stress σ^s_{ref} at any point while continuing to satisfy the shakedown test of Step 7.

Where the full elastic stress field has been considered in Step 7 (hence the difference between the full stress field and linearized stress field, referred to in codes as peak or F-stresses, has been included) the estimated shakedown reference stress and temperature, σ^s_{ref} and T^s_{ref}, provide a conservative estimate of the creep usage factor in Step 11, below.
If the loadings or temperatures vary slowly over long periods it is permissible to divide the time interval concerned into blocks during which the variation is small and assign a shakedown reference stress and temperature to each block. A pessimistic assessment is achieved by using the highest values of σ^s_{ref} and T^s_{ref} from any block.

If the initial elastic solution satisfies the requirements of the shakedown tests in Step 7, then the residual stress is null and $\overline{\sigma}_s$ (x,t) is identical to $\overline{\sigma}_{el}$ (x,t). In this case the structure is well within strict shakedown and the stress at the start of creep may be expected to diminish with repeated relaxations. It is then permissible to adjust the mean stress in the cycle to minimize the shakedown reference stress, provided the maximum stress which occurs at any point in the cycle, where there is no creep, does not exceed $(K_sS_y)_{nc}$.

It is also necessary to calculate a start-of-dwell stress, σ_0. This can be taken as equal to a revised shakedown reference stress with peak or F-stresses included in the shakedown calculations. The greatest elastically calculated equivalent stress range, $\Delta\overline{\sigma}_{el,max}$, between the stress level at the start of a creep dwell and any stress level in the load cycle at which creep does not occur is established and a revised steady state stress at the start of the creep dwell, σ_0 is estimated from:

$$\sigma_0 = \overline{\sigma}_s(x,t)_{rev} = \Delta\overline{\sigma}_{el,\max} - (K_s S_y)_{nc}$$

For tensile dwells at the peak of a cycle, if the above equation gives a negative value, σ_0 is set equal to 0.

For complex cycles, for example when the dwell is not at the hysteresis loop tip, it may be necessary to consider the elastic stress range between the stress level at the start of the creep dwell and the stress level at a number of points in the cycle where creep does not occur.

The derivation of the start-of-dwell stress, σ_0, from $\bar{\sigma}_s(x, t)$ uses elastic calculations of stress throughout. If the point of interest is outside strict shakedown, then the resulting value for σ_0 may be unrealistically above yield. A less pessimistic value may be estimated following detailed procedures that are given in R5.

Step 9. Estimate the elastic follow-up factor and associated stress drop during the creep dwell

Step 10. Calculate the total strain range

Step 11. Check limits on cyclically enhanced creep and calculate creep usage factor

Step 12. Summarize the assessment parameters
The above steps lead to the determination of all the parameters required for the basic assessment of a component. Where a more detailed analysis is warranted, this is undertaken by use of appropriate appendices in R5.

Step 13. Treatment of weldments
Modifications are needed to Steps 3-11 for welded structures. Complications include:

potential mismatch of materials tensile and creep properties,

the introduction of welding defects,

the presence of high local residual stress,

The effects of surface finish creating a difference between 'dressed' and 'undressed' (as-welded weldments).

In essence, these factors are taken into account by the use of Fatigue Strength Reduction Factors (FSRFs) derived from tests on actual weldments. FSRFs are provided for dressed and un-dressed weldments and are applied to the analysis of the structure assuming parent material properties.

Step 14. Calculate the fatigue damage per cycle.
Fatigue Usage Factors (FUFs) are calculated using the same approach as in design codes, i.e. based on the number of applied cycles divided by the number allowable cycles from an S-N fatigue curve, with the total FUF being limited to 1.0. However, in R5 fatigue damage accumulation is considered to consist of two stages. The first corresponds to the nucleation of a defect of size, $a_i = 0.02\text{mm}$. The second stage is the growth of this defect to a specified depth, a_0, which corresponds to the initiation criterion. This separation enables assessments to be made for thin sections in which a_0 must be specified to be smaller than the crack size, a_ℓ, corresponding to failure in a laboratory specimen. The separation also enables allowance to be made for the order in which cycles are applied and for the different effects of multiaxial stress state on the nucleation and growth processes.

Step 15. Calculate the creep damage per cycle.

Step 16. Calculate the total damage.

Step 17. Assess significance of results and perform a sensitivity analysis.
Further action is required if the criterion for safe operation of the component defined in terms of initiation of a crack of specified depth is not met. Also, if the result is marginal, sensitivity analyses should be performed to identify those parameters which have the most significant effect on the results and whether any cliff-edge effects are present.

Step 18. Report results.
The results and methods employed in an assessment must be properly reported so that the data and procedures used can be scrutinized and verified.

2.8.4 First conclusion on R5 and open points

2.8.4.1 Elastic-plastic analysis requirements

The R5 procedure is a UK nuclear power industry set of rules, frequently used in safety cases for structural integrity assessments of advanced gas-cooled Reactor (AGR) components operating in the creep range. The procedures include many novel features which are intended to give more accurate life assessments compared to existing design codes. An example is the shakedown procedure which is considered to provide a rigorous simplified method to establish that a structure will not ratchet under repeated cyclic loading. The procedure can be applied to both cyclically hardening and softening materials provided the supporting cyclic K_s data.

Whilst the R5 procedure creep-fatigue oriented, the approach to non-linear analysis is of interest to this report.

2.8.4.2 Open points

Validation of R5 fatigue and plastic shakedown non-linear analysis for light water reactors is needed

3 Status of non-linear analysis in the different non-nuclear codes

3.1 ASME Code Section VIII – Edition 2010

3.1.1 Introduction

ASME BPVC- Section VIII Division 2, Part 5: *Design by Analysis Requirements* provides requirements for the design of vessels and components using analytical methods.

Design calculations and analysis that establish that the design as shown on the drawings complies with the requirements of this Division for the design conditions that have been specified in the user's design specification.

Results from stress analysis are used in the detailed design procedures provided in Section VIII Part 5 to evaluate components for plastic collapse, local failure, buckling, and cyclic loading; specifically:

5.1 Material Properties
5.2 Protection Against Plastic Collapse
5.3 Protection Against Local Failure
5.4 Protection Against Collapse From Buckling
5.5 Protection Against Failure From Cyclic Loading
5.6 Supplemental Requirements for Stress Classification in Nozzle Necks

The following material properties for use in the stress analysis shall be determined using the data and material models in Section VIII Part 3:

- Physical properties – Young's modulus, thermal expansion coefficient, thermal conductivity, thermal diffusivity, density, Poisson's ratio.
- Strength parameters – allowable stress, minimum specified yield strength, minimum specified tensile strength.
- Monotonic stress-strain curve – elastic-perfectly-plastic and elastic-plastic true stress-strain curve with strain hardening.
- Cyclic stress-strain curve – stabilized true stress-strain amplitude curve.

3.1.2 Transient category and criteria level

The transient category and associated criteria level are specified by the user in the user's design specification. For non-nuclear vessel, the transients considered are mainly normal and upset, without consideration of accidental conditions. The design specification should define hazard loads and associated criteria, like seismic events , on a case-by-case basis.

3.1.3 Scope of non-linear analysis

In Section VIII Part 5, the major failure modes and degradation mechanisms are considered – plastic collapse, local failure, collapse from buckling (not considered in this report) and failure from cyclic loading (fatigue and shakedown). Only plastic instability is not directly considered. For each of them, different methods are proposed: elastic stress analysis, limit load analysis or elastic-plastic stress analysis.

3.1.4 Plastic collapse (excessive deformation)

Three different methods are proposed in ASME Section VIII-2 Part 5.2:

- **Elastic stress analysis method** – stresses are computed using an elastic analysis and classification into categories (primary and secondary, general and local). Criteria are based on stress comparison with allowable values that have been conservatively established such that a plastic collapse will not occur.
- **Limit-load method** – a calculation is performed to determine a lower bound of the limit load of the component. The allowable load for the component is established by applying design factors to the limit load such that the onset of gross plastic deformation (plastic collapse) will not occur.
- **Elastic-plastic stress analysis method** – a collapse load is derived from an elastic-plastic analysis considering both the applied loading and deformation characteristics of the component. The allowable load on the component is established by applying design factors to the elastic-plastic collapse load.

3.1.5 Plastic instability

Plastic instability is not directly considered in Section VIII Part 5.

3.1.6 Local failure requirements

Two analysis methodologies are provided in ASME Section VIII-2 Part 5.3 for evaluating protection against local failure to limit the potential for local fracture under applied design loads:

- Section VIII-2 Paragraph 5.3.2 provides an approximation of the protection against local failure based on the results of an elastic analysis,
- Section VIII-2 Paragraph 5.3.3 provides a more accurate estimate of the protection against local failure of a component using the elastic-plastic stress analysis procedures.

3.1.7 Plastic shakedown requirements

Under certain combinations of steady state and cyclic loadings there is a possibility of ratcheting. A rigorous evaluation of ratcheting normally requires an elastic-plastic analysis of the component; however, under a limited number of loading conditions, an approximate analysis can be used based on the results of an elastic stress analysis (Paragraph 5.5.6).

Protection against ratcheting shall be considered for all operating loads listed in the user's design specification and shall be performed even if the fatigue screening criteria are satisfied (see Paragraph 5.5.2 of Section VIII-2). Protection against ratcheting is satisfied if one of the following three conditions is met:

- The loading results in only primary stresses without any cyclic secondary stresses.
- Elastic stress analysis criteria – protection against ratcheting is demonstrated by satisfying the rules of Section VIII-2 paragraph 5.5.6.
- Elastic-plastic stress analysis criteria – Protection against ratcheting is demonstrated by satisfying the rules of Section VIII-2 Paragraph 5.5.7.

3.1.8 Fatigue analysis requirements

Fatigue rules are specified in Section VIII-2 Part 5.5.

3.1.8.1 General overview

A fatigue evaluation shall be performed in accordance with Section VIII-2 Part 5.5 if the component is subject to cyclic operation. The evaluation for fatigue is made on the basis of the number of applied cycles of a stress or strain range at a point in the component. The allowable number of cycles should be consistent with the specified number of cycles given in the user's design specification.

Screening criteria are provided in Section VIII-2 Paragraph 5.5.2 that can be used to determine if fatigue analysis is required as part of design analysis. If the component does not satisfy the screening criteria, a fatigue evaluation shall be performed using the techniques in Section VIII-2 Paragraphs 5.5.3, 5.5.4 or 5.5.5.

Fatigue curves are typically presented in two forms: ones based on smooth bar test specimens and ones based on test specimens that include weld details of quality consistent with the fabrication and inspection requirements of Section VIII Division 2.

Smooth bar fatigue curves may be used for components with or without welds. The welded joint curves shall only be used for welded joints. The smooth bar fatigue curves are applicable up to the maximum number of cycles given on the curves. The welded joint fatigue curves do not exhibit an endurance limit and are acceptable for all cycles.

If welded joint fatigue curves are used in the evaluation, and if thermal transients result in a through-thickness stress difference at any time that is greater than the steady state difference, the number of design cycles shall be determined as the smaller of the number of cycles for the base metal established using either paragraph 5.5.3 or 5.5.4, and for the weld established in accordance with paragraph 5.5.5.

Stresses and strains produced by any load or thermal condition that does not vary during the cycle need not be considered in a fatigue analysis if the fatigue curves used in the evaluation are adjusted for mean stresses and strains. The design fatigue curves referenced in paragraphs 5.5.3 and 5.5.4 are based on smooth bar test specimens and are adjusted for the maximum possible effect of mean stress and strain; therefore, an adjustment for mean stress effects is not required. The fatigue curves referenced in paragraph 5.5.5 are based on welded test specimens and include explicit adjustments for thickness and mean stress effects.

3.1.8.2 Screening criteria for fatigue analysis

3.1.8.2.1 *Overview:*

The provisions in Paragraphs 5.5.2.2, 5.5.2.3 and 5.5.2.4 can be used to determine whether a fatigue analysis is required as part of the vessel design. The screening options to determine the need for fatigue analysis are described below. If any one of the screening options is satisfied, then a fatigue analysis is not required as part of the vessel design.

- Provisions of Paragraph 5.5.2.2, experience with comparable equipment operating under similar conditions.
- Provisions of Paragraph 5.5.2.3, method A based on the materials of construction (limited applicability), construction details, loading histogram, and smooth bar fatigue curve data.
- Provisions of Paragraph 5.5.2.4, method B based on the materials of construction (unlimited applicability), construction details, loading histogram, and smooth bar fatigue curve data.

The fatigue exemption in accordance with this paragraph is performed on a component or part basis. One component (integral) may be exempt, while another component (non-integral) is not exempt. If any one component is not exempt, then a fatigue evaluation shall be performed for that component.

If the specified number of cycles is greater than a specified amount, then the screening criteria are not applicable and a fatigue analysis is required.

3.1.8.2.2 *Fatigue analysis screening based on experience with comparable equipment.*

Fatigue analysis screening, method A

The following procedure can only be used for materials with a specified minimum tensile strength that is less than or equal to 552 MPa (80,000 psi).

Step 1. Determine a load history based on the information in the user's design specification. The load history should include all cyclic operating loads and events that are applied to the component.

Step 2. Based on the load history in Step 1, determine the expected (design) number of full-range pressure cycles including startup and shutdown, and designate this value as $N_{\Delta FP}$.

Step 3. Based on the load history in Step 1, determine the expected number of operating pressure cycles in which the range of pressure variation exceeds 20% of the design pressure for integral construction or 15% of the design pressure for non-integral construction, and designate this value as $N_{\Delta PO}$. Pressure cycles in which the pressure variation does not exceed these percentages of the design pressure and pressure cycles caused by fluctuations in atmospheric conditions do not need to be considered in this evaluation.

Step 4. Based on the load history in Step 1, determine the effective number of changes in metal temperature difference between any two adjacent points, ΔTE, as defined below, and designate this value as $N_{\Delta TE}$. The effective number of such changes is determined by multiplying the number of changes in metal temperature difference of a certain magnitude by the factor given in Table 5.8 of Section VIII-2, and by adding the resulting numbers. In calculating the temperature difference between adjacent points, conductive heat transfer shall be considered only through welded or integral cross sections with no allowance for conductive heat transfer across un-welded contact surfaces (e.g. vessel shell and reinforcing pad).

Step 5. Based on the load history in Step 1, determine the number of temperature cycles for components involving welds between materials having different coefficients of thermal expansion that causes the value of $(\Delta 1 - \Delta 2)\ \Delta T$ to exceed 0.00034, and designate this value as $N_{\Delta T\alpha}$.

Step 6. If the expected number of operating cycles from steps 2, 3, 4 and 5 satisfy the criterion in Table 5.9 of Section VIII-2, then a fatigue analysis is not required as part of the vessel design. If this criterion is not satisfied, then a fatigue analysis is required as part of the vessel design. Examples of non-integral attachments are: screwed-on caps, screwed-in plugs, shear ring closures, fillet welded attachments, and breech lock closures.

Fatigue analysis screening, method B

The following procedure can be used for all materials.

Step 1. Determine a load history based on the information in the user's design specification. The load histogram should include all significant cyclic operating loads and events that the component will be subjected to. Note, in Equation 5.18 of Section VIII-2, the number of cycles from the applicable design fatigue curve (see Annex 3-F) evaluated at a stress amplitude of Se is defined as $N(Se)$. Also in Equations 5.19 through 5.23 of Section VIII-2, the stress amplitude from the applicable design fatigue curve (see Annex 3-F) evaluated at N cycles is defined as $Sa(N)$.

Step 2. Determine the fatigue screening criteria factors, C1 and C2, based on the type of construction in accordance with Table 5.10 of Section VIII-2 (see paragraph 4.2.5.6(j)).

Step 3. Based on the load histogram in Step 1, determine the design number of full-range pressure cycles including start-up and shutdown, $N_{\Delta FP}$. If the following equation is satisfied, proceed to Step 4; otherwise, a detailed fatigue analysis of the vessel is required.

Step 4. Based on the load histogram in Step 1, determine the maximum range of pressure fluctuation during normal operation, excluding start-ups and shutdowns, ΔPN, and the corresponding number of significant cycles, $N\Delta P$. Significant pressure fluctuation cycles are defined as cycles where the pressure range exceeds $Sas/3S$ multiplied by the design pressure. If the following equation is satisfied, proceed to Step 5; otherwise, a detailed fatigue analysis of the vessel is required.

Step 5. Based on the load histogram in Step 1, determine the maximum temperature difference between any two adjacent points of the vessel during normal operation, and during start-up and shutdown operation, ΔTN, and the corresponding number of cycles, $N_{\Delta TN}$. If the following equation is satisfied, proceed to Step 6; otherwise, a detailed fatigue analysis of the vessel is required

Step 6. Based on the load histogram in Step 1, determine the maximum range of temperature difference fluctuation, ΔTR, between any two adjacent points (see paragraph 5.5.2.3, Step 4) of the vessel during normal operation, excluding start-ups and shutdowns, and the corresponding number of significant cycles, $\Delta N\Delta TR$. Significant temperature difference fluctuation cycles for this Step are defined as cycles where the temperature range exceeds allowable ranges. If the equations defined in the screening procedure are satisfied, proceed to Step 7; otherwise, a detailed fatigue analysis of the vessel is required.

Step 7. Based on the load histogram in Step 1, determine the range of temperature difference fluctuations between any two adjacent points (see paragraph 5.5.2.3, Step 4) for components fabricated from different materials during normal operation, ΔTM, and the corresponding number of significant cycles, $N_{\Delta TM}$. Significant temperature difference fluctuation cycles for this step are defined as cycles where the temperature range exceeds $S_{as}/[2(E_{y1}\Delta T1 - E_{y2}\Delta T_{2)].}$ If the equations defined in the screening procedure are satisfied, proceed to Step 8; otherwise, a detailed fatigue analysis of the vessel is required.

Step 8. Based on the load histogram in Step 1, determine the equivalent stress range computed from the specified full range of mechanical loads, excluding pressure but including piping reactions, ΔSML, and the corresponding number of significant cycles, $N\Delta S$. Significant mechanical load range cycles for this Step are defined as cycles where the stress range exceeds S_{as}. If the total specified number of significant load fluctuations exceeds the maximum number of cycles defined on the applicable fatigue curve, the S_{as} value corresponding to the maximum number of cycles defined on the fatigue curve shall be used. If the equations defined in the screening procedure are satisfied, a fatigue analysis is not required; otherwise, a detailed fatigue analysis of the vessel is required.

3.1.8.3 Elastic analysis and simplified elastic-plastic fatigue analysis

Step 1. Determine the load history.

Step 2. Determine the individual stress-strain cycles.

Step 3. Determine the equivalent stress range for the k_{th} cycle.

Step 4. Determine the effective alternating equivalent stress $S_{alt,k.}$

(a) If the local notch or effect of the weld is accounted for in the numerical model, then $K_f = 1.0$

(b) The fatigue penalty factor, $K_{e,k}$, is evaluated using the following equations where the parameters are determined from Table 5.13 of Section VIII-2and SPS and $\Delta S_{n,k}$ are defined in Paragraph 5.5.6.1. For $K_{e,k}$ values greater than 1.0, the simplified elastic-plastic criteria of paragraph shall be satisfied:

Equation 36: Fatigue penalty factor, $K_{e,k}$

$$K_{e,k} = 1.0 \qquad for \quad \Delta S_{n,k} \le S_{PS}$$

$$K_{e,k} = 1.0 + \frac{(1-n)}{n(m-1)}\left(\frac{\Delta S_{n,k}}{S_{PS}} - 1\right) \qquad for \quad S_{PS} < \Delta S_{n,k} < mS_{PS}$$

$$K_{e,k} = \frac{1}{n} \qquad for \quad \Delta S_{n,k} \ge mS_{PS}$$

(c) The Poisson correction factor, $K_{v,k}$ in Equation 37 is computed using Equation 38.

Equation 37: Poisson correction factor

$$K_{v,k} = \left(\frac{1 - v_e}{1 - v_p}\right)$$

Where:

Equation 38: derivation of v_p for the calculation of the Poisson correction factor

$$v_p = \max\left[0.5 - 0.2\left(\frac{S_{y,k}}{S_{a,k}}\right), v_e\right]$$

(d) The Poisson correction factor, $K_{v,k}$, in Equation 37 need not be used if the fatigue penalty factor, $K_{e,k}$, is used for the entire stress range (including $\Delta S_{LT,k}$). In this case, $S_{alt,k}$ is calculated using Equation 39:

Equation 39: $S_{alt,k}$

$$S_{alt,k} = \frac{K_f \cdot K_{e,k} \cdot \Delta S_{P,k}}{2}$$

Step 5. Determine the permissible number of cycles, $N_{k.}$

Step 6. Determine the fatigue damage for the k cycle.

$$D_{f,k} = \frac{n_k}{N_k}$$

Step 7. Repeat Steps 3 through 6 for all stress ranges.

Step 8. Compute the accumulated fatigue damage using the following equation:

$$D_f = \sum_{k=1}^{M} D_{f,k} \leq 1.0$$

Step 9. Repeat Steps 2 through 8 for each point in the component.

In Step 4 of paragraph 5.5.3.2, $K_{e,k}$ may be calculated using one of the following methods:

(a) Method 1 –The equivalent total strain range from elastic-plastic analysis and the equivalent total strain range from elastic analysis

$$K_{e,k} = \frac{\left(\Delta\varepsilon_{t,k}\right)_{ep}}{\left(\Delta\varepsilon_{t,k}\right)_{e}}$$

Where:

$$\left(\Delta\varepsilon_{t,k}\right)_{ep} = \frac{\sqrt{2}}{3}\left[\left(\Delta e_{11,k} - \Delta e_{22,k}\right)^2 + \left(\Delta e_{22,k} - \Delta e_{33,k}\right)^2 + \left(\Delta e_{33,k} - \Delta e_{11,k}\right)^2 + 1.5\left(\Delta e_{12,k}^2 + \Delta e_{23,k}^2 + \Delta e_{31,k}^2\right)\right]^{0.5}$$

(b) Method 2 – The alternate plasticity adjustment factors and alternating equivalent stress may be computed using Annex 5-C of Section VIII-2.

3.1.8.4 Elastic-plastic analysis

The following procedure can be used to evaluate protection against failure due to cyclic loading using elastic-plastic stress analysis.

Step 1. Determine a load history based on the information in the user's design specification and the methods in Section VIII-2 Annex 5-B. The load history should include all significant operating loads and events that are applied to the component.

Step 2. For a location in the component subject to a fatigue evaluation, determine the individual stress-strain cycles using the cycle counting methods in Annex 5-B. Define the total number of cyclic stress ranges in the histogram as M.

Step 3. Determine the loadings at the start and end points of the k^{th} cycle counted in Step 2. Using this data, determine the loading ranges (differences between the loadings at the start and end points of the cycle).

Step 4. Perform elastic-plastic stress analysis for the k^{th} cycle. For cycle-by-cycle analysis, constant-amplitude loading is cycled using cyclic stress amplitude-strain amplitude curve. For the twice yield method, the loading at the start point of the cycle is zero and the loading at the end point is the loading range determined in Step 3. The cyclic stress range-strain range curve is used. For thermal loading, the loading range in Twice-Yield Method may be applied by specifying the temperature field at the start point for the cycle as an initial condition, and applying the temperature field at the end point for the cycle in a single loading step.

Step 5. Calculate the effective strain range for the k^{th} cycle using Equation 40.

Equation 40: Effective strain range for k^{th} cycle

$$\Delta\varepsilon_{eff,k} = \frac{\Delta S_{p,k}}{E_{ya,k}} + \Delta\varepsilon_{peq,k}$$

where, the stress range $\Delta S_{peq,k}$ is given by the following equation:

$$\Delta\varepsilon_{peq,k} = \frac{\sqrt{2}}{3}\left[\left(\Delta p_{11,k} - \Delta p_{22,k}\right)^2 + \left(\Delta p_{22,k} - \Delta p_{33,k}\right)^2 + \left(\Delta p_{33,k} - \Delta p_{11,k}\right)^2 + 1.5\left(\Delta p_{12,k}^2 + \Delta p_{23,k}^2 + \Delta p_{31,k}^2\right)\right]^{0.5}$$

The component stress and plastic strain ranges (differences between the components at the start and end points of the th cycle) for the k cycle are designated as $\Delta\sigma_{ij,k}$ and $\Delta p_{ij,k,}$ respectively. However, since a range of loading is applied in a single load step with the twice yield method, the calculated maximum equivalent plastic strain range, $\Delta\varepsilon_{peq,k}$ and the von Mises equivalent stress range $\Delta S_{p,k}$ defined above are typical output variables that can be obtained directly from a stress analysis.

Step 6. Determine the effective alternating equivalent stress for the k^{th} cycle using Equation 41.

Equation 41: Effective alternating equivalent stress at kth cycle

$$S_{alt,k} = \frac{E_{ya,k} \cdot \Delta\varepsilon_{eff,k}}{2}$$

Step 7. Determine the permissible number of cycles, N_k, for the alternating equivalent stress computed in Step 6. Fatigue curves based on the materials of construction are provided in Annex 3-F, paragraph 3-F.1,

Step 8. Determine the fatigue damage for the k^{th} cycle, where the actual number of repetitions of the k^{th} cycle is n_k.

$$D_{f,k} = \frac{n_k}{N_k}$$

Step 9. Repeat Steps 3 through 8 for all stress ranges, M, identified in the cycle counting process in Step 2.

Step10. Compute the accumulated fatigue damage using the following equation. The location in the component is acceptable for continued operation if this equation is satisfied.

$$\sum_{k=1}^{M} D_{f,k} \leq 1.0$$

Step11. Repeat Steps 2 through 10 for each point in the component subject to a fatigue evaluation.

3.1.9 Material properties

The following material properties for use in the stress analysis shall be determined using the data and material models in Section VIII-2 Part 3.

- Physical properties: Young's modulus, thermal expansion coefficient, thermal conductivity, thermal diffusivity, density, Poisson's ratio
- Strength Parameters: allowable stress, minimum specified yield strength, minimum specified tensile strength
- Monotonic Stress-Strain Curve: elastic perfectly plastic and elastic-plastic true stress-strain curve with strain hardening
- Cyclic Stress-Strain Curve: stabilized true stress-strain amplitude curve

3.1.10 Piping stress classification

For the nozzle to piping transition zone, the following classification of stresses shall be used for stress in a nozzle neck. The classification of stress in the shell shall be in accordance with Section VIII-2 Paragraph 5.2.2.2.

(a) Within the limits of reinforcement given by Section VIII-2 Paragraph 4.5, whether or not nozzle reinforcement is provided, the following classification shall be applied.

1. A P_m classification is applicable to equivalent stresses resulting from pressure induced general membrane stresses as well as stresses, other than discontinuity stresses, due to external loads and moments including those attributable to restrained free end displacements of the attached pipe.
2. A P_L classification shall be applied to local primary membrane equivalent stresses derived from discontinuity effects plus primary bending equivalent stresses due to combined pressure and external loads and moments including those attributable to restrained free end displacements of the attached pipe.

3. A ($P_L + P_b + Q$) classification shall apply to primary plus secondary equivalent stresses resulting from a combination of pressure, temperature, and external loads and moments, including those due to restrained free end displacements of the attached pipe.

(b) Outside of the limits of reinforcement given, the following classification shall be applied.

1. A P_m classification is applicable to equivalent stresses resulting from pressure induced general membrane stresses as well as the average stress across the nozzle thickness due to externally applied nozzle axial, shear, and torsional loads other than those attributable to restrained free end displacement of the attached pipe.
2. A ($P_L + P_b$) classification is applicable to the equivalent stresses resulting from adding those stresses classified as Pm to those due to externally applied bending moments except those attributable to restrained free end displacement of the pipe.
3. A ($P_L + P_b + Q$) classification is applicable to equivalent stresses resulting from all pressure, temperature, and external loads and moments, including those attributable to restrained free end displacements of the attached pipe.

(c) Beyond the limits of reinforcement, the S_{PS} limit on the range of primary plus secondary equivalent stress may be exceeded as provided, except that in the evaluation of the range of primary plus secondary equivalent stress, $P_L + P_b + Q$, stresses resulting from the restrained free end displacements of the attached pipe may also be excluded. The range of membrane plus bending equivalent stress attributable solely to the restrained free end displacements of the attached piping shall be less than S_{PS}.

3.1.11 First conclusion on Section VIII and open points

3.1.11.1 Elastic-plastic analysis required

ASME Section VIII Division 2 considers all the major damage, including plastic collapse, local failure, buckling, fatigue (including exemption rules), ratcheting and elastic stress classification for reinforced nozzles, except strictly plastic instability.

Detailed non-linear analysis design rules are provided, including:

- Two main methods for analyzing failure modes under monotonic loading: limit load and elastic-plastic methods
- alternative elastic-plastic rules for cyclic loadings: fatigue, K_e, K_v and ratcheting

All material properties required for the analyses are available in ASME Section VIII-2 Part 3, and most procedures are presented in a set of clear step-by-step processes.

3.1.11.2 Open points

Tresca versus Von Mises and transferability of results has to be confirmed

Use of Finite Element Analysis (FEA) for lower bound limit load evaluation,

Detailed recommendations for analysis need to be reviewed or added in the Code, as:

There are still a number of open issues in the use of elastic-plastic analysis when applying the AFCEN RCC-MRx requirements:

- Detailed requirements for the transferability of results based on Tresca or von Mises analysis.
- Guidelines for the use of classical finite element analysis (FEA) for limit load evaluation would be a useful addition to the code.
- Requirements for the analysis of accidental conditions and associated flow stress value.

Detailed recommendations for finite element analysis should be in the code, such as:

- Temperature to use for each step of these analyses.
- Tolerances and precise geometry to perform inelastic analysis.

- More general FEA recommendations (mesh refinement, small versus large displacement, convergence criteria, etc.).
- Strain criteria for different elastic-plastic, with possible modification in the user's design specification.

The code would also benefit from having specific validation and theoretical background of all the original methods proposed in the Code

3.2 European Standard EN 13445 – Unfired Pressure Vessel

3.2.1 Introduction

EN 13445 Part 3 specifies requirements for the design of unfired pressure vessels. The failure modes considered are:

- Gross Plastic Deformation Design Check (GPD-DC),
- Progressive Plastic Deformation Design Check (PD-DC),
- Instability Design Check (I-DC)
- Fatigue Design Check (F-DC)
- Static Equilibrium Design Check (SE-DC)

The design part of this standard gives the rules to be used for design and calculation under internal and/or external pressure (as applicable) of pressure bearing components of pressure vessels, such as shells of various shapes, flat walls, flanges, heat exchanger tube-sheets, including the calculation of reinforcement of openings. Rules are also given for components subject to local loads and to actions other than pressure.

For all these components the design-by-formulae (DBF) method is generally followed. However general prescriptions are also given for design-by-analysis (DBA) in Appendix B to evaluate the design of any component under any loading conditions. Appendix B is currently limited to sufficiently ductile materials.

3.2.2 Transient category and criteria level

The transient category and associated criteria level are specified by the user in the design specification. For non-nuclear vessel loads and transients considered are usually normal, specific and exceptional loads without consideration of accidental conditions. The design specification should define hazard loads and associated criteria, such seismic events on a case-by-case basis.

3.2.3 Scope and non-linear analysis

The constitutive law to be used in the model depends on the design check.

- In the gross plastic deformation design check (GDP-DC), a linear-elastic ideal-plastic law with Tresca's yield condition (maximum shear stress condition) and associated flow rule should be used.
- In the progressive plastic deformation design check, a linear-elastic ideal-plastic law with von Mises' yield condition (maximum distortion energy condition) and associated flow rule should be used.
- In the fatigue design check, a linear-elastic law should be used.
- In the instability design check, either a linear-elastic or a linear-elastic ideal-plastic law, depending on the approach should be used.

In the GPD-DC, von Mises yield condition may also be used, but the design material strength parameter (design yield strength) shall then be modified accordingly.

The design value of the material strength parameter (design yield strength) of plastic constitutive laws R_{Md} shall be determined by the division of the parameter's characteristic value by the relevant partial safety factor, in general terms:

$$RM_d = RM / \gamma_R$$

Where: RM is the characteristic value of the relevant material strength and γ_R the relevant partial safety factor.

Details for the determination of the characteristic values of the material strengths, and the partial safety factors, are specified in the sub-clauses of the design checks.

For exceptional situations, the partial safety factor γ_R shall be agreed upon by the parties concerned, but shall not be less than the one used for testing situations.

In the determination of these characteristic values R_M the minimum specified material strength data shall be used (e.g. R_{eH}, $R_{p0.2/T}$, $R_{p1.0/T}$, $R_{m/T}$) which apply to the materials in the final fabricated condition, and which shall conform with the minimum specified values of the appropriate material specification.

3.2.4 Plastic collapse (excessive deformation)

Gross plastic deformation (GPD) is calculated using linear-elastic ideal-plastic constitutive law, under Tresca's yield condition (maximum shear stress hypothesis) and associated flow rule. The design material strength parameter RM, as well as the associated partial safety factor γ_R, is defined a range of materials, for both normal operating load cases (B.8.2.3 c)) and testing load cases (B.8.2.4 c)).

Proportional increase of all actions is assumed, and a stress-free initial state is postulated. The maximum absolute value of the principal structural strains being less than :

- 5% in normal operating load cases.
- 7% in exceptional and testing load cases.

3.2.5 Plastic instability

Plastic instability is not directly considered in EN 13445 Part 3.

3.2.6 Local failure requirements

Local failure is not considered in EN 13445 Part 3.

3.2.7 Plastic shakedown requirements

The plastic shakedown procedure is based on:

- First-order-theory.
- A linear-elastic ideal-plastic constitutive law.
- Von Mises yield criterion (maximum distortion energy criterion) and associated flow rule.
- Design strength parameters RM_d as specified in the Standard.

3.2.7.1 Application rule 1: technical adaptation

Technical adaptation is fulfilled, if it can be shown that the maximum absolute value of the principal structural strains is less than 5 % after the application of the number of cycles specified for the considered load case. If the number is not specified, then a reasonable number, but at least 500 cycles shall be assumed.

Total strains may be used instead of structural strains in any model which deviates only in the local stress/strain concentrations.

3.2.7.2 Application rule 2: shakedown (SD)

Shakedown is fulfilled, if the model with stress/strain concentrations shakes down to linear-elastic behaviour under the action cycles considered

3.2.8 Fatigue analysis requirements

3.2.8.1 Elastic analysis

Two clauses (17 and 18) define Fatigue analysis rules. Claude 17 is attached to pressure cycling loads. Claude 18 consider detailed analysis, based on component fatigue tests or material (S,N) fatigue tests.

3.2.8.2 Simplified Elastic-plastic analysis

Non-linear analysis is partially considered in Clause 18[9] through simplified elastic-plastic analysis.

---

[9] Clause 18 is currently under revision

For mechanical loading, the corrected structural stress range should be derived using Equation 42.

Equation 42: Corrected structural stresses

$$\Delta\sigma_{\text{struc,eq}} = k_{\text{e}}\, \Delta\sigma_{\text{eq,l}}$$

With:

$$k_{\text{e}} = 1 + A_0 \left(\frac{\Delta\sigma_{\text{eq,l}}}{2R_{\text{p0,2/T*}}} - 1 \right)$$

With:

$A_0 = 0{,}5$	for ferritic steels with $800 \leq Rm \leq 1000(MPa)$
$A_0 = 0{,}4$	for ferritic steels with $Rm \leq 500(MPa)$ and for all austenitic steels;
$A_0 = 0.4 + (R_m - 500)/3000$	for ferritic steels with $500 \leq R_m \leq 800(MPa)$

For thermal loadings, in the case of a thermal stress distribution which is non-linear through the material thickness and for welded joints, the equivalent thermal stress range is calculated using Equation 43.

Equation 43: equivalent thermal stress range for non-linear through wall thermal stress distribution

$$\Delta\sigma_{\text{eq}} = k_v\, \Delta\sigma_{\text{eq,l}}$$

For un-welded zones, the equivalent thermal stress range is calculated using Equation 44:

Equation 44: equivalent thermal stress range in un-welded zones

$$\Delta\sigma_{\text{f}} = kv\, \Delta\sigma_{\text{eq,t}}$$

In both cases, k_v is calculated using Equation 45.

Equation 45: calculation of k_v

$$k_\nu = \max \left(\frac{0{,}7}{0{,}5 + \dfrac{0{,}4}{\Delta\sigma_{\text{eq,l}} / R_{\text{p0,2/T*}}}} ; 1{,}0 \right)$$

3.2.8.3 Elastic-plastic analysis

No elastic-plastic fatigue analysis methods are proposed in EN 13445 Part 3.

3.2.9 Piping stress classification

Piping stress classification falls outside the scope of EN13445 Part 3.

3.2.10 First conclusion on EN 13445 and open points

3.2.10.1 Elastic-plastic analysis required

EN 13445 proposes detailed elastic-perfectly-plastic analysis methodologies limit load, collapse load, buckling and plastic shakedown based on von Mises material behavior. Material strength parameters and associated partial safety parameters are provided for a range of materials.

For all the other cases only very general openings are done in the code. There are currently no recommendations and detailed data on material properties for elastic-plastic analysis which takes into account strain hardening.

No methods are proposed for K_e direct plastic evaluation or for fatigue direct strain amplitude evaluation or plastic shakedown analysis under cyclic plastic analysis. Furthermore, EN 13445 has no proposal for local failure analysis, or for plastic instability.

3.2.10.2 Open points

There are still a number of open points in the use of elastic-plastic analysis when applying the EN 13445 requirements, notably:

- EN 13445 uses both Tresca and von Mises plasticity criteria. The consistency and validity between the criteria should be checked.
- The use of Finite Element Analysis (FEA) for limit load evaluation needs to be validated in accordance with lower bound approach.
- No theoretical background is referenced for the proposed simplified elastic-plastic analysis based on (K_f, K_v).

Detailed recommendations and criteria for finite element analysis should to be added to the Standard, such as:

- Temperature to use for each step of these analyses.
- Tolerances and precise geometry to perform inelastic analysis.
- More general FEA recommendations (mesh refinement, small versus large displacement, convergence criteria, etc.).
- Cyclic elastic-plastic analyses for fatigue and shakedown.
- Strain criteria for elastic-plastic analysis.
- Local failure requirement has to be added to the Standard.
- All the material properties for all these analysis (engineering/ true and cyclic stress-strain curves, material constitutive equations…) should be added to the Standard.

4 Comparison synthesis

The section contains two tables that compare the scope covered by existing codes in term of non-linear design rules (Table 21 and Table 22) and a review of the major open points discussed in this report.

4.1 Comparison tables

The overview of the scope covered by the different mechanical design codes investigated in this report can be found in Figure 1 and Table 22. Table 21 presents the extent to which the codes define specific requirements for the use of non-linear analysis to investigate failure modes occurring under monotonic loading. Table 22 presents extent to which the codes define specific requirements for the use of non-linear analysis to investigate failure modes occurring under cyclic loading.

Table 21: Overview of the Non-Linear Analysis Methodologies Covered in the Compared Codes for Monotonic Loading

	Plastic collapse				**Plastic instability**				**Stress triaxiality**	
	Limit analysis		**Direct elastic-plastic FEA**		**Limit analysis**		**Direct elastic-plastic FEA**		**Direct elastic-plastic FEA**	
	Material properties	Criteria	Material properties	Criteria	Material properties	Criteria	Material properties	Criteria	Material properties	Criteria
RCCM	Y	Y	N	N	N	N	N	N	N	N
ASME III	Y	Y	N	N	Y	Y	N	N	N	N
JSME	Y	Y	N	N	N	N	N	N	N	N
RCC-MRx	Y	Y	Y	Y	Y	Y	Y	P	N	N
KEPIC	Y	Y	N	N	Y	Y	N	N	N	N
PNAEG	N	N	N	N	N	N	N	N	N	N
KTA	N	N	N	N	N	N	N	N	N	N
R5	Y	Y	N	N	N	N	N	N	N	N
ASME VIII	Y	Y	Y	Y	Y	Y	P	Y	P	Y
EN 13445	Y	Y	N	N	N	N	N	N	N	N

Y = covered; N = Not covered; P = Partially covered

Table 22: Overview of the Non-Linear Analysis Methodologies Covered in the Compared Codes for Cyclic Loading

	Plastic shakedown				**Fatigue K_e**		
	Direct elastic -plastic analysis using FEA				**Direct elastic-plastic analysis using FEA**		
	Material properties	**Material constitutive equation**	**Criteria**	**Extrapolation rules**	**Material properties**	**Material constitutive equation**	**Method**
RCCM	N	N	N	N	N	N	N
ASME III	N	N	N	N	N	N	N
JSME	Y	P	Y	N	Y	N	Y
RCC-MRx	P	P	N	Y	Y	P	N
KEPIC	N	N	N	N	N	N	N
PNAEG	N	N	N	N	Y	Y	Y
KTA	N	N	N	N	N	N	N
R5	N	N	Y	N	N	N	N
ASME VIII	Y	N	Y	N	Y	N	Y
EN 13445	N	N	N	N	N	N	N

Y = covered; N = Not covered; P = Partially covered

4.2 Comparison by failure modes

Three failure modes (plastic failure, plastic instability and local failure) and three degradation mechanisms (fatigue, shakedown and ratcheting) are generally considered in the codes investigated in this report.

4.2.1 Plastic collapse

Most of the codes investigated in this report consider plastic collapse (RCC-M, RCC-MRx, ASME III, JSME, KEPIC, ASME VIII-2 and EN 13445). Only PNAEG has no non-linear proposal for plastic collapse.
All these codes propose the lower bound limit load method and elastic-plastic analysis. Only JSME has a third method, the elastic compensation method.

The major differences in limit load are the flow stress and associated criteria:

- $1.5\ S_m$ and 0.66 times the corresponding load in ASME III, JSME, KEPIC, ASME VIII-2.
- S_y with associated criteria for levels A, B, C and T in RCC-M and RCC-MRx.

When S_m is used, the margin factor is different depending on the material analyzed (ferritic versus stainless steels). The margins provided in each code are applied yield strength as well as maximum stress data, with different margin factor values.

The twice elastic slope method is consistently used for the derivation of the plastic collapse load using elastic-plastic approaches. No code provides data on material properties, strain criteria, or detailed recommendations on the method to be used.

The detailed step-by-step procedure used in Section VIII can be considered for the harmonized proposed rules in *Non-Linear Analysis Design Rules; Part 2: Good Practices*.

4.2.2 Plastic instability

Plastic instability is only considered formally in RCC-M and RCC-MRx through direct elastic-plastic analysis (not limit load method), with associated criteria connected to levels A, B, C and D. The other codes consider that S_m covers both plastic collapse and plastic instability failure modes, applying different safety factors depending on the failure mode considered (on $R_{P0.2\%}$ and R_m).

A number of omissions from the nuclear design codes were noted in this comparison, notably:

- Material data.
- Effect of large displacement on FEA.
- Strain criteri.
- Step-by-step procedure associated with recommendations.

4.2.3 Local failure

Local failure is only considered in RCC-M, ASME III and ASME VIII, with the same requirements defined in all three codes (see Equation 46). The main difference is under which levels local failure needs to be considered, namely A, B C and D for RCC-M and only A, B and C in ASME.

Equation 46: Local failure analysis

$$\sigma_I + \sigma_{II} + \sigma_{III} < 4S_m$$

Only ASME VIII-2 proposes an elastic-plastic analysis alternative without any detailed method.

4.2.4 Fatigue analysis

All nuclear mechanical design codes considered propose a simplified elastic-plastic fatigue analysis method based on correction of elastic strain amplitude using K_e, K_n, K_v. The main difference between the codes arises from the variations in the tabulated values of K_e.

A synthesis of existing rules and a harmonized proposal should be developed.

A method for direct computation of K_e or $\Delta\varepsilon_T$ using FEA should be proposed in accordance with shakedown analysis.

4.2.5 Plastic shakedown and ratcheting

All the codes provide an elastic and an elastic plastic-analysis method for the calculation of plastic shakedown and ratcheting, but these methods are often limited in detail and scope. RCC-MRx and ASME VIII-2 provide more detailed requirements for the calculation of plastic shakedown.

Some codes suggest the use of elastic-perfectly-plastic material behaviour (ASME VIII-2 and EN 13445). The other codes mention an acceptable alternative through elastic-plastic cyclic behaviour of the material without any detailed procedure.

4.2.6 Stress classification in reinforced nozzle

There is very little consistency between the different codes considered in this report on the methodologies proposed for the classification of elastic stresses in reinforced nozzles.

The complexity of the application of the stress classification approaches to components under large loads reinforces the importance of elastic-plastic approaches as useful alternatives.

4.2.7 Difference between nuclear and non-nuclear codes

Due to the safety margins applied in nuclear, the loads analyzed are significantly higher than the loads that would be expected in components subjected to normal or emergency conditions. This makes non-linear analysis particularly attractive, allowing for the accurate analysis of components' behavior beyond yield. This becomes particularly useful when investigating faulted conditions or the impact of seismic loads on the components.

Non-nuclear design codes are more concerned with the real limitations of the material and may allow some plastic deformation to occur in very specific cases. This has led to detailed non-linear analysis methodologies being incorporated into non-nuclear mechanical design codes, such as ASME Section VIII-2 and EN 14445.

ASME Section VIII Division 2 could be considered for the harmonized proposal due to the large scope of failure modes considered, and the detailed step-by-step procedures and all the material data that it provides.

4.3 Summary of open points

This report provides a detailed comparison of the current requirements that are defined in the nuclear and non-nuclear mechanical design codes considered. During the comparison, a number of open points were identified by the authors. The following areas need to be explored in more detail in *Non-Linear Analysis Methodology; Part 2: Good Practices:*

- Use of Tresca or von Mises criteria in the analyses. Most codes base their elastic material deformation on Tresca theory (except for RCC-M), which is used for multiaxial stress combination based on the maximum shear stress theory. Non-linear analysis is conventionally based on von Mises plastic criteria. There is no guidance for the use of finite element analysis results based on von Mises plastic criteria to meet the Tresca-based code requirements.
- Clarification of finite element analysis validity to determine lower bound limit loads.
- Limits on the use of limit analysis for level D criteria (possible large displacement) and flow stress value.

The authors have identified the need for detailed recommendations for analysis, such as:

- Tolerances and precise geometry to perform inelastic analysis.
- General FEA recommendations (mesh refinement, small versus large displacement, convergence criteria etc.).
- Cyclic elastic-plastic analysis procedures for fatigue and shakedown analysis: detailed step by step procedure, method, material properties and criteria.
- Strain criteria for elastic-plastic analysis have to be defined in the code, with possible alternative in the user's design specification.
- All the material properties for all these analyses (engineering/true and cyclic stress-strain curves, material constitutive equations, etc.) should be collected and included in the code for major materials of interest.
- A dedicated Appendix for level D criteria has to be proposed, which could be based on existing non-mandatory appendices in ASME Section III and RCC-M.
- Dedicated section for class 2 vessels, piping and supports should be developed
- Limitations encountered in different codes, such as S_y/S_u should listed, reviewed and supported by associated background material.

5 Concluding remarks

All codes define limitations to protect components from failure resulting from the application of operational mechanical or thermal loads. The following failure mechanisms are considered in the nuclear design codes reviewed in this report:

- Excessive deformation (plastic collapse).
- Plastic instability.

Furthermore, most codes consider degradation mechanisms generally associated with cyclic loading:

- Progressive deformation induced by repeated loads (ratcheting/shakedown).
- Fatigue.

It is important to note that AFCEN RCC-M and ASME Section III & VIII codes consider an additional damage mechanism, associated with stress triaxiality and leading to local failure by decohesion. No background is provided in the code, and a clarification of the background and basis for this rule is needed.

The main areas where the non-linear analysis methodologies differ are:

- Limit analysis associated with elastic-perfectly-plastic material; the corresponding criteria are based on load comparison.
- Monotonic elastic-plastic analysis associated with material stress-strain curve; the corresponding criteria are based on a maximum strain level (sufficiently low compared to material maximum elongation).
- Cyclic elastic-plastic analysis associated with material cyclic stress-strain curve for fatigue plasticity correction factor.
- Material constitutive equations for shakedown and ratcheting analysis.

All the codes considered in this report would benefit from the development of detailed non-linear analysis methodology.

Some other applications of non-linear analysis are associated with stress classification improvements and alternative rules, such as:

- Pipe/nozzle neck area analysis.
- Piping systems thermal expansion stress classification (elastic follow-up).
- Piping systems under seismic loads, in particular for high-level seismic events.

The review of all the existing codes and existing non-linear analysis design rules has highlighted key issues that will be investigated in more detail in the *Non-Linear Analysis Design Rules; Part 2: Good Practices*. This report will present detailed procedure proposals as well as their associated theoretical background.

6 References

[1] Design and Construction Rules for Mechanical Components of PWR Nuclear Island (RCC-M), AFCEN 2010 Edition

[2] ASME Boiler & Pressure Vessel Code, Section III - Rules for Construction of Nuclear Facility Components, ASME 2010 Edition

[3] RCC-MRx: Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN 2012 Edition

[4] KTA: Safety Standards of Nuclear Safety Standards Commission; KTA 3201.2 Components of the Reactor Coolant Pressure Boundary of Light Water Reactors, Part 2: Design and Analysis , Edition 2010

[5] JSME Code: JSME nuclear codes and standards for design and operation of domestic nuclear power plant facilities, Edition 2010

[6] KEPIC Code: Korea Electric Power Industry Code, Edition 2010

[7] PNAEG: Standards to the Tensile Strength of Equipment and Pipework at Nuclear Power Plants, PN.6X-G7-002-86, 1986 Edition

[8] R5 Rule: procedures for assessing structural integrity of components under creep and creep–fatigue conditions, EDF Energy 2010 Edition

[9] ASME Boiler & Pressure Vessel Code, Section VIII: Rules for Construction of Pressure Vessels - Division 2: Alternative Rules, ASME 2010 Edition

[10] EN 13445: Unfired pressure vessels European Standard, Part 3: Design, 2009 Edition

World Nuclear Association
Tower House
10 Southampton Street
London WC2E 7HA
United Kingdom

+44 (0)20 7451 1520
www.world-nuclear.org
info@world-nuclear.org

Non-Linear Analysis Design Rules – Part 1: Code Comparison