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Non linear analyses in the RCC-MRx code

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ABSTRACT

Codes and standards have their origin in times where finite element calculation and especially non-linear analyses were not developed and commonly used. Times have changed and now design is strongly associated to computation and the question is raised of the place of these analyses in the codes and standards. This paper gives an overview of the work undertaken in the RCC-MRx committee to have a better balance of the design rules and inelastic analyses.

INTRODUCTION

The design and construction rules for mechanical components of nuclear installations (RCC Codes) published by AFCEN primarily apply to safety class components. These Codes are used as a basis for contractual relations between Client and Supplier, in which case they shall be accompanied by a list of components to which they shall be applied.

RCC-MRx is developed especially for Sodium Fast Reactors (SFR), Research Reactors (RR) and Fusion Reactors (FR-ITER).

The scope of application of this Code exclusively covers mechanical components of a Nuclear Installation:

- important from a safety or availability point of view,
- having a leaktightness, partitioning, guidance and retaining or supporting role,
- classified as vessels, pumps, valves, piping, bellows, box structures, heat exchangers, irradiation devices and their supports, handling or drive mechanisms.

The design rules for components which are subject to irradiation were drawn up on the basis of standard nuclear installations.

Due to its specific domain of application, and especially to cover the creep damage, the RCC-MRx included annexes dedicated to non-linear analyses (appendices A10 and A11):

- Appendix A10: Elastoplastic analysis of a structure subjected to cyclic loading ,
- Appendix A11: Elasto-visco-plastic analysis of a structure subjected to cyclic loading.

These types of analyses were introduced in the code in order to give to the designers the possibility to justify the criteria by improving the representativeness of material behavior and so on the computation.

However, it appeared that a work had to be done regarding the evolution of the designer’s practices and the evolution of computation capacity, at least to clarify the articulation of code rules and finite element calculations.

In a first part, the article describes how the non-linear analyses are implemented today in the RCC-MRx code, particularly it details the origin of the current texts.

In a second part, the difficulties encountered by the users are developed.

Then it details the work initiated by the working group in charge of design to modify the existing text with the final objective to help the users in consistency with the whole code content.

CONTENT OF RCC-MRx, HISTORICAL BACKGROUND

RCC-MRx brief description

The RCC-MRx [1] which is one of the AFCEN Codes in the collection of design and construction rules for nuclear plants initiated by RCC-M for Pressurized Water Reactors (PWR). This Code is developed specifically for Sodium Fast Reactors (SFR), Research Reactors (RR) and Fusion Reactors (FR - ITER) and can be used for components of other types of Nuclear Installations (see illustration Fig. 1).

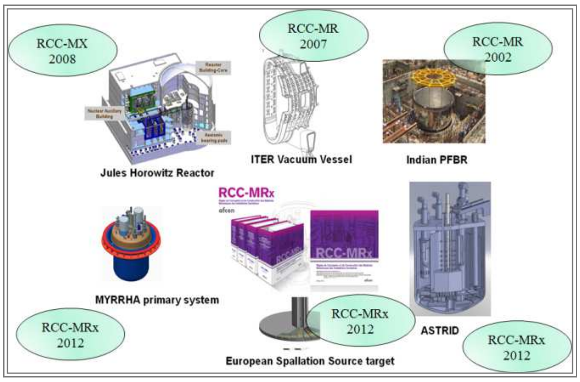


Figure 1. Illustration of RCC-MRx references

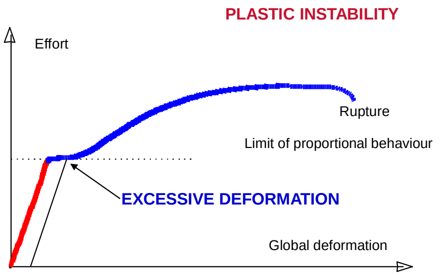
The RCC-MRx Code constitutes a single document that covers in a consistent manner the design and construction of mechanical components of Nuclear Installation within its scope of application. The three levels of design and construction proposed (N1Rx, N2Rx and N3Rx) correspond to decreasing levels of assurance of ability to withstand different types of mechanical damages to which the component might be exposed as result of loading corresponding to specific operating conditions. The specificities of RCC-MRx is to deal with high temperature damages (creep, ratchetting, creep-fatigue) and irradiation induced damages.

Inelastic analyses in RCC-MRx

The table 1 gives an overview of the content of the codes in terms of inelastic analyses references.

Table 1: References to the inelastic methods in RCC-MRx Tome 1

Damages	***§ applicable of the code***
Definition	RB 3228 Collapse load RB 3228.1 limit Analysis RB 3228.2 Elastoplastic analysis and experimental analysis RB 3240 Analysis methods
Type P damages	**RB 3250**
Negligible creep Negligible irradiation	***comments:*** *If thermal ageing is significant according to RB 3216.3, Sm, (Rp0.2)min, and (Rm)min have to be multiplied by Fv given in A3.51; for an elastoplastic analysis, loading is divided by Fv*
	RB 3251.113 Limit analysis So≤Sm(Qm) with $So=(C/C_L)R_L$ C loading C_L collapse loading R_L yield strength
	RB 3251.114 Elastoplastic analysis

Damages	***§ applicable of the code***
	Level A criteria • under C_{EP}=1,5 x C, no excessive deformation • under C_{EP}=2,5 x C, no plastic instability C nominal loading Level C criteria: (1,5 – 2,5) -> (1,2 – 2) Level D criteria: (1,5 – 2,5) -> (/ – 1,35) ***comments***: *excessive deformation is attained when the overall permanent deformation exceeds the deformation which would occur with purely elastic behaviour*.  *Plastic instability considered here is an overall phenomenon. It must be distinguished from ductile tearing which is a form of fast fracture and must be examined separately.*
Negligible creep significant irradiation	RB 3251.213 Limit analysis Limit analysis of a structure according to RB 3228 is excluded when irradiation is significant. RB 3251.214 Elastoplastic analysis • swelling shall be negligible or insignificant by checking • criteria given in RB 3251.114
significant creep	RB 3252.112 Limit analysis $U_{A,C}(\Omega' So) \leq 1$ with Ω' depending from collapse load ***comments***: *A10.2000 and A10.3000 not applicable*
Type S damages	**RB 3260**
Negligible creep Negligible irradiation	RB 3261.12 elastoplastic analysis $\varepsilon_m < \varepsilon_{dp1}$ $\varepsilon_m + \varepsilon_p < \varepsilon_{dp2}$ Fatigue : V≤1,0 ***comments***: *In significant irradiation, same approach provided that material behaviour is justified*
Significant creep Negligible irradiation	RB 3262.12 Elasto-visco-plastic analysis RB 3262.121 Progressive deformation $(\varepsilon_m)_{pl+fl} < \varepsilon_{dpf1}$ $(\varepsilon_m + \varepsilon_p)_{pl+fl} < \varepsilon_{dpf3}$ RB 3262.122 Creep-fatigue Evaluation of V and W using creep-fatigue interaction diagram ***comments***: *In significant irradiation, same approach provided that material behaviour is justified and using 10xW*
Welded joints	RB 3290 account for welded joints RB 3291 Rules for the prevention of type P damages RB 3291.2 Elastoplastic or limit analysis RB 3292 Rules for the prevention of type S damages RB 3292.12 Inelastic analysis ***comments***: *Welded joints are taken into account through specific weld coefficients for type P damages*

RCC-MRx has been published for the first time in 1985, and since the first edition, rules and recommendations regarding this type of calculations were already implemented in the code. However, it is easily understandable that, regarding the numerical tools available in the 70th-80th, main methods developed in the code were not based on sophisticated calculation methods. Major analysis criteria of codes at that time were based on elastic calculation and the use of inelastic calculations was limited, as reflected by the following text, still in the RCC-MRx:

"Elastic analysis should be the most commonly used method, the other methods of analysis only being used when it has not been possible to check certain criteria associated with elastic analysis."

However, when the French Sodium Fast Reactor program Superphenix was launched, it appeared quickly that, regarding the specific damage of creep-fatigue, the rules based on linear elastic calculations were difficult to be met and that there was a need to take into account the material behaviour of the component (as illustrated in figure 2). Indeed, inelastic analysis is more precise about stress calculations and strains than elastic analysis. Nevertheless, the margins on the criteria are unchanged due to uncertainties on the materials and the possible coupling, for example, mechanical damage and the aging of the materials or environmental conditions and fatigue life.

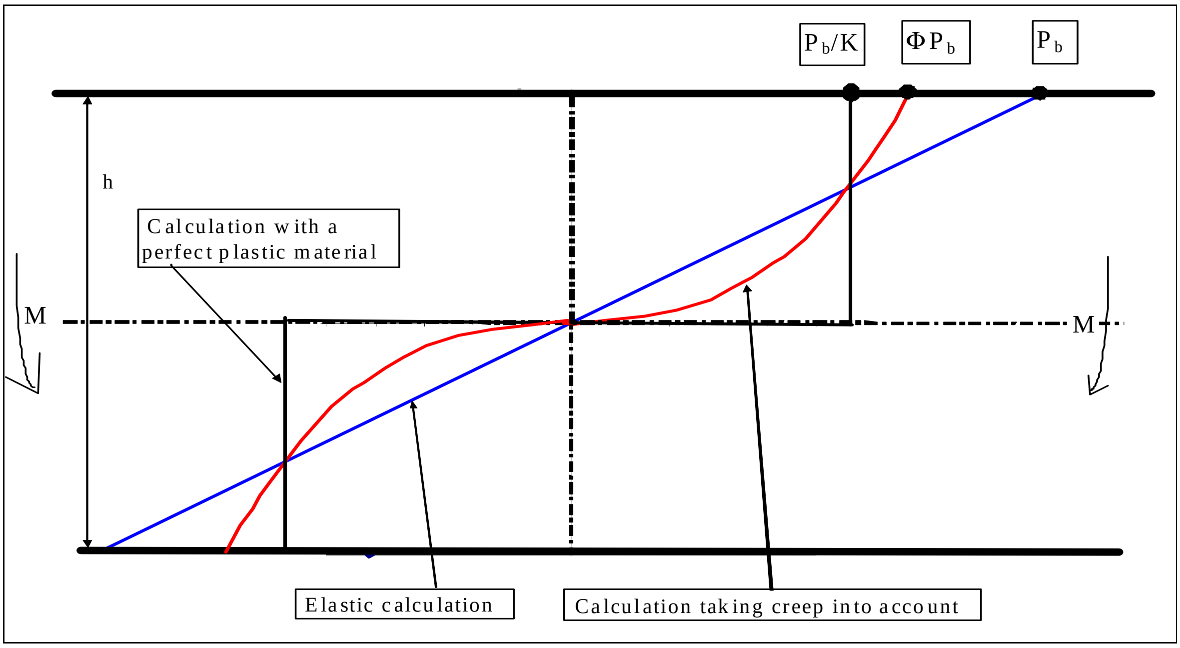


Figure 2. Comparison of bending stress distributions in an elastic calculation and in a calculation taking creep into account

A large study program was thus launched with one main objective: to develop inelastic evaluations for creep fatigue, mostly focused on 316 stainless steel family [3]. The expectations of this work were that the proposed models were able to describe local deformations (especially in stress concentration area) and were able to represent the whole cycle shape (and not only the extrema values) in all the points of the structure (to take into account the stress redistribution).

The texts included in the code have their origins in the first texts for high temperature reactors and especially the ASME Code Case N47 [2] which gave strain limitations for inelastic calculations. These texts have been associated to recommendations for the use of inelastic calculations and more precisely for the mathematical model to be taken into account for the material constitutive laws in appendix A10

(Elastoplastic analysis of a structure subjected to cyclic loading) an A11 (Elasto-visco-plastic analysis of a structure subjected to cyclic loading) as illustrated in table 2. In a first time, three mathematical models were tested (isotropic behavior, kinematic behaviour and Chaboche model), with several hypotheses on the material data used (mean curves, minimum curves, consolidated or cyclic curves) and different way to transform the curves in bi-linear curves. The models have been completed and validated through times based on research and developments programs of CEA and Framatome ([4], [5] and [6]), in short we can say that bilinear kinematic models are not sufficient to represent consolidation phenomena and stress redistribution, more complex models are needed especially for progressive deformation (see table 2).

Table 2: Overview of the A10 and A11 content

Collapse mode → **Constitutive models ↓**		**Excessive deformation, Plastic instability**	**Buckling**	**Progressive deformation**	**Fatigue**
Perfect plastic		*Suitable (1)*	*Suitable* (4)	*Avoid*	*Avoid*
Isotropic strain hardening	Bilinear hardening	*Avoid*	*Avoid*	*Avoid*	*Avoid*
	Multilinear hardening	*Suitable (2)*	*Suitable*	*Avoid*	*Avoid*
	Non-linear hardening	*Suitable (2)*	*Suitable*	*Avoid*	*Avoid*
Linear kinematic hardening	Bilinear hardening	*Avoid*	*Avoid*	*Avoid*	*Use with care (5)*
	Multilinear hardening	*Avoid*	*Avoid*	*Use with care (3)*	*Use with care (5)*
	Non-linear hardening	*Avoid*	*Avoid*	*Use with care (7)*	*Use with care (5)*
Combined hardening (Chaboche elastoplastic, etc.)		*Suitable*	*Suitable* (6)	*Use with care*	*Suitable*
Perfect plastic + creep rule		*Suitable (1)*	(9)	*Avoid*	*Avoid*
Isotropic strain hardening + creep rule		*Suitable (2)*	(9)	*Avoid*	*Avoid*
Linear kinematic hardening + creep rule		*Avoid*	(9)	*Use with care (3)*	*Use with care (8)*
Combined hardening (Chaboche viscoplastic, etc.)		*Suitable (2)*	(9)	*Use with care (4)*	*Suitable*

1 Model used mostly for limit analysis.
2 Identification with minimum monotonic curves for the material.
3 Results may not be conservative.
4 Satisfactory results although often too conservative.
5 Identification with reduced cyclic curves except where the strain amplitude is small, in which case mean monotonic tensile curves should be used, if the strain amplitude is high and in case of variable amplitude (or pre-loading), memory effect shall be taken into account (Combined hardening model with hardening memory).
6 Satisfactory results but unnecessarily complex.
7 Results may be conservative in the presence of considerable strain.
8 Results may not be conservative if the hold times are on residual stress states.
9 Not available yet.

DIFFICULTIES AND FEEDBACK OF USERS

The RCC-MRx allows to use inelastic analyses with adapted criteria but some information is missing, and interpretations or sensitive computations have to be performed in order to select the good hypothesis. Two main problems are identified: choice of the material law and its identification and numerical hypothesis in order to have results in reasonable time.

For P-Type damages and more precisely for the limit analysis, the R_L value is indicated as the yield strength of the material. Nevertheless, since the name of this variable cannot be found in the rest of the code, an interpretation must be performed to choose a correct value which can be pertinent for the analysis. This issue can be reinforced when different materials are represented in the EF model. In this case, the choice of the different R_L values can directly change the behavior of the structures if the yield strengths are quite different.

In A10 and A11 appendices, RCC-MRx presents the different types of material law. Each law has some specificities which can help to improve the material behavior according the type of performed analysis. In addition, table A10.7200 gives some recommendations about the using of this law. Nevertheless, when the used law is sophisticated as combined strain hardening law, the identification of material parameters can be a difficult point.
Firstly, the number of material characteristics needed for the identification is important in order to represent the whole of material behavior. Material characteristics of appendix A3 of RCC-MRx can help but it is rarely enough. Experimental data must be found in order to complete the database, by performing bibliography or experimental tests. It is important to notice that the identification must be performed for each temperature. So, the number of tests can increase. Interpolation or extrapolation on the parameters or material characteristics can be performed but the results must be checked in order to prove their consistency.
Secondly, the complex constitutive laws present many parameters which are linked so they must be varied not individually by rather in combinations. Consequently, the identification can be iterative and time consuming. In addition, the temperature evolution of the parameters cannot to be erratic (succession of increase and decrease of the values).

Moreover, due to the fact that numerical calculations are not part of the code, for such analyses, sensitive to the way to model the component, to the load application, it appears clearly that some documents (inside or outside of the code) are missing to guide and supervise calculations. The way to analyse results on sophisticated models available now are not in the code, still fixed on the linearization of the 2D axisymmetric model, and more suitable criteria, based on local strains for instance are also missing.

PERSPECTIVES AND CONCLUSION

Long set aside in the codes, inelastic analyses methods and associated criteria have clearly to be examined again in regards to the progress in data through the 30 last years. It is also the case of the RCC-MRx, despite strong efforts put on these topics in the early editions of the code, which were crucial for high temperature reactor components justification. Today, it appears even more important to work again on the consistency between codes and numerical simulations, as they will be inextricably linked to innovative reactors.
Some initiative are already on board, we can quote the World Nuclear Association initiative: in September 2014, the CORDEL MCSTF Pilot Project was launched a project to investigate divergences and to promote international convergence of code requirements for non-linear analysis methods [7]. This study highlights the needs of detailed recommendations to guarantee to have a representative and reproducible result.
The RCC-M [8] had also implemented in its last version some important improvements on this topic.

It appears also clearly from the users' feedback that material data are not sufficient regarding the components to be covered. If, in the 70th, the focus point was stainless steel and especially 316L family, there is today a more extended need in terms of materials and models to be covered, and some issues, as for instance materials with cyclic softening, have to be considered.

Codes have to be adapted also in terms of criteria usable with complex 3D calculations, and it is important also to start already a work of understanding and connection with the new generation of tools, such as the artificial intelligence, numerical twins that are likely to be used in the future of nuclear industry.

Regarding the RCC-MRx development, a first step has been to clarify the existing A10 and A11 with the objective to launch since 2022 a reflection on how to take into account the evolution of the numerical tools in the design process of the code.

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NOTATIONS

Rp0.2	0,2% offset yield strength at 0,2%, function of temperature
Rm	rupture strength
Sm	allowable stress
Fv	thermal ageing factor
Qm	Secondary membrane stress
C_{EP}	Load applied for the elastoplastic calculation
C_L	collapse loading
R_L	yield strength
level A criteria	criteria to be met for the first and second category operating conditions (normal operation, including normal operating incidents, start-up and shutdown)
level C criteria	criteria to be met for third category operating conditions (emergency conditions)
level D criteria	criteria to be met for fourth category operating conditions (highly improbable)
$U_{A,C}(\Omega' So)$	creep usage fraction
Ω'	creep correction factor
So	characteristic stress
ε_m	significant mean total strain
ε_p	significant linear total strain
ε_{dp1}	allowable strain for the significant mean total strain (material dependant value, 1% for 316L family)
ε_{dp2}	allowable strain for the significant linear total strain (material dependant value, 2% for 316L family)
ε_{dpf1}	allowable strain for the sum of plastic strain and associated creep strain at 1.25 times the effective primary membrane stress intensity (material dependant value, 1% for 316L family)
ε_{dpf3}	allowable strain for the sum of plastic strain and associated creep strain at 1.25 times the effective primary stress intensity of the sum of primary stresses corrected by the effect of creep (material dependant value, 2% for 316L family)
Type P damages	Types of damage referred to by the expression "type P damages" are those which can result from the application to a structure of a steadily and regularly increasing loading or a constant loading.
Type S damages	Types of damage described by the expression "type S damages" are those which can only result from repeated application of loadings.

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