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CORDEL MCSTF: Harmonization of non-linear analysis design rules within international codes and standards

Ronan Tanguy[1]

[1] Project Manager, World Nuclear Association, London, UK (ronan.tanguy@world-nuclear.org)

ABSTRACT

This papers covers the work performed by members of the World Nuclear Association's Mechanical Codes & Standards Task Force in proposing harmonized non-linear analysis design rules for international codes and standards. This work was undertaken in three parts; an initial comparison of current code requirements, a benchmarking exercise to highlight differences between the codes and finally recommendations for harmonization of the codes.

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. The World Nuclear Association's (WNA) Cooperation on Reactor Design Evaluation and Licensing (CORDEL) Mechanical Codes and Standards Task Force (MCSTF) developed a project on non-linear analysis design rules in order to investigate the differences in various codes and propose recommendations for industrial practices.

The project was completed in 2021 with the publication of the final report in the Non-Linear Analysis Design Rules series. Four reports were published over the course of the projects in total, the first compared existing codes and standards, the second specified two benchmark exercises to determine differences between the codes, the third presented the results of the benchmarking exercises and the final report proposed recommendations for industrial practices.

CODE COMPARISON

The first report in the series reviewed and compared 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. No specific code was considered as a baseline reference for this comparison and requirements for each of the codes presented in Table 1 were considered independently. The UK R5 rule, while not a code or standard was also studied along with AFCEN RCC-MRx which covers design rules for mechanical components of high-temperature, research and fusion nuclear installations.

Table 1: Codes considered.

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 comparison examined requirements to protect against three major failure modes; excessive deformation (or plastic collapse), plastic instability (or ultimate load) and fracture-decohesion with no crack initiation (local failure). Two major degradation mechanisms; fatigue (simplified elastic-plastic method using plasticity correction factors) and elastic and plastic shakedown (ratcheting) were examined. Two types of loads were considered for the comparison; monotonic loads and cyclic loads. The initial comparison exercise examined the scope of each mechanical design code, the results of which are presented in Table 2 and Table 3 below:

Table 2: 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
RCC-M	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 3: 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
RCC-M	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

Failure mode comparisons

With regards to 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; with 1.5 S_m (design stress intensity) and 0.66 times the corresponding load in ASME III, JSME, KEPIC, ASME VIII-2 and 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.

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, the effect of large displacements on finite element analysis (FEA), strain criteria and a step-by-step procedure associated with recommendations.

Local failure is only considered in RCC-M, ASME III and ASME VIII, with the same requirements defined in all three codes. 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.

With regards to 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 and K_ν. The main difference between the codes arises from the variations in the tabulated values of K_e.

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.

Comparison findings

All codes define limitations to protect components from excessing deformation and plastic instability failures resulting from the application of operational mechanical or thermal loads. Furthermore, most codes consider degradation mechanisms generally associated with cyclic loading such as fatigue and ratcheting/shakedown. 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.

CODE BENCHMARKING

Following the code comparison, two typical LWR components were proposed for benchmarking: a large class 1 vessel nozzle and a class 1 reinforced piping nozzle, in order to analyze plastic collapse, plastic instability, local failure, fatigue, and ratchetting. The benchmarks aimed to compare different practices, (usability of the plastic limit load, the monotonic elastic-plastic, and the cyclic elastic-plastic), adopted by different international companies or analysts for given material non-linear properties. The results of the benchmarks would then be analyzed to propose harmonized industrial practices. These benchmarks consider 2D geometries under axisymmetric loads, and will be supplemented by sensitivity analysis, effects of 3D geometry, effects of non-axisymmetric piping loads or effects of multi-materials as dissimilar metal welds. The full details of the benchmarks' initiating parameters (geometry, material properties, mechanical and thermal loadings) can be found in the Part 2a report.

Ten international participants from China, France, Germany, India, Russia, South Korea, the UK and the USA contributed to the benchmarking exercise. Four different software packages were used to undertake the simulations; ABAQUS, ANSYS, FASEM and SYSTUS.

LWR vessel nozzle outcomes

The first benchmark, for the LWR vessel nozzle, was defined in five parts (1.0 Elastic Codified Approach, 1.1 Plastic Collapse and Local Failure, 1.2 Plastic Instability, 1.3 Piping Load Effect and 1.4 3D Effects). In the elastic codified approach (Benchmark 1.0), there is a good agreement of predicted membrane and combined stresses in the vessel and main coolant line outside of transition areas. The largest discrepancies are in inclined sections corresponding to the transitions from the vessel to the nozzle and from the nozzle reinforcement to the pipe, respectively. Differences also originate from the type of element, mesh refinement used in the model and the way stresses have been linearized, particularly bending stress. Variations in bending stress are believed to primarily come from the way bending stress values have been derived. There is also a need to discuss the limits of the approach to analyze a 3D geometry using a 2D model. In Benchmark 1.1, plastic collapse values are obtained using three methods. There is a good agreement in the values of the limit load pressure predicted by the participants based on the yield stress. All results lie within 5% margin. The limit loads predicted by the other two methods (double slope and max 0.5% strain) show similar trends. It is clear from the results that the limit load is primarily influenced by the FEA method used in the simulation. It should be noted that the limit loads estimated based on strain criterion depend on the location where strain is being monitored.

Benchmark 1.2 focused on plastic instability predictions under pressure load based on flow stress, 5% strain and 10% strain. As expected, the results indicate that the 10% strain criteria give higher plastic instability load compared to those predicted by the 5% strain limit. It should be noted that strain-based criteria are influenced by the location of the strain. Another factor that influences the results is the value of the yield stress used to calculate the flow stress. Since the value of the flow stress is less than the stress at 5% strain, the flow stress criteria predicts the lowest plastic instability load and is a function of the material characteristic represented by the stress-strain curve.

The fourth part on pipe load effects (Benchmark 1.3) has not added much value to the nonlinear analysis methods. For the exercise to be meaningful, a higher piping load, potentially including bending, should have been specified.

The fifth part (Benchmark 1.4) has shown that the assumptions made to represent a real 3D geometry as a 2D axisymmetric geometry are pessimistic. Higher and more realistic limit loads can be obtained if real 3D geometry is modelled. It can be concluded that the 3D model has confirmed that the limit loads and plastic instability loads obtained from the 2D model are within 10% margin.

Reinforced piping nozzle outcomes

The second benchmark problem was focused on fatigue assessment and was done in two parts (2.0 Codified Elastic Fatigue and 2.1 Simplified Non-Linear Analysis). In this benchmark, two quantities are derived, the plasticity correction factor, K_e, and fatigue usage factor (FUF) at the inner and outer surface at various locations using methods specified in ASME III and RCC-M. For the codified elastic fatigue assessment (Benchmark 2.0), two transients were specified. Generally, there is good agreement of the trend in the K_e and FUF results calculated for both transients. Some differences in the K_e and FUF results were observed which could be due to the way stresses are resolved with respect to a cylindrical coordinate system defined locally to the section.

Benchmark 2.1 was aimed at applying simplified methods of elastic-plastic FEA to take account of plasticity in evaluating fatigue life. This benchmark has highlighted an important difference between ASME III and RCC-M. The consensus amongst participants was that the highest K_e and FUFs according to ASME III occur in the branch pipe and main coolant line. Comparatively, the nozzle experiences less damage according to ASME III. In contrast, two participants found that the highest K_e and FUF according to RCC-M are at the nozzle crotch corner. The reason for this is due to the effect of the pressure drop, which contributes to a higher mechanical stress intensity range at this location, which must be addressed explicitly in RCC-M calculations. However, it was recognized that significant differences could arise in the RCC-M fatigue results for Transient 2 depending on analyst assumptions, which are highlighted in the report. The method used to account for fluctuating mechanical loads in RCC-M calculations can also have a significant effect. A number of FEA assumptions were considered as having potential effects on the fatigue analysis results. The choice of linearization method may also have an influence on the results. Neither ASME III nor RCC-M provide explicit guidance on stress linearization and it is left to the judgement of the analyst.

Benchmarking findings

It is acknowledged that whilst the stress ranges calculated by the participants were similar overall, even minor differences can have a significant ‘knock-on effect’ for downstream fatigue calculations. The reason for this is twofold. Firstly, it is due to the high non-linearity of the design fatigue curve in the low-cycle regime, where even a small difference in stress amplitude can result in a rather large difference in fatigue usage; secondly, slight differences in the stress intensity range may lead to potentially large differences in K_e which can also have a dramatic effect on the fatigue usage. A major source of difference between the K_e and FUF values reported by participants was due to the difference in the selection of the two distinct pairs of time points corresponding to their respective maxima and minima. A second major source of difference identified by the results for Transient 2 arose due to the methodology adopted for calculating the mechanical and thermal stress ranges in accordance with RCC-M.

Finally, a further comment raised by participants concerned the application of an alternative ASME III K_e factor, which, at the time of writing, has received approval from the 68 ASME Board on Nuclear Codes and Standards for publication as an ASME Section III Code Case (Record 17-225). There was interest to observe how this new K_e factor, denoted K_e*, compared with the other K_e factors analysed. One participant investigated this difference for Benchmark 2.0 and found that overall, the new ASME III K_e* factor exhibited a similar trend to the RCC-M K_e factor, and accordingly the FUFs calculated using this new approach are much more closely aligned to RCC-M compared with the standard ASME III, Appendix XIII-3450 approach. However, there were found to be some cases where more significant divergence can occur between K_e* and the RCC-M K_e factors, which can arise depending on the loading condition.

Close assessment of the differences in the results submitted by the participants has identified three main causes:

- Modelling assumptions made by the analysts;
- Analysis and assessment methods adopted by the analysts;
- Differences in the design code rules.

However, it should be noted that the benchmark problem conditions would be more severe than the challenges faced by industry practitioners in real-life scenarios, since the two benchmark problems were designed to identify areas the where consensus appears to be emerging and areas where further discussions are needed to harmonize the non-linear analysis approach used by the analysts.

RECOMMENDATIONS FOR INDUSTRIAL PRACTICES

Following the benchmarking exercise, a need for consensus in certain areas of design codes was identified, the final report (Part 3) in the Non-Linear Analysis Design Rules series therefore proposed recommendations for a harmonized approach to these areas.

Linear mechanical analysis

Guidance has been lacking for linear mechanical analysis as it is sometimes believed to be straightforward and well understood. Currently practices are not satisfactory when treating complex shapes with discontinuity areas. This report offers some guidelines for dealing with such scenarios which could be further developed within design codes. The guiding principle for undertaking the analysis is to perform sensitivity runs until convergence is reached to establish control of the calculation's parameters. The rules for the classification of stress (primary or secondary) could also be harmonized between codes where possible. For linear mechanical analysis, three categories of stress are defined in nuclear codes: membrane, membrane + bending, and peak, as well as the damages that these stresses produce. The damages that were discussed were excessive deformation and plastic instability. The section provided recommendations to aid analysts with the initialization of their modelling. Geometric choices have a considerable impact on both the accuracy of results and the computation time. It was therefore recommended to split large components into distinct zones for faster calculation where possible while ensuring that boundary conditions match and that discontinuities are appropriately managed. In the case of asymmetric geometries, a minimum recommended distance between boundaries and discontinuities is proposed. Recommendations were also made to assist analysts with their choice between a 2D or 3D model. These are presented in Table 4 below.

Table 4: Comparison of 2D and 3D modelling.

	Advantages	Drawbacks
2D model	Faster computation Straightforward to interpret results	Lack of stress or strain in third dimension Forced approximation for certain geometries Inability to apply some loads with all tensor components
3D model	Precise and detailed results Complete tensors can be applied Realistic geometries	Slower computation Obtaining results is more difficult as an area to analyse must be chosen

Accurate modelling results require an astute selection of the FEA mesh applied to the geometry. Several elements are typically at the disposal of analysts (solid, shell, beams etc.) but their choice must be consistent with the behaviour of the structure and the domain in which the elements are valid. The density of the mesh and variations in density are also important choices which not only affect the accuracy of the results but also the computation time. It is recommended that the density should be increased when approaching discontinuity zones where stresses concentrate while ensuring that the mesh is fine enough to capture bending stress gradients through the model in zones away from discontinuities. When thermal loads are being considered, the analyst should ensure that the meshing density is increased through the thickness towards surfaces. The selection of time discretization must also ensure that the thermal field is stable and avoids temperature oscillations.

Following the computation, the stresses revealed by the computation are post-processed. Two aspects of post-processing that are of particular importance are defining stress classification lines and linearizing stresses. The definition of cross-sections is crucial as the stresses present in these sections are directly compared to the allowable stresses in codes and standards. Maximum stress values must be captured within line segments, but it should be noted that the maximum stresses are not always at the same point. It is recommended that certain special locations be therefore treated differently as FEA calculations can be affected by stress classification lines that contain a singularity. It is therefore important to linearize the stresses appropriately. Recommendations for this procedure are presented for through thickness stress and shear stresses. Stress analysis is covered in the final part of the linear mechanical analysis section, which presents recommendations for the classification of stresses within the model. Analysts much verify triaxiality criteria and other categories of stress to check for excessive deformation and plastic instability.

Plastic analysis

The design codes offer the possibility to assess plastic collapse using limit load and double slope methods which provide consistent results as long as consistent material data is used. This was observed through the benchmarking performed in the preceding reports. Guidance is required for the choice of flow stress for plastic instability which is not currently provided in most design codes. Maximum local strain methods are not proposed in design codes as these are very sensitive to the maximum strain value and the post-processing of FEA results. For plastic analysis, several methods for calculating collapse loads were presented (limit load, double slope, and maximum strain 0.5%) along with recommendations for performing each type. A series of recommendations for the maximum strain 0.5% method are also provided. It was noted that the limit load analysis assumes an elastic-perfectly plastic material and as such is less practical and instructive than the elastic-plastic stress analysis. Plastic instability is covered next, identifying the von-Mises yield function as a better choice than Tresca for metallic materials as it does not include any singularities in its formulation.

Elastic fatigue analysis

Guidance for elastic fatigue problems is issued in the following section with clear recommendations for the linearization of stresses in such scenarios. Firstly, the linearization should be performed at each time-step and not only for those that feature extreme stresses. Secondly the time-steps used for both thermal and mechanical analysis should be adequately refined during the loading event and following it for long enough to capture the maximum P+Q stress. Finally, the calculation of membrane and bending stress resultants should be performed for all the unique stress components by default. Recommendations for cyclical fatigue analysis are then put forward following coverage of the static scenarios. To ensure appropriately conservative results, the S_p and S_n for each counted cycle should be determined independently for calculating K_e and S_{alt}. Material properties are then examined as these have a considerable influence on the results of fatigue calculations. A straightforward approach for obtaining the design stress intensity, S_m, is presented based upon the RCC-M and ASME code requirements in Section 0 which has the advantage of being more meaningful and being compatible with most cycle counting algorithms. It should be noted that this approach is for selecting the most appropriate temperature to set the value of S_m for the plasticity correction factor and that S_m is not a FEA result. Two options for the calculation of the representative elastic modulus are recommended in Section 0 due to their ability to reduce the conservatism within fatigue calculations. As previously mentioned for static loads, the properties accorded to a material during analysis significantly impact the results of a simulation. This is no different for cyclical loads, and it is therefore recommended that temperature-dependent material properties should be employed for stress analysis where possible. Fixed temperature properties do have their place however, if analysts are aiming to maximize stress for example. In this case, is it recommended that analysts undertake sensitivity studies to understand the competing effects of various material properties on the fatigue damage.

Harmonization across design codes for some aspects of elastic fatigue analysis is currently underway, notably for the K_e factor however other areas still require further examination and comparison work such as cycle counting for example. CORDEL will be covering these topics in a future publication on Fatigue Life Analysis, in close cooperation with the SDOs.

Plastic fatigue analysis

The final section covering plastic fatigue analysis presents two different approaches to the topic. The first of which uses a direct analysis to obtain the ranges of elastic-plastic strain while the second one uses an elastic-plastic concentration factor K_e, which is employed when the yield strength of a material is exceeded to refine plastic corrections in the linear fatigue analysis. In both cases, material properties play an important role and similarly to recommendations in the elastic fatigue analysis section, it is best practice to employ anisothermal material properties to reduce conservatism despite the increased complexity. The second approach is of greater interest due to the recommendations for the K_e factor, which is the ratio of the elastic-plastic strain range to the elastic strain range. Both these ranges must be calculated themselves and the same method (Tresca or von Mises) must be employed for both. When the modulus of elasticity used in these calculations is a function of temperature, it is recommended that the value of the modulus that maximizes the K_e factor be used. In the case of complex loading conditions, it is recommended that analysts carry out a sensitivity study to ensure that the chosen solution is conservative and to provide the domain in which the solution is applicable. Plasticity models are discussed, stating that the isotropic hardening model does not consider the Bauschinger effect and therefore FEA results obtained following the first stress reversal cannot be relied upon for accuracy. It is therefore recommended that a non-linear kinematic hardening rule be employed instead. The Armstrong-Frederick model and the Chaboche model are suitable alternatives. It should be noted however for the Armstrong-Frederick model that compromises will need to be made with regard to the target strain domain as it only defines a single kinematic component.

It should be noted that while it is feasible to employ non-linear methods for plastic fatigue analysis, they can be challenging to implement in industrial practices. This is due to the amount of care required in determining appropriate parameters to fit the material cyclic behaviour and the considerable computational power require to perform the calculations.

CONCLUSION

The work and recommendations presented within this paper are the culmination of two years of work by the MCSTF based upon the outcomes of code comparisons and benchmarking. The methods employed in some of the benchmarks are not codified but present insight into the possibilities offered by different approaches that the MCSTF recommends for examination by SDOs. The findings of the report also demonstrate the importance and influence of choices made by analysts during the post-processing of their non-linear analysis. The selection of postprocessing parameters, notably for plastic instability, is an area in which standard operating procedures should be developed to ensure a consistent approach. The MCSTF will continue to build upon the work presented in this report, notably with regard to fatigue for which a subsequent report is currently under preparation.

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