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Non-Linear Design Evaluation of Class 1-3 Nuclear Power Piping

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1. Introduction

A nuclear piping system which is found to be disqualified, i.e. overstressed, in design evaluation using linear analysis software in accordance with ASME *Boiler & Pressure Vessel Code, Section III* (ASME, 2009a), denoted as ASME III below for convenience, can still be qualified if further design requirements can be satisfied in refined nonlinear finite element analyses in which material plasticity and other non-linear conditions are taken into account. For clarity, a design evaluation using such linear analysis software will throughout this chapter be called a *linear design* evaluation, and a design evaluation involving a non-linear finite element analysis a *non-linear design* evaluation.

The *linear design* evaluation according to ASME III is purely based on stress limits. Stresses in piping components are first divided into membrane, bending and localized stresses for formulation consistency with beam and/or shell structures. Thereafter, stresses are further categorized into primary, secondary and peak stresses. The primary stresses are the “not self-limiting” part of responses typically resulted from external forces such as dead-weight, internal pressure, earthquake and so on, and they are important to avoid catastrophic failure and to control plastic deformation. The secondary stresses refer to the “self-limiting” part of responses resulted typically from thermal effects and gross structural/material discontinuities, and they are responsible for eventually progressive/incremental deformation. The peak stresses are the combined “peak” responses which are used to control fatigue failure. In ASME III, design criteria are defined in terms of stress intensity or principal stresses. For Class 1 piping systems, the criteria are defined by the stress intensity which is the largest absolute value of the principal stress difference, or equivalently twice of the maximum shear stress, and for Class 2 and 3 piping systems by the largest absolute value of the principal stresses. In connection with the design-by-analysis approach, the *linear design* evaluation is performed through comparing stress intensities of above-mentioned stress categories with their allowable limits. Among software commercially available for performing such a linear design evaluation, PIPESTRESS from DST Computer Services S.A. (DST, 2005) is widely used in Sweden.

Furthermore, the *linear design* evaluation is conducted for each of the following load sets: Design Condition and 4 so-called Service Limits of Level A, B, C and D. For different load sets, different design criteria and requirements are used. Through defining various loads

into different load sets and using different design criteria and requirements, the safety degree consideration and the occurrence probability of a given load can be introduced in the design evaluation.

In accordance with ASME III, *non-linear design* evaluation is an alternative to the *linear design* evaluation. Depending on which stress intensity limit is violated in the *linear design* evaluation, there are two types of non-linear analysis required in ASME III for the alternative *non-linear design* evaluations: (1) collapse-load analysis and (2) non-linear transient analysis. For clarity, such alternative design criteria and requirements which are specified in connection with such non-linear analyses are termed hereby as the *non-linear design* criteria and requirements. Such non-linear finite element analyses can generally effectively be conducted using general-purpose finite element software, such as ANSYS (ANSYS, 2010) and most other well recognized software.

This Chapter is devoted to describe the general procedure for the alternative non-linear piping design and to clarify those relevant *non-linear design* criteria and requirements. Our emphasis will be placed on the later task as unclear and inconsistent issues have been observed in ASME III when non-linear design criteria and requirements applied. In recent years, quite many non-linear analyses and design evaluations have been conducted in Sweden for several power uprate projects. Unfortunately, most of such work has always ended with, or can never be ended without, long discussions on such unclear and inconsistent issues.

The Chapter is organized as follows: In Section 2, an overview on loading conditions is given. In Section 3, we review the *linear design* evaluation and discuss the *non-linear design* evaluation for Class 1 piping systems. In Section 4, the review and discussion are continued for Class 2 and 3 piping. In Section 5, we briefly address the computational procedures for collapse-load analysis and, in Section 6, we discuss the computational procedures for non-linear transient analysis. Finally, in Section 7 concluding remarks are given. We note that the discussion given in this Chapter is mainly based on our experiences on the application of ASME III under Nordic conditions, see e.g. Zeng (2007), Zeng & Jansson (2008), Zeng et al. (2009, 2010).

As this chapter covers a large amount of design rules and requirements of ASME III, an attempt has been made to keep the presentation brief and concise, yet still sufficiently clear. Unless otherwise stated, notations will be kept to be identical to those used in ASME III, equations specified in ASME III will not be repeated here unless necessary, and fundamental design requirements e.g. *Pressure Design* etc., will not be discussed here. In particular, the description of the *linear design* evaluation will be kept brief whenever possible and, for a more detailed description, we refer to ASME (2009), Slagis & Kitz (1986), Slagis (1987) and references therein.

2. Load conditions

The design evaluation rules in ASME III are for Class 1, 2 and 3 piping specified in terms of 5 loading conditions: Design Condition, and Service limits of Level A, B, C and D.

Under each loading condition, loads are combined to one or several load set(s) according to Design Specifications. The rules for load-combinations are defined in accordance with probabilities in which corresponding loads (events) should occur and consequences that may result in. Thus, a given load set defines the following:

1. Loads and their combinations to be considered in piping analysis.
 2. Stress intensity limits to be used in the subsequent design evaluation.
- In Tab. 1 we show an example of how these load sets are specified in Sweden. The design evaluation must be conducted in accordance with this table and the piping design is not qualified unless all evaluation rules specified for each load set are met.

We note that in Tab. 1 notations are of self-explaining, e.g. PD for Design Pressure and SSE for Safe-Shutdown Earthquake etc. Rather than explaining how load-combinations are defined in Tab. 1, which is not our purpose, we should observe the followings from this table:

1. Loads given under Design Condition are not only static loads of Design Pressure (PD) and Dead Weight (DW), but also dynamic loads (GV/SRV1) which represents here those generated by opening or closing one safety valve.
2. Loads in Service limit Level A include static loads (PO+DW) and dynamic loads GV/SRV1, where PO denotes the operating temperature. We note that GV/SRV1 are generally not included according to ASME III, and they appear here due to additional requirements specified in Swedish design specifications.
3. Loads in Service limit Level B include static loads (PO+DW), time-dependent loads generated by opening or closing of *seven* safety valves (GV/SRV7).
4. Loads in Service limits of Level C and D include static loads (PO+DW), dynamic loads generated by e.g. opening or closing of several safety valves, and Safe-Shutdown Earthquake (SSE) and so forth.

Tab. 1 is only an example for our discussion purpose. In practice, more load cases and combinations need to be considered, such as Water-Hammer loads (WH), local vibration due to safety relief of valves, Local vibration due to chugging, Pool swell drag due to internal pipe break, Pool swell impact due to internal pipe break and several others.

Load-combinations	Design and/or Service limit Level	Pressure	Temp.
PD + DW	Design	PD	TD
PD + DW + GV/SRV1*	Design	PD	TD
PO + DW + GV/SRV1*	Level A	PO	TO
PO + DW + GV/SRV7 (E-3)	Level B	PO	TO
PO + DW + SRSS(GV/SRV7(E-2), WH/VO1)	Level C	PO	TO
PO + DW + SRSS(GV/SRV7(E-3), GV/SSE)	Level D	PO	TO

Table 1. Load-combinations and their evaluation specifications

It should be noticed that time-dependent loads can be either given in form of response spectra, which are the case when GV/SSE and GV/SRV or other global vibration (GV) related events considered, or in form of time-dependent “nodal forces” $F(t)$ which are in most cases generated in separate fluid dynamic analyses.

Time-dependent loads $F(t)$ can be reversing, non-reversing or non-reversing followed by reversing, see NB-3620, NC-3620 (ASME, 2009a). In Fig.1 we show an example of non-reversing followed by reversing $F(t)$ caused typically by an initial water slug followed by

reflected pressure pulses. As we will see later, some design rules, in particular, those non-linear ones are given in terms of the types of dynamic loads. When dealing with dynamic loads, it is therefore important to distinguish reversing and non-reversing types.

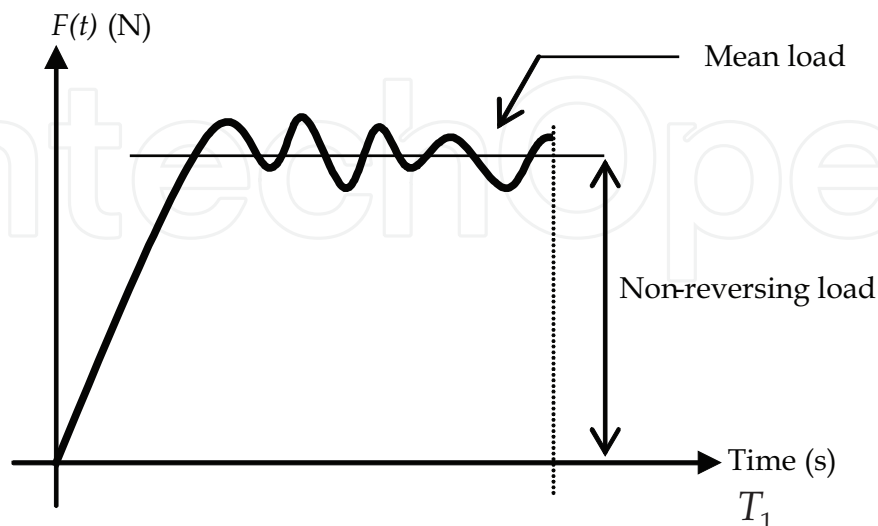


Fig. 1. Dynamic loading of a non-reversing type followed by a reversing type

3. Class 1 piping

The *linear design* rules for Class 1 piping are given in NB-3600 for general rules and in NB-3650 – NB-3656 for specific rules. When the *linear design* rules unsatisfied, in other words, the piping design found to be disqualified, the piping can still be qualified if alternative *non-linear* design requirements specified generally in NB-3200 Design by Analysis, where material plasticity are treated in NB-3228, can be met. In this section, we follow the rules specified in NB-3600 for each specific load set to clarify these *non-linear design* requirements.

In ASME III, different design requirements are, in general, specified in terms of two types of loads: (1) Loads including non-reversing dynamic loads or non-reversing followed by reversing dynamic loads; (2) Loads including reversing dynamic loads. The definitions for reversing and non-reversing dynamic loads are given in NB-3622 and repeated below:

Reversing dynamic loads are those loads which cycle about a mean value and include building filtered loads, earthquake, and reflected waves in piping due to flow transients resulting from sudden opening/closure of valves. A reversing load shall be treated as non-reversing when the following condition is met: The number of reversing dynamic cycles, excluding earthquake, exceeds 20.

Non-reversing dynamic loads are those which do not cycle around a mean value, and include initial thrust forces due to sudden opening/closure of valves and water-hammer resulting from entrapped water in two-phase flow.

3.1 Design condition

The *linear design* evaluation for this load set is to evaluate Eq.(9) given in NB-3652 to ensure the primary (primary membrane plus primary bending) stress intensity is within its limit $1.5S_m$, where S_m is the allowable design stress intensity value. According to NB-3228.1 or NB-3228.3, the *non-linear design* requirements can be formulated as follows: If Eq.(9)

unsatisfied, a non-linear analysis can be made to predict the collapse-load and the design can still be considered to be qualified if the applied loads do not exceed 2/3 of the collapse-load. The collapse-load may be predicted either by a *Limit Analysis* procedure specified in NB-3228.1 or a *Plastic Analysis* procedure specified in NB-3228.3.

There is a fundamental difference between these two procedures. While the *Limit Analysis* procedure aims at predicting the lower bound of the collapse-load, the *Plastic Analysis* procedure implies a prediction of the whole load-displacement history until the structure reaches, or passes through, its collapse point. The prediction of the collapse-load will be elaborated in Sect. 5.

In addition to this fundamental difference, NB-3228 requires the following:

For the *Limit Analysis*, the material is assumed to be perfectly elastic-plastic, and the yield stress is set to $1.5S_m$. The yield stress can be reduced for some materials, see NB-3228.1. A von Mises yield criterion is used. The lower bound of the collapse-load can be computed incrementally or by other available procedures. Here, the historic behavior in the piping during the loading process, such as plastic strains, is of no interest.

The *Plastic Analysis* requires that the true material stress-strain relation, including strain hardening behavior, should be used. A von Mises yield condition is still assumed and the initial yield stress must be set to the true yield stress S_y . The collapse-load can only be computed by an incremental procedure and it can only be determined when (almost) the whole historic behavior in the piping during the whole loading process is computed. Moreover, the collapse-load in this context is a load-level that is determined using a specific procedure given in NB-3213.25, not the load-level corresponding to the collapse point predicted numerically, see Section 5.

The *Limit Analysis* is simpler but predicts, however, the lower bound of the collapse-load. It implies generally an application of a stronger evaluation requirement. Nevertheless, it is reasonable to use the *Limit Analysis* as the first choice when Eq.(9) unsatisfied.

3.2 Level A

In the *linear design* evaluation for all load sets for which Service limit Level A is designated, two types of requirements are to be satisfied: (a) fatigue requirements and (b) thermal ratchet requirements, see NB-3653.

3.2.1 Fatigue evaluation

The fatigue requirements are specified in NB-3653.1 – 3653.6. In principle, the following two conditions are verified:

1. Primary plus secondary stress intensity range.
The evaluation is done by using Eq.(10), NB-3653.1, to ensure the stress intensity range $S_n \leq 3S_m$. The evaluation must be made for all load sets in Level A.
2. Peak stress intensity range.
The evaluation is done by using Eq.(11), NB-3653.2, to determine a so-called *alternating stress intensity* S_{alt} (NB-3653.3), which is in turn used to find the allowable number of load cycles N in design fatigue curves (NB-3653.4). Thereafter, a procedure defined in NB-3222.4(e)(5) is applied to estimate the cumulate damage (NB-3653.5). The design is qualified if we find a so-called cumulative usage factor $U \leq 1.0$. This evaluation must be made for all load sets in Level A.

Remark: These fatigue requirements (1) and (2) must also be verified for all load sets which are designated in Service limit *Level B*, see Section 3.3. When computing the cumulative

usage factor U , all load-sets in Level A and all load sets in Level B must together be taken into account.

Now we shall clarify what we can do if the fatigue requirements (1) and (2) cannot be fulfilled. NB-3653.6 states that if Eq.(10) unsatisfied, one may apply a so-called *simplified elastic-plastic discontinuity analysis* to evaluate Eqs. (12) and (13), and the cumulative damage factor using a slightly modified procedure, NB-3653.6 (a), (b) and (c). The design is qualified if Eqs.(12) and (13) satisfied, and $U \leq 1.0$.

At this point, one may ask: What can we do if Eq.(10) satisfied, but the cumulative damage factor in Condition (2) found to be $U > 1.0$? ASME NB is unclear on this point. One may realize that, in the simplified elastic-plastic discontinuity analysis, the alternating stress intensity is increased by a factor $K_e \geq 1.0$ through Eq.(14), which in turn reduces the limit of load-cycles, and consequently increases the cumulative damage factor U . In such cases, the simplified elastic-plastic discontinuity analysis will not help in one's attempt to further verify the piping design.

NB-3653.1(b) states that, as an alternative to the simplified elastic-plastic discontinuity analysis in NB-3653.6, one may apply a *Simplified elastic-plastic analysis* specified in NB-3228.5. When discussing this issue, we must remark the following: NB-3600 provides design rules/criteria for only piping. Whereas NB-3200 provides design rules/criteria which are more general and detailed and applicable for all nuclear facility components including piping. In other words, NB-3600 states simplified methods of NB-3200 for performing design-by-analysis for piping. Hence, a piping component which fails to meet conditions in NB-3600 can still be qualified if it meet conditions given in NB-3200. As far as piping concerned, the design rules and requirements given in NB-3200 and NB-3600 should be the same.

We look now back to Eq.(10). Recall that Eq.(10) ensures the primary plus secondary stress intensity range being within its limit $3S_m$. By examining NB-3220 we find, however, that none of rules given in NB-3228 seems to be *directly* applicable for doing a further evaluation when $U > 1$ found in a simplified elastic-plastic analysis. Furthermore, that NB-3200 does not state any further design requirement if the peak stress intensity range leads to a cumulative usage factor $U > 1$.

Now, a question arises: Can we apply non-linear analyses to do a further design assessment when Eq.(10), or Eqs.(12) and (13), unsatisfied and/or the cumulative usage factor found to be $U > 1$? In Section 3.2.3, we shall attempt to answer this question.

3.2.2 Thermal stress ratchet evaluation

The thermal stress ratchet evaluation is given in NB-3653.7 which ensures the range of temperature changes, $\Delta T_{1 \text{ range}}$, is within its limit. NB-3653.7 does not state any further assessment rule if the range of temperature changes overshoots its limit. However, in NB-3228.4 *Shakedown Analysis*, it is stated that a refined non-linear analysis, which will be reviewed and discussed in detail in the next Section, can be used to further check if the piping components can still be qualified.

3.2.3 Non-linear design evaluation

In NB-3228.4 *Shakedown Analysis*, both Thermal Stress Ratchet in Shell (NB-3222.5) and Progressive Distortion of Non-integral Connections (NB-3227.3) are discussed. In NB-3228.4(b), it is stated that the design can be considered to be acceptable provided that the following two conditions satisfied:

1. The maximum accumulated local strain at any point, as a result of cyclic operation to which plastic analysis applied, does not exceed 5%.
2. The deformations which occur are within specific limits.

These two conditions will, for convenience in the later discussion, be termed as *the 5% strain limit rule*.

The *5% strain limit rule* is according to NB-3228.4(b) a design requirement which replaces the following specific requirements: (1) NB-3221.2 Local membrane stress intensity being less than $1.5S_m$; (2) NB-3222.2 Primary plus secondary stress intensity range being less than $3S_m$, i.e. Eq.(10) in NB-3653; (3) NB-3222.5 Thermal stress ratchet, and (4) NB-3227.3 Progressive distortion (deformation) control. In other words, this rule sets a limit of progressive deformation in a shakedown process that may eventually take place. We note that this rule applies for both general piping components and non-integral connections (screwed on caps, screwed in plugs, closures etc).

By thermal stress ratchet it is meant in NB-3222.5 an action, more exactly speaking, a response, in that deformation caused during thermal cyclic loading increases by a nearly equal amount in each cycle. The danger does not lie in the response (deformation) caused in any particular load cycle, but the accumulated amount irreversible (plastic part) response, which may lead to uncontrollable progressive distortion. This may explain why ASME III limits the temperature range $\Delta T_{1 \text{ range}}$ in the *linear design* evaluation, but imposes *the 5% strain limit rule* when plasticity considered. In all load sets of Service limit Level A, thermal transients (TT) are of main concern. This implies that a shakedown process is irremissible and *the 5% strain limit rule* becomes the right choice.

Now, we consider again the fatigue control or evaluation. Does this *5% strain limit rule* cover also the need for fatigue control? Generally speaking, it does not! Damage due to fatigue is a totally different damage phenomenon than that caused by material (plastic) yielding. While the former is mostly dominated by brittle failure in form of micro-fracture and cracking, the later is entirely a ductile failure process in which the dislocation of material crystalline grains is dominating. These two damage mechanisms must be dealt with separately.

To answer how a Class 1 piping under Service limit of Level A should be verified through a non-linear analysis when the *linear design* evaluation found unsatisfied, the author suggests the following:

1. If the thermal stress ratchet condition unsatisfied, the *5% strain limit rule* can always be applied.
2. If Eq.(10) unsatisfied, the simplified elastic-plastic discontinuity analysis should be the first choice for further evaluation.
3. If Eqs.(12) and (13) unsatisfied, and $U > 1$ (evaluated by the procedure given in NB-3653.6), *the 5% strain limit rule* will be applied first. If this rule unsatisfied, the design cannot be qualified (or must at least be further questioned)! If satisfied, we shall first notify the owner of the nuclear power plant. If the owner requests a further evaluation, a refined approach for calculating the cumulative factor U , which is based on the numerical results from non-linear analyses, should be suggested to the contractors (and the owner of the nuclear power). This should be handled on a base of individual cases. If such an approach agreed, the evaluation goes further. Otherwise, the design is declared to be disqualified.

One may argue that the simplified elastic-plastic analysis cannot help if $U > 1$ predicted in Step (2) above. The point is, when the simplified elastic-plastic analysis requested in PIPESTRESS for fatigue evaluation, Eqs.(12), (13) and (14) will be evaluated together and, at

the same time, a updated cumulative factor U will be reported. We remind that, as discussed earlier in Section 3.2.1, if Eq.(10) satisfied but $U > 1$, this simplified elastic-plastic analysis cannot alter the result $U > 1$.

Furthermore, one may think that it may be possible that, one obtains the following results from a linear analysis using e.g. PIPESTRESS: Eqs.(12) and (13) unsatisfied, but $U \leq 1$. This situation should actually not happen as, according to NB-3653.6, Eqs.(12) and (13) should first be satisfied before computing U .

3.3 Level B

The *linear design* evaluation for all load sets for which Service limit Level B is designated, is the same as that for Service limit Level A, see NB-3654. The evaluation requirements are basically given in terms of loads including non-reversing and reversing load types. We notice that the formulation in NB-3654 is unclear with regard to fatigue requirements. More specifically, the first paragraph in NB-3654 contradicts with NB-3654.2, stating whether all load sets in Level A and B, or all load sets in Level A and (only) reversing loads in Level B, should all together be considered when computing the cumulative damage factor in fatigue evaluation. We agree the following:

- To satisfy Eq.(9) in NB-3652 for non-reversing loads, or reversing loads combined with non-reversing loads (NB-3654.2(a)).
- To satisfy the fatigue requirements specified in NB-3653.1 through NB-3653.6 for both reversing and non-reversing loads (NB- 3654.2(b)).
- To satisfy the thermal ratchet requirement given in NB-3653.7 for all load sets including thermal loads (NB-3654.2(b)).

3.3.1 Non-reversing dynamic loads

When Eq.(9) verified, the stress intensity limit is according to NB-3654.2 set to $1.8S_m$, but no greater than $1.5S_y$. Recall that it sets to $1.5S_m$ for Service limit Level A loads, implying a 20% relaxation of the stress intensity limit for Level B loads as compared to that for Level A loads.

Any direct instruction for further evaluation has not explicitly been given in NB-3654 and NB-3223 if Eq.(9) unsatisfied. We note that the first statement in NB-3654 is "The procedures for analysing Service Loadings for which Level B Service Limits are designated, are the same as those given in NB-3653 for Level A Service Limits". This should allow us, as we do for Level A loads, to apply NB-3200 to use a non-linear analysis to predict the collapse-load, or its lower bound, and the design can still be qualified if the applied loads are less than 2/3 of the collapse-load. The remaining question is how various parameters, such as the yield stress and so on, should be set in a non-linear analysis.

If the collapse-load is predicted in accordance with the *Plastic Analysis* specified in NB-3228.3, there will be no ambiguity as the true material yield stress and true stress-strain relation are used, see also Section 5.1. However, if a *Limit Analysis* is chosen, we may then ask: Should the yield stress be set to $1.5S_m$ as for Level A loads? Or should it be set to a value corresponding to the stress intensity limit $1.8S_m$ (but no greater than $1.5S_y$) that is used in connection with the linear design evaluation?

The authors favor to set the yield stress to $1.8S_m$ (but no greater than $1.5S_y$) based on the following "engineering" reasoning: (1) Setting $1.5S_m$ as the yield stress in a *Limit Analysis* for Level A loads is because the stress intensity limit for Level A loads sets to $1.5S_m$, which

should be an important correlation between the linear and non-linear designs. (2) The linear and non-linear design principles can differ in many ways, but they are set in order to achieve, for an ideal design, the same safety margin. (3) The fact that the stress intensity limit for Level B loads is 20% relaxed as compared to that for Level A loads in a linear design should be “accounted or compensated” somewhere in its corresponding non-linear design, through e.g. raising the yield stress by 20% or, equivalently the factor $2/3$ to $1.2 \times 2/3 = 4/5$.

There are different views about the above choice in Sweden. Some colleagues advise that the yield stress must set to $1.5S_m$ in the *Limit Analysis* for all loads no matter which Service limits they are designated to. We will return to this issue in Section 5.2.

Remark: All load sets in Level A and B (both reversing and non-reversing) must be together taken into account when computing the cumulative usage factor U .

3.3.2 Reversing dynamic loads

The evaluation of the fatigue and thermal ratchet requirements are the same as those given in Section 3.2. Additionally, it is required (NB-3654.1(b)) that any deflection limit prescribed by the design specification must be met. Our suggestions for a non-linear evaluation are described in Section 3.2.3.

Remark: All load sets in Level A and B (both reversing and non-reversing) must be together taken into account when computing the cumulative usage factor U .

3.4 Level C

The *linear design* evaluation for all load sets for which Service limit Level C is designated, is given in NB-3655. The evaluation rules are again given in terms of reversing and non-reversing loads.

We note in advance that for Service limit Level C deformation limits prescribed by design specifications are explicitly required to be verified, see NB-3653.3. This is required for loads of both *non-reversing* and *reversing* types.

3.4.1 Non-reversing dynamic loads

For non-reversing loads, Eq.(9) in NB-3652 should be applied with a relaxed stress intensity limit $2.25S_m$, but no greater than $1.8S_y$, which is relaxed by 25% as compared to Service limit Level B.

If Eq.(9) unsatisfied, similarly to cases for Level B loads, any direct instruction for further evaluation has not explicitly been given in NB-3655 and NB-3224.

Referring to our discussion in Section 3.3.1 for Level B loads, it should be reasonable to use the same approach that handles Level B loads to do a further evaluation. That is, a non-linear finite element analysis is used to predict the collapse-load or its lower bound. The design can still be qualified if the applied loads are less than $2/3$ of the collapse-load.

Again, if the collapse-load is predicted in accordance with the *Plastic Analysis* specified in NB-3228.3, there will be no ambiguity as the true material yield stress and true stress-strain relation are used. However, if a *Limit Analysis* is chosen, we may again ask: Should the yield stress be set to $1.5S_m$ as for Level A loads? Or should it be set to a value corresponding to the stress intensity limit $2.25S_m$ (but no greater than $1.8S_y$) that is used in connection with the linear design evaluation?

The author favor again, based on the same reasoning given in Section 3.3.1, the choice of setting the yield stress to $2.25S_m$ (but no greater than $1.8S_y$) or, equivalently setting the yield

stress to $1.5S_m$ but increasing the factor $\frac{2}{3}$ to $\frac{2.25}{1.5} \times \frac{2}{3} = 1.0$. There are different views on such a choice. A few co-workers believe that the yield stress should always be set to $1.5S_m$ in a *Limit Analysis* for all loads no matter which Service limits they are designated to, see a more in-depth discussion in Section 5.3.

3.4.2 Reversing dynamic loads

The evaluation rule for reversing loads is given in NB-3655.2(b). The evaluation is done by applying conditions given in NB-3656(b), which are given for loads in Service limit Level D. When applying these conditions, the stress intensity limit given in NB-3656(b)(2) remains the same, and those given in NB-3656(b)(3,4) are reduced by 30%. The fatigue evaluation is not required.

If the evaluation of NB-3656(b) is disqualified, a further assessment can be done by applying the 5% strain limit rule described in Section 3.2.3 without any modification. This follows from the following reasoning:

1. When NB-3656(b) cannot be fulfilled, one checks further the conditions in NB-3656(c). NB-3656(c) states that design rules in Appendix F can be used as an alternative to NB-3656(a,b). One observes however that Appendix F is not specified for reversing loads.
2. Although no explicit rules found in Appendix F for reversing loads, one can fortunately find in NB-3228.6 the following statements: "As an alternative to meeting the requirements of Appendix F, for piping components subjected to reversing type dynamic loading ..., the requirements of (NB-3228.6) (a)(1) and (a)(2) below shall be satisfied".
3. NB-3228.6(a)(2) concerns the fatigue control which is not required for *Level C* loads. This means that only NB-3228.6(a)(1) needs to be followed.
4. NB-3228.6(a)(1) states that "The effective ratchet strain averaged through the wall thickness of the piping component due to the application of all simultaneously applied loading including pressure, the effect of gravity, thermal expansion ranges, earthquake inertia ranges, anchor motion ranges, (including thermal, earthquake etc.) and reversing dynamic loading ranges shall not exceed 5%". (Notice the badly formulated texts!)

Remark: There are different views on the above reasoning as Appendix F is not given for reversing loads. A few people argue that the only alternative to NB-3655.2 is the application of NB-3224.7, which requires fulfilling the requirements of through NB-3224.1 to NB-3224.6. It indicates in turn by NB-3224.7 that NB-3228 *Plastic Analysis*, with 70% of the specified allowable strain values, can be applied. Namely, we require (i) the maximum accumulated local strain being less than $0.7 \times 5\% = 3.5\%$, and (ii) $\varepsilon_{an} \leq 0.7 \cdot \frac{S_{a10}}{E\sqrt{N}}$, see Section 3.5.2.

3.5 Level D

The *linear design* evaluation for all load sets for which Service limit Level D is designated, is done similarly to that specified for Service limit Level C, and the general evaluation rules are given in NB-3656. The evaluation rules are again specified in terms of the two types of loads as defined for Level B and C loads, i.e. *non-reversing* and *reversing loads*.

3.5.1 Non-reversing loads

For non-reversing loads, the linear evaluation rule is given in NB-3656 (a), which states that Eq.(9) in NB-3652 should be applied with a relaxed stress intensity limit $3.0S_m$, but no greater than $2.0S_y$.

If Eq.(9) unsatisfied, NB-3656(c) can be applied, which in turn refers to Appendix F, indicating that a non-linear evaluation can be done through the prediction of the collapse-load or its lower bound.

Appendix F states general rules and acceptance criteria for piping analyses when Service limit Level D considered. Roughly speaking, the requirements specified for Service limit Level D are relaxed as compared with Service limits of Level A, B and C. Below we shall have a close look at Appendix F.

The general acceptance criteria when material plasticity taken into account are given in F-1340. It is stated (F-1341) that the acceptability may be demonstrated using *one* of the following methods: (a) Elastic analysis; (b) Plastic analysis; (c) Collapse-load analysis; (d) Plastic instability analysis; and (e) Interaction methods. This is, in our opinion, obviously not a consequent and clear statement.

First, the option (a) is no longer applicable when plasticity considered. Secondly, plasticity instability is a phenomenon that may for some cases, depending on both structure itself and applied load, not always occur and, for other cases, can definitively occur long before the applied load reaches its collapse point. Nevertheless, with reference to this statement and the evaluation rule for non-reversing loads in Service limit Level C, it should be a correct choice that we apply the option (c) Collapse-load analysis and, meanwhile, check if any plastic instability shall take place. We note these two options can be examined in one non-linear analysis, see below.

F-1341.3 states in connection with the collapse-load analysis that: The applied static load, or its equivalent, should not exceed 100% of the collapse-load, or 90% of the lower bound of the collapse-load obtained in a limit analysis.

When the limit analysis used, the yield stress is according to F-1341.3 set to $\min(2.3S_{mv}, 0.7S_u)$, where S_u is the ultimate strength (A relaxation of about 2% as compared to Service limit Level C). Notice here that a different relaxation is used when setting the yield stress as compared to that used for the *linear design* evaluation, where the stress intensity limit is set to $3.0S_m$, that is, a relaxation of about 33% as compared to Service limit Level C. Apparently, the advice of setting the yield stress to $1.5S_m$ is not appropriate here.

F-1341.4 states that "the applied load should not exceed 70% of the so-called plastic instability load P_I ". Generally speaking, P_I can only be determined if an incremental solution, with both material plasticity (true stress-strain relationship) and large deformation taken into account, applied to numerically trace the response history. However, it is generally not an easy task from numerical point of view, and requires finite element software that are able to accurately handle various difficulties in so-called "path-searching", such as snap-back, snap-through and so forth, see Fig. 2, where local buckling or instability appears, resulting a temporally and partly lost of the load-carrying capacity. Notice that if thin-walled piping structures are under consideration, instability phenomena can in most cases occur before the collapse-load reached, and P_I can then be much less than the collapse-load if there exist any material or geometric imperfection. Hence, it is equally important to verify P_I and the collapse-load. Unfortunately, it is often the case that plastic instabilities cannot be accurately predicted and P_I cannot be observed in numerical results.

In Fig.2, two careless finite element (FE) solutions are shown. Both solutions fail to predict the plastic instability phenomena. While the solution which diverged early leads to a much conservative design, the other solution may result in a catastrophic design.

Fig. 2 also indicates that both the collapse-load and plastic instability load can be predicted in the same non-linear analysis through tracing the responses history. This implies that a

collapse-load analysis should be the first choice. Whereas a limit analysis should be avoided when the non-reversing loading considered and Eq.(9) in NB-3652 unsatisfied. Otherwise, one cannot be sure if plastic instability is under control.

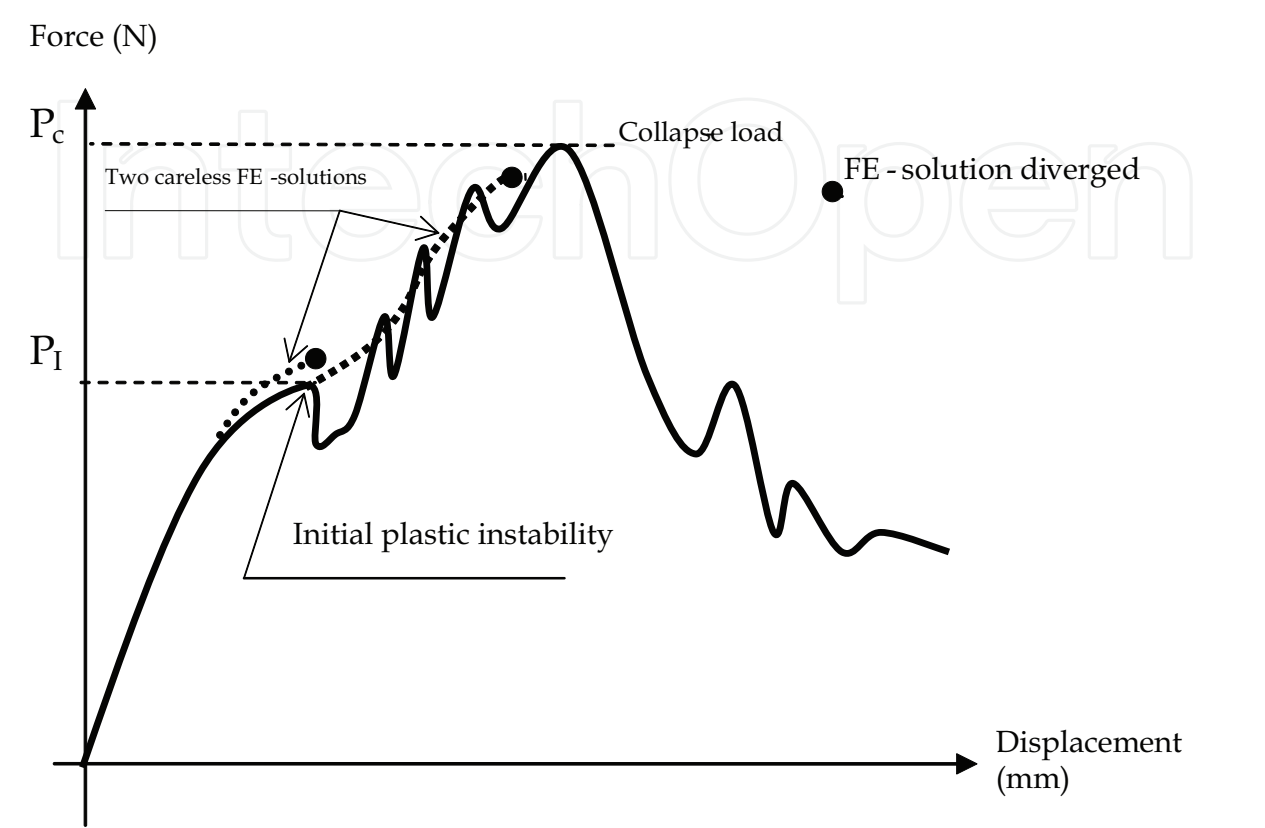


Fig. 2. Load-displacement relation including plastic instabilities typically observed in structures of thin-walled members and two careless FE-solutions

3.5.2 Reversing dynamic loads

For the reversing loading, the *linear design evaluation* is done by evaluating conditions given in NB-3656(b)(1)-(5). The fatigue evaluation is not required as for load sets in Service limit Level D.

If the *linear design evaluation* disqualified, a further assessment can be done according to NB-3228.6 (a)(1)-(2). The design is qualified if

1. the 5% strain limit rule is satisfied, NB-3228.6(a)(1); and
2. a thermal ratchet limit is satisfied through NB-3228.6(a)(2)

$$\varepsilon_{an} \leq \frac{S_{a10}}{E\sqrt{N}}$$

Above, ε_{an} is an effective cyclic single-amplitude strain, S_{a10} is the allowable fatigue stress limit at 10 cycles according to the design fatigue curves given in ASME III Appendix I, and E the Young's modulus, $N \geq 10$ the number of cycles for general reversing dynamic loads prescribed in design specifications, and $N=10$ for earthquake events.

For computing ε_{an} a procedure described in NB-3228.6(a)(2) should be applied. This procedure requires operating at material-points of interest, e.g. element's Gaussian points,

where the results of strain components are available, over a typical load cycle which is considered to be of interest. Denote one chosen material-point by p and the procedure can be summarized (in a standard tensor notation) as follows:

Step 1. Extract and record the strain results ε_{ij}^k at all considered time-steps $k=1,2, \dots, N$ in a complete load cycle of interest.

Step 2. Calculate the strain change $\Delta\varepsilon_{ij}^k$ between each time-step k and a reference time-step k_0 , e.g. $k_0=1$. That is, for each $k \neq k_0$, we calculate $\Delta\varepsilon_{ij}^k = \varepsilon_{ij}^k - \varepsilon_{ij}^{k_0}$.

Step 3. Calculate the (von Mises) equivalent strain change at time step $k \neq k_0$, i.e.

$$\Delta\varepsilon_{eq}^k = \sqrt{\frac{2}{3} \Delta\varepsilon_{ij}^k \Delta\varepsilon_{ij}^k}.$$

Step 4. Find the maximum equivalent strain range by

$$\varepsilon_{\max} = \max(\Delta\varepsilon_{eq}^k), \quad k = 1, 2, \dots, N.$$

Step 5. The effective cyclic single-amplitude strain is $\varepsilon_{an} = \frac{1}{2} \varepsilon_{\max}$.

Notice that it is important to find the material-point at which the maximum equivalent strain range takes place. Notice that software e.g. ANSYS does not directly provide such output. Additional efforts must be made in order to evaluate this quantity.

4. Class 2 and 3 piping

The *linear design* evaluation rules for Class 2 are given in ASME III, NC-3652 – 3655 and relevant rules are given in other items in NC-3600. The following discussion will first be made by following the rules given in NC-3600. Thereafter, we describe alternative *non-linear design* evaluation rules for Class 2 piping.

The rules for Class 3 piping (ND-3600) are basically the same as those for Class 2 piping (NC-3600) and their difference is minor. They are, however, also applicable for Class 3 piping.

Similarly to Class 1 piping, different design requirements are, in general, specified for loads including non-reversing dynamic loads or those including reversing dynamic loads.

4.1 Linear design evaluation

The *linear design* evaluation rules for all load sets in Design Condition, Service Limits of Level A, B, C and D, are given in NC-3652 – 3655. These rules are summarized below. We remark in advance that, except for Service limit Level D, no further design assessment instruction has been provided if the *linear design* evaluation disqualified.

Design condition

For the *Design Condition* the effects of sustained loads should satisfy Eq.(8) in NC-3652 to ensure the primary stress intensity within its limit $1.5S_h$, where S_h is the basic material allowable stress at design temperature. In addition, the moment term M_A in Eq.(8) should be given based on conditions according to NCA-2142.1(c) Design Mechanical Loads.

We note that for Class 1 piping the stress intensity limits are always defined in term of S_m . Notice the difference that for Class 2 the “hot” allowable stress S_h is in use. This happens for all load conditions, see below.

Level A and B

The design requirements for Levels A and B are given in a badly formulated text. In particular, requirements given in NC-3653.2 are confusing and can be interpreted in several ways. We agree the following interpretation:

For the Service limit Level B, the effects of sustained loads, occasional loads including non-reversing dynamic loads should satisfy Eq.(9) in NC-3653.1 to ensure the primary stress intensity within its limit $1.8S_h$.

For the Service limit of Levels A and B, the effects of thermal expansion should satisfy Eq.(10), and the effects of any single non-repeated anchor movement Eq.(10a), see NC-3653.2. As an alternative to the fulfilment of, Eq.(10), Eq.(11) shall be satisfied.

For the Service limit of Levels A and B, the effect of reversing loads must always meet the condition given in Eq.(11a) in NC-3653.2(d).

Level C

For the Service limit Level C, the evaluation rules are also specified in terms the two types of loads as defined for Class 1 piping, i.e. *non-reversing* and *reversing loads*.

The effects of the *non-reversing* loads should satisfy Eq.(9) with a relaxed stress intensity limit $2.25S_h$ (but no greater than $1.8S_y$).

For the *reversing* loads, conditions given in NC-3655(b) should be satisfied, using the allowable stress in NC-3655(b)(2), and 70% of the allowable stresses in NC-3655(b)(3-4). Furthermore, deformation limits given by design specifications should be verified.

Level D

For the Service limit Level D, the evaluation rules are again specified in terms of the two types of loads as defined for Class 1 piping, i.e. *non-reversing* and *reversing loads*.

NC-3655(a) requires that the effects of the *non-reversing* loads should satisfy Eq.(9) with a relaxed stress intensity limit $3.0S_h$ (but no greater than $2.0S_y$). For the *reversing* loads, conditions given in NC-3655(b) should be satisfied. NC-3655(c) states that "the rules given in Appendix F, where non-linear design requirements are given, can be used as an alternative to verify both non-reversing and reversing loads".

4.2 Non-linear design evaluation

The review that we made in Section 4.1 indicates that, except for Level D, no further evaluation instruction has been provided if the *linear design* evaluation disqualified. The question becomes: For other load sets, can we apply non-linear analyses to further assess the piping design as we do for Class 1 piping?

It has been discussed and argued that piping and vessels are similar, and one may apply NC-3200 Alternative Design Rules for Vessels to do such job. Hence, evaluation rules given in Appendix XIII, and in particular those given in Appendix XIII-1150 Plastic Analysis, Limit Analysis and Shakedown Analysis, can directly be used as advised in NC-3221.1.

We note that there is one major difference between design rules for Class 2 vessels (NC-3300) and piping (NC-3600), see e.g. Slagis (1987). Vessels are required to meet stress limits on "primary" stresses only. Whereas for piping, thermal expansion stresses including concentration effects are explicitly evaluated against relevant limits through Eqs.(10-11), see NC-3653.2, which is a control on fatigue. From this point of view, it is not appropriate to apply NC-3200 Alternative Design Rules for Vessels for Class 2/3 piping.

4.2.1 A Class-upgrade alternative

When Level D considered, the application of Appendix F to verify a Class 2 piping in cases when the *linear design* evaluation disqualified is, in fact, equivalent to consider the Class 2 piping as Class 1. This can be straightforward realized by carefully examining how a Class 1 piping is verified for Level D, see Section 3.5. This observation is, to the authors' point of view, important as it implies two design principles for Level D when material plasticity taken into account:

1. The Class 2 piping is considered as a Class 1 piping.
2. The design requirements specified for Class 1 in accordance with the considered load set, without any modification/relaxation, are applied.

One may naturally ask why these principles are only applied to Level D, but not to all load sets. There are different guesses/explanations and attempts to justify them. To find the answer is not the scope of this report. We note only that the load sets in Level D includes loads resulted from the most extreme accidents e.g. the lost of coolant, leading generally to (large amount) plastic deformations, which implies consequently that the *linear design* evaluation that is purely based on stress limits becomes for some cases too easy to be violated, and can no longer play an appropriate role as a criterion to justify the acceptability of the piping design.

Our experiences have indicated that design evaluation for Class 2 piping with material plasticity taken into account for all other load sets has been of a great concern and become a natural request. Under the circumstances that no clear rules have been given for load sets of Design Condition and Levels A, B and C, we think it should be a reasonable alternative to apply the above two principles. One may argue that such an alternative is conservative and possible involves partly unnecessary work. To compromise these, we think it should be reasonable to partly introduce a "relaxation" in the second principle above.

4.2.2 More on the Class-upgrade alternative

The difference between the Class-upgraded alternative, discussed in the previous section, and the argued alternative discussed in Section 4.2.1, needs possibly to be further clarified. These two treatments are fundamentally different. To apply NC-3200 Alternative Design Rules for Vessels for Class 2/3 piping does not have a principal support. They are made for vessels and there are, as discussed earlier, differences between vessels and piping.

However, to raise a Class 2/3 piping to Class 1 does not fundamentally change the type of a structure, but *only* strengthens the design requirements or design safety considerations. The strengthened design safety will be loosen or, speaking in more appropriate words, balanced through relaxing those individual Class 1 design requirements. There may be many ways to relax those requirements and will, in some cases, have to find an "engineering" compromise between requirements for Class 1 and 2/3. The relaxation needs to be done on a base of concrete "individual case" and engineering judgments, which should be documented in detail. We believe that it coincides with the general design principles that ASME III has built.

5. Collapse-load analysis

As we discussed in Ch. 3 and 4, an alternative to the fulfilment of Eq.(9) in NB-3652 for Class 1 piping (Design, Level B, C and D), and of Eq.(9) in NC-3653 for Class 2/3 piping (Level D), is to apply a non-linear finite element analysis to predict the collapse-load, and to ensure

that the applied load does not exceed a certain percentage of the collapse load. We shall here discuss such a non-linear evaluation in a more detailed setting.

One must first realize that a collapse-load analysis deals only with cases when applied loads are static, such as PD+DW and PO+DW+D/B shown in Tab. 1. We remember, however, that ASME III suggests that it may also be applied for cases where non-reversing dynamic loads are involved. We notice that a direct application of a collapse-load analysis when dynamic loads involved is not possible. In the following, we shall first focus us on cases with static loads.

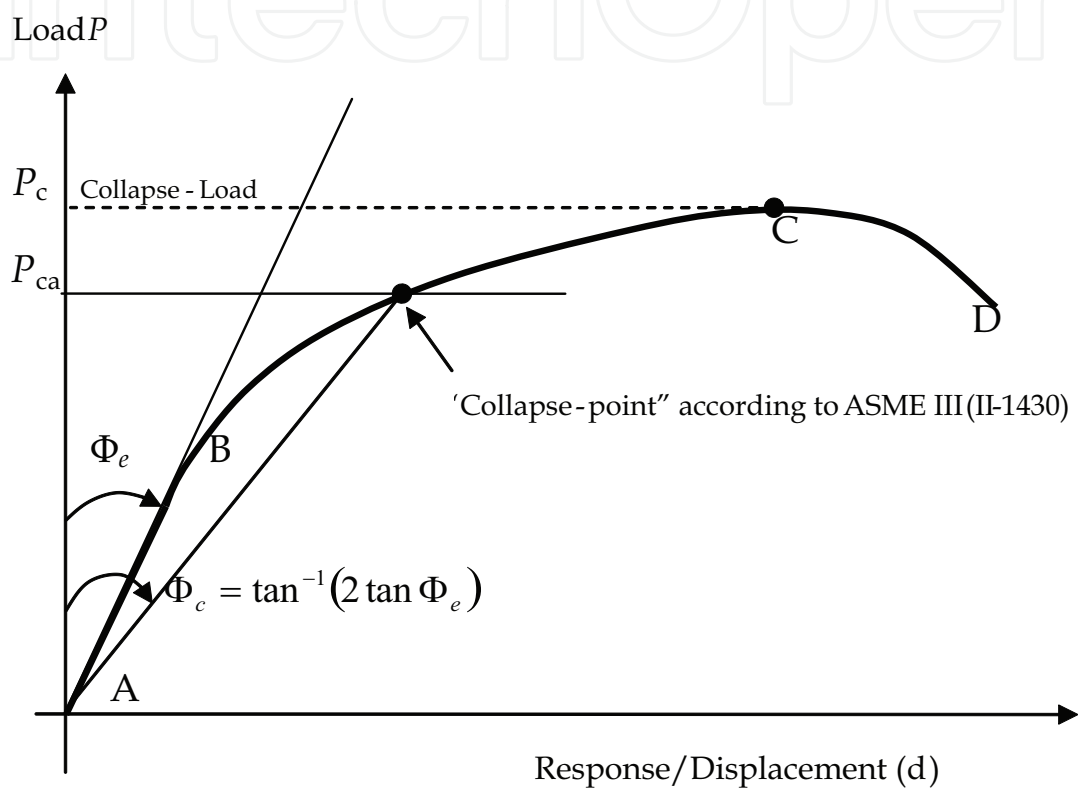


Fig. 3. Load-response history and the collapse-load

5.1 General

When plasticity and/or geometric non-linearities taken into account, a structure will loose its load-carrying capacity when the applied load P reaches a critical level, or collapse-load, P_c . To determine the collapse-load, it is required to numerically predict the load-response history, see e.g. Fig. 3 for the simplest cases, from an early stage A until the collapse point C and, in many cases, until a stage D far after the collapse point. The numerical prediction of a load-response history in connection with finite element analysis is not a simple task as pointed out in Section 3.5.1 and relevant publications (Jansson, 1995). For a comprehensive discussion of corresponding computational procedures and numerical difficulties, we refer texts e.g. Bathe (1996) and Crisfield (1996). We remark the following:

1. At the collapse point the so-called tangent stiffness matrix is singular, implying usually a divergence of solution or computation. However, a diverged solution or computation does not necessarily imply that the collapse point has been reached or passed through. The divergence can be resulted by instability as mentioned in Section 3.5.1 or many other reasons.

2. A load set includes generally several loads. When plasticity taken into account, the structural responses (deformation and stress state) depend on how and in what order these loads are applied.
3. The “collapse-load” defined in ASME III is generally less than the true collapse-load, ASME PVB Code, Section II-1430 (ASME, 2009b). This implies that one cannot determine the collapse-load by simply taking the load-level at which a computational divergence occurred, see also Fig. 2.
4. In practice, when a piping system found to be “overstressed” somewhere in the piping system, one attempts to avoid to analyze the whole piping system in a non-linear finite element analysis. (We do analyze the whole piping system in many cases.) Instead, a critical part, for example, a bend or a T-branch, where the maximum overstress taken place, is first identified, and “cut” out from the piping system. Thereafter, a refined finite element model using e.g. 3-dimensional or shell elements is built for this critical part. Finally, relevant displacement solutions on the “cut” faces from the linear analysis are used as boundary conditions for the refined finite element model. This means that, the collapse-load analysis is made on a component level.

5.2 Plastic analysis according to ASME III

The prediction of the collapse-load according to ASME III should be done in accordance with the *Plastic Analysis* specified in NB-3213.25, 3228.3 and Appendix II-1430. Below we first discuss the modeling issues and, thereafter, describe briefly how the “collapse” load according to NB-3213.25 can be determined.

NB-3228.3 states that the true material stress-strain relationship should be used. Explicitly, it means that the true yield stress and strain hardening rule should be used. It has been observed in earlier performed work that the material is modeled by specifying the following when using non-linear finite element software e.g. ANSYS: (1) the true yield stress in a von-Mises material and, (2) a small plastic modulus (e.g. 10 MPa) in bilinear kinematical hardening. Strictly speaking, this is far away from what NB-3228.3 requests. In such a modeling, no hardening has been taken into account.

Notice that for some metals strain hardening is significant and, in addition, exhibits a strong Bauschinger’s effect. In such cases, a correct prediction of the response history can most likely not be made without considering hardening effects. This will particularly be true if cyclic loading and shakedown process should be modeled, see Section 6. Intuitively, one may think that the prediction of the collapse-load is in nature static analysis, where external loads are increased incrementally and, hence, repeated unloading-loading processes are not involved. This leads, in turn, to a conclusion that hardening effects are not important. Such reasoning is fundamentally wrong. The following facts must be reminded: While increasing external loads, the development of plastic deformation somewhere in a structure, changes the way that the structure carries the external loads. Consequently, stresses in the structure must be redistributed. That is to say, stresses at some material-points will increase and at some other material-points decrease. In other words, some material-points undergo a loading process and some others an unloading process. The loading and unloading processes will, depending on the structure and applied loads themselves, repeatedly take place during the entire course of the development of plastic deformation.

NB-3228.3 suggests also taking large deformation into account in predicting the collapse-load. This is explicitly required especially when Service limit *Level D* considered. For this case plastic instability should be examined, see Section 3.5.1.

Again, we remind that the load-level, at which the computation diverges, cannot be considered as the collapse-load. Instead, a load-displacement curve should be plotted, see e.g. Figs. 2 and 3. Thereafter, the “collapse point” should be determined using a procedure described in NB-3213.25. In Fig. 3 this procedure is illustrated, where P_{ca} and P_c stands for the “collapse” load according to ASME III and the true collapse-load, respectively. As illustrated, P_{ca} can be far less than the true collapse-load P_c , which will definitively be the case if thin-walled structures dealt with.

5.3 Limit analysis according to ASME

The *Limit Analysis* described in ASME III differs from the *Plastic Analysis* discussed previously in two aspects: (1) In the *Limit Analysis*, an elastic-ideally-plastic material is assumed, and (2) the yield stress $\bar{\sigma}$ needs not necessarily be set to the true material yield stress S_y , instead, to some allowable stress value which, for example, is $1.5S_m$ for Class 1 piping when Design Condition considered, and $\min(2.3S_m, 0.7S_u)$ for Class 1 piping when Level D loads considered.

In this sense, the limit analysis specified in ASME III provides only a useful estimation of the lower-bound of the collapse-load. Other related results, e.g. plastic strains at particular material points, are much less reliable and, thus, should not be used for decisive judgement purposes.

We have mentioned earlier that the setting of the yield stress in a *Limit Analysis* has only been explicitly stated in ASME III for two cases: Class 1 piping when loads of Design Condition considered, and Class 1 piping when Level D considered. We have suggested that, for other cases, the yield stress can be set to the stress limit value that is used in connection with the *linear design* evaluation. Namely, we suggest to set $\bar{\sigma}$ for Class 1 piping to $1.5S_m$, $\min(1.8S_m, 1.5S_y)$, $\min(2.25S_m, 1.8S_y)$, $\min(2.3S_m, 0.7S_u)$ for Design, Level B, C and D loads, respectively. In such a way, the yield stress $\bar{\sigma}$ depends on the piping Class, the load set under consideration, and the design requirement (equation number) which is not satisfied in the *linear design* evaluation. And so will be the predicted collapse-load.

Suppose that a piping system is subjected to a non-reversing load P , which should be considered as a load in four different conditions: Design, Level B, C, and D conditions, respectively. The above suggestion can be more clearly illustrated in Fig. 4, where P_A , P_B , P_C and P_D denotes collapse-loads are predicted in the *Limit Analyses*.

In Fig. 4 we also illustrate the consequence if the yield stress is *always* set to $1.5S_m$ in the *Limit Analysis*. That is, it always requires $P \leq \frac{2}{3}P_A$ no matter which Service limits a load P is designated to.

Alternatively, as discussed in Sections 3.3.1 and 3.5.1, we may set the yield stress $\bar{\sigma}$ to $1.5S_m$ in the *Limit Analysis* and, instead of using the factor $\frac{2}{3}$ when determine the “collapse-load”,

we use a “relaxed” factor, $\frac{4}{5}$ (for Level B loads) and 1.0 (for Level C loads).

In a common engineering language, the design philosophy may be interpreted as below: Under a normal operating condition (Level A), stresses in piping components shall be kept low within elastic range. In connection with emergency events (Level C), various components can be subjected to so high stresses that those components, which undergo a sufficiently high deformation, may continue to be used if certain specific tests can be passed.

In connection with faulted events (Level D), components which undergo a sufficiently high deformation should be replaced by new components. We consider that our suggestions coincide with the design philosophy upon which AMSE III has been built.

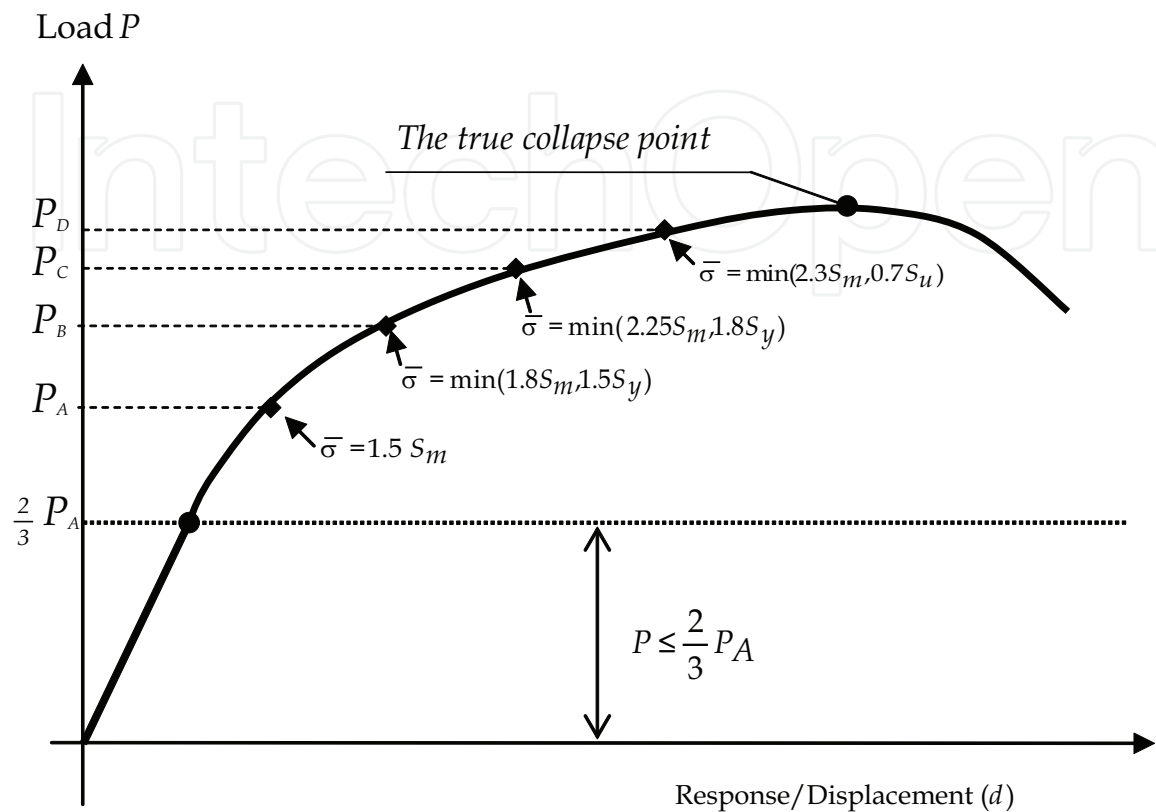


Fig. 4. Principal sketch of using a *Limit Analysis* to predict the collapse-loads for *Design, Level B, C, and D*, when yield stresses set to different $\bar{\sigma}$

6. Non-linear transient analysis

For reversing loads, a non-linear evaluation requires generally to use a non-linear finite element analysis to trace transient structural responses. This is directly applicable for all load cases which do not include any dynamic load defined by floor response spectra. For such cases, the first essential goal of the evaluation is for most cases to examine if *the 5% strain limit rule* can be satisfied. When material plasticity involved, the non-linear transient analysis should be conducted with direct integration algorithms such as Newmark's integration, see e.g. Bathe (1996) and Crisfield (1996), as the tangent stiffness (matrix) has to be updated at each time-increment. Notice that it is the *Plastic Analysis* specified in NB-3213.25 that we conduct in a non-linear transient analysis, which implies that the true material stress-strain relationship, i.e. the true yield stress and the true strain hardening behavior, should be used.

Unlike a collapse-load analysis which can be conducted on a component level, a non-linear transient analysis must always be conducted on the whole system level. Furthermore, when the non-linear analysis is made on the whole piping system, it is normally not possible to model all components with sufficient accuracy, as too simple element models may be used for certain components, for example, T-branches and bends. In such cases, in addition to the

non-linear transient analysis, one needs possibly cut these components out from the whole piping system and try to find their equivalent “static problem” and to predict their “equivalent” collapse-loads.

In non-linear transient analysis, one focuses on historic transient responses, such as transient stresses and strains. Hence, the use of realistic non-linear material models is of vital importance. Among several important issues, the strain hardening behavior of piping materials have been intensively discussed in recent years.

The ultimate strength of the many materials that are listed in ASME is about twice as much as their initial yield strength and, for some exceptional cases, more significant hardening effects can be observed. For example, the yield stress is 35 *ksi*, whereas the ultimate strength reaches 90 *ksi* for materials SB-581 through SB-626, see Tab.1B, Division II, Part D (ASME, 2009b). To predict a correct transient response, the strain hardening effect is an important part in a non-linear transient analysis as cyclic loading and possibly a shakedown process are of main concern.

The strain hardening behaviour is better illustrated in Fig. 5, where two typical hardening rules, i.e. isotropic and kinematic rules, associated with von Mises yield criteria are shown on a deviatoric plane. In isotropic hardening, the von Mises yield surface expands in the radial direction only during the development of the plastic deformation. (The “initial” cylinder expands and forms the “current” one.) In kinematic hardening, however, the size and shape of the yield surface remain unchanged, but the centre of the yield surface (the central axis of the cylinder) moves during the development of the plastic deformation. (The “initial” one moves and forms the “current” one.) In this way, the kinematic hardening rule allows to include the Bauschinger’s effect. There is a third available rule which is a combination of the isotropic and kinematic rules, and requires a more elaborated material test-data when it should be used.

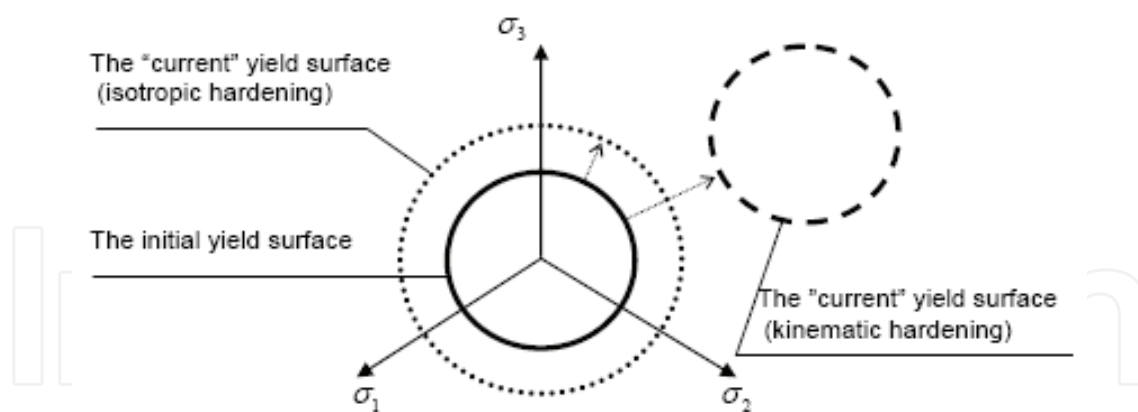


Fig. 5. Isotropic and kinematic hardening behavior on a deviatoric plane

Linear or multi-linear kinematic hardening models in commercial finite element software, e.g. ANSYS or others, are frequently found to be used for non-linear piping analysis. It has been, however, shown in recent reports by Rahman et al. (2008), Hassan et al. (2008) and Krishna et al. (2009) that such non-linear finite element analyses can only provide a reasonable modeling of plastic shakedown phenomena after a few initial load cycles. For continuous ratcheting responses, such analyses cannot provide reasonable results, neither for the accumulated local strain nor for the global dimension change. They showed through experiments on straight and elbow pipe components that several nonlinear constitutive

models available in most general finite element software, such as Chaboche (1986), Ohno and Wang (1993), and other more recently developed models (Abdel Karim and Ohno, 2000; Bari and Hassan, 2002; Chen and Jiao, 2003) can provide a much improved prediction.

7. Concluding remarks

We have in this chapter categorized the design evaluation given in ASME III for nuclear piping of Class 1, 2 and 3 into *the linear design* and *non-linear design evaluations*. The corresponding design requirements, in particular, those *non-linear design requirements*, have in the report been reviewed, analyzed and clarified in association with every defined load set, through *Design Condition* to *Service Limit Level D*. Efforts have been made to formulate the *non-linear design* evaluation requirements in a format so that they are easy to be followed, understood and applied in connection with piping analysis.

The *non-linear design* evaluation requires in principle two types of non-linear finite element analyses: collapse-load analysis and non-linear transient analysis. We have in the chapter attempted to describe in detail their computational aspects in a close accordance with the requirements given in ASME III.

The design requirements given in ASME III for nuclear piping have been developed in more than several decades. However, it has been a known issue that its formulation and specification of design requirement items are far from fully clear, which are caused by endlessly nested references in multiple levels to a large amount of contents. This is, unfortunately, particularly true when design-by-analysis rules are considered. We hope this chapter should be able to serve as a constructive source for a better understanding of and a potential improvement for the design requirements for nuclear power piping.

8. Acknowledgement

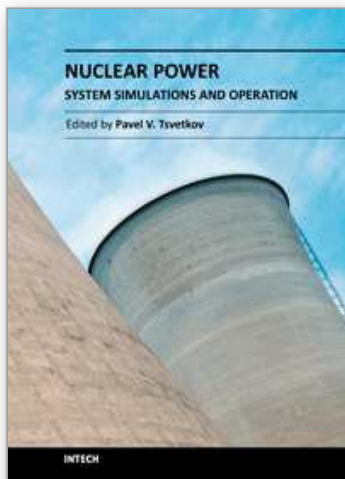
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At the onset of the 21st century, we are searching for reliable and sustainable energy sources that have a potential to support growing economies developing at accelerated growth rates, technology advances improving quality of life and becoming available to larger and larger populations. The quest for robust sustainable energy supplies meeting the above constraints leads us to the nuclear power technology. Today's nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. Catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, requirements and facilitated growing interests in designs, which can withstand natural disasters and avoid catastrophic consequences. This book is one in a series of books on nuclear power published by InTech. It consists of ten chapters on system simulations and operational aspects. Our book does not aim at a complete coverage or a broad range. Instead, the included chapters shine light at existing challenges, solutions and approaches. Authors hope to share ideas and findings so that new ideas and directions can potentially be developed focusing on operational characteristics of nuclear power plants. The consistent thread throughout all chapters is the "system-thinking" approach synthesizing provided information and ideas. The book targets everyone with interests in system simulations and nuclear power operational aspects as its potential readership groups - students, researchers and practitioners.

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