STP-PT-070

DESIGN GUIDELINES FOR THE EFFECTS OF CREEP, FATIGUE & CREEP-FATIGUE INTERACTION

WITH DESIGN-BY-ANALYSIS AND NONDESTRUCTIVE INSPECTION ACCEPTANCE CRITERIA

ASME STANDARDS TECHNOLOGY, LLC

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Date of Issuance: June 20, 2014

This report was prepared as an account of work sponsored by ASME Pressure Technology Codes & Standards and the ASME Standards Technology, LLC (ASME ST-LLC).

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ISBN No. 978-0-7918-6946-8

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FOREWORD

A task group of ASME Boiler and Pressure Vessel Committee on Power Boilers initiated a project through the ASME Pressure Technology Codes (PTCS) and Standards Committee to identify, prioritize and address technology gaps in the PTC Codes. The key aspect of this project was to review an extensive selection of current Codes and Standards which relate to power boilers and develop guidelines for component design and flaw acceptance criteria. These rules were to be used for the design of new advanced supercritical boilers operating at higher steam cycle conditions. This main focus of this project is to evaluate the current state of understanding with regard to creep-fatigue interaction for intended boiler materials to support the development of effective design by analysis (DBA) rules.

The authors acknowledge, with deep appreciation, the activities of the Peer Review Group (PRG) that consist of Maan Jawad, Dave Anderson, Benjamin Hantz, George Komora, Peter Molvie, and Edward Ortman, and the ASME staff and volunteers who have provided valuable technical input, advice and assistance with review of, commenting on, and editing of, this document. The authors further acknowledge Robert Jetter and Dave Dewees for their contributions in reviewing and commenting on the document.

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ABSTRACT

As part of the modernization of Section I – Rules for Construction of Power Boilers of the ASME Boiler and Pressure Vessel Code (Section I), a project was established to develop design guidelines for the effects of creep-fatigue interaction and flaw size acceptance criteria within the overall framework of Design-By-Analysis (DBA). The existing methods within Section I, which are based around Design-By-Rule/Formula and do not explicitly consider creep, fatigue or their interaction. The oversimplifications involved are such that the safety of boilers operating at higher steam cycle conditions, and under cyclic service, has been questioned. Design-By-Analysis (as an alternative to Design-By-Rule/Formula) is gaining acceptance as a viable approach for design of components that will experience cyclic loading and which will operate at elevated temperatures where creep may occur. Such Design-By-Analysis approaches have been introduced into other international codes, including other sections of the ASME Boiler and Pressure Vessel Code (ASME Code) and the EN Code.

This report has been prepared to recommend design guidelines for components in Section I - Power Boilers. As such, it does provide a comprehensive review of issues. However, to properly introduce the context of the recommendations, some background is provided to a number of philosophical topics that surround Design-By-Analysis, Design-By-Formula, Design-For-Safety and Design-For-Lifetime. As several other recognized Codes and Standards have approaches that are relevant to Design-By-Analysis, or which provide methods for including creep-fatigue interaction effects, a summary of these documents is provided. In particular, the summary compares and contrasts key aspects to provide insight into benefits and shortcomings (or inconsistencies) associated with particular approaches. From this review it is evident that no single Code or Standard has a method that can be universally adopted, particularly when the methods have to be used in the context of other Sections of Codes, such as material properties, or standardized design features. That is, a particular Design-By-Analysis methodology needs to be developed that could be used within the overall context of the ASME Code (particularly Section I).

To that end, a Design-By-Analysis approach is recommended that is both relevant and technically consistent, and which considers the key modes of structural behavior and material response. Some features of the recommended approach are:

- It provides design checks for the structural failure modes relevant to modern Power Boiler, including cyclic service with checks on local creep and fatigue damage as well as the possibility of creep-fatigue interaction.
- It requires minimal material data (most of which is already available within Section II - Materials, Part D of the ASME Boiler and Pressure Vessel Code (Section II, Part D), or which is a logical extension of that based on Section III, Rules for Construction of Nuclear Facility Components Subsection NH of the ASME Boiler and Pressure Vessel Code (Section III, Subsection NH)).
- All design checks are accomplished with an elastic or elastic-perfectly-plastic material representation (thereby avoiding the need for complex constitutive models or analytical procedures).
- It incorporates weld strength reduction factors where weldments operate in the time dependent (creep) regime.

The recommended approach is based on validated methods and the explanation of the methodology highlights where particular features are adopted or adapted from other Codes (most particularly from Section VIII, Rules for Construction of Pressure Vessels Division 2 of the ASME Boiler and Pressure Vessel Code (Section VIII, Div. 2), Section III, Subsection NH and from EN13445-3, Annex B). The approach includes all aspects of a Design-By-Analysis methodology because without considering the

complete design procedure any proposals on specific aspects, such as creep-fatigue interaction, may not be technically consistent with the overall framework.

Flaw size criteria and previous work in this area are reviewed to provide context to the development of future methods. While flaw size criteria can be developed based on engineering mechanics considerations, this can invoke arbitrary assumptions which limit the generality and practical value of the results. Because of this it is highlighted that flaw size criteria should primarily be defined by workmanship quality standards; as is the approach adopted in many other Codes. It is also recognized that if flaw size criteria are to be established using engineering mechanics then this can be accomplished independently of the overall approach to Design-By-Analysis.

In addition to the complexities highlighted by the outline of a Design-By-Analysis methodology, the implications for the overall structure and implementation of Design-By-Analysis methods within Section I are documented as a basis for future discussions to facilitate reaching consensus among the technical community on the best approach for specific aspects, and for the overall approach to adoption within the ASME Code.

1 INTRODUCTION

The objective of this document is to summarize the various practices used by various US and International Codes with respect to "Design-By-Analysis" (DBA) methods, particularly in the context of creep, fatigue and creep-fatigue interaction with the aim of identifying elements of these Codes that can provide beneficial input during the modernization of Section I [1]. The document also includes a discussion of flaw size acceptance criteria and provides recommendations on how this should be incorporated in an overall framework.

Development and implementation of procedures for "Design-By-Analysis" should consider relevant experience from research and practice. However, as will become evident in this document, there is currently no universally accepted or consistent approach. Thus, compromises have to be made between the practicality of the methods for use at design and the fidelity of the analysis for particular failure modes. In many cases, certainly within the realm of creep-fatigue interaction, there are a very broad range of scenarios that can occur and the development of analytical methods continues to be a very active area ongoing research. The intent here is not to delve in great depth into those details but rather to provide a practical review of techniques and methods that could be implemented as part of the Section I modernization.

This document is structured into a number of sections that address particular aspects associated with "Design-By-Analysis". The document begins with a preamble which covers background to some of the conceptual aspects associated with "Design-By-Analysis" and the associated aspects of material and structural behavior, such as creep-fatigue interaction. The next section, Section 3, provides a review of a number of International Codes and Standards that incorporate "Design-By-Analysis" approaches and provides some commentary to compare and contrast these. The focus of this comparison is on methods for creep and fatigue damage and their subsequent combination in circumstances of creep-fatigue interaction. Following that, Section 4 discusses the development of a "Design-By-Analysis" approach and provides an outline of a methodology and describes some of the challenges that need to be addressed if this is to be incorporated into an update of Section I. Section 5 discusses flaw acceptance criteria. Section 6 provides a summary of some key recommendations and needs for future work. Section 7 provides a summary of some key implications and changes for the ASME Code if the "Design-By-Analysis" method were implemented. Finally, in Section 8 a collection of key references is summarized.

2 PREAMBLE

Design Codes provide rules and guidance on the sizing of components at the design stage to ensure that the intended service will not result in premature failure. The principal concern of such Codes is safety. That is, ensuring that sufficient design margins are included to provide (in the words from the preamble of the ASME Code) "a margin for deterioration in service so as to provide a reasonably long, safe, period of usefulness." The primary focus on safety provides a rational methodology to develop design limits in the range in which material properties are not time dependent (that is, at temperatures below where creep becomes an important factor). In this regime, the time-independent yield or tensile strength can be used to establish appropriate design margins. At higher temperature, where creep becomes important, then analysis supporting "Design-For-Lifetime" should be considered to complement "Design-For-Safety". Historically, the ASME Codes have focused on safety and provide allowable stress values in the creep regime that are derived from factoring creep rupture data, but the ASME Code has been quite specific in various interpretations that no design lifetime can be implied or inferred.

Thus, in considering the development of design rules, particularly for high temperature service, or cyclic operation, then a key decision is the choice of design margins and if there basis is related to the service lifetime of a component. Given the diversity of equipment that is covered by the rules of the ASME Code, the time has come to move toward a "Design-For-Lifetime" philosophy as a supplement to "Design-For-Safety". To be more particular, given the diversity of equipment and operating regimes covered by the ASME Code, a simple "Design-For-Safety" criterion based on a set of allowable stress values does not necessarily ensure the "safest" design. For example, if the component is subject to extensive cyclic operation (such as some heat recovery steam generators, or potentially solar receiver steam generators) then using a "safe" set of allowable stresses that are based on providing protection against long-term creep rupture will likely result in components with greater wall thickness and hence less tolerance to cycling and the associated thermal transients thereby increasing the likelihood of fatigue damage.

Historically, largely for simplicity and convenience, design Codes (such as Section I) have been based on a "Design-By-Rule" or "Design-By-Formula" philosophy. Note that in this report the terminology "Design-By-Formula" is adopted because invariably no matter what approach is adopted "Rules" are inevitable. This has served well in the context of "Design-For-Safety" because the rules used have very sound mechanical principles (which are generally traceable to underlying structural concepts such as limit analysis) that have been combined with practical experience of features and configurations that have proven to be robust and reliable. However, in the context of "Design-For-Lifetime" an appropriate set of "Formulas" can become very protracted and complex, without in some cases, resulting in a "safe" design. Hence the concept of "Design-By-Analysis" in which a more direct analytical approach is used to ensure that the component is within appropriate design boundaries. This "Design-By-Analysis" approach will be explained in more detail within this document as approaches used in various Codes and Standards are reviewed. However, a key consideration for practical implementation of "Design-By-Analysis" is consistency with "Design-By-Formula". The use of a "Design-by-Analysis" approach provides for either a more economical or a technically justifiable design. The more rigorous analysis required in a "Design by Analysis" approach may allow for the use of lower design margins; or may cover geometries, loadings, or modes of failure that are not easily dealt with in the context of "Design-By-Formula".

The two approaches can, and have, been shown to be able to be incorporated into common sets of rules. If the two approaches are consistent then they can be used in a complementary fashion. It is possible to use "Design-By-Formula" for basic sizing and for sizing of non-critical features on a component. For critical features, where perhaps it is necessary to strike a compromise between creep and fatigue, or a creep-fatigue interaction when both mechanisms might be active, then "Design-By-Analysis" can be used for that feature. Such interchangeability provides a very powerful, practical, safe and modern design approach.

The "Design-By-Analysis" approach should not be confused with detailed mechanical integrity calculations for life assessment of a component or structure. Much of the power and utility of design Codes lies in their separation of the structural response from the material behavior. In its simplest form, it is understood that for a particular geometry and loading, a stress can be calculated that does not depend on the material properties (strength) and this stress can then be compared against the material properties (strength) to determine acceptability of the design. By contrast, mechanical integrity calculations for lifetime evaluation utilize a constitutive equation (deformation response of the material) that aims to provide a representation of material behavior so that the most accurate lifetime prediction can be obtained. "Design-By-Analysis" however, seeks to retain the separation of structural response and material behavior by utilizing simplistic constitutive models that bound response for the principal deformation mechanism of interest, and which do not require an elaborate set of material property data.

Another key feature of design Codes is the use of standardized features and configurations, such as construction details, that are known to have endured typical service conditions for many years, thereby proving integrity, despite perhaps having what appear to be built-in flaws or features that cannot be specifically proven through a "Design-By-Formula" or even through a "Design-By-Analysis" approach. Using standard, proven, construction details, in combination with materials that are inherently tough and ductile, avoids the need for complex calculations that invoke fracture mechanics and defect tolerance concepts.

This, in turn, leads to criteria for flaw size acceptance which, historically, are largely based on what should be a typical quality of workmanship for the fabrication practice employed, rather than the size of flaw that could be accepted based on the actual service conditions under which the component will operate. Justifying serviceability of flaws that exceed quality of workmanship limits has traditionally been the realm of "Fitness-For-Service" Standards (such as ASME FFS-1).

A key driver to modernize design Codes is to better address failure mechanisms such as fatigue, creep and creep-fatigue that become more relevant as plant designs move to higher pressures and temperatures to improve efficiency, while at the same time requiring flexible operating characteristics to adapt to dispatch needs and fuel pricing. A key challenge is defining these operating conditions (time, cycles, etc.) at the design stage in a way that is meaningful to the intent of the design Code. Specifically, conservatively bounding creep by assuming a very long overall operating time will inevitably result in a requirement for thicker wall components, which may compromise their fatigue capability. Likewise, a conservative bound on cycling by assuming a worst-case temperature ramp rate or worst case combination of thermal and mechanical stress could result in severe limits to component operation that make the design uneconomic from the perspective of the user. Therefore, how the operating history is specified at the design phase (and what inherent conservatisms and margins are built-in) will drive the economic feasibility of the design and hence, potentially, the overall power plant project.

Traditionally design Codes such as Section I that are based on steady operation have not had to address these issues. Other Codes that do attempt to address cyclic operation include statements requiring the user to specify the cycles, or blanket statements to the effect that all sources of fluctuating loading shall be identified.

At a high level this may be possible, for example, by specifying a number of hot, warm and cold starts. However, this does not define the local cyclic fluctuations at the point of interest on the component. That requires knowledge of the process design and in many cases complex thermo-hydraulic phenomena that are not discussed or defined within the ASME Code. In some Codes, relevant experience is permitted to define local thermal and mechanical transient boundary conditions, but more generally in design of "new" components such as heat recovery steam generators behind next generation gas turbines, or solar receiver steam generators, such "experience" does not exist and therefore detailed transient thermo-hydraulic evaluations become essential to determine local conditions for use in design assessment.

Obviously the care and attention to detail in those simulations can have a significant effect on the local conditions that are computed for the component (or feature of interest), but very little guidance, let alone rules, exist for these transient thermo-hydraulic calculations. Unless all phases of the calculation process (definition of thermo-mechanical transients, and assessment against design limits) are performed consistently and appropriately there is potential for unconservative, or inappropriate, designs. For example, linearizing startup transients might result in a significant averaging over the startup period whereas reality is a rapid ramp followed by a gentler ramp – the latter has potential for more damage. Hence, in evaluation of cycles, consideration should be given to how the cycles are defined and calculated, not just relying on the resulting design assessment. Currently, the authors are not aware of any Codes or Standards that address the issue of defining thermal transients in an appropriate manner.

A key aspect of design rules that this document addresses is rules for creep-fatigue interaction. Much has been written about this subject (and much more will be), because of its technical complexity (which does not lead to a universally accepted practice for assessments) and because of its increasing relevance as plants are demanded to operate at higher temperature and to cycle more.

Good background discussions of creep-fatigue interaction and the associated technical complexities are found in references such as those by Penny and Marriott [2] and Parker [3], so such discussions are not repeated in this document. The calculation of the life of a component which experiences both creep and fatigue damage is commonly considered to be a very complex subject. The crux of the complexity centers around how creep and fatigue deformation and damage interact. The two types of damage are typically calculated separately, and then combined into an overall measure of damage. The independently calculated creep and fatigue damage values are often plotted on what is known as an interaction diagram where if both mechanism are active it is invariably determined that the permissible damage must be less than a simple sum of the two contributions.

The difficulty with this approach is that depending on how creep and fatigue affect one another (is fatigue enhancing creep or is creep enhancing fatigue – which depend on the type of cycle and where creep and fatigue occur within that cycle) then a single interaction rule cannot possibly account for the subtleties of these combinations. In some cases, a very conservative "worst-case" interaction can be assumed, but that invariably unfairly penalizes the majority of cases resulting in overly conservative, uneconomic, designs. An alternate strategy is to more carefully evaluate the respective creep and fatigue contributions based on the deformation characteristics of the material. That is, phenomena such a yielding at one instant in a cycle can result in enhancement of the stress for a creep dwell in another portion of the cycle. If this is known, then the creep damage calculation can then more accurately evaluate this effect, and the effect of this creep strain on the plastic strain range for the cycle can also be evaluated, thereby potentially enhancing the calculated fatigue damage. In this way, the separate calculation of creep and fatigue damage consider the interaction effects and the resulting creep and fatigue damage values can then be more readily summed and assessed against a so-called linear interaction rule.

This again illustrates the challenge of simple calculations resulting in potentially overly conservative uneconomic designs verses more complex calculations that require a better understanding of the structural mechanics and material response with the prize of lower conservatism. Design Codes need to strike an appropriate balance between acceptable conservatism and simplicity of calculation; this is the crux of the challenge for implementation of creep-fatigue rules within design ASME Codes.

Also within this document, criteria for flaw size acceptance are discussed. This is an increasingly relevant topic because historically criteria have been based on experience of acceptable fabrication practice and quality of workmanship. However, with the development of increasingly sophisticated non-destructive examination equipment it is possible to detect indications that were previously "invisible" (below the detection limit) and also with increasing analytical capability it is possible to use fracture mechanics to determine the influence of flaws on future serviceability. The challenge here, as with many other aspects of Code development, is striking an appropriate balance between practical, but conservative (safe), criteria and the complexity of technology to locate and then develop disposition for indications. Also, practical limits on the allowable sizes of flaws need to be established, based not only on theoretical calculations, but by application of practical experience and workmanship standards which may put an upper bound on the size of flaws that is generally acceptable to the industry. Some of these trade-off and potential opportunities are discussed in the section of this document entitled Flaw Acceptance Criteria.

Another challenge in the development of "Design-By-Analysis" methods, and one which is inextricably linked with the foregoing discussion on flaw acceptance criteria, is that of weldments. Weldments are an inevitable part of boiler construction and often involve the use of filler metals with differing strength to the base metal, and the welding process itself may result in creation of heat affected zones with different properties to either the base or weld metals, and may leave residual stresses. Any method for "Design-By-Analysis" must practically deal with the geometric and material complexities introduced by weldments. ASME has already recognized some of these complexities, most notably the lower creep strength of ferritic steel weldments at high temperatures, and has introduced weld strength reduction factors. Such weld strength reductions factors can be incorporated within the overall framework of "Design-By-Analysis" as will be discussed later in this report. In addition to providing such methods, it may be prudent given the increasing complexity of materials introduced to the ASME Code (particularly for high temperature service) for the ASME Code to provide additional guidance on well-engineered weldments (e.g. location, geometry, process, etc.).

To summarize, there are many aspects that must be considered in the introduction of "Design-By-Analysis" but the underlying theme is that the overall approach must have due consideration for key modes of structural response and material behavior, and must be self-consistent. That is, the analytical approaches (and their inherent assumptions), must be consistent with margins applied to loads and to material properties. Achieving this consistency is more complex than it may initially appear, and it is something that is often lacking when particular Codes are examined in detail (as will be illustrated with some examples in the next section).

3 REVIEW OF CODES AND STANDARDS

In order to develop some recommendations for a path forward on Design-By-Analysis rules, a review was performed of a number of International Codes and Standards that incorporate "Design-By-Analysis" methods. Particular attention was given to how these Codes and Standards deal with Creep and Fatigue and their interaction.

The Codes and Standards reviewed were:

- ASME BPVC Section VIII, Div. 2: Rules for Construction of Pressure Vessels (Alternative Rules) [4][5].
- ASME FFS-1: Fitness for Service with methods for life evaluation in Creep Fatigue service [6].
- ASME BPVC Section III, Rules for Construction of Nuclear Facility Components Subsection NH: Class 1 Components in Elevated Temperature Service [21].
- EN12952-3: Water tube boilers, Design calculations for pressure parts [7].
- EN19252-4: Water tube boilers, In-service boiler life expectancy calculations [8].
- EN13445-3: Unfired pressure vessels, Design [9].
- R5: Assessment procedure for the high temperature response of structures [10].
- BS7910: Guide to methods for assessing the acceptability of flaws in metallic structures [11].
- RCC-MR: Design construction rules for mechanical components of nuclear installations applicable to high temperatures [12].

The comparison of these Codes and Standards, and documentation of some of their key features, has been accomplished by a combination of tabular comparison of key attributes, design margins and approaches, and by general review presented here as a discussion of some of the more notable features that represent similarities and differences in approach between Codes.

The specific comparison tables are shown in Appendix A:

- Table 1: Comparison of key features, methods and scope.
- Table 2: Comparison of design margins for low temperature.
- Table 3: Comparison of design margins for high temperature.
- Table 4: Protection against collapse / global failure.
- Table 5: Protection against shakedown / ratcheting.
- Table 6: Protection against fatigue.
- Table 7: Protection against creep.
- Table 8: Protection against creep-fatigue.

It is evident from these comparisons that many Codes and Standards have quite similar fundamental approaches for "Design-By-Analysis" but there are significant differences in specific interpretations, margins and restrictions. As a result it is not possible to directly compare the inherent conservatism or utility of one Code or Standard against another without recourse to a particular example in which the full Code calculations are completed (which is beyond the scope of the present project). Even if such calculations were completed it is evident that in some cases one Code or Standard would apparently provide a distinct advantage, but in most cases a contrary example could also be developed.

3.1 Notable Items in Code Reviews

There are a few notable items that are discussed in the following subsections, prior to the separate reviews of each of the Codes.

3.1.1 Yield Criterion

For overall limit analysis to determine the maximum load bearing capacity, some Codes (notably EN13445-3, Annex B; Section III, Subsection NH) use a Tresca criterion, whereas many other Codes (e.g. Section VIII, Div. 2) use a Mises criterion. Within EN13445-3, Annex B the limit analysis can actually be performed with a Mises criterion (largely due to the fact that few finite element programs provide a Tresca yield criterion) but then the result must be "corrected" to the Tresca criterion. Hence, when comparing conservatism on loads and allowable stresses this "additional" conservatism (which is theoretically dependent on the stress state) should also be considered. This also raises the question as to "what is the most appropriate criterion?" The state-of-knowledge for yielding of steels indicates that for the time-independent regime the von-Mises criterion is appropriate. However, for the time dependent regime then the multiaxial stress rupture criterion varies somewhat between materials with numerous models existing that combine von-Mises, principal and/or hydrostatic stress. Hence, for the time dependent regime, for protection against creep rupture, it would appear more reasonable to simplify to a Tresca criterion (per EN13445-3, Annex B).

3.1.2 Reference Temperature for Calculations

Another topic that can complicate interpretation of conservatism and comparison of design margins, particularly for cyclic analysis, between Codes is that of temperature. In simple terms, the Section VIII, Div. 2 specifies that the temperature for calculations (material properties such as stress-strain response and S-N curve) shall be the average temperature of the cycle; implying an average between the maximum and minimum temperature of the cycle. The EN Codes (e.g. EN13445-3, Annex B) specifies that the temperature for calculations shall be 25% of the minimum temperature plus 75% of the maximum temperature, thereby producing a bias toward the higher temperature portion of the cycle and thus likely resulting in lower property (strength) values than would be used for an equivalent calculation in the Section VIII, Div. 2. The Section III, Subsection NH generally requires that calculations are performed using properties for the maximum temperature of the cycle. To complicate comparisons further, within the EN Codes the distinction is made that the maximum and minimum temperatures shall be taken at the respective instants of the maximum and minimum stress in the cycle (and thereby might not have any correlation to the actual maximum and minimum temperatures for the cycle). This definition of maximum and minimum temperatures coinciding with maximum and minimum stresses does not appear to be inferred or implied by the rules in the Section VIII, Div. 2, although it is incorporated into some aspects of Section III, Subsection NH (e.g. selection of hot and cold yield strength).

3.1.3 Perfectly Plasticity vs. Strain Hardening

For the basic load bearing capacity and shakedown / ratcheting design checks, the majority of Codes base the material behavior on a simplified elastic-perfectly plastic constitutive model. This simplification makes both monotonic and cyclic analysis easier to interpret (particularly in the case of cyclic analysis where it removes the need to define a hardening criterion). While ASME (e.g. Section VIII, Div. 2) provides this option (at least for monotonic analysis), the option is also given to use the strain-hardening characteristic in monotonic (collapse) and cyclic (fatigue) calculations. The Section VIII, Div. 2 also allows the use of a strain hardening based on the average temperature for the cycle because of the restriction to the time-independent regime. For the time-dependent (creep) regime, the strain-hardening response can be quite different between extremes of the cycle (low temperature and high temperature), so using an average is likely inappropriate, plus the strain hardening response will affect the stress in creep dwells (and hence the creep damage calculation). Properly accounting for these aspects in the time-dependent regime is complex and of the Codes and Standards reviewed, only the extensive procedures (and associated material data requirement) of the R5 Assessment Procedure appear to provide a comprehensive and consistent technical treatment.

3.1.4 Cyclic Hardening or Softening

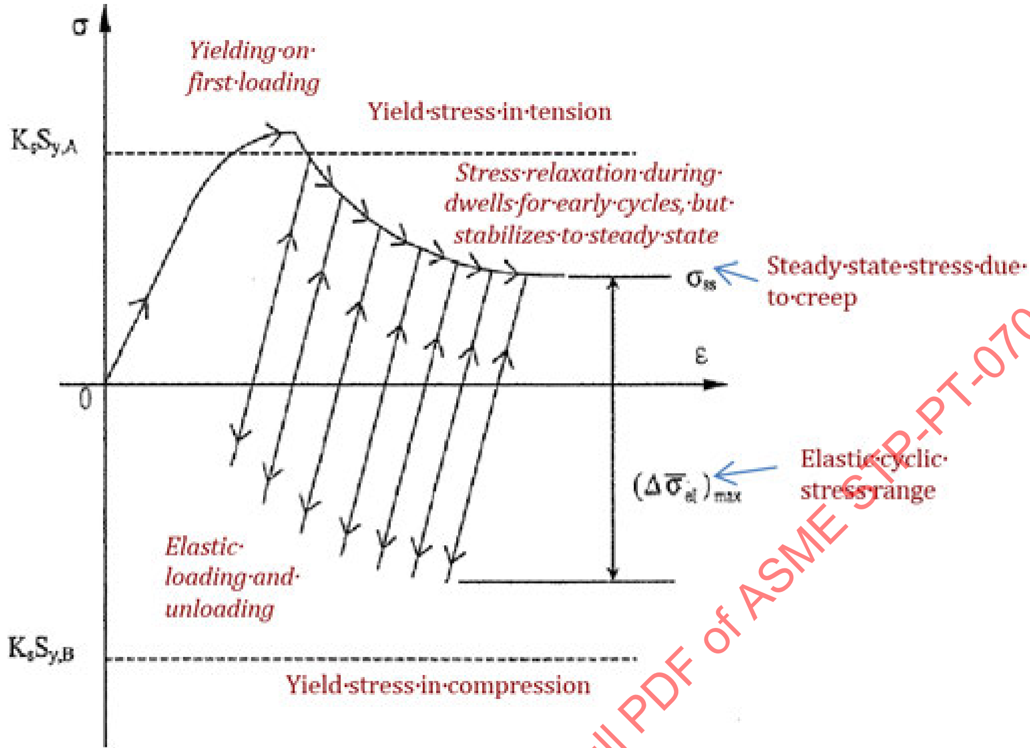
Somewhat related to the foregoing, is the question as to which yield strength should be used in various calculations. The yield strength quoted in Codes is invariably derived from monotonic tensile testing, which certainly provides valid strength values for collapse calculations, and for onset of cyclic plasticity (such as shakedown calculations). However, under cyclic plasticity materials generally either cyclically harden or soften to attain an apparent cyclic yield strength that is either higher (cyclic hardening, e.g. Grade 22 steel) or lower (cyclic softening, e.g. Grade 91 steel) than the monotonic value. This is accounted for in detailed assessment procedures, such as R5, and to a limited extent by the use of stabilized cyclic stress-strain curves in Section VIII, Div. 2, but is not considered in any of the EN Codes.

3.1.5 Creep-Fatigue Interaction

The approaches for creep-fatigue interaction differ between the various Codes and Standards. A very idealized treatment is given in ASME FFS-1 where the creep and fatigue damage contributions are calculated independently (as if one did not have any influence on the other) and then the resulting damage values are plotted on an interaction diagram. This approach, while straightforward, is overly simplistic because it does not address the deformation interaction that drives creep-fatigue interaction in components. To this end, some Codes (notably R5, Section III, Subsection NH and EN13445-3, Annex B) have checks to determine if there is deformation interaction between creep and fatigue. If there is not, then cyclic loading is judged insignificant and a simple creep and fatigue damage summation can be made based on each acting independently. If, however, there is deformation interaction then it is necessary to calculate the effects, such as enhancement of creep by repeated relaxation, or enhancement of the strain range controlling fatigue. It is noted that only R5 provides a detailed treatment of these detailed deformation interaction calculations (although a simplified, idealized, approach is included in Section III, Subsection NH).

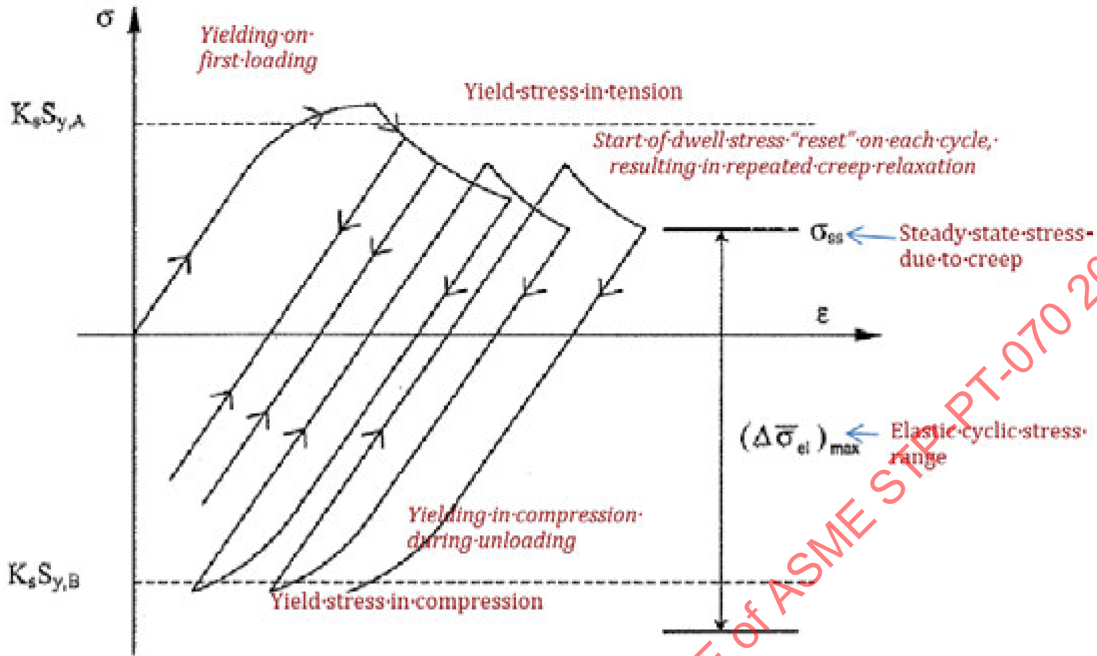
The concept of insignificant cyclic loading is very important to R5 and to EN13445-3, Annex B so is now explained in a little more detail. Figure 3-1 shows a situation in which yielding occurs on the first loading and creep relaxation occurs at the peak of the cycle. The unloading and reloading is within the elastic range, and for the first few cycles creep relaxation continues to occur at the peak of the cycle. After several cycles, during which the peak stress is relaxed by creep, a steady state is reached in which creep at essentially constant load occurs at the peak of the cycle and the cyclic stress range does not cause any yielding. In this case, it is clear that creep and fatigue are not interacting (insignificant cyclic loading), because both are occurring but creep continues unaffected by fatigue, and fatigue (the stress range) is unaffected by creep.

Figure 3-1: Illustration of Insignificant Cyclic Loading (Excerpted from R5)



Contrast that with Figure 3-2 which shows a similar loading-unloading scenario but now the stress range is sufficiently large that after a few cycles (during which creep relaxation is occurring at the tensile peak of the cycle) yielding occurs at the compressive end of the cycle. This causes the start of dwell stress at the tensile peak of the cycle to be "reset" each cycle resulting in repeated creep relaxation and yielding in compression on every cycle. In this case cyclic loading is said to be significant, because the simple steady state stress would underestimate the creep damage and the strain range is enhanced compared to the simple elastic stress range. Therefore, detailed calculations must be performed to determine the creep and fatigue damage due to the effect of one on the other (this is only addressed in detail in R5, and approximately in Section III, Subsection NH).

Figure 3-2: Illustration of Significant Cyclic Loading (Excerpted from R5)



The following sub-sections provide a summary of features of each of the Codes and Standards, particularly with regard to their approach of dealing with creep, fatigue and their interaction.

3.2 ASME BPVC Section VIII, Division 2

This ASME Code covers alternate rules for the construction of pressure vessels. In 2007, this ASME Code was revised and updated and the new version includes the option of "Design-By-Analysis" (Part 5), so this is the focus of this review. It is noted that Section VIII, Div. 2 allows for parts of a vessel to be designed using the "Design by Rule" approach where applicable, and use the "Design by Analysis" approach where the rules do not cover "all loadings, geometries, and details", (see 4.1.1.2 in Section VIII, Div. 2). "Design by Analysis" may also be used for any area where rules do exist (4.1.1.5 in Section VIII, Div. 2).

The "Design by Analysis" procedure seeks to protect the component from plastic collapse, from local failure, from buckling and from cyclic loading. The use of the procedure is restricted to the temperature regime in which the design temperature is governed by time-independent material properties; hence the rules do not consider creep or creep-fatigue interaction.

The procedures provide assessments that can utilize elastic analysis (using stress categorization methods) or inelastic analysis. The review here focuses on the inelastic approach since this overcomes many of the inherent difficulties of the stress classification approach (indeed, 5.2.1.2 in Section VIII, Div. 2 recommends use of the inelastic approach for complex stress fields and loadings) and this approach can be compared and contrasted with other Codes following similar approaches.

For global plastic collapse the Code offers a limit load analysis method which follows the normal approach using an elastic perfectly-plastic constitutive model where the yield strength is equal to the appropriate material design strength. The von-Mises yield function is used for the calculation. The Code also offers an elastic-plastic analysis method where the actual strain hardening characteristic of the material may be considered, providing that the model provides perfectly plastic behavior beyond the true ultimate stress. This also uses a von-Mises yield function. As with a conventional limit analysis, the loading is increased monotonically until plastic collapse occurs. The Code also requires a check on the local strains as protection against local failure (the plastic equivalent strain should be less than a limiting triaxial strain).

A procedure is provided for protection against collapse from buckling, but this is not reviewed here because this mode of failure is generally not relevant for internally pressurized boiler components.

The Code does not include a specific check on global shakedown, but does include a ratcheting assessment using a cyclic elastic perfectly-plastic analysis with the minimum specified yield strength. In this method a number of load cycles must be analyzed to demonstrate that either: (a) there is no plastic action, (b) there is an elastic core in the primary load bearing boundary, or (c) there is not a permanent change in the overall dimensions. Thus, this check basically encompasses proving there is an elastic core, which is essentially the intent of the shakedown rules in other Codes. Here, however, there is no defined size for the elastic core (unlike other Codes that require at least 80% of the section to be elastic, within shakedown).

For fatigue assessment, the Code provides some screening criteria which are quite similar to those from the original Section VIII, Div. 2 Code. For detailed fatigue assessment, two routes are offered: one based on elastic analysis and another based on elastic-plastic analysis. The latter (elastic-plastic) is reviewed here. Two approaches are offered for elastic-plastic analysis. The so-called Twice Yield Method, in which elastic plastic analysis is performed in a single load step representing the complete load range for the cycle with a constitutive model representing the stabilized cyclic stress range – strain range curve. This method is quite simple with the advantage that the cyclic problem is reduced to a monotonic loading problem, however, this requires that the cycle can be simplified to a single loading step (which is often the case for a single load source, but can be quite complex to define for a thermo-mechanical loading history). The second method offered is cycle-by-cycle analysis in which elastic-plastic analysis is performed for several loading cycles, using a constitutive model representing the stabilized cyclic stress amplitude – strain amplitude curve. The approach requires that kinematic hardening is utilized. The approach provides more flexibility in that the cycle does not have to be simplified to a single loading step, but consequently requires significantly more computational effort to analyze several cycles to obtain a stabilized cyclic response for the structure. Also, this cycle-by-cycle methods imposes the requirement that the computer program used for the analysis must allow a non-linear stress-strain response in combination with kinematic hardening (this material response model is not present in all finite element codes).

The analysis by either Twice Yield or cycle-by-cycle ultimately provides a cyclic stress range and an equivalent plastic strain range which in turn used to determine an effective alternating equivalent stress for use in the fatigue damage calculation (with an appropriate S-N curve). It is noted that the analysis approach adopted should adequately represent the cyclic stress / strain range, but with either approach the mean stress for the cycle (and hence the stress and strain at any point in the cycle) will likely be inaccurate, because neither of the methods (Twice Yield or cycle-by-cycle with kinematic hardening) are likely to properly capture the cyclic mean stress reduction that generally occurs with most steels used in boiler pressure part construction. In any case, the fatigue (S-N) curves provided in the Code incorporate the maximum effect of mean stress (so accurate determination is not necessary). This combined, with the fact that all parameters (elastic modulus, stress-strain curves, etc.) are taken for the average temperature of the cycle limits, means that this analysis approach would not be valid for computations at high temperatures (in the time dependent regime); but it is noted that the present Section VIII, Div. 2 is restricted to the time independent regime (although it is further noted that in Annex 3-D, which provides the cyclic stress-strain curves, parameters are given at temperatures that extend into the time-dependent regime for some materials).

The Code provides a specific approach, based on the “Structural Stress Method”, for the fatigue evaluation of welds. This method has been discussed extensively elsewhere so is not reviewed here, except to note that the basic approach is valid in the time-independent regime but is of limited applicability in the time-dependent (creep) regime.

Section VIII Rules for Construction of Pressure Vessels, Division 3 (Section VIII, Div.3) also provides methodology for “Design by Analysis”. This includes both inelastic and elastic stress analysis and provides limits for the applicability of each in a time-independent regime. Section VIII, Div.3 uses fracture mechanics as a primary means of calculation of the fatigue life of a component. Simplified S-N fatigue assessment is permitted for certain situations where “leak-before-burst” modes of failure can be demonstrated. It is noted that Section VIII, Div. 3 does contain a fatigue method which includes methods for the direct incorporation of the mean stress effect in the computation of the life of a component. The overall approaches for “Design by Analysis” are similar between Section VIII, Div.2 and Section VIII, Div.3, so the Section VIII, Div.2 will be the focus of the discussion and only reference Section VIII, Div.3 where needed.

3.3 API 579-1 / ASME FFS-1 Fitness for Service (FFS-1)

The FFS-1 Code was first published as a joint document between ASME and API in 2007 with input from selected individuals. The document contains “a compendium of consensus methods for reliable assessment of the structural integrity of equipment containing identified flaws or damage.”

The document is primarily focused on the evaluation of in-service equipment and evaluation of potential operational issues or flaws in that equipment and the evaluation of the equipment for future operation. However, many of the methodologies used in the document are similar to general “Design by Analysis” approaches and it is worth noting the scope of the document here.

The document is divided into parts with the main sections including assessment of:

- brittle fracture
- general metal loss
- local metal loss
- pitting and corrosion,
- hydrogen blisters and hydrogen damage associated with HIC and SOHIC
- weld misalignment and shell distortion
- crack like flaws
- components operating in the creep range
- fire damage
- dents, gouges, and dent-gouge combinations
- laminations

Appendix A contains the “Design by Formula” methods typically found in Section I today.

Annex B1 contains methods for performing stress analysis for the determination of the fitness-for-service of a component. The methods are very similar to the ones found in many of the other standards such as a Limit Load Analysis and Elastic-Plastic Stress Analysis. As these are covered in other parts of this document, they will not be covered in great detail here.

Part 10 entitled “Components Operating in the Creep Range” discusses methods of life assessment for components operating in the creep range. This includes methods for calculation of the life based on the “damage fraction” incorporating creep (based on time fraction) and fatigue (Miner’s rule), or using a traditional fracture mechanics approach for crack-like features. The life calculation methods include both

Larson-Miller and Omega for the calculation of the life of components. The methods, particularly for Level 3 calculations involving more detailed analytical approaches, have some similarities with other Codes reviewed here (indeed, the user is offered the option of using procedures such as R5). The use of the Omega creep model is, however, unique but the generality of this approach and the use of the multiaxial creep rupture law is quite different to that adopted in other documents (even those referenced as alternatives) and has not received expert review and hence has very limited acceptance.

The approach for life assessment does include an evaluation for creep-fatigue interaction (10.5.3 in ASME FFS-1). However, this simply requires that creep and fatigue are evaluated independently (without consideration for deformation interaction; that is, no enhancement of creep due to plasticity or vice versa is considered) and that the resulting independent damage values are then plotted on an interaction diagram that is material dependent. While a bi-linear interaction diagram is used suggesting stronger than linear interaction, the predictions could be non-conservative because any true creep-fatigue damage interaction is not accounted for. Appendix F provides the majority of material data required for deformation calculations. It should be noted that the Omega creep model does not include primary creep which should be considered for accurate prediction of stress relaxation in many creep-fatigue cycles. Overall, this approach appears far from the state-of-the-art for creep-fatigue interaction calculations.

Mode I and Mode II Creep-Fatigue assessment of Dissimilar Metal Weld (DMW) Joints are also included, although this is restricted to 2.25Cr1Mo ferritic to austenitic steels with either a stainless-steel or nickel-based filler metal.

3.4 ASME BPVC Section III, Subsection NH

This subsection of the ASME Code contains rules for nuclear facility components covering so-called Class 1 Components in Elevated Temperature Service. The rules in this portion of the Code date back many years, with this originally being Code Case N47 (which is often the designation found in open literature referencing the ASME Nuclear Creep-Fatigue Rules). These rules are unique within the ASME Codes because they state the need to address time dependent behavior including creep-fatigue interaction.

Within this subsection, Article NH-3000 Design includes NH-3200 Design-By-Analysis which provides background and definitions associated with the underlying approach which is based on stress categorization from an elastic analysis. However, inelastic analysis is also permitted (NH-3214.2) and it is noted that Appendix T (which will be discussed later) was established with the expectation that inelastic analysis would sometimes be required.

For limits on primary stress, the Code provides time and temperature dependent strength values (rather than just a time independent, temperature dependent strength value as is the case for the current edition of Section I). The specific treatment of primary membrane, local and bending stresses, and the associated margins applied to the material strength data vary with the level classification applied to the service loadings. To apply the rules, the operating times for various service loadings must be classified into a Load Histogram (NH-3114) and a linear time fraction damage summation is used to control their cumulative effect.

The effects of secondary stresses are managed through Limits on Deformation Controlled Quantities (NH-3250) for which acceptability criteria and material properties are contained in Appendix T (although it is noted that alternative criteria may be applied subject to approval by the owner). The non-mandatory Appendix T is entitled "Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures." This appendix includes limits for inelastic strains which can be demonstrated to be satisfied by either elastic analysis, simplified inelastic analysis, or detailed inelastic analysis. The methods for detailed inelastic analysis are not specified but the description of inelastic analysis provided in NH-3214.2 notes "The constitutive equations, which describe the inelastic behavior, should reflect the following features when they have a significant influence on structural response: the effects of plastic strain hardening including cyclic loading effects and the hardening or softening that can occur with high temperature exposure; primary creep and the effects of creep strain hardening as well as softening (due to reverse loadings); and the effects of prior creep on subsequent plasticity, and vice versa." Practically, such constitutive equations are not available and hence elastic or simplified inelastic analyses are the only feasible options.

If elastic analysis is used then some simple tests are provided to demonstrate that the combination of primary and secondary stress remains within the elastic range and that creep damage and strains are negligible. Such restrictions are invariably prohibitive thereby requiring simplified inelastic analysis. In addition to some basic tests on deformation (NH-T-1330), a general procedure for creep-fatigue evaluation is provided (NH-T-1400) which is the widely referenced "ASME Creep-Fatigue approach".

A number of calculations utilize a core stress, which is defined as the stress controlling the ratcheting creep strain for the cycle (which is approximately the stress within the core of the structure). In other methodologies, such as R5 which will be discussed later, this would be termed a shakedown reference stress. Estimation of this core stress is based on the O'Donnell/Porowski modification of the Bree diagram (Figure NH-T-1332-1) which was derived for the wall of a pressurized tube with constant membrane stress (due to pressure) combined with a cyclic bending stress (due to through-wall temperature gradient). For this specific case, the diagram provides the core stress for any combination of primary and secondary stress. An alternative diagram (Figure NH-T-1332-2) is provided for determination of core stress in general structures but this is highly conservative in many cases. Strictly the core stress is a function of both the geometry and loading so the simplifications introduced are quite dramatic.

Much has been written about the overall approach to creep-fatigue calculation within these rules so only an outline is provided here of some of the key features.

(a) The total strain range is estimated (NH-T-1432) using Neuber's method in conjunction with the (modified) time independent isochronous stress-strain curve. This strain range includes adjustments for multiaxial plasticity and Poisson's ratio. Also, an enhancement is applied for the creep strain increment during the cycle due to creep at the core stress. The fatigue damage is calculated based on this total strain range.

(b) Creep damage is calculated (NH-T-1433) by considering the stress relaxation during the cycle. The stress history is estimated by assuming that stress relaxation occurs at constant strain (no elastic follow-up) using isochronous stress strain curves. However, the stress cannot relax to a value less than 1.25 times the core stress. This provides a stress history from which creep damage is evaluated using a life fraction rule.

(c) The calculated creep and fatigue damage values are plotted on an interaction diagram to demonstrate that the combined effect is acceptable. The interaction diagram is material dependent, but in all cases a bi-linear interaction is specified with the result that the sum of the creep and fatigue damage is less than unity (in some cases greatly so).

This methodology has been in place for many years without significant modification but the principal concerns with the approach stem from the lack of generality in some of the simplifying assumptions. Specifically, calculation of the core stress is overly simplified so, for complex geometry and/or complex loading the core stress estimates – which are key to both creep and fatigue damage predictions in the time dependent range – are invariably inaccurate.

The other principal contention with the approach is that stress relaxation is assumed to occur without elastic follow-up from the peak stress in the cycle. Few real components would satisfy that requirement which results in a more rapid stress relaxation than would likely occur. Furthermore, the creep damage during this period of stress change is calculated using a life fraction approach which is known to be inaccurate for such stress histories.

Added to this are some of the inherent conservatisms associated with the stress categorization approach for which it is often difficult to define an appropriate stress categorization line and stress redistribution is only considered to occur on that line and not between other regions of the structure. Also, frequent concerns are expressed about the interaction diagram and the high degree of conservatism that is regarded to exist for some materials – most notably modified 9Cr-1Mo-V-Nb (Grade 91).

It is these shortcomings that other approaches, such as that of R5 (which will be discussed later), have sought to overcome, increasing the generality, applicability and accuracy of a creep-fatigue evaluation procedure. Even with a number of somewhat contentious simplifying assumptions the Section III, Subsection NH methodology is relatively complex and arduous to apply.

3.5 EN12952-3

This Code is for design calculations of water tube boilers. It is basically the European equivalent to Section I. The fundamental approach is based on a number of former well established European Codes, particularly the German TRD. At a very high level, this Code has made a step toward "Design-For-Lifetime" by providing allowable stress values for specified operating periods (e.g. 100,000 hours or 200,000 hours). Although it is reviewed here (principally because of the fatigue damage calculation) the Code follows a typical "Design-By-Formula" approach. The methodology also includes a fatigue evaluation procedure which has been widely cited as a helpful approach for cycling boilers, such as heat recovery steam generators. Indeed, some customer design specifications even require the boiler design to Section I, but with supplementary fatigue calculations to EN12952-3. These fatigue calculations will be discussed at greater length below. Although the Code implicitly accounts for both creep (through allowable stress) and fatigue (through an evaluation procedure) it does not specifically calculate a creep damage fraction, or consider the addition of creep and fatigue damage. For creep – fatigue interaction EN 12952 Part 4 can be used for design life assessment; even though this Part is directed to in-service life expectancy calculations.

The fatigue methodology of EN12952-3 is documented in Clause 13. This begins with some notes and exclusions including, perhaps somewhat strangely, "*isolated holes not larger than 20mm in diameter need not be subjected to fatigue analysis*." A screening procedure is provided to identify the most critical components that require more detailed evaluation. This screening is based on limiting the pseudo steady state temperature ramp rate (or more particularly the through-wall temperature gradient) in a pipe that is assumed to have a nozzle/penetration with a bounding stress concentration factor. This is probably adequate in many cases, but certainly not applicable to all cases (e.g. where temperature gradient across a vessel (top-to-bottom) may exceeds that through the wall).

The basic fatigue methodology seeks to calculate a stress range for the cycle that can then be "corrected" and compared against an appropriate fatigue endurance curve to determine the fatigue lifetime. Section 13.4 provides a simplified methodology for stress calculation due to combinations of internal pressure and through-wall temperature gradients at nozzles / penetrations. The thermal stress concentration factors are somewhat questionable, often resulting in values less than unity. The restriction on simple geometries and transients is lifted by giving the user the option of following the methods for EN13445 for more complex situations. Also, it is noted (13.1.1) that "*Due to the simplicity of the analysis, the results may be conservative with respect to life prediction. More complex methods, e.g. finite element analysis, may be applied to obtain more exact life predictions*."

The methodology for fatigue life calculation is documented in Annex B. This provides a number of modifications to the stress range including: surface finish stress enhancement based on roughness, weld stress enhancement based on weld geometry and required cyclic life, mean stress correction based on Gerber's rule, plasticity correction based on Neuber's rule with a perfectly plastic material and a temperature correction (for which the technical basis is not known). In common with the other EN Codes (e.g. 13445), restriction is also placed on the stress range for water touched components to avoid cracking of the magnetite layer. This is a go/no-go criterion requiring a redesign of the component or operating transient if the stress range is too large.

Within the fatigue calculation where is no explicit limit on the temperature applicability of the fatigue evaluation. The reference temperature (defined as 25% of the temperature in the cycle at which the minimum stress occurs plus 75% of the temperature in the cycle at which the maximum stress occurs) is limited to 600°C which, in reality, allows the procedure to be applied for all practical boiler designs including for modern supercritical plant with steam temperatures approaching 650°C.

The fatigue endurance curves themselves are quite conventional with dependence on tensile strength as the endurance limit is approached.

3.6 EN12952-4

This section of the EN Code is for In-service boiler life expectancy calculations (and therefore is not strictly a design Code). Indeed, the Code begins by stating "*This European Standard specifies procedures for calculating the creep and/or fatigue damage of boiler components during operation. These calculations are not required to be carried out by the manufacturer as part of his responsibilities within the European Standard.*" However, it is reviewed here because it does include calculations for both creep and fatigue.

The Code includes an upfront statement to address the combination of creep and fatigue "*NOTE: In some cases, the influence of both creep and fatigue damage will be significant. It is normally conservative to combine the creep and fatigue damage mechanisms by adding the calculated usage factors. If necessary, more detailed methods of assessment may be used (see [1] PD7910 Published by British Standards Institute, London, UK). Thus, the components are not necessarily to be replaced if the calculated usage factor exceeds the value of 1.*"

The procedure then goes on to provide the method for creep damage calculation (Annex A) and fatigue damage calculation (Annex B) and provides no further discussion of creep-fatigue interaction.

The creep damage calculation procedure basically inverts the design equations from the EN12952-3 Code, thereby providing a primary, or reference, stress value that is used in combination with creep rupture data taken from the European Collaborative Creep Committee (ECCC) data package (which underlies the Code allowable stress values). Thus the creep calculation is very simplistic and takes no account of local stress concentrating features, or of any influence of fatigue (yielding) on creep. Creep damage for periods of different operating conditions are summed using Robinson's time fraction rule.

The fatigue damage calculation procedure is essentially the same as that documented in EN12952-3 clause 13 and Annex B. The key addition being the discussion of defining cycles from a stress history by extracting peaks and valleys, then using a cycle counting algorithm (range-pair or rainflow are suggested).

3.7 EN13445-3

This Code is intended for the design calculation of unfired pressure vessels. It is basically the European equivalent of Section VIII. The Code predominantly offers a conventional approach based on "Design-By-Formula" combined with predetermined construction features. However, the Code also includes a "Design-By-Analysis" approach which is documented in Annex B. It is also noted that the Code includes a design by stress categorization approach (Annex C) but this has a number of limitations imposed (such as not permitted in the creep range) that greatly limit its value, so it is not discussed further in this document.

A key feature of this Code is that "Design-By-Formula" and "Design-By-Analysis" can be used somewhat interchangeably and in a complementary fashion. That is "Design-By-Analysis" can be used where "Design-By-Formula" is deficient or if so chosen. It is stated in the Code that the rules of Annex B can be applied to whole vessels or vessel parts. This is a very pragmatic approach and allows use of "Design-By-Analysis" approaches only for situations and features where it really makes sense; otherwise use the simpler "Design-By-Formula".

The "Design-By-Analysis" approach in Annex B is based on limit analysis, shakedown theory and ratcheting concepts, that are proven with inelastic analysis using an elastic perfectly-plastic material model. Because of the need to perform inelastic calculations, B.1.3 Special Requirements, states "*Due to advanced methods applied, until sufficient in-house experience can be demonstrated, the involvement of an independent body qualified in the field of DBA, is required in the assessment of the design (calculation) and the potential definition of particular NDT requirements*." It is not stated what specific qualifications are needed, or how sufficient in-house experience is demonstrated.

The basic philosophy of Annex B is to protect against the main failure modes of:

- Plastic collapse at design loads (Gross Plastic Deformation – GPD)
- Ratcheting / Shakedown due to cycles (Progressive Plastic Deformation – PD/SD)
- Fatigue due to cyclic loads (Fatigue – F)
- Creep rupture at design loads (Creep Rupture – CR)
- Creep lifetime (Excessive Creep Strain – ECS)
- Creep-fatigue (Creep Fatigue Interaction – CFI)

As stated previously this basic methodology used is a combination of limit analysis and elastic analysis based on shakedown and ratcheting theory. This approach has many features in common with the first few steps of the R5 volume 2/3 assessment procedure (see review of R5 section to follow).

The GPD check uses short term yield strength and requires Tresca yield condition with design loads and required factors of safety on material properties. This is the conventional lower bound limit analysis method. The complication is that for some load combinations the factors of safety are based on national Codes (e.g. wind or snow) not on the EN code – therefore there is no consistent LRFD approach in the EN Code and a designer will need to refer to the relevant national standard (the base EN code is really written for internal pressure).

The PD/SD check uses von-Mises yield condition with design loads and no additional safety factors on loads or material properties. The basic requirement is that the stress concentration free model shakes down to elastic behavior or the model with stress concentrations shakes down to elastic behavior over 80% of every wall thickness. Therefore, ratcheting is avoided by the presence of an elastic core.

The fatigue (F) check is not specifically given in Annex B, but is included in Clause 18 of the main body of the Code. It is also recognized that a simplified assessment of fatigue life is given in Clause 17, but this is only applies to assessment of fatigue damage due to pressure fluctuations. The detailed assessment of fatigue life given in Clause 18 follows a fairly conventional fatigue evaluation approach using S-N curves and corrections for the usual parameters (mean stress, plasticity, surface finish, welds, temperature). The applicability of the procedures at higher temperatures is limited by statements in 18.1.5 "*This method is not intended for design involving elastic follow-up*" and in 18.4.3, "*These requirements are only applicable to vessels which operate at temperatures below the creep range of the material.*

Thus, the fatigue design curves are applicable up to 380°C for ferritic steels and 500°C for austenitic steels."

The fatigue methodology in EN13445 is similar to that of EN12952 but the correction factors and S-N curves are different. That is, some difference in calculated fatigue damage would likely be obtained for the same input data. Also, EN13445 has the temperature restriction of 380°C for ferritic steels but EN12952 permits fatigue damage calculation up to 600°C for ferritic steels.

The check on creep rupture (CR) is essentially a limit analysis, using the von-Mises yield criterion with a yield strength equal to the appropriate time-dependent strength value, at design loads and required factors of safety. The other creep check (ECS) is related more particularly to the creep lifetime and requires calculation of a representative rupture stress (using the formula from the R5 procedure), which accounts for the effect of stress concentrating features and thereby is more conservative than simply using the primary, or reference, stress. For periods of creep at different operating conditions then a creep damage fraction summed using Robinson's life fraction rule.

The closest that EN13445-3 gets to creep-fatigue interaction, is in B.9.5.4 which requires a check that the cycles that interrupt periods of creep do not result in any plastic deformation. This the basic "resetting" check to verify that the residual stress state established after long-term creep deformation is not modified by plastic deformation due to the transient history experienced during operating cycles. This test is actually quite restrictive because it implies that 100% of the cross section must be within strict shakedown and the long-term dwell stress must be taken at as determined by limit analysis.

The formal check on creep-fatigue interaction is in B.9.6 which requires that the sum of the creep damage and fatigue damage shall not exceed unity (linear interaction). With the restrictions imposed so that fatigue does not cause perturbation of the residual stress field (no resetting of start of dwell stress) then creep and fatigue may both be occurring but their deformation is not interacting, so the linear summation appears reasonable.

3.8 R5

The R5 procedure is included in this review because it represents probably the most complete and consistent treatment of creep and fatigue, and their effect on each other, both in terms of damage and deformation. R5 is, however, distinguished from the other documents in that it is not a statutory Code or Standard (at least not for the design of boilers and pressure vessels). It is intended as an assessment, or fitness-for-service procedure, not as a design procedure. It is very comprehensive considering both the initiation and the propagation of defects. As a result, it requires extensive material data and knowledge for proper application. The roots of R5 can be traced back approximately 30 years, beginning as assessment procedures for high temperature components within the former UK Central Electricity Generating Board (CEGB) for both fossil and nuclear plant. Over the years this has evolved into the present R5 procedure which is now at Issue 3 [13].

R5 is based on very fundamental concepts related to structural response such as reference stress, limit analysis and shakedown theory which certainly have a place when considering evolution of design Codes.

The latest edition, R5 Issue 3, is divided into two principal volumes:

- Volume 2/3: Creep-Fatigue Crack Initiation Procedure for Defect Free Structures.
- Volume 4/5: Procedure for Assessing Defects and Creep and Creep-Fatigue Loading.

This scope allows initiation of defects to be computed with methods of Volume 2/3 and subsequent growth to be computed with methods of Volume 4/5, allowing the total useful lifetime to be assessed.

This review will only consider Volume 2/3, as related to initiation because these methods are the most relevant to design Codes and, as noted previously, some of these concepts have been incorporated into Annex B of EN13445-3. Also, Volume 4/5 is the basis for creep and fatigue crack growth procedures that are now incorporated in BS7910 (see following section on BS7910).

Features of the R5 procedure are its systematic approach to assessment with a step-by-step methodology. Nevertheless, the complexity is indicated by Volume 2/3 running to several hundred pages, including many appendices to explain the complexities and highlight difficulties. Also, none of the material data for assessments is included in R5; this must be obtained from other sources.

At the heart of Volume 2/3 are methods to assess the significance of creep-fatigue interaction and compute that effect if needed. The procedure begins with some basic checks on short term plastic collapse (Step 3), and then on long-term creep rupture at an appropriate rupture reference stress (Step 5). The procedure then moves on to consider cyclic behavior (Step 6) which tests for shakedown and insignificant cyclic loading, for which the fundamental requirements are:

- The most severe cycle is within the elastic range of the material (stress range for the cycle does not exceed the yield stress range).
- The total fatigue damage for all cycles is less than 0.05.
- Creep behavior is unperturbed by cyclic loading (this is the so-called "resetting" check which is quite straightforward for a creep dwell at the peak tensile stress, but can be more complex in other scenarios).

If these criteria are all satisfied the cyclic loading is regarded as insignificant and creep will control the lifetime. It should be noted that "*Criteria to demonstrate insignificant cyclic loads for weldments are not currently available and it is therefore necessary to perform all steps in the procedure when assessing weldments*."

If the criteria for insignificant cyclic loading (which are essentially the same as those included in EN13445-3, Annex B) cannot be satisfied then a complete assessment is required. In essence, this involves the following calculations:

- Determine residual stress distributions.
- Calculate the shakedown reference stress.
- Calculate the start of dwell stress.
- Estimate the elastic follow-up factor and associated stress drop during the creep dwell.
  - Calculate the total strain range, accounting for enhancement of plastic strain range due to creep in the cycle.
  - Calculate the fatigue damage per cycle.
  - Calculate the creep damage per cycle, using a ductility exhaustion model with proper account for the change in strain rate during the dwell.
  - Calculate the total damage as the linear sum of the creep and fatigue damage.

These detailed cyclic assessments require extensive material data, including the following which are not normally found in Codes for boiler design:

- Cyclic stress-strain data (shape of hysteresis loops).
- Stress relaxation data.
- Isochronous stress-strain curves.
- Creep ductility data (as a function of strain rate, and with multiaxiality criterion).

Such data are often quite limited, even in the open literature, and often show significant variability, sometime reflective of different material processing history, sometimes reflective of different test methodologies.

While the overall approach shares some commonality with that of other approaches, such as Section III, Subsection NH, there are a number of aspects that are unique to R5 to provide boarder applicability and improved accuracy. Some specific features include the use of a shakedown reference stress as an upper bound estimate of the core stress for creep ratcheting during a cycle; this approach is applicable to any geometry and loading history. Also, stress relaxation during dwells accounts for follow-up and the associated creep damage is calculated using a strain-rate dependent ductility exhaustion model (rather than time fraction). It is these innovations that have set R5 apart from other approaches. However, this does come at the expense of some complexity. As noted earlier the material data requirement is substantial and also a number of calculation tools are needed to generate residual stress fields and calculation of creep relaxation and follow-up during the dwell.

Another essential element of the R5 methodology is Step 17 (Assess significance of results). This requires a number of sensitivity studies to explore the effect of assumptions, largely due to the complexity and variability of inputs. For example, use of lower bound yield stress in the analysis will maximize the strain range (resulting in more fatigue damage), but may minimize the start of dwell stress (resulting in less creep damage). Looking at the many combinations can be time consuming and complex.

3.9 BS7910

This document includes methods and procedures that are essentially identical to those in R5 volume 4/5. The scope of the document clarifies "*This guide outlines methods for assessing the acceptability of flaws in all types of structures and components… …The methods described can be applied at the design, fabrication and operational phases of a structure's life.*"

The introduction to the procedure distinguishes acceptance criteria for flaws based on quality control and fitness for purpose. This discussion highlights that criteria based on fitness for purpose should not be used to justify poor workmanship, nor can be provided in every scenario, hence the need for flaw acceptance based on quality criteria.

The methods within the procedure are based entirely on fracture mechanics. Fatigue crack growth is based principally on elastic stress intensity (K) with appropriate corrections for plasticity and other effects. Creep crack growth is based principally on the C* parameter. The basic methodology follows conventional practice for fatigue and creep crack growth evaluations (yielding and creep in the ligament ahead of the crack are also considered). Fatigue uses a modified Paris growth law and the Nikbin-Smith-Webster model is used for creep crack growth. The procedure provides relevant crack growth equations and some stress intensity solutions, but not the relevant materials data.

Creep-fatigue interaction follows the R5 approach. First checks are made to determine if the insignificant cycling criteria can be met. Specifically, fatigue crack growth should be sufficiently small as to not influence the creep fracture mechanics calculations. Cyclic loading should not prevent steady state creep conditions from applying during the dwell periods at high temperature. And, fatigue crack growth should not exceed $1/10^{th}$ of the creep crack growth.

If these criteria are not satisfied then the user is directed to Appendix T4 (Assessment to include creep-fatigue loading), in which a procedure is given to separately calculate creep and fatigue crack growth and linearly sum the respective contributions to obtain an overall crack growth.

3.10 RCC-MR

The RCC-MR Code entitled "Design Construction Rules for Mechanical Components of Nuclear Installation Applicable to High Temperatures, Applicable to ITER Vacuum Vessel," was published by the French Society for Design and Construction Rules for Nuclear Island Components (AFCEN). The 2007 version is the 3rd Edition. The RCC-MR Codes is a very comprehensive Code organized into five main sections and very similar to Section III except it also provides rules for high temperature applications. Because rules are provided for high temperature application, this Code has provisions that might be useful in the modernization efforts of Section I even though the RCC-MR Code appears to be geared towards nuclear power plants and hence the similarity to Section III. The fact that it is also organized along the lines of Section III also offers some advantages in that it provides a flavor that already resides in an existing ASME Code. The organization of this Code is as follows:

- Section 1
  - Subsection A – General Requirements
  - Subsection B – Class 1 Components
  - Subsection C – Class 2 Components
  - Subsection D – Class 3 Components
  - Subsection H – Supports
  - Subsection K – Examination and Handling Mechanisms
  - Subsection Z – Technical Appendix
- Section 2 – Materials
- Section 3 – Examination Methods
- Section 4 – Welding
- Section 5 – Fabrication

As can be seen from above, Section 1 of the RCC-MR Code distinguishes between various Classes as in Section III. Defect acceptance criteria during construction are provided for the various classes. A non-mandatory Appendix (Appendix Z/A16, “Guide for Leak Before Break Analysis and Defect Assessment” is provided for evaluation of defects identified during service. This Appendix is very similar to Section XI, Rules for Inservice Inspection of Nuclear Power Plants Components of the ASME Boiler and Pressure Vessel Code (Section XI) except rules are provided for fatigue, creep and creep-fatigue interaction.

Four types of damage are considered in this Code. The first is P-Type damage which can result from the application to a structure of a steady and regular loading or constant loading. Included in P-Type damage are immediate excessive deformation, immediate plastic instability, time-dependent excessive deformation, time-dependent plastic instability, time-dependent fracture and elastic/elasto-plastic instability. The second is S-Type damage which can only result from repeated application of loading. Included in S-Type damage are progressive deformation and fatigue (progressive cracking). The third damage is buckling. Included in buckling damage are load controlled buckling, strain-controlled buckling and time-dependent buckling. The last form of damage considered in RCC-MR is fast fracture which occurs without being preceded by an appreciable global deformation. Two types of fracture are generally considered, one by ductile tearing, the other by fragile or semi-fragile tearing.

Operating conditions during normal, emergency and test conditions are described. Conditions SF1 and SF2 are the first and second categories of operating conditions and both refer to conditions to which the equipment may be subjected in the course of normal operation, including normal operating incidents, start-up and shutdown. Condition SF3 is associated with emergency conditions, corresponding to very low probability of occurrence. SF4 are conditions which are highly improbable but whose consequences on components are studied among others for safety reasons. Test conditions are the conditions to which the component is subjected to during hydrotest.

Loads to be considered in the analysis are also described in the RCC-MR Code and consist of but not limited to:

- Internal and external pressure.

- Dead weight of equipment including content, and the static and dynamic loads by liquids under each condition analyzed.
- Forces resulting from weight, thermal expansion, pressure and dynamic loads which originate outside the zone studied and which are applied to the boundary.
- Seismic loads and vibration loads, if any.
- Support reaction loads.
- Temperature effects, either constant or transients.

Similar to Section III, various criteria or service levels are described in the RCC-MR Code.

Level A – The aim of Level A criteria is to protect the equipment against the following types of damage:

- Immediate or time-dependent excessive deformation,
- Immediate or time dependent plasticity\time-dependent fracture.
- Elastic or elasto-plastic instability, immediate or time-dependent.
- Progressive deformation.
- Fatigue.

Level B – Although described and required in Section III, this service level is not a feature of the RCC-MR Code.

Level C- The aim of level C is to protect the equipment against the following types of damage;

- Immediate or time dependent excessive deformation.
- Immediate or time dependent plastic instability.
- Time-dependent fracture.
- Elastic or elasto-plastic instability, immediate or time-dependent.

Level D – The aim of this service level is the same as level C but with a lower safety margin
For each of the damage type described above, rules are provided in the RCC-MR Code for all service levels when creep is negligible and when creep is significant.

Similar to ASME, the RCC-MR Code uses a stress classification system for elastic analyses separating stresses into general membrane (P_m), primary bending (P_b), local primary membrane (P_L), secondary (Q) and peak stress (F). Stress intensity (yield criterion) calculations based on either the maximum shear stress theory or octahedral shear theories are acceptable for use in this Code. Creep usage fraction, fatigue usage fraction and creep fracture usage fraction calculations are very well described in the RCC-MR Code. In addition, the use of limit load analysis and elastic-plastic /experimental analysis are also included as options. Constitutive equations for materials used in various analyses (elastic, elasto-plastic analysis subjected to monotonic loading, elasto-plastic analysis subjected to cyclic loading and elasto-visco-plastic analysis subjected to cyclic loading) are provided. For elasto-plastic analysis, isotropic material behavior is assumed and the Von Mises plasticity criterion is used. A hardening rule based on isotropic behavior is also provided.

Design rules are provided for shells, bolts, piping, box structures and heat exchanger elements. The arrangement of these sections in RCC-MR Code is also very similar to that in ASME.

3.11 Other Codes, Standards and Technical Publications Reviewed

Other standards and documents were suggested for review as part of this project. These included:

- ASME Post Construction Standard "Inspection Planning Using Risk-Based Methods", 2007 [14].

- Asayama, T. DOE / ASME NGNP/Generation IV Materials Project Task 10 – "Update and Improve Subsection NH – Alternative Simplified Creep-Fatigue Design Methods", September 2009 [15].
- Brust, F. W., G. M. Wilkowski, P. Krishnaswamy, ASME STP-NU-039 "Creep and Creep-Fatigue Crack Growth at Structural Discontinuities and Welds", ASME New York, NY 2011 [16].
- Asayama, T., ASME STP-NU-041 "Update and Improve Subsection NH – Alternative Simplified Creep-Fatigue Design Methods", ASME New York, NY 2011 [17].

These are not summarized specifically in this document, but their contents and methods are considered in the final recommendations made in Sections 4 through 7.

4 DEVELOPMENT OF DESIGN-BY-ANALYSIS RULES

The foregoing review of "Design-By-Analysis" approaches defined in various Codes and Standards illustrates that there is no single Code or Standard that provides a method that could be universally adopted. The most thorough of all the documents reviewed is the R5 Assessment Procedure, which considers many aspects of material and structural behavior in both time-independent and time-dependent regimes. Indeed, this procedure appears to have the most thorough and technically consistent approach for dealing with the specific topic of creep-fatigue interaction. However, this comes at the expense of significant complexity. To use the procedure:

- Requires significant expertise to understand the structural mechanics and material response characteristics to properly use the procedure.
- Although the procedures look "cook-book" the calculations are complex, particularly when the creep dwell does not occur at a stress extreme for the cycle.
- Requires extensive material data (cyclic stress-strain, relaxation, creep ductility, etc.) that are not widely available.
- Requires the calculations to account for variability in material properties because results when using minimum properties are not necessarily the most conservative.

Hence the R5 procedure is not viable for design calculations of boilers and pressure vessels (indeed it was not intended as such).

Of the ASME Codes, Section VIII, Div. 3 and the modernization of Section VIII, Div. 2 introduced "Design-By-Analysis" methods that provide protection against plastic collapse, ratcheting and fatigue. However, the methods are confined to use in the time-independent regime, which means that they cannot be used for Power Boiler design in general.

The European Code EN12952-3, while offering a fatigue assessment approach, represents a relatively simple extension to a basic "Design-By-Formula" approach that has much in common with the current underlying philosophy of Section I. By contrast with Section I, EN12952-3 does offer the option to design entire components or features of components by using rules of EN13445-3, including the "Design-By-Analysis" methods of EN13445-3, Annex B. Indeed, from the perspective of providing practical approaches for design that are consistent and scalable, the EN Code is particularly convenient and flexible. This is achieved by allowing use of "Design-By-Analysis" either as an alternative to design-by-formulas or as a complement to design-by-formulas. This is similar to the approach taken by Section VIII, Div. 2. In any further development of the Section I, it is recommended that the practicality of this approach is adopted.

Of the Design Codes reviewed, the "Design-By-Analysis" approach of EN13445-3, Annex B has the broadest applicability. It can be used in the time-independent and time-dependent regimes, and it protects against all reasonable structural failure modes – including creep-fatigue interaction. The methods are consistent with those of the R5 Assessment Procedure (up to, and including, the test for insignificant cycling). Because EN13445-3, Annex B, only seeks to protect against major structural failure modes and not, for example, provide detailed procedures for calculation of creep-fatigue interaction, it does not require extensive material databases, nor does it require particularly complex material constitutive models or analysis techniques (basically the methodology only requires elastic and elastic-perfectly plastic analysis capability). This means that this approach has utility and practicality.

In addition to the Codes and Standards reviewed, a number of other technical papers [22][23] and [24] provide insight into use of simplified methods based around the fundamental concepts of limit analysis, shakedown and ratcheting for design evaluation, including the use of extended or creep-modified shakedown limits. While some of these papers focus on the use of optimization algorithms to generate solutions, the same design checks and insight into the structural response can equally be gained with simple elastic-perfectly-plastic constitutive models with the base functionality of many finite element programs.

However, it is recognized that while the methods of EN13445-3, Annex B are practical to use, the simplicity of the creep-fatigue interaction evaluation may, in reality, prove to be too restrictive (in that it basically forbids any deformation interaction between fatigue and creep) for design of high temperature components subject to cycling and high temperature service. To assess if this is a genuine concern, it would be prudent to perform some example calculations for sample components operating at high temperature with cyclic service, which are known to have endured a reasonable period of operation. This test of the restrictiveness of the creep-fatigue interaction approach of EN13445-3, Annex B is important to identify if a more elaborate calculation methodology is needed for design of components in the next generation of heat recovery steam generators and solar receiver steam generators.

4.1 General Overview of Proposed Design by Analysis Approach

The general approach for the "Design-by-Analysis" Rules includes the following:

- Protection Against Collapse (Gross Plastic Deformation).
- Protection Against Shakedown and Ratcheting (Alternating Plasticity and Progressive Plastic Deformation).
- Protection Against Buckling.
- Protection Against Fatigue.
- Protection Against Creep Rupture.
- Protection Against Creep-Fatigue Interaction.

The subsections below outline a proposed approach for a basic "Design-By-Analysis" methodology with the intent of:

(a) Using basic structural mechanics approaches to provide design methods and criteria that provide a conservative bound on the actual structural response and which, therefore, are inherently safe.
(b) Drawing upon existing methodologies from international design Codes.
(c) Ensuring, where possible, consistency with existing rules and approaches with Section I, to permit such design-by-analysis methods to be used as an extension or complement to the present design-by-formula approach.
(d) Minimizing the material data and complexity of constitutive models required for the design checks.
(e) Minimizing the overall complexity of the calculations to permit them to be performed using conventional structural analysis programs (e.g. finite element software) without need for special features or complex, resource consuming, calculations.

The proposed approach forms the basic outline for a consistent methodology drawing on methods and approaches from various Codes included within the reviews documented earlier. Indeed, elements of the methodology are drawn from Section VIII, Div. 2, Section III, Subsection NH, EN13445-3, Annex B, and from R5. In describing the approach, notes are also included to discuss the origin of the methods proposed, their likely shortcomings / conservatisms and their practicality. This highlights some aspects where additional information or further refinement would be required, or beneficial, to improve the generality or utility of the approaches. Some of the more significant recommendations for future work (e.g. method development) and additions / modifications to the ASME Codes are summarized in Sections 6 and 7, respectively.

The approach recommended here is technically appropriate and practical for routine application during boiler design. The methodology uses the simplest and most expedient approach possible to provide verification that the design is safe from the particular deformation or damage mechanism. Hence we seek to minimize both the material data requirement and the complexity of material description (constitutive model). Also, the approach is selected from the perspective that a finite element model will exist for the components evaluated by this route and that the designer will have access to a finite element program that can perform basic elastic-plastic analysis (only perfect plasticity is required, avoiding the need for constitutive models that appropriately account for changes in the yield surface due to plastic deformation). Such an approach builds on the inherent simplicity and utility of the current Section I methods and, in the limit of simple geometries and steady loading, will result in essentially the same criteria that presently exist within Section I, hence assuring compatibility with the successful history of Section I.

This simplicity and utility comes at a price: conservatism. In the context of a design code this is judged to be prudent. Should the method proposed herein prove too prohibitive (which, per later recommendations given in this report, requires some practical test examples using the proposed methods), then perhaps Section I could allow use of a more elaborate creep-fatigue evaluation procedure – such as those being investigated by other groups associated with ASME Codes and Standards. Such a scalable approach to component design and verification has practicality and economy.

Before presenting the outline design methodology the next sections provide some further background as overall clarifications to the approach (what it is, and what it isn't).

4.1.1 Design Margins

The design margin is one of the most philosophically fundamental issues that need to be determined. However, it should be noted that the factors used are highly interdependent. For example, a high design margin on plastic collapse or creep rupture can lead to excessively thick components which may never meet the minimum requirements for cyclic life of a component.

Many modern Codes use what is termed as Load Resistance Factor Design (LRFD) methodology. This method specifies the combinations of loadings that should be considered and applies design margins to those loads for evaluation of the various design criteria. However, such an approach is quite different to the current methodology of Section I, where internal pressure is the primary design load and little direct guidance is given for other loads, other than they need to be appropriately (conservatively) included within calculations to satisfy stress limits.

As a result, the approach proposed here aims to be consistent with the current approach in Section I, to ensure continuity and consistency, and facilitate switching between the classic design-by-formula approach and design-by-analysis (e.g. basic sizing using design-by-formula and further validation of particular features by design-by-analysis). As development and use of a design-by-analysis method evolves it may prove effective to place it more formally within the context of a LRFD methodology.

4.1.2 Design Life Assessment

The recommended methodology provides protection against creep and fatigue failure modes which have a defined lifetime in terms of service duration or number of cycles, respectively. The philosophy is that key modes of component failure such as creep and fatigue are evaluated according to specification requirements (e.g. time and cycles), rather than against some arbitrary allowable stress or cyclic limit. This "design life assessment" is differentiated from a "life assessment" because it is based on simplified, conservative, analysis approaches combined with information available at the time of design both for component details and for operating procedures.

Actual components may not conform to this design information and, therefore, the "design life assessment" cannot be regarded as a definitive calculation of the operating life of the component. Specifically, the simplifications of material constitutive models for design are intended to result in conservative bounds on behavior and not represent the actual material response. Furthermore, it is recognized that certain information may not be available at time of design (e.g. actual operating transients) and hence assumptions will be made. Also, the actual fabricated dimensions of the component may differ from dimensions (such as minimum wall thickness) specified at design. Therefore, satisfaction of the design methodology related to creep or fatigue (that include defined time and cycles) does not represent a detailed lifetime assessment for the component and hence the actual life for the component may be significantly different than indicated by the methodology proposed here.

This outcome is a direct consequence of the simplifications that must be made at the design stage to provide a practical methodology. As a result, it is recommended that for components designed using the approach proposed here (or for that matter any design-by-analysis methodology) that a life management strategy should be established for components designed to this approach. This could include a variety of approaches including:

- *(a)* On-line monitoring for creep and fatigue damage to provide actual data that can be compared with the assumptions and predictions at the design stage.
- *(b)* Detailed life assessment accounting for actual component geometry and operation, and – where appropriate – using more detailed life assessment approaches (such as those given in ASME FFS-1 or R5).
- *(c)* Periodic in-service nondestructive inspection using appropriate techniques based on the likely mechanism of damage and location on the component.

The results of the "design life assessment" following the approach outlined in this report will provide information on the relative criticality of key components (based on design margin and on the deviation of actual operation from the design assumptions) which can be used to select appropriate inspection intervals or trigger more detailed life assessment or monitoring (although these should not be a prerequisite for using such a "design life assessment" procedure).

4.2 Proposed Design-By-Analysis Method for ASME BPVC Section I

4.2.1 Scope

The design-by-analysis procedure can be used to establish the design for any part or portion of a component which the designer chooses. This could be an area which there may or may not presently be rules for it in Section I. However, the part or portion of the vessel which utilizes "Design-by-Analysis" shall be meet all of the rules of "Design-by-Analysis". This allows the flexibility to use a "Design-by-Rule" approach for, say, basic sizing of a header, but then the "Design-by-Analysis" approach can be used to optimize the local geometry of, say, tube penetrations and verify that these local features will meet the lifetime requirements defined in a specification.

4.2.2 Design Specification

It is recommended that the new Code, or portion/section thereof, require a Design Specification to define necessary parameters in the design of the boiler. It is recognized with the wide variety of boilers that are presently designed, that some of the basic parameters which are inherent to the design process in the current Section I may be variable in the "Design-by-Analysis" approach. Solar boilers, cycling gas boilers, advanced ultra-supercritical boilers, and other potential new technology may have significantly different operational lifetimes and conditions from the traditional base loaded boilers which have been in service for many years.

The parameters which may be affected include design temperatures, pressures, startup/shutdown types and frequency, etc. In order for a designer to adequately design a boiler, there will likely need to be collaboration / interaction between the Manufacturers and the Owners of this equipment. In addition, since in many cases the actual cycles and associated transients experienced by the boiler can be very dependent on other plant equipment outside the scope of the boiler (e.g. steam turbines, by-pass systems, etc.) then to perform the design checks, particularly for cyclic service (in which the pressure, temperature and fluid flow histories to which the boiler components will be subjected need to be defined), relevant details of the operating sequence and fluid parameters will need to be communicated to the boiler supplier.

It can be debated whether this type of information for a boiler is most appropriate to come from a Manufacturer or from an Owner (User) of this type of equipment, or from the plant architect engineer. It would be recommended that an Owner take ownership of the design specification, and associated modes of operation, prior to the design or construction of the equipment and therefore, regardless of which party generates the specification, it could be termed a "Owner's Specification" as they will be the one operating the final product.

The following parameters shall be defined for each period of prolonged steady operation for each component:

- Design load (P_{des})
- Design temperature (T_{des})
- Operating load (P_{op})
- Service duration (t_s)

The following parameters shall be defined for each cycle of operation for each component:

- Cycle definition (name designating the type of cycle)
- Number of such cycles required
- Identification of the steady operating parameters that relate to dwell periods within the cycle
- Detailed description of the variation of process conditions during the cycle to permit derivation of appropriate boundary conditions for subsequent design checks.

4.2.3 Material Properties

In recommending a design-by-analysis methodology to be used in association with Section I, consideration has been given to keeping the defined material data requirement to the minimum necessary. The current version of Section I only requires an allowable stress value (which may be modified by a weld strength reduction factor for certain alloys and certain loading in the creep range). To expand Section I to cover cyclic service and protect against creep-fatigue, additional data are required but, as will be seen later in the design approach, the aim is to keep the data requirement as small/simple as possible and in any event commensurate with other international boiler design Codes (such as EN12952-3). There are three main categories of properties that are required for the design-by-analysis method defined later: thermo-physical properties, strength properties and fatigue endurance. These are each discussed in the following subsections.

Thermo-Physical Properties

These material properties are required for general design calculations, particularly for transient thermo-mechanical analysis of operating cycles that require an understanding of the transient temperature distribution and resulting stresses. The properties required, as a function of temperature, are:

- Elastic modulus, Poisson's ratio, coefficient of thermal expansion, thermal conductivity, density, specific heat capacity.

These properties are available in the current edition of Section II, Part D. Hence no further modifications or additions are required (other than ensuring that data are available for all properties at all temperatures of interest)

Strength Properties

Presently Section I only utilizes an allowable stress, provided in Table 1A of Section II, Part D. The design by analysis methodology proposed later in this document requires some additional strength parameters, all of which vary with of temperature:

- Time Independent Allowable Stress (factored by yield and tensile strength), S_m
- Yield Stress, S_y
- Time Dependent Creep Stress, S_t

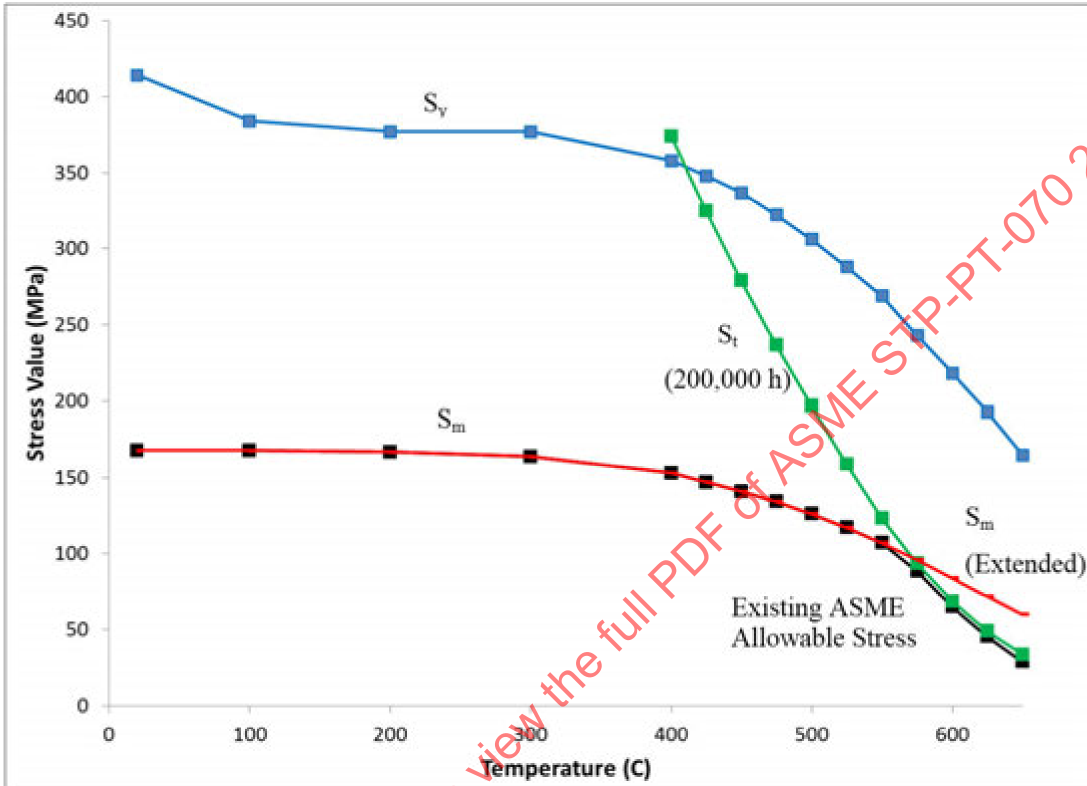
The Time Independent Allowable Stress (designated S_m) is defined to be the same as the currently used Section I allowable stress in the time independent regime. This gives continuity and consistency with the existing Section I. For the methods proposed here, this allowable stress based on yield and tensile strength is extended to higher temperatures, at which the existing Section I time dependent criteria result in the allowable stress being lower than that defined by yield or tensile criteria. Extension of these time independent stress values to higher temperatures is already present in Section III, Subsection NH (NH-3221, and Figures I-14.3). Hence this adaptation is only a minor extension of the present methodology utilized by Section I. The allowable stress at higher temperature, which is defined by the creep criteria in the existing Section I, will be appropriately accounted for by the Time Dependent Creep Stress which is discussed later in this section.

The Yield Stress (designated S_y) is defined to be the same as the currently tabulated yield stress in Table Y1 of Section II, Part D. Although for some materials, notably those used for higher temperature service, then it will be necessary to extend the tabulated values to higher temperatures. Again it is noted that this has already been accomplished for some materials in Section III, Subsection NH (Table I-14.5). The present definition of the yield stress in Section II, Part D is based on the monotonic tensile properties of the material. Under reversed plastic straining, some materials can exhibit notable cyclic hardening or softening and therefore the monotonic tensile yield strength does not reflect their cyclic response. In the design approach proposed later in this report, the yield strength is only used in the context of cyclic evaluations for shakedown, ratcheting and fatigue. Hence consideration should be given to possible adaptation of the yield strength values (perhaps with a separate cyclic loading multiplier, as adopted in R5) to provide a better representation of the cyclic yield strength for materials that significantly cyclic harden, or perhaps more significantly those that cyclically soften (such as Grade 91).

The Time Dependent Creep Stress (designated S_t) is defined as the stress corresponding to the minimum creep rupture strength at a given time. This is similar to the stress to rupture values provided in Section III, Subsection NH or in EN10216 (and other similar EN Codes defining material properties). The time dependent creep stress is used to ensure that acceptable creep rupture lifetime will be achieved. It is recommended that the strength is defined as 80% of the average stress to cause creep rupture in a given time. This is consistent with other definitions of minimum creep rupture strength (notably the EN Codes) and provides stress values that are not prohibitively conservative. As a point of reference, taking the EN10216 strength values as an example, then 80% of the average stress to cause rupture in 200,000 hours is, for many materials, quite similar to the current allowable stress values used in Section I in the time dependent regime. Thus, if a design life of 200,000 hours was specified then the component sizing would be quite similar to that presently obtained with the Section I allowable stresses (this provides continuity and consistency with established practice and experience).

For reference, Figure 4-1 below illustrates these strength values for Grade 91 steel, based on data from Section II, Part D (where it exists), from Section III, Subsection NH (for yield strength at high temperature) and from EN10216-2 (for minimum creep strength, based on 80% of the stress values provided in that document, with extrapolation to lower temperatures).

Figure 4-1: Strength Properties Required for Recommended Design Method (Values are Proposed for Grade 91 Steel, Based on Values from Various Sources)



For the time dependent creep stress values, it is recommended that values are provided at convenient times to facilitate analysis. Since creep rupture is conveniently plotted on a logarithmic timescale then providing values at times of 10,000 h, 30,000 h, 100,000 h, 200,000 h would allow interpolation (on a log stress – log time basis) for most required service intervals. For certain evaluations (notably creep damage calculation), it is convenient to have time dependent creep stress values for longer time periods (beyond 200,000 h). However, it is recognized that such data rarely exist and hence extrapolation is needed. For this purpose, it is recommended that a linear extrapolation is utilized on a log stress – log time plot based on the two longest durations for which stress values are provided (likely 100,000 h and 200,000 h). Such extrapolation is approximate, but simple to achieve without complex mathematics, while respecting the slope of the stress rupture data that is available for the longest times (EN12952-4 utilizes a similar extrapolation method).

Fatigue Properties

It is proposed to adopt the fatigue curves from Section VIII, Div. 2, given in Annex 3-F. These curves, which are provided for a variety of materials, have the advantage that they implicitly incorporate a number of parameters such as mean stress and surface finish. These same fatigue curves are also adopted by other ASME documents, such as FFS-1. While this may be conservative in some situations, this is judged prudent for a simplified design methodology (particularly where residual stresses from fabrication may have an influence which is not directly accounted for in some other design Code methods, such as the EN Codes). In many cases, the ASME fatigue curves do not result in substantially different fatigue lifetime predictions from other Codes (although the base fatigue curves may be substantially different, the various adjustments to stress ranges for use with the fatigue curves often compensates for these apparent discrepancies).

In the aforementioned ASME documents, the fatigue endurance curves are restricted for use at temperatures in the time-independent regime (specifically stated as 371°C (700°F)). It is proposed here to utilize the same fatigue endurance curves at higher temperatures. The rationale for this is based on:

(a) There is relatively small variation in fatigue strength as a function of temperature for many alloys (often this is adequately accounted for by a Young's modulus correction which is currently used with the ASME fatigue endurance curves).

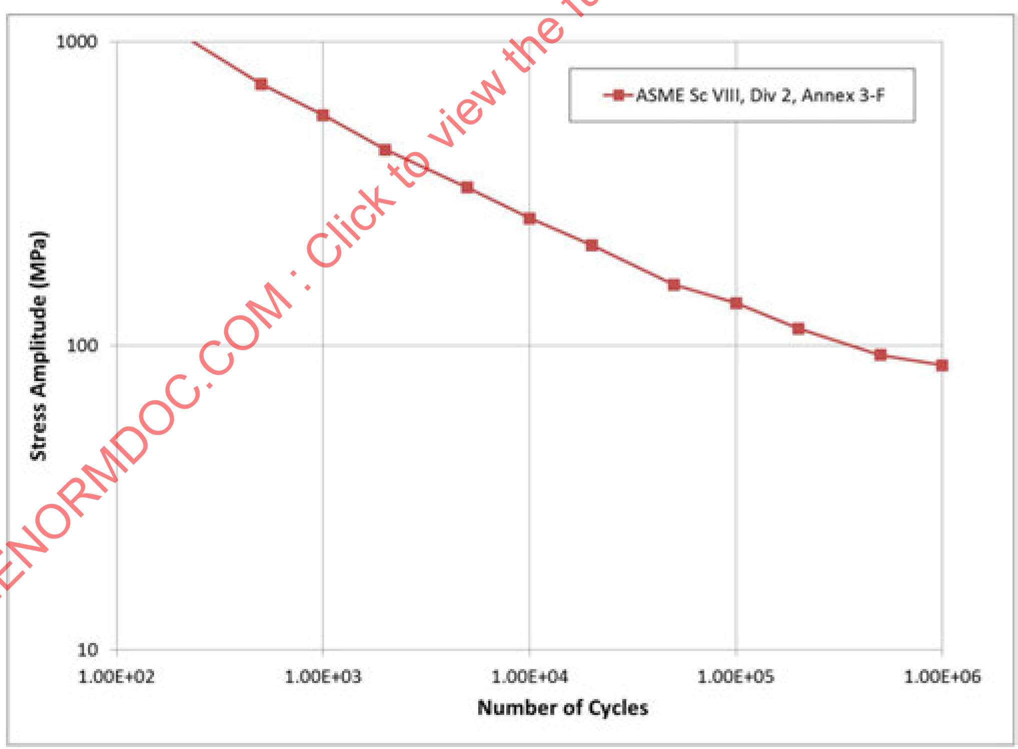
(b) At higher temperatures, the yield strength of the material is diminished and the proposed design methodology based on inelastic analysis will provide a strain range (and hence alternating stress) enhancement; at least in the case for cyclic plasticity at strain concentrations.

(c) The use of a creep-modified shakedown limit for the time-dependent regime to avoid enhancement of creep by fatigue (or vice-versa).

For reference the fatigue curve for carbon and low alloys steels with tensile strength not exceeding 552MPa (80ksi) is shown in Figure 4-2.

Also, with respect to fatigue curves for temperatures in the creep range of the material, it is noted that EN13445-3 (Annex B and the fatigue evaluation of Clause 18) notes that the fatigue curves are limited to temperatures up to 380°C for ferritic steels. Therefore, although the approach of EN13445-3 Annex B is the only option for design-by-analysis in the creep range, the defined approach for fatigue assessment is not valid in that regime.

Figure 4-2: ASME Fatigue Curve for Carbon and Low Alloy Steels



4.2.4 Proposed Design Checks

Protection against Collapse and Net Section Creep Rupture (Gross Inelastic Deformation)

Background

This analysis is used to verify that the collapse load (P_L) with the design material properties (S_m, S_t) is greater than the design loads (P_{des}). The purpose of this is to ensure that there is sufficient margin against gross inelastic deformation (yielding at lower temperatures, net section creep at higher temperatures) under anticipated design loading (design values of mechanical load resulting in primary stress: pressure, weight, supports, etc.).

If, per the design specification, multiple combinations of design loads (P_{des}) and design temperatures (T_{des}) exist, potentially with different service durations (t_s) then each combination, and their cumulative effect, shall be verified according to this procedure.

Method

This evaluation shall be performed using limit analysis with the following parameters:

- Linear elastic perfectly plastic constitutive law.
- Tresca yield condition (maximum shear stress) [von-Mises yield condition may be used instead of Tresca but the material strength parameter shall be multiplied by $\sqrt{3}/2$].
- Material strength parameter equal to the lesser of S_m and S_t (for the specified service duration, t_s) at design temperature.
- For components in the creep range (governed by time dependent creep stress, S_t) containing weldments then such weldments shall be explicitly modeled and the weldment volume, including the adjacent heat affected zone) shall be prescribed a material strength parameter based on the base metal allowable stress factored by the weld strength reduction factor (WRSF).
- Component geometry representing design minimum wall thickness.
- All loads causing primary stress shall be included and shall increase proportionally during the analysis (loads causing secondary stress may be omitted from the analysis). Where different combinations of design loads and design temperatures are possible, then all possible combinations shall be verified by this design check.
- First order deformation theory (except in cases were deformation has a weakening effect in which case geometrical non-linearity shall be taken into account).

Acceptance

If the limit analysis converges at these conditions the specific design load (P_{des}) and temperature (T_{des}) combination is acceptable. In addition, to protect against local ductility exhaustion, the maximum absolute value of the principal structural strain shall not exceed 5%.

The cumulative effect of multiple design load (P_{des}) and design temperature (T_{des}) combinations shall be assessed using the following procedure to protect against net section creep rupture:

- For each combination of $P_{des}^{(i)}$ and $T_{des}^{(i)}$ identify the associated service duration $t_s^{(i)}$.
- Record the collapse load, $P_L^{(i)}$, from the associated limit analysis (i.e. continue the limit analysis beyond design loads).
- Calculate a reference stress for the design load ($P_{des}^{(i)}$) and design temperature ($T_{des}^{(i)}$):

  $$S_{ref}^{(i)} = P_{des}^{(i)} / P_L^{(i)} * S_t^{(i)}$$
- Calculate the net section creep rupture lifetime based on the reference stress and design temperature, $t_R^{(i)}(S_{ref}^{(i)}, T_{des}^{(i)})$ from interpolation or extrapolation of time dependent creep stress (S_t) at the design temperature.
- Calculate the cumulative net section creep damage by summing the life fraction at each combination of reference stress and design temperature:

$$d_C = \sum_i \left(t_s^{(i)} \Big/ t_R^{(i)} (S_{ref}^{(i)}, T_{des}^{(i)}) \right)$$

- The creep damage sum, d_C, shall be less than unity.

Notes

In the low temperature regime where the material strength parameter is defined by S_m then this procedure is consistent with the existing method in Section I. Specifically, the material strength (S_m) is identical to that presently specified for the lower temperature time independent stress. The use of limit analysis with a Tresca yield criterion will, for the case of a pressurized cylinder, provide an identical result to that of the existing Section I, A-317 formula. That is, the defined method is entirely consistent with using basic sizing of a design-by-formula approach, where such formulas exist. This ensures continuity and consistency with the existing Section I and builds on its heritage of safety. Where formulas do not exist (e.g. more complex geometric forms) then the proposed method provides an advantage, but maintain the underlying philosophical design margins of Section I.

In the higher temperature regime, where the material strength parameter is defined by St, this procedure represents a deviation from the current methodology of Section I by allowing the use of time dependent allowable stress values. However, the underlying philosophy of verifying that the primary load bearing capacity of the component at design loads and temperature is greater than the allowable stress is consistent with the existing Code. The use of the Tresca yield criterion in the time dependent range is somewhat more conservative than the existing version of Section I which permits the use of a modified hoop stress calculation using a so-called 'y' factor of 0.7 (which results in a lower stress than the Tresca limit load for the same geometry and loading).

It is noted that the Tresca yield criterion is adopted for this method to (a) provide consistency with existing Section I formulas, (b) provide a lower estimate of the limit load than for von-Mises when the loading is not uniaxial or equibiaxial, (c) the Tresca criterion is likely more appropriate for some materials in the creep range where it is known that maximum principal stress can significantly influence creep damage formation and consequently creep lifetime.

The design check ensures that the design conditions (P_{des}, T_{des}) can be sustained for the required operating period (t_s) and that the cumulative effect of these operating periods does not result in the possibility of net section creep rupture. The use of a creep damage sum recognizes that the cumulative effect of multiple operating scenarios must be verified. This is particularly important where some may be of relatively short duration while others may be longer. The use of design pressure and temperature ensures conservatism for these design checks.

The calculation of creep damage is based on the primary (Tresca) reference stress. This provides a lower bound on the stress to cause creep rupture (and hence theoretically an upper bound on the lifetime). This is, however, judged to be appropriate for this design check because of other inherent conservatisms (use of Tresca yield criterion, use of design pressure and temperature, use of minimum creep rupture data). It should, however, be recognized that this effectively provides a lifetime for net section creep rupture for a material with good creep damage tolerance (ability to redistribute stress through tertiary creep). Local regions associated with strain concentrations may exhibit creep damage before this net section creep rupture lifetime, however, the structure is still functional (providing the material has appropriate damage tolerance). It is for this reason that a later design check ensures that local creep damage (at strain concentrations) is within acceptable limits.

The use of the time fraction rule for creep damage summation is judged to be appropriate since this is applied to periods of steady operation at essentially steady and temperature, for which the time fraction approach has proven to be applicable.

The design check incorporates weld strength reduction factors in the creep regime (material strength controlled by S_t). The proposed methodology assigns this strength (S_t x WRSF) to the entire weld volume thereby minimizing the effect of any deformation constraint that might exist to ensure a conservative approach. There are no restrictions on the weld geometry or orientation with respect to the loading. For example, seam welds would effectively be limited by the reduced strength imposed by a weld strength reduction factor since they are directly exposed to the primary (hoop) stress. Girth welds, on the other hand, under predominantly pressure loading are inherently constrained (providing their volume is not too large) and the limit analysis methodology can effectively account for this deformation constraint.

The acceptance criteria include a limit on the maximum principal strain of 5%. This protects against local ductility exhaustion. The limit of 5% provides a conservative bound based on the actual ductility of the material (assuming that appropriate materials that do not exhibit low ductility, or in-service embrittlement, are defined elsewhere in Code rules), and is consistent with limits in other Codes such as EN13445-3, Annex B.

The methodology inherently assumes that the materials permitted by the Code are tough (high fracture toughness) and that restrictions elsewhere in the Code placed on imperfections / defects / construction features ensure that brittle / fast fracture is avoided. Some of these aspects are addressed in a later section of this report on flaw acceptance criteria.

Protection against Shakedown and Ratcheting

Background

A shakedown analysis is required for a component that undergoes cyclic loading; this is to ensure that any cyclic plastic strain is appropriately contained by an elastic core, and that there is no possibility of accumulated structural displacement (e.g. incremental collapse or ratcheting). This requires analyses to simulate repeated application of the operating cyclic loads. Where different loading scenarios that form a unique cyclic action are possible then all such scenarios shall be separately subject to this check.

Method

This evaluation shall be performed using cyclic inelastic analysis with the following parameters:

- Linear elastic perfectly plastic constitutive law.
- Von-Mises yield condition (maximum distortion energy).
- Material strength parameter shall be taken as the yield strength (Sy) with the yield strength varying in accordance with the temporal and spatial variation of temperature.
- Component geometry representing design minimum wall thickness.
- Weld regions shall be assigned the material strength parameter associated with the adjacent base metal.
- All operational loads (including temperature differentials) causing primary stress and secondary stress shall be included and shall vary in accordance with the expected cyclic variation associated with the operating cycle being subject to the design check.
- First order deformation theory.
- The number of load cycles analyzed shall be sufficient to demonstrate a stabilized cyclic state has been attained. In no case shall less than three load cycles be analyzed.
- All loading cycles shall be closed. That is, the load sequence shall return to its starting condition to form a complete cycle.
- The load (e.g. pressure and temperature) variations shall be representative of the true operating characteristics and shall be selected to bound reasonably foreseeable combinations, and rates of change.

Acceptance

The following checks must be satisfied to demonstrate that each of the defined cyclic loading scenarios (per specification) is acceptable:

(1) There shall be no progressive plastic deformation. This shall be demonstrated by showing that there is no cumulative growth in structural displacements on successive load cycles, or growth of local plastic strain magnitude on a cycle-by-cycle basis.

(2) For a model without stress concentrations, the analysis shall demonstrate shakedown to elastic behavior (there shall be no cyclic plastic deformation on successive load cycles).

(3) For a model with stress concentrations the analysis shall demonstrate shakedown to elastic behavior over at least 80% of any structural section (e.g. the wall thickness). This shall be demonstrated by a plot of cyclic plastic strain.

(4) Permanent change in overall dimensions of the component.

Notes

The proposed approach uses classic shakedown theory and takes advantage of cyclic inelastic analysis to simplify the task. Using this approach provides valuable insight into the structural behavior. Specifically, the history of plastic strain from the analysis will indicate if plasticity occurs, if it is only on the first cycle or two to establish a residual stress field to cause shakedown, or if alternating plasticity occurs and over what extent of the component. While this can be accomplished with simplified calculations for some limited configurations, the proposed approach is not limited by complexity of geometry or the cycle. Post-processing tools for many finite element programs allow rapid analysis of results to demonstrate that the acceptance criteria are met.

The use of elastic-perfectly plastic material response simplifies the material property requirement (avoids the need for cyclic stress-strain curves) and provides a conservative bound on the structural response. It is noted that for components and cycles that include a dwell at high temperature then this check using the short-term yield strength (S_y) is necessary but not sufficient to ensure their safe operation. A creep-shakedown check is included in the methodology and may effectively replace the present check for components and cycles with a high temperature dwell.

The proposed approach to verify global shakedown and absence of ratcheting is very similar to that adopted in other design codes (Section VIII, Div. 2 and EN13445-3).

<u>Protection against Fatigue</u>

Background

Fatigue damage shall be calculated for all cycles defined in the specification to protect against local fatigue crack initiation. The basic approach is to determine a stress range for each cycle that is subsequently used with a fatigue endurance curve to estimate the likely number of cycles to fatigue crack initiation, and hence develop a fatigue life fraction. The design-by-analysis approach proposed here takes direct advantage of the results of the preceding shakedown/ratcheting check. If that check is passed, then the results can be directly used for a fatigue damage calculation. The cyclic response may be elastic or exhibit local cyclic plasticity (at least in the time-independent regime). The elastic stress range can be calculated using usual methods (described below) and the effect of cyclic plasticity is directly captured using the plastic strain range from the foregoing shakedown analysis. The fatigue endurance curve utilized was discussed in an earlier section of this report.

Method

For each cycle (i) considered in the shakedown / ratcheting assessment, determine the associated effective stress range and, where present, effective plastic strain range as follows:

Effective stress range:

$$\Delta S^{(i)} = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11}^{(i)} - \Delta\sigma_{22}^{(i)}\right)^2 + \left(\Delta\sigma_{11}^{(i)} - \Delta\sigma_{33}^{(i)}\right)^2 + \left(\Delta\sigma_{22}^{(i)} - \Delta\sigma_{33}^{(i)}\right)^2 + 6\left((\Delta\sigma_{12}^{(i)})^2 + (\Delta\sigma_{13}^{(i)})^2 + (\Delta\sigma_{23}^{(i)})^2\right)\right]^{1/2}$$

where:

$$\Delta\sigma_{jk}^{(i)} = \sigma_{jk}^{(i)}\Big|_m - \sigma_{jk}^{(i)}\Big|_n .$$

In which m and n are different instants during cycle (i) such that the stress range is maximized. This is the usual approach to determination of the cyclic stress range for the case when principal stress direction may change during the cycle.

Effective plastic strain range:

$$\Delta\varepsilon_{peeq}^{(i)} = \frac{\sqrt{2}}{3}\left[\left(\Delta p_{11}^{(i)} - \Delta p_{22}^{(i)}\right)^2 + \left(\Delta p_{11}^{(i)} - \Delta p_{33}^{(i)}\right)^2 + \left(\Delta p_{22}^{(i)} - \Delta p_{33}^{(i)}\right)^2 + 1.5\left((\Delta p_{12}^{(i)})^2 + (\Delta p_{13}^{(i)})^2 + (\Delta p_{23}^{(i)})^2\right)\right]^{1/2}$$

where $\Delta p_{jk}^{(i)}$ is the difference in the component of plastic strain between the start and end of the cycle.

The average temperature for the cycle, $T_a^{(i)}$ shall be determined as the arithmetic mean of the temperatures at the location of the largest stress range corresponding to the instants during the cycle at which the stresses are at their extremes. A reference elastic modulus $E_a^{(i)}$ shall be evaluated at the average temperature for the cycle.

An equivalent effective strain range shall be calculated from:

$$\Delta\varepsilon_{eff}^{(i)} = \frac{\Delta S^{(i)}}{E_a^{(i)}} + \Delta\varepsilon_{peeq}^{(i)}$$

An equivalent alternating stress shall be calculated from:

$$S_{alt}^{(i)} = E_a^{(i)}\Delta\varepsilon_{eff}^{(i)} / 2$$

Determine the permissible number of cycles, N(i), for the equivalent alternating stress using the fatigue curve defined in the material property section. Determine the cumulative fatigue damage for all cycles using Miner's rule:

$$D_F = \sum_{(i)} n^{(i)} / N^{(i)}$$

Acceptance

The cumulative fatigue damage sum for all cycles defined in the specification shall be less than unity.

Notes

The proposed approach for fatigue damage calculation follows conventional practice and is very closely aligned with Section VIII, Div. 2. The key difference here that the inelastic response is based on elastic perfectly-plastic behavior, rather than utilizing cyclic stress-strain curves that incorporate strain hardening. This simplification was introduced to (a) decrease the material data requirement, (b) complexity that would be associated with use of cyclic stress-strain curves at different temperatures within the cycle (and dealing with the associated implementation of kinematic hardening algorithms within analysis programs) and (c) to ensure consistency with other aspects of the proposed approach which are also based on an elastic perfectly-plastic material response (e.g. where a portion of the cycle is within the creep regime).

The use of an elastic perfectly-plastic constitutive model is consistent with that adopted by EN13445-3 for fatigue assessment. It is recognized that other than the decreased yield strength associated with higher temperatures, this procedure does not address cycles in which there could be significant creep during creep dwells in the cycle (e.g. temperatures above the time independent regime). It is for that reason that the creep-modified shakedown design check is introduced, as discussed later in this report. In some cases, that check may effectively replace the foregoing shakedown and fatigue design checks. These checks have not, however, been combined because the foregoing shakedown and fatigue design checks allow local cyclic plasticity (and hence a local strain range enhancement) which is not permitted by the subsequent creep-shakedown check which is intended to avoid creep-fatigue interaction.

It is also noted that in the calculation of equivalent effective strain range and equivalent alternating stress that the uniaxial elastic modulus is used without correction for multiaxial deformation. Also, no term is added to the equivalent effective strain range to account for the strain enhancement due to constant volume deformation. These simplification approximations simply follow those adopted by Section VIII, Div. 2 (they are no worse approximations in the temperature regime above that currently permitted by Section VIII, Div. 2).

No specific guidance or method is proposed for fatigue evaluation of weldments. This, among other items, is discussed further in a subsequent section of this report.

Protection against Local Creep Damage

Background

The foregoing check on net section creep rupture at design pressure and temperature does not provide protection against local creep damage at strain concentration features, or an appropriate creep damage estimate for use in creep-fatigue evaluation. For this purpose an estimate of the local stress, with due account for stress redistribution due to creep, at such strain concentrating features must be obtained and used to verify that creep damage is not significant in the defined operational period per the specification. An estimate of the local rupture reference stress can be based on an approximate model that interpolates between the elastic and limit state stress distributions (such as is employed in the EN13445-3 Annex B and R5 procedure). The purpose of this is to ensure that there is sufficient margin against local creep damage under anticipated operational loading (fixed mechanical actions: pressure, weight, supports, etc.).

Method

The rupture reference stress and associated creep damage fraction shall be calculated using the following procedure for each service period (i):

(1) Calculation of maximum elastic stress at strain concentrating feature:

- Linear elastic constitutive law.
- Component geometry representing design minimum wall thickness.
- All operational loads causing primary stress shall be included at the corresponding design temperatures.
- First order deformation theory.
- An elastic stress analysis shall be performed. The maximum value of the Tresca stress at the strain concentrating feature shall be designated $S_{el,max}^{(i)}$.

(2) Calculation of primary load reference stress

- Linear elastic perfectly plastic constitutive law.
- Tresca yield condition (maximum shear stress) [von-Mises yield condition may be used instead of Tresca but the material strength parameter shall be multiplied by $\sqrt{3}/2$].
- Material strength parameter equal to S_m at design temperature.
- Component geometry representing design minimum wall thickness.

- All concurrent operational loads causing primary stress shall be included and shall increase proportionally during the analysis [loads causing secondary stresses may be omitted from the analysis]. Where different combinations of design loads and design temperatures are possible, then all possible combinations shall be verified by this design check.
- First order deformation theory [except in cases were deformation has a weakening effect in which case geometrical non-linearity shall be taken into account].
- The maximum absolute value of the principal structural strain shall not exceed 5%
- A limit analysis shall be performed to determine the maximum load P_L sustained by the component at the designated strength S_m.

(3) Calculation of rupture reference stress and local creep damage fraction.

The cumulative effect of multiple operating load (P_{op}) and design temperature (T_{des}) combinations shall be assessed using the following procedure to protect against net section creep rupture:

- For each combination of $P_{op}^{(i)}$ and $T_{des}^{(i)}$ identify the associated service duration $t_s^{(i)}$.
- Record the collapse load, $P_L^{(i)}$, from the associated limit analysis (this is the value determined during the first design check for collapse).
- Calculate a reference stress for the operating load ($P_{op}^{(i)}$) and design temperature ($T_{des}^{(i)}$):

$$S_{ref\text{-}op}^{(i)} = P_{op}^{(i)} / P_L^{(i)} * S_t^{(i)}$$

- Calculate the rupture reference stress

$$S_{rup}^{(i)} = S_{ref-op}^{(i)}\left[1 + 0.13\left(S_{el,\max}^{(i)} / S_{ref-op}^{(i)} - 1\right)\right]$$

- Calculate the net section creep rupture lifetime based on the rupture reference stress and design temperature, $t_R^{(i)}(S_{rup}^{(i)}, T_{des}^{(i)})$, from interpolation or extrapolation of time dependent creep stress (S_t) at the design temperature.
- Calculate the cumulative local creep damage by summing the life fraction at each combination of rupture reference stress and design temperature:

$$D_C = \sum_i \left(t_s^{(i)} / t_R^{(i)}(S_{rup}^{(i)}, T_{des}^{(i)}) \right)$$

Acceptance

The local creep damage sum (D_C) for all service durations shall be less than unity.

Notes

This check provides an estimate of the local creep damage sum at strain concentrations based on the widely accepted and used (EN13445-3, Annex B; R5) interpolation between the elastic and reference stress distributions. The use of the coefficient of 0.13 in the rupture reference stress equation is consistent with other Codes that adopt this approach, and with the original reference from which it is derived [25].

The methodology here adopts the Tresca criterion for both the elastic stress and limit load; as discussed elsewhere, this is to ensure consistency with existing Section I methods and conservatism.

This check is relatively straightforward to apply because it requires one elastic analysis and one limit analysis for each defined service duration. The limit analysis result (to provide the limit load) can be taken directly from the results of the first design check for collapse.

Operational loads are used in this design check because conservatism is assured by use of Tresca criterion and by use of design temperature.

Protection against Creep-Fatigue Interaction

Background

Creep-fatigue interaction can occur when cyclic operation causes perturbation of the stress distribution established during steady state operation. If it can be shown that cyclic loading does not affect steady state (dwell period) stress distribution then the respective, independent, creep and fatigue contributions can be summed, and elaborate procedures for evaluating the enhancement to creep and fatigue damage as a result of interaction are not needed.

Method

Two options are offered to demonstrate insignificant creep-fatigue interaction. The first is relatively straightforward to apply essentially using an extended (or creep modified) shakedown method. This approach can be overly conservative in some circumstances (e.g. differing cycles with significantly different operating times) and for such cases a second approach is provided (although this is often less simple to apply).

Option *1: Inelastic cyclic analysis with simplified creep-modified shakedown limit*

This evaluation shall be performed using cyclic inelastic analysis with the following parameters:

- Linear elastic perfectly plastic constitutive law.
- Von-Mises yield condition (maximum distortion energy).
- Material strength parameter shall be taken as the minimum of the yield strength (S_y) and the time dependent creep stress for the longest operating time (S_t ($t_s^{(i)}|_{max}$). The resulting material strength parameter shall vary in accordance with the temporal and spatial variation of temperature.
- Component geometry representing design minimum wall thickness.
- Weld regions shall be assigned a time dependent creep stress material strength parameter (S_t) multiplied by the appropriate weld strength reduction factor (WSRF). For the temperature regime where the material strength parameter is controlled by the yield strength (S_y) then weld regions shall be assigned the material strength parameter associated with the adjacent base metal.
- All operational loads (including temperature differentials) causing primary stress and secondary stress shall be included and shall vary in accordance with the expected cyclic variation associated with the operating cycle being subject to the design check.
- First order deformation theory.
- The number of load cycles analyzed shall be sufficient to demonstrate a stabilized cyclic state has been attained. In no case shall less than three load cycles be analyzed.
- All loading cycles shall be closed. That is the load sequence shall return to its starting condition to form a complete cycle.
- The load (e.g. pressure and temperature) variations shall be representative of the true operating characteristics and shall be selected to bound reasonably foreseeable combinations, and rates of change.

Note that this evaluation shall be performed for all operating cycles, but that the evaluation for each cycle shall use the same material strength parameter based on the time dependent creep stress for the longest operating time.

Acceptance criteria are defined in the subsection below:

Option *2: Elastic analysis based on dwell stress equal to reference stress*

A cyclic elastic analysis for the operational load history with a starting stress equal to the reference stress ($S_{ref}^{(i)}$) shall not result in stresses greater than the short term yield stress (S_y) at any time during the cycle.
This shall be verified for all cycles (i) with the following calculation:

- Linear elastic material
- Initial stress distribution shall equal $S_{ref}^{(i)}$.
- Material strength parameter shall be taken as the yield strength (S_y) with variation in accordance with the temporal and spatial variation of temperature.
- Component geometry representing design minimum wall thickness.
- Weld regions shall be assigned the material strength parameter (S_y) associated with the adjacent base metal.
- All loads causing primary stress and secondary stress shall be included and shall vary in accordance with the expected cyclic variation associated with the operating cycle being subject to the design check.
- First order deformation theory.

Acceptance criteria are defined in the subsection below.

Acceptance

Option 1: The analysis shall demonstrate shakedown to elastic behavior (there shall be no cyclic plastic deformation on successive load cycles) for all cycle types defined in the specification and the sum of the creep (D_C) and fatigue (D_F) damage indicators, at the same spatial location, shall not exceed unity.

Option 2: The elastic von-Mises equivalent stress during the operational load cycle shall not exceed the material strength parameter (S_y) and the sum of the creep (D_C) and fatigue (D_F) damage indicators, at the same spatial location, shall not exceed unity.

Notes

Option 1 is based on the classic extension of the time independent shakedown limit to the time dependent range. This is the more convenient method to use because of its simplicity from an analysis perspective. However, it may be overly conservative in some cases. Specifically, for an operating scenario with cycles having quite different service times (t_s) at differing temperatures then it is possible that the method could be quite conservative because the stresses are limited to ensure they are acceptable for the longest service duration at all temperatures. This is necessary because if the method is separately used for each cycle with the time dependent strength based on the service time for each cycle it is possible that different residual stress fields could result which could result in an additional creep strain increment.

Option 2 is essentially the same criterion as that adopted in EN13445-3 Annex B for verification of "action cycles without plastification". This is essentially the same as the check for insignificant cycling utilized in R5. This is based on the concept that if the stresses in the redistributed state after a creep dwell (represented here by the reference stress) are not changed by plastic deformation during the remainder of the cycle (e.g. the remainder of the cycle does not exceed yield) then there will be no change to the start of dwell stress, and hence no additional creep strain increment (creep life is therefore controlled by the steady state stress and fatigue life is controlled by the elastic stress range). This option, unlike option 1, does not permit the possibility of shakedown by plastic deformation on the first few cycles.

In either option, the effect of reduced creep strength associated with weldments is approximately represented in option 1 through reduction of the time dependent material strength parameter (S_t) by

the appropriate weld strength reduction factor, or for option 2 by use of the reference stress ($S_{ref}^{(i)}$) which inherently accounted for the weld strength reduction factor. No specific account of weldments is considered for the fatigue portion of the cycle.
If either option 1 or 2 criteria for no repeated plastic deformation within a cycle are satisfied then fatigue does not enhance creep and hence direct summation of the independently calculated creep and fatigue damage is permitted. This is consistent with methodologies adopted in EN13445-3, Annex B and in R5.

4.2.5 Miscellaneous Items

In the context of providing practical "Design-By-Analysis" methods several topics require some additional commentary.

Weldments

In the proposed methodology, the weld strength reduction in the time dependent regime can be incorporated (if available). If a weld strength reduction factor is not available then for weldments that are not normalized and tempered in ferritic steels it is recommended that a value of 0.8 is adopted. This is consistent with available data for low alloy steels (such as grades 11 and 22) and is also consistent with recommended practice in EN13445-3, Annex B. It should be recognized that the creep strength enhanced ferritics (e.g. Grades 91 and 92) exhibit a much more significant weld strength reduction factor and, therefore, in most cases a value less than 0.8 should be used (the existing Section I has some, conservative, guidance).

This approach for weldments in the creep range is a practical approximation, but further work should be completed to ensure that it provides appropriate conservatism because in some cases a weaker weldment zone can be effectively reinforced by stronger surrounding material but the increased ratio of principal stress to von-Mises stress (triaxial constraint) may result in accelerated creep damage formation.

The proposed methodology does not include an approach for assessment of weldment subject to fatigue loading. Approaches documented in the Codes and Standards reviewed do not incorporate easily within the framework of inelastic analysis proposed for the other design rules, and methods that are available are for the time independent regime (non-creep). This is largely because weldment geometry (particularly fillets) is often indeterminate and cannot be modeled simply as a geometric fillet. Indeed, some weld configurations inherently include stress singularities that must be dealt with through use of a structural stress (either through an extrapolation technique such as in EN13445 or through the structural stress method as in Section VIII, Div. 2), or potentially fracture mechanics. Hence this is an area recommended for future work; in the interim, the structural stress method from Section VIII, Div. 2 appears to be the most appropriate to be adopted for the time independent regime.

Certain weldments that operate in the time-dependent regime may also suffer cracking early in life due to mechanisms such as reheat or stress relaxation cracking. It is proposed that Code rules should provide appropriate fabrication methodologies (e.g. use of post weld heat treatment (PWHT)) rather than provide design methods to cover such circumstances since treatment of residual stress and phenomenon such as elastic follow-up are too complex to deal with in the context of design-by-analysis.

For dissimilar metal weldments the recommended methodology can incorporate some aspects of the life limiting features of such weldments through the use of specific property data for the weld deposit and weld strength reduction factors. However, it is not intended that the design-by-analysis methodology can incorporate all contributors that limit the life and serviceability of dissimilar metal weldments and hence other sections of the Code must provide advice on permissible material combinations and associated weld filler metals, as well as possible restrictions on geometry and loading.

Environment
In general, protection against wall loss due to general environmental attack (oxidation, corrosion, etc.) should be assured by making appropriate material selections and, where appropriate, by using additional thickness margins to provide a so-called "corrosion allowance".

Such an approach is not necessarily appropriate for corrosion fatigue (or related mechanisms of magnetite cracking). While the EN Codes include specific stress limits with the intent of avoiding magnetite cracking there are cases of components satisfying these stress limits but still exhibiting such cracking. Hence stress limits are not recommended and corrosion fatigue (and magnetite cracking) should be managed by good operating (and lay-up) practices, combined with periodic inspection of vulnerable locations.

4.3 Example Problem

To illustrate the recommended design-by-analysis methodology an example problem is presented. This example has been selected to represent most aspects of the methodology through use of a typical component geometry (a portion of a header with tube penetrations), subject to steady loading at high temperature (time dependent regime) and a cycle (to illustrate shakedown and fatigue methods). In creating this example, selections have been made to give geometry and loading that might be typical of an actual header to help illustrate the recommended approach (note that this is purely illustrative and hence may not represent a viable actual design).

To simplify the explanation of the methodology, the example excludes consideration of weldments. Each of the steps of the design-by-analysis is explained in the subsections that follow.

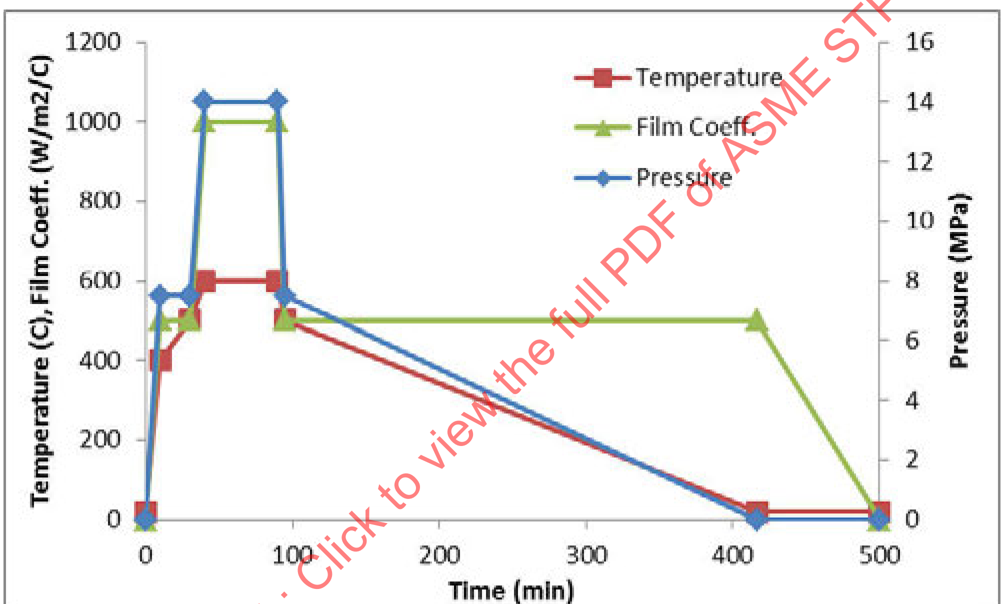
4.3.1 Specification

The component is a header with an array of tube penetrations (two in-line rows) along its length. The component shall be designed to operate for 200,000 hours of continuous service. The design pressure shall be 165 barg. The corresponding operating pressure is 140 barg. The design temperature shall be 600°C (based on a steady operating temperature of 585°C and a margin of 15°C to allow for temperature imbalances).

The component shall be designed to endure a minimum of 5,000 startup-shutdown cycles. For this example which illustrates the approach only one cycle type is defined. The idealized cyclic variation of pressure, temperature and film heat transfer coefficient is defined in Figure 4-3.

Figure 4-3: Parameters for Example Cycle

Time (min)	Pressure (MPa)	Temperature (C)	Film Coeff. (W/m^2/C)
0	0	20	0
10	7.5	400	500
30	7.5	500	500
40	14	600	1000
90	14	600	1000
95	7.5	500	500
417	0	20	500
500	0	20	0



4.3.2 Material Properties

The component is fabricated from grade 91 steel (header body SA335-P91; tube SA213-T91). Properties have been compiled from relevant sections of the Code as tabulated below (Figure 4-4).

Figure 4-4: Material Properties for Design-By-Analysis Example

Density	7750	kg/m^3		
Temperature	CTE mean	Thermal Conductivity	Thermal Diffusivity	Elastic Modulus
(C)	(/C)	(W/m/C)	(m2/s)	(MPa)
20		22.3	6.61E-06	213000
100	1.09E-05	24.4	6.74E-06	208000
200	1.13E-05	26.3	6.71E-06	205000
300	1.17E-05	27.4	6.39E-06	195000
400	1.20E-05	27.9	5.87E-06	187000
500	1.23E-05	27.9	5.22E-06	179000
550	1.25E-05	27.8	4.85E-06	174000
600	1.27E-05	27.6	4.42E-06	168000

Temperature	S_y	S_m	S_t (100,000h)	S_t (200,000h)
(C)	(MPa)	(MPa)	(MPa)	(MPa)
20	414	168		
100	384	168		
200	377	167		
300	377	164		
400	358	153	382.9	374.0
425	348	147	333.7	324.8
450	337	141	288.0	279.1
475	322	134	245.3	236.4
500	306	126	206.4	196.8
525	288	117	168.4	158.8
550	269	107	132.8	123.2
575	243	96	101.6	93.6
600	218	84	75.2	68.8

E_{ref} (MPa)	206850
N	S_{alt}
(cycles)	(MPa)
1.00E+02	1413.5
2.00E+02	1068.7
5.00E+02	724.0
1.00E+03	572.3
2.00E+03	441.3
5.00E+03	331.0
1.00E+04	262.0
2.00E+04	213.7
5.00E+04	158.6
1.00E+05	137.9
2.00E+05	113.8
5.00E+05	93.1
1.00E+06	86.2

4.3.3 Basic Component Dimensions

Other (process and mechanical) requirements define that the header shall be DN300 (outside diameter 273.05mm), and the tube shall be 38.1mm outside diameter.

The primary loading is internal pressure (no other external mechanical loads are included).

Basic sizing of the components can proceed with the design-by-formula approach from the existing Section I, using Appendix A-317 for consistency with the overall design-by-analysis approach (namely use of Tresca limit load for primary stress design).

From the material data, S_t = 68.8MPa (S_t at 600°C, 200,000h)

Tube thickness:

Calculated required minimum wall thickness:

$t_c = D(1-\exp(-P/S_t E))/2$, from which t_c = 4.062mm

Selected tube minimum wall thickness: t_{min} = 4.5mm

Hence tube internal diameter: d = 29.1mm (taken as diameter of hole in header)

Ligament efficiency for header:

Tube pitch, p = 100mm

$E = (p - d)/d$, from which E = 0.709

Header thickness:

Calculated required minimum wall thickness:

$t_c = D(1 - \exp(-P/S_t E))/2$, from which t_c = 39.18mm

Selected header minimum wall thickness: t_{min} = 40mm

Hence header internal diameter: d = 193.05mm

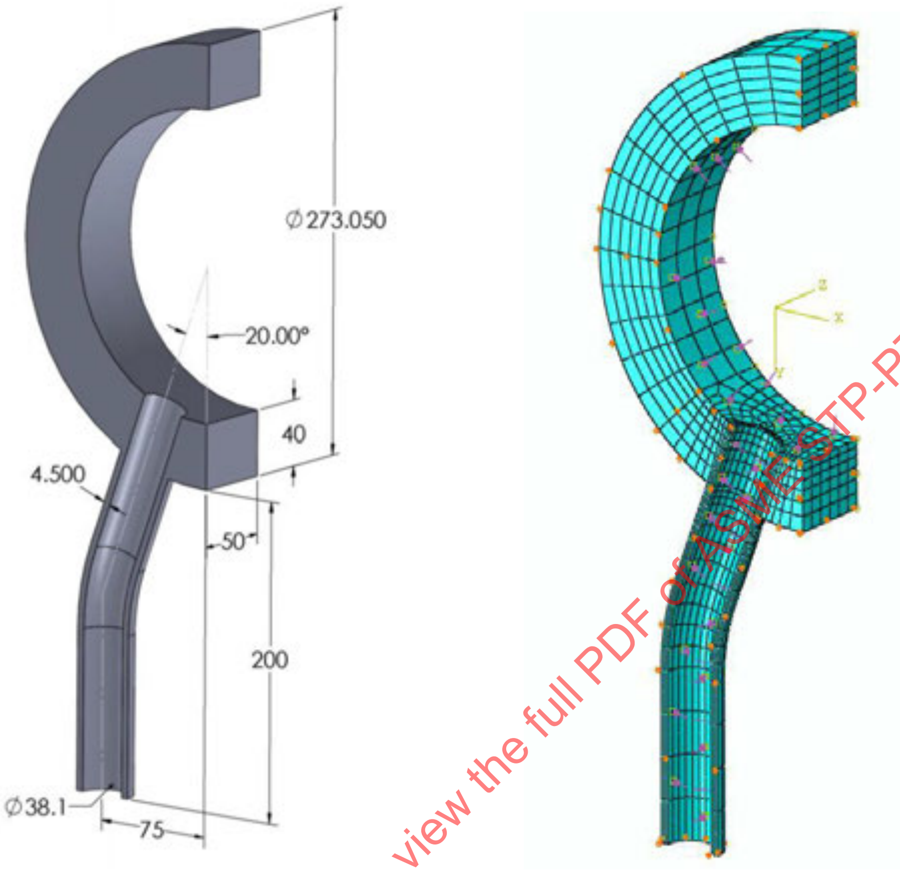
A sketch of the analysis geometry with key dimensions is shown in Figure 4-5. A slice of the header and tube penetration is modeled with a symmetry plane along the header axis and the repeating portion of a tube with an axial length equal to half the axial tube spacing. The planar cut through the header and tube is constrained with a symmetry boundary condition. The planar cut between tube penetrations is constrained to remain planar (using a multipoint constraint equation), respecting the repeating symmetry. Additionally, the free end of the tube is constrained normal to the cut face. This discretization is sufficient to capture the thermal (through-wall temperature gradient from internal heating/cooling, top-to-bottom temperature gradient from more rapid heating/cooling in the tube ligaments) and mechanical (pressure with balancing end load) loads.

The thermal boundary condition (film heat transfer coefficient) is applied on the internal surface of the header and tube; note that for simplicity, identical heat transfer conditions are used for the header and tube (no account is taken of different flow rates or other factors such as turbulence).

Pressure is applied on the internal surface of the header and tube. The end load applied on the axial cut face of the header to balance the internal pressure is:

$$S_{end} = p\frac{d^2}{D^2 - d^2} = p$$

Figure 4-5: Geometry of Analysis Model, and View of Finite Element Mesh and Boundary Conditions



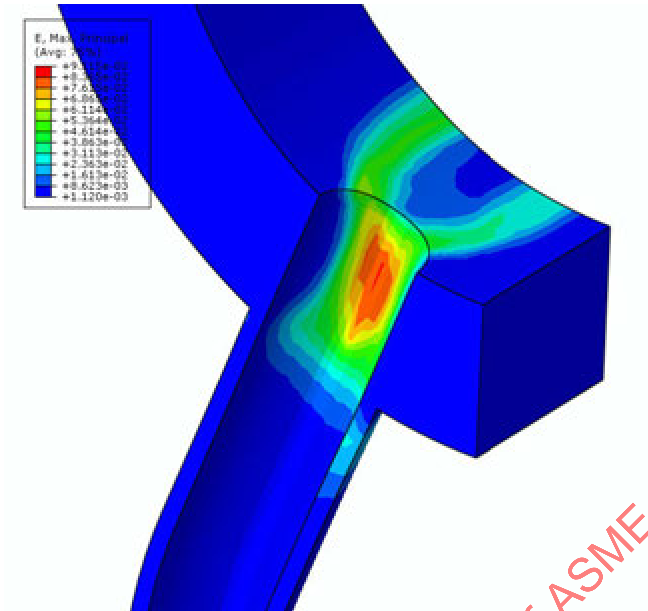
4.3.4 Protection against Collapse (Net Section Rupture)

A limit analysis is used to verify that the limit pressure is greater than the design pressure. The material strength parameter is S_t (200,000h, 600°C) = 68.8 MPa. The finite element program only has a von-Mises yield criterion so the strength parameter (yield stress) entered into the program is corrected to $68.8\sqrt{3}/2=59.6$ MPa.

A limit analysis is performed, giving the load at collapse P_L = 17.1MPa. The distribution of principal strain close to collapse is shown in Figure 4-6. It is evident that the limiting section is the axial ligament between the tube penetrations.

The collapse load (17.1MPa) is greater than the design pressure (16.5MPa) so the design check is passed. The net section creep damage sum is not necessary since there is only one operating period specified and it has been verified that the design loads are less than the collapse loads. Hence, by inspection, the net section creep damage is less than unity.

Figure 4-6: Color Contour Plot of Principal Strain Close to Collapse



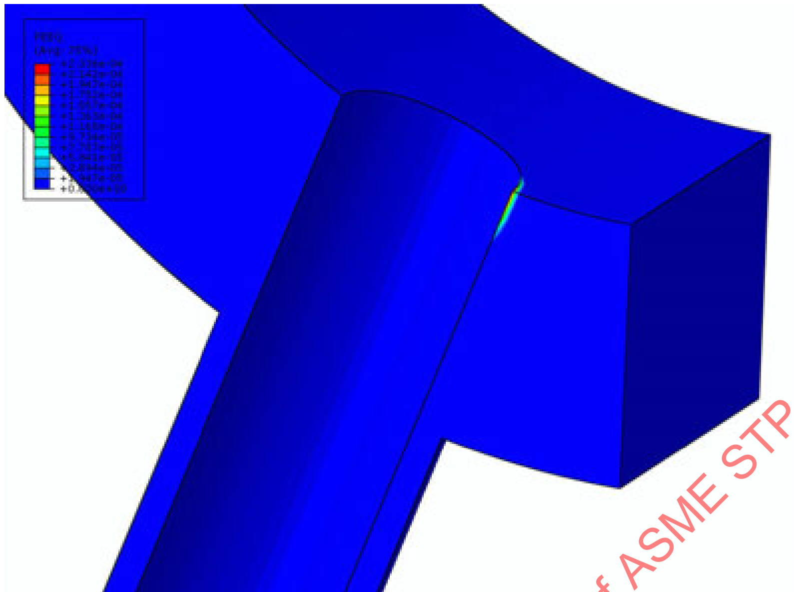
4.3.5 Protection against Shakedown and Ratcheting

A cyclic inelastic analysis is performed for 3 cycles using the yield strength defined by Sy (from Figure 4-4) and the load history specified in Figure 4-3. This was performed as a separated transient thermal-mechanical analysis to provide the history of temperature, stress and plastic strain throughout the 3 cycles.

The analysis demonstrates that shakedown is achieved after one cycle. That is, on cycles 2 and 3 there is no plastic deformation (all stresses remain within the elastic limit). Hence the structure is within strict shakedown and does not ratchet. The design check is passed.

The small plastic strain increment on the first cycle (to establish a residual stress) occurs at the edge of the tube penetration on the circumferential ligament (Figure 4-7). This indicates that the specified cycle results in higher stresses on the circumferential ligament, whereas the limit analysis previously performed indicates that steady loading results in higher stresses on the axial ligament.

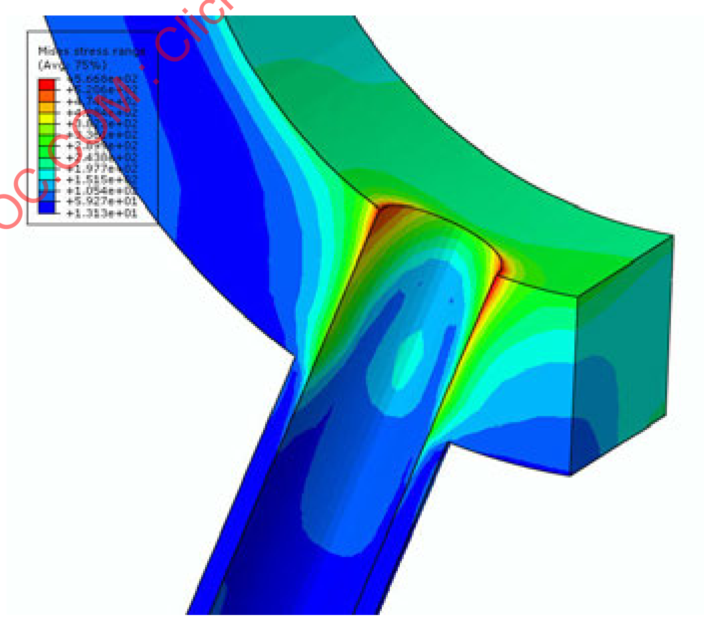
Figure 4-7: Color Contour Plot of Equivalent Plastic Strain on First Cycle from Shakedown Analysis. No Increase in Plastic Strain Occurs on Subsequent Cycles



4.3.6 Protection against Fatigue

Since strict shakedown is achieved (entire section shakes down to elastic behavior) then the elastic stress range can be obtained from cycle 2 or cycle 3 of the preceding shakedown analysis. A post-processing algorithm was used to calculate the von-Mises stress range taking account of possible rotation of the stress tensor. The resulting stress range is shown in Figure 4-8. This shows that the largest stress range occurs at the edge of the tube penetrations on the circumferential ligament.

Figure 4-8: Color Contour Plot Showing the Range of Von-Mises Stress for the Loading Cycle



Fatigue damage can now be calculated. Two fatigue damage values are calculated and shown below: one for the circumferential ligament where the stress range is largest (but where creep damage is negligible) and one for the axial ligament where the stress range is lower (but where creep damage is more significant).

Figure 4-9: Fatigue Damage in Circumferential Ligament

von-Mises Stress range	566.8	(MPa)
Effective plastic strain range	0	(abs)
Temperature at min stress	265	(C)
Temperature at max stress	535	(C)
Mean temperature for cycle	400	(C)
Elastic modulus at mean temp.	187000	(MPa)
Equivalent effective strain range	0.00303	(abs)
Equivalent alternating stress	283.4	(MPa)
Modulus correction for fatigue	1.106	
Alternating stress to enter fatigue curve	313.5	(MPa)
Number of cycles permitted	5873	(cycles)

The required number of cycles is 5,000. The fatigue damage fraction is $D_F = 0.851$

The fatigue damage fraction for the circumferential ligament is less than unity so the design check is passed.

Figure 4-10: Fatigue Damage in Axial Ligament

von-Mises Stress range	307	(MPa)
Effective plastic strain range	0	(abs)
Temperature at min stress	265	(C)
Temperature at max stress	560	(C)
Mean temperature for cycle	412.5	(C)
Elastic modulus at mean temp.	186040	(MPa)
Equivalent effective strain range	0.00165	(abs)
Equivalent alternating stress	153.5	(MPa)
Modulus correction for fatigue	1.112	
Alternating stress to enter fatigue curve	170.7	(MPa)
Number of cycles permitted	39908	(cycles)

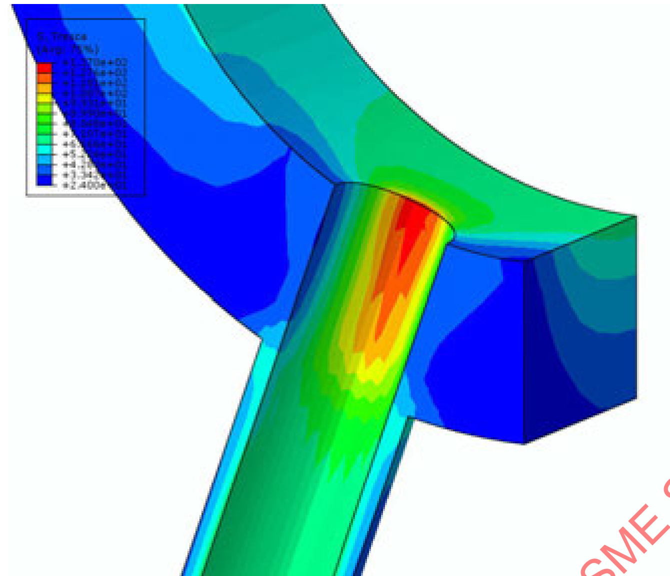
The required number of cycles is 5,000. The fatigue damage fraction is $D_F = 0.125$

The fatigue damage fraction for the axial ligament is less than unity so the design check is passed.

4.3.7 Protection against Local Creep Damage

An elastic analysis is performed first, using operating loads, to determine the maximum elastic Tresca stress. The elastic stress distribution is shown in Figure 4-11, where it can be seen that the highest stress is at the edge of the penetration for the axial ligament. The stress at that location is $S_{el,max}$ = 137MPa.

Figure 4-11: Color Contour Plot of Elastic Tresca Stress Distribution at Operating Load



The primary load reference stress can be obtained from the first design check on plastic collapse:

$$S_{ref\text{-}op} = (14.0/17.1)68.8 = 56.3\text{MPa}$$

The rupture reference stress can be calculated from the preceding stress values:

$$S_{rup} = S_{ref-op}\left[1 + 0.13\left(S_{el,\max} \big/ S_{ref-op} - 1\right)\right] = 66.8\text{MPa}$$

The creep lifetime at this rupture reference stress can be calculated from logarithmic extrapolation of the 100,000h and 200,000h stress values given in Figure 4-4. Specifically, constructing an extrapolation using these values gives:

$$t_R(S_{rup}, T_{des}) = 251{,}469 \text{ hours}$$

Hence the creep damage indicator, $D_c = 0.795$

Since the creep damage indicator is less than unity the design check is passed.

4.3.8 Protection against Creep-Fatigue

For protection against creep-fatigue it is necessary to demonstrate that the sum of the creep and fatigue damage indicators is less than unity, and that there is no enhancement of creep by fatigue (resetting of start of dwell stress) – which is checked here by use of option 1 from the recommended methodology (use of creep-modified shakedown limit).

The creep and fatigue damage indicators and their sums for the axial and circumferential ligaments are summarized below:

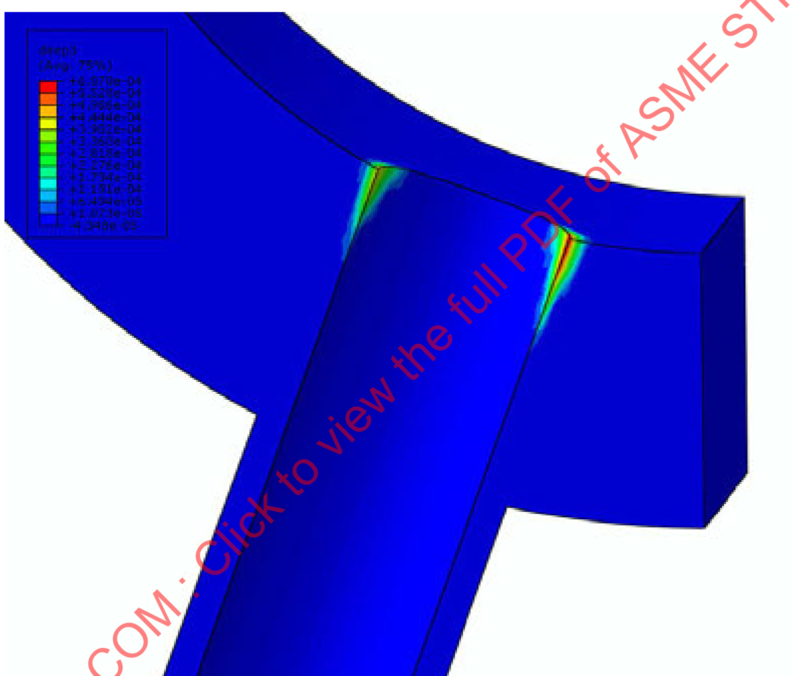
Figure 4-12: Creep Fatigue Damage Indicators and Sums

	Axial Ligament	Circumferential Ligament
Fatigue Damage, D_F	0.125	0.851
Creep Damage, D_C	0.795	0
Total Damage (D_F+D_C)	0.92	0.851

Using option 1 for the creep-modified shakedown check, the material strength parameter (yield stress) in the cyclic inelastic analysis is defined as the minimum of the yield stress (S_y) and the creep stress (S_t) for the operating period of 200,000 hours. With these parameters, the cyclic analysis is performed to determine if the structure shakes down to an elastic response.

Review of the plastic strains from the analysis indicates that during the first cycle plastic deformation occurs at the edge of the tube penetration on both the axial and circumferential ligaments. However, by the third cycle the axial ligament shakes down to an elastic response (indicating that a residual stress field exists that will ensure that creep and fatigue do not interact). The circumferential ligament, however, does not shake down and has an equivalent plastic strain range of approximately 0.06%. The equivalent plastic strain range for the third cycle is shown in Figure 4-13. This indicates that cyclic operation will enhance creep damage at this location by, potentially resulting in a creep-fatigue interaction.

Figure 4-13: Color Contour Plot of Equivalent Plastic Strain Range for Third Cycle of Creep-Modified Shakedown Analysis



The lack of strict shakedown in this analysis indicates that the creep-fatigue design check is not passed. To pass this check it would be necessary to reduce the cyclic stresses.

The region of potential creep-fatigue interaction is contained within an elastic core, suggesting that local crack initiation and growth would occur in a stable manner (which is consistent with general experience of circumferential ligament cracking). Also, it is noted that the design check employed here can potentially be overly conservative because it considers that the stress at any instant during the cycle should be within the limit defined by the 200,000 hour minimum stress rupture strength (S_t) regardless of how long of a duration that stress would actually occur. To explore if this is a possible reason for the indicated creep-fatigue interaction, the material strength parameter for the creep-modified shakedown check was adjusted so that the 200,000 hour creep stress is only governing at temperatures above 575°C (utilizing the short term yield strength, S_y, at all other temperatures). This analysis also resulted in a local cyclic plasticity, indicating that creep-fatigue is a distinct possibility with this particular configuration and transient. Evaluation of the actual creep-fatigue damage would have to be performed with a life assessment procedure, such as that documented in R5.

With regard to modifications to avoid the possible creep-fatigue interaction, since the circumferential ligament is a concern, then it may be possible to decrease the top-to-bottom temperature differential that drives the stress by spreading the tube penetrations in the circumferential direction or by decreasing the rate of heating/cooling in the cycle. If either of these, or other options, are explored then it would be necessary to repeat the complete set of design checks associated with the proposed design-by-analysis methodology.

It is noted that in this example the sum of the creep and fatigue damage is largest in the axial ligament but the creep-modified shakedown calculation demonstrates that a higher risk of creep-fatigue interaction exists in the circumferential ligament (this is consistent with practical field experience in similar headers).

4.4 Resources Required for Design Checks

This section provides some insight into resources required for the recommended design-by-analysis methodology.

Based on some limited trials with the proposed methodology (and experience with other similar methods, such as EN13445-3, Annex B) the majority of the time to complete the design checks is spend gathering the necessary data for the analysis (geometry, materials data, definition of transients/cycles, specification of load history). Indeed, the time spent selecting how to simplify the actual component geometry (e.g. symmetry planes and other boundary conditions) for finite element analysis and defining thermo-mechanical boundary conditions for cyclic analysis will likely far outweigh the time required to complete the necessary design checks. In the case of a relatively simple geometry and load history then the model definition, analysis and post-processing to verify the design can be completed in a few hours.

The computational requirements to complete the defined analyses are generally very modest. For example, the setup, analysis and design checks for the example problem in Section 4.3 were performed in a few hours using a standard laptop computer. Hence, for the vast majority of cases the computational requirements (CPU speed, memory, disk space, etc.) are very modest and well within the capacity of any laptop or desktop computer. Scenarios which may create a larger demand for computational resource include:

- When it is not possible to isolate an individual feature of a component for evaluation (e.g. when features are in sufficient proximity that their interaction might be a concern). Hence the finite element model might become quite large.
- When a finite element model for design-by-analysis must include (at least approximately) other components to which the region under evaluation is attached (e.g. loads transferred from other regions or components). Hence the finite element model might become quite large.
- When the cycle under evaluation is complex (e.g. significant rapid thermal transients) requiring a combination of detailed heat transfer and stress analysis.

However, in each of these cases, it is usually the case that the computational requirements may be larger to complete an analysis in a given time (or the analysis will take longer) but the time associated with data gathering and model setup will generally be substantially larger than the time required for the computational analyses.

In general, no special finite element programs or proprietary algorithms are needed to complete the analyses necessary for the design checks. Most finite element programs have capability for elastic and elastic-perfectly-plastic constitutive models, and can be made to follow a load history to simulate a cycle (in most cases including any associated transient thermal calculations to determine temperature distributions). Therefore, the recommended methodology is practical and accessible.

5 FLAW ACCEPTANCE CRITERIA

This section of the report discusses some aspects of flaw acceptance criteria and provides some recommendations for methodologies and guidelines for initial construction of equipment.

The flaws to be evaluated are, in general, the flaws which are already defined within the scope of Section I for evaluation during construction. These flaws to be considered include the current acceptance criteria as referenced in Section I paragraph PW-51 for radiographic testing or PW-52 for ultrasonic testing.

The two most common methods of inspection of these flaws is the use of either ultrasonic (UT) or radiographic (RT) methods for this inspection.

5.1 Radiographic Inspection Criteria (RT)

The current inspection criteria used in radiographic examination is based on traditional "workmanship standards". This criterion has a long time tested track record of experience. Some of the issues with this technique are well known. However, it should be recognized that some geometrical features (notably crack-like (planar) indications at particular orientations with respect to the orientation of the image) cannot be evaluated with this technique. Nevertheless, radiographic inspection remains the most appropriate technique for detection of volumetric indications related to workmanship (slag, porosity, lack of penetration). Hence it is recommended that current Section I criteria based on workmanship standards continue to be used. However, this approach may not detect some workmanship indications that can be more planar in nature, such as reheat cracking or hydrogen cracking – although such cracking phenomena are best addressed by appropriate selection of materials and welding practices (which should be mandated by Codes).

5.2 Ultrasonic Inspection Criteria (UT)

A more recent approach for flaw detection is the methods involved in UT. UT, using appropriate procedures and qualified staff, should have an improved detection capability for linear (planar) flaws than RT. This was originally used in generation of Code Case 2235 and has since been expanded in Section VIII to include thickness down to ¼ inch (13mm) and to thickness as large as 12 inches (300 mm). This Code Case was adopted for use several years ago and the methodology has since been adopted directly into in Sections I, VIII Div 1, VIII Div 2, VIII Div 3, and XII. This is a technically based approach for acceptance standards for flaws where the typical RT acceptance criteria is a workmanship based approach.

The adoption of this original Code Case was based on the principle that the stresses were low enough to eliminate any time dependent effects on the materials being used. The flaws sizes were based on flaws of sufficient size to allow for a significant margin between an assumed conservative fracture toughness of the material and the stress intensity factor of a semi-elliptical flaw. Stresses were assumed to be equal to that of the allowable stresses for Section VIII, Div.2 and residual stresses were assumed to be equal to the yield strength in a non-PWHT vessel.

However, the derivation of the currently accepted criteria do not account for any type of cycle or time basis in its development and, therefore, are only applicable to primary loading of magnitude similar to the Code allowable stress in the time independent regime. Furthermore, the criteria do not consider the actual loading that might be possible for a particular component in a particular application (e.g. secondary stresses that may exceed yield). Therefore, this is purely a hypothetical fracture mechanics based approach with "engineering judgment" coming into play to establish the design margins that are used. Such an empirical approach should not be considered to be part of a general design-by-analysis philosophy as it has little relevance to the actual loading experienced by a component. However, it is appropriate for the generation of basic flaw acceptance criteria.

There are several factors in the design of a Section I boiler which are outside the original assumptions used in the derivation of the current UT in lieu of RT criteria.

- The current criteria was developed using room temperature toughness properties and did not consider elevated temperature failure of flaws. Extension of these criteria to the time dependent (creep) regime is particularly complex because, invariably, flaw acceptance criteria are required for weldments where the differing material regions of the base metal, weld metal and heat affected zone will generally have different strength properties resulting in stress redistribution, and in some cases, enhanced triaxiality which complicate crack assessments.
- The materials considered in the original Code Case criteria adopted were limited to SA-516 Grade 70, SA-517 Grade F, SA-553 (9 Ni), SA-240 (304ss). Whereas a much more varied selection of materials (and corresponding weld filler metals) are permitted within Section I.
- The stresses used in the fracture mechanics assessment were derived from Section VIII, Division 2 allowable stresses in effect in 2001. Again, this assumes that only primary loading is of significance to flaw acceptance criteria.

The flaw acceptance criteria developed for Code Case 2235 should be re-evaluated based on conditions which are relevant to the construction of power boilers and high temperature equipment. BS-7910 has information and examples regarding the assessment of flaws in the high temperature regime. A process which utilizes the philosophy followed in the derivation and justification of the original flaw acceptance criteria, combined with the flaw evaluation techniques found in the BS-7910 annexes, will result in a set of criteria appropriate for use in Section I construction. Similar evaluation methods can be found in Section XI. The following is a description of the methodology.

The original work performed by Rana, et. al. was done performed using linear elastic fracture mechanics (LEFM) to calculate the fracture margin defined by the materials fracture toughness (K_{Ic} or K_c) divided by the applied stress intensity factor (K_{IA}). The analysis was performed using semi-elliptical shaped cracks using a flat plate solution.

The methodology for the evaluation would be to follow a similar approach to that used to support the existing criteria, except to use some different techniques for demonstration of the design margin. In the previous work, a range of crack sizes were evaluated for plates from a thickness of ¼ inch through 16 inches for flaws with aspect ratios (a/l) from 0.05 to 0.5. Allowable crack sizes were calculated for these geometries were generated which had a margin (K_{Ic} / K_{IA}) of 1.8 (minimum) based on the evaluation of all of the materials involved. The partial safety factors (PSFs) used were based on PD: 6493, 1991:

Parameter	**PSF**
Stress	1.4
Flaw Size	1.2
K_{Ic}	1.2

The equation for stress intensity factor used is: $K_{IA} = M \sigma (\pi a / Q)^{0.5}$

Application of the PSFs to this equation results in:

$$K'_{IA} = M (1.4\sigma) (\pi (1.2 a) / Q)^{0.5} = 1.53 M \sigma (\pi a / Q)^{0.5} = 1.53 K_{IA}$$

Also, the limit with a PSF is then $K'_{Ic} = K_{Ic} / 1.2$. Therefore,

$$(K_{Ic} / 1.2) = (1.53\ K_{IA})$$

Hence the fracture margin, $FM = K'_{Ic} / K'_{IA} = 1.53 * 1.2 = 1.8$

Failure Assessment Diagram

A number of fracture assessment procedures, including BS-7910, recommend the use of the Failure Assessment Diagram (FAD) approach. This methodology combines both the potential brittle fracture, as well as potential ductile collapse of the remaining ligament. The maximum allowable flaw sizes generated may be additionally evaluated using the FAD approach combined with the appropriate PSFs. Figure 5-2 shows an example of a failure assessment diagram, including the various failure modes which may occur.

This methodology is dependent on the strength of the material (based on the Section II, Part D Table 1 allowable stress of the material), the yield strength of the material (Section II, Part D Table Y-1) and the fracture toughness of the material (FFS Annex F).A limited parametric study of the use of the FAD was done to determine the applicability of the method. Grade 22 (2 ¼ Cr – 1 Mo) was evaluated for the case of a two inch thick plate to demonstrate the use of the FAD on the determination of the allowable crack size to show the effect that the FAD would have on the acceptance criteria.

The material properties for Grade 22 used in the study are as shown below. The properties are from Section II, Part D.

Figure 5-1: Grade 22 Properties

Temperature (°F)	Modulus of Elasticity (ksi)	Yield Strength (ksi)	Tensile Strength (ksi)	Allowable Stress (ksi)	Assumed Critical Stress Intensity K_{Ic} (ksi-in$^{0.5}$)
72	30,600	30	60	17.1	67
500	28,300	26.9	58.2	16.6	100
850	25,950	26.2	58.2	16.6	100
1000	24,700	23.7	53.9	8.0	200

The study included iteratively determining a semi-elliptical surface connected crack with a 3:1 aspect ratio in a plate. For each temperature, the crack sizes were varied from a 0.01 deep x 0.03 inch deep crack and increased incrementally until a critical crack size was found using the FAD approach. All of the conditions evaluated were for the same series of crack sizes as the initial 72°F temperature.

The study consisted of temperatures of 72, 500, 850 and 1000°F. The 850°F temperature was selected as the highest temperature listed in the temperature independent regime. Figure 5-3 shows the results of this study.

The three curves in the time independent temperature regime show that the most conservative of the initial critical crack size studies are the 72°F results. The same crack sizes, as shown in Figure 5-3, were evaluated at 500°F, 850°F, and 1000°F. Due to the elevated toughness at elevated temperature it is predicted that the cracks do not reach critical crack size at the elevated temperature. Additionally, for the 1000°F case, the time dependent allowable stress used for determination of the applied stress is much lower than the time independent applied stress when compared to the yield strength at each temperature. This is also shown in Figure 5-3

An additional issue is the use of yield strength in the FAD evaluation. Two additional evaluations were performed to evaluate the series of crack sizes with the yield strength lowered with a PSF of 1.4. The figure shows that the results from these two plots (72* and 1000*) are more conservative than the initial evaluations, as expected. This could be an additional level of conservatism which was not included in the original criteria, originally included in Code Case 2235.

The takeaways from the evaluation are:

- The FAD shows that the critical crack sizes are actually determined at approximately 80% of the critical stress intensity factor.
- The 72°F evaluation will result in the most conservative critical crack sizes over the elevated temperatures in either the time dependent or time independent temperature regimes
- A PSF added to the yield strength in the FAD method will result in even more conservative results than was included in the original analysis for Code Case 2235. This is not considered necessary because:
  - This methodology already includes additional conservatism due to the use of the FAD
  - The yield strength listed and used are minimums as listed in Section II, Part D. Actual properties are typically higher than these.

Methodology

The overall methodology recommended is the following:

(a) Some of the assumptions which need to be made for the generation of the acceptance criteria are the loading basis for the analysis. It is recommended that the evaluation be performed assuming:

(1) Materials to be evaluated include as a minimum:

i. SA-516 Gr 70
ii. SA-517 Gr F
iii. SA-553 (9 Ni)
iv. SA-240 (304SS)
v. Grade 11(1 ¼ Cr – ½ Mo – Si)
vi. Grade 22 (2 ¼ Cr – 1 Mo)
vii. Grade 91 (9 Cr – 1 Mo – V)

(2) The applied stress is equal to the allowable stress for the materials in question (II_D Table 1A).

(3) Secondary stresses, except for some cases of weld residual stresses, are not included in the evaluation to keep the analysis simple, as was done for the CC 2235 evaluation. Note that the weld residual stresses are only included in the K_r axis and not the L_r axis of an FAD assessment. Relative to weld residual stresses:

i. For non-PWHT thicknesses, a residual stress field equal to the yield strength of the material will be assumed.
ii. For PWHT thicknesses, a residual stress field equal to 0.15 * yield strength of the material will be assumed.

(4) The crack aspect ratios to be evaluated include crack aspect ratios including, 0.05, 0.10, 0.15, 0.20, 0.25, 0.33 and 0.50.

(5) The range of thicknesses of material to be evaluated include, 0.25 in, 0.375 in, 0.5 in, 0.75 in, 1.0 in, 2.5 in, 4 in, 12 in, and 16 in. The recommended thicknesses are used to reflect the current range of the UT in lieu of RT criteria in Section VIII, and Section XII, Rules for Construction and Continued Service of Transport Tanks.

(6) PSFs of 1.4 on stress (in final definition of PSFs, consideration could be given to the use of a factor of 1.5 on stress to be consistent with loading applied during hydrostatic testing), 1.2 on K_{Ic}, and 1.2 on flaw size should be used for the evaluation.

(7) A key parameter needed to perform the fracture mechanics evaluation of these materials is toughness. Charpy impact test (CVN) / fracture toughness correlations from FFS