UKAEA-CCFE-PR(25)381

Sreeram Madabusi (UKAEA), Giacomo Aiello (EUROfusion), Dmitry Terentyev (SCK CEN), Gerald Pintsuk (Forschungszentrum Juelich).

DEMO Design Criteria for In-Vessel Components – Strategic vision and overarching considerations

DEMO Design Criteria for In-Vessel Components – Strategic vision and overarching considerations

Sreeram Madabusi (UKAEA), Giacomo Aiello (EUROfusion),
Dmitry Terentyev (SCK CEN), Gerald Pintsuk
(Forschungszentrum Juelich).

This is a preprint of a paper submitted for publication in
Fusion Engineering and Design

DEMO Design Criteria for In-vessel Components – Strategic vision and overarching considerations

Sreeram Madabusi[a*], Giacomo Aiello[b], Dmitry Terentyev[c], Gerald Pintsuk[d]

[a] UK Atomic Energy Authority, Abingdon, United Kingdom
[b] EUROfusion – Fusion Technology Department, Boltzmannstrasse 2, 85748 Garching, Germany
[c] SCK CEN, Mol, Belgium
[d] Forschungszentrum Juelich GmbH, Jülich, Germany

Keywords – *DEMO Design Criteria, Fusion in-vessel components, Inelastic design, Structural integrity.*

Highlights

- *Inelastic design by analysis using "direct route" and limit state design approach.*
- *Novel design criteria supported by refined FE based assessment approaches.*
- *Strategic assignment of design margins using R6 failure assessment curve.*
- *Tailored damage limit(s) considering component limit state requirements.*
- *Constitutive models to characterize material behaviour in non-linear regime.*

* Corresponding author

Email addresses: sreeram.madabusi@ukaea.uk, giacomo.aiello@euro-fusion.org, dmitry.terentyev@sckcen.be, g.pintsuk@fz-juelich.de

Abstract

In-Vessel components in fusion nuclear systems have to withstand a very harsh combination of loads and environmental conditions which leads to designs that are significantly more complex and distinct from those of fission components. The ability to accurately predict component performance in in-vessel conditions, factoring in suitable design margins against critical failure mechanisms, is an overarching concern from a safety as well as investment protection perspective for the realisation of DEMO fusion power plant.

This requires a critical evaluation of the typical failure mechanisms that are usually considered for design assessment of existing nuclear components considering both their relative individual significance from a limit state design perspective as well as their applicability for the selected in-vessel components' materials and the fusion in-vessel operating conditions. Furthermore, the possibility of ductile and brittle failure mechanisms being intertwined over the design life of a fusion component requires clear understanding and evaluation of potential synergistic effects to optimise the component life and prevent premature failures in service.

To that end, this paper will highlight the driving objectives, structure and status of the DEMO Design Criteria for In-Vessel Components (DDC-IC), currently under development in EUROfusion. The paper will also highlight the salient aspects associated with the design principles and associated design rules that are under consideration within the DDC-IC. This will include the arguments serving to investigate the core assumptions and theoretical basis associated with selected design rules within existing Codes and Standards as well as the avenues being explored to address the "gaps".

Section 1- Introduction

Amongst other pressing challenges, the viability of commercial fusion technology hinges upon unique design concepts that can reliably withstand combined structural and thermal loads and radiation damage during plant operation without prematurely losing the intended functionality. With the ever-increasing complexity inherent in the evolving fusion component concept designs in order to address the harsh operating conditions foreseen within the DEMO in-vessel environment, the ability to accurately predict component performance in in-vessel conditions and building in suitable design margins against critical failure mechanisms is a key concern from a safety as well as investment protection perspective for the realisation of DEMO fusion power plant. This requires dedicated design codes that can identify the relevant failure criteria under all (foreseen) operating states and provide appropriate design rules to claim protection against the pertinent failure mechanisms that may come into play. Currently, such a dedicated design code that can comprehensively address the unique design requirements of commercial fusion reactor components does not exist. The Structural Design Criteria for In-vessel Components (SDC-IC) [1] was developed specifically to address fusion-relevant damage mechanisms for ITER components, but it is limited in scope to the relatively low irradiation doses, thermal loads, and material sets applicable to ITER, and thus does not cover the broader, more demanding conditions expected in DEMO. As such, much of the pre-concept design validation studies have been done using existing design codes developed for the fission plant systems and components.

Design of DEMO in-vessel components involves significant challenges given the unprecedented nature of the foreseen operational environment. Among other aspects, the foreseen synergistic impact of extreme operational conditions characterised by 14MeV neutrons and temperature ranging from 500k (divertor heat sink) to 2500k (Tunsgten plasma facing) along with significant temperature cycling and disruption loads would likely introduce irradiation creep, helium induced embrittlement/ transmutation effects and the degradation of fatigue strength and ductility. This necessitates an extensive evaluation of the validity of the design rules contained in existing Codes and Standards prior to their adoption especially for special candidate materials.

The development of the design rules and assessment criteria in fission design codes draw considerable benefit from the relatively standardized and matured technology supported by empirical knowledge derived from extensive operational experience. These effectively inform and guide the underpinning assumptions and justifications for continuous evolution of the design codes. However, this is not the case with fusion in-vessel components where the fundamentally unprecedented nature of the commercial fusion tokamak operation exacerbates the concerns surrounding the safe reactor operability as well as commercial viability of plant operation. As a consequence, emphasis on investment protection is equally warranted in addition to aspects pertaining to operational safety at least until fusion technology achieves sufficient standardization and a proven track record for commercial sustainability.

There is hence a need for a detailed evaluation of pertinent failure mechanisms that need to be considered for assessment of fusion in-vessel components from the viewpoint of their relative individual significance from a limit state design philosophy perspective as well as the remit of their applicability for the candidate in-vessel component materials and the fusion in-vessel operating conditions. Furthermore, the possibility of interplay between ductile and brittle failure mechanisms over the design life of a fusion component due to changes in operating environment and/or loading conditions requires clear understanding and evaluation of potential synergistic effects to optimise the component life and prevent premature component failures in service.

Additionally, validation of proposed in-vessel component design concepts through testing is unfeasible under (foreseen) representative conditions of fusion operation environments. While this is partly due to the lack of adequate test facilities (at present) that can effectively mimic the foreseen operational conditions, such an endeavour can also be grossly expensive given both the evolving status of the design concepts as well as the need to test proposed design concepts against a "sufficient" number of representative load cases. This, in effect, places significant emphasis on the need for standardised and validated procedures for structural integrity assessment of unique fusion systems and component designs to ensure consistency and coherence in the concept and detailed design activities.

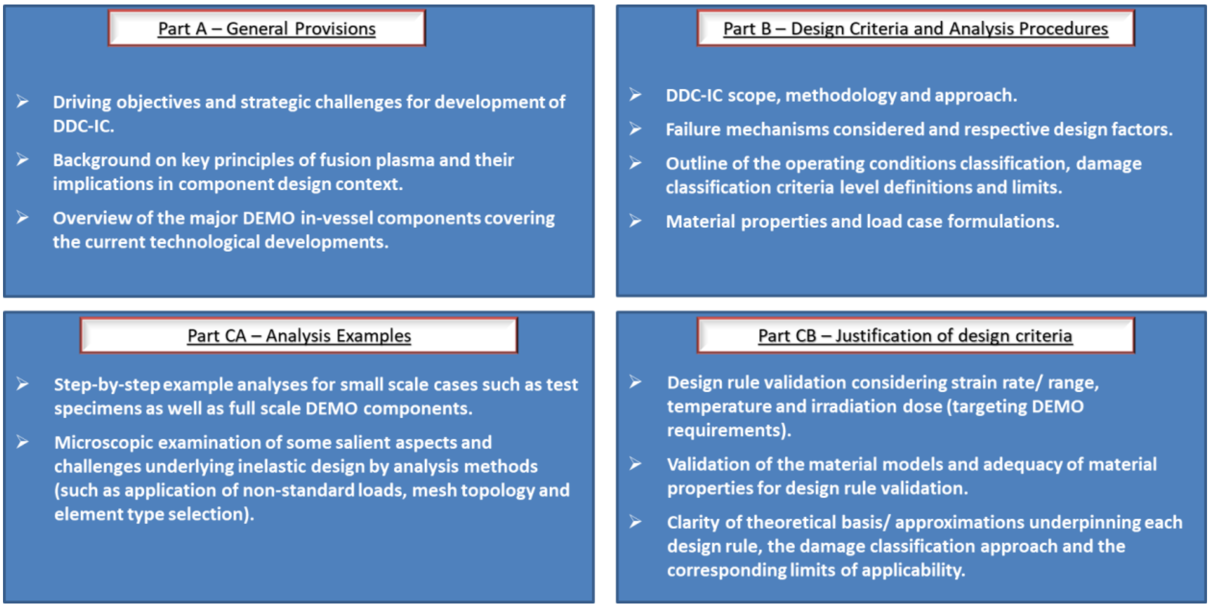
On the other hand, refined predictive visualisation of the component response under different loading conditions are made possible by advanced non-linear FE methods. These methods must be supported by dedicated material models characterising the constitutive behaviour of candidate materials in monotonic and cyclic loading conditions. They provide scope for recalibration of the stringent limits imposed against different failure mechanisms within the conventional nuclear design Codes and Standards. This, in effect, affords the opportunity to expand the design space supported by a clear basis for apportionment of effective allowable damage margins assigned against different failure mechanisms to address the plant-level requirements for a stipulated maintenance free operational period as mandated by the DEMO project whilst also ensuring overall congruence with the broader IAEA definitions [2] and foreseen regulatory expectations. These aspects necessitate the need to develop dedicated design rules and analysis procedures for fusion in- vessel components.

To that end, the DEMO Design Criteria for In-Vessel Components (DDC-IC) is being developed as a fully integrated and coherent guideline to complement existing fission Codes and Standards through provision of design rules and assessment procedures for failure mechanisms deemed most critical from a structural integrity perspective for fusion in-vessel components. The following areas constitute the key considerations in this regard.

- Validation of the design rules against target design constraints (e.g. applicable stress/strain ranges, temperature and hold times during operation) through comprehensively formulated test load cases.
- Inclusion of full range of DEMO IVC material properties relevant to forecasted DEMO operating conditions and considering material transition behaviours under the combined effects of irradiation and temperature.
- Development of material models considering irradiation effects.
- Statistical approaches to convert experimental test data into design/limit data within the DDC-IC for different confidence bounds (potentially long-term target).
- Development of guidelines on quality classification scheme/ assignment of quality classes to IVCs.
- Development of dedicated modelling and design guidelines for brazed joints.

The DDC-IC initiative is unique in being potentially the only design guideline currently under development for commercial fusion reactor in-vessel components which is supported by comprehensive validation testing and material qualification programs. This includes high heat flux testing and irradiation campaigns to allow evaluation of material properties that would be pivotal for qualification of concept designs in conditions well exceeding the limits of applicability of other Codes and Standards.

The DDC-IC (currently under development) comprises of three Parts as highlighted below covering the general provisions, design criteria and analysis procedures and appendices. There are two dedicated appendices for example analysis to demonstrate the application of the design rules and justification arguments in support of the proposed design criteria respectively.



The sections to follow will elucidate the driving objectives, methodology and developmental considerations of the DEMO Design Criteria for in-vessel components (DDC-IC) in order to address the "gaps" in existing nuclear Codes and Standards and meet the design requirements in a more targeted fashion. Salient aspects associated with the safe life assessment approach, damage classification rationale and methodology and an overview of the theoretical basis associated with selected design rules that are under development within the DDC-IC will also be presented.

Section 2- DDC-IC Driving objectives, methodology and developmental considerations.

At a broader level, there are two overarching objectives driving the development of the DDC-IC.

The first objective of the DDC-IC, targeting a notable shift from conventional design assessment approaches for nuclear plant components, is to develop comprehensive FE based approaches for structural integrity assessments of designs against selected failure mechanisms using a "direct" inelastic 'design by analysis' methodology. This approach can be defended on the basis of the following arguments:

- While using elastic design by analysis approaches from other design codes against different failure mechanisms (where available) may be possible, there may be a risk of imposing overly conservative margins in the component design in doing so. Alternatively, such an approach may not provide a route to assess the real damage "level" with respective to the ultimate failure thus making it difficult to assess the actual state of the component at the end of the design life for a given load case. i.e. one cannot really assess what is the state of the component.

- The DEMO in-vessel component designs are characterised by unique and complex design features (required to meet the basic energy efficiency requirements) and specific candidate materials which would also necessitate advanced fusion-specific manufacturing techniques. The existing nuclear Codes and Standards may be "insufficient" to qualify potential DEMO IVC design concepts since they either do not have the design rules applicable to pertinent component geometries resulting from such non-conventional manufacturing processes or the design rules have not been qualified for the DEMO IVC candidate materials. Inelastic material models can be used to also reproduce the manufacturing sequence taking into account the presence of residual stresses in design analyses.

- The operating conditions foreseen in the DEMO reactor would be unprecedented. The in-vessel components would be subjected a different nature and "quality" of concurrent loads (heat loads, pressure, electromagnetic, neutron irradiation) compared to what is typically the case with fission reactors. The conventional classification of elastic stresses into primary and secondary categories (as per the stress classification route of design by analysis method) may no longer be fully appropriate or sufficient under the complex, evolving load combinations and environmental conditions expected within DEMO. Hence, the existing design codes may not be adaptable for DEMO IVC assessment if the design rules have not been ratified to the representative DEMO in-vessel conditions.

The "direct" assessment route is underpinned by dedicated constitutive material models (specific to each candidate material) that can accurately describe the stress-strain response of a material over the full inelastic regime under monotonic or cyclic loading conditions. It is hence expected that this would provide a refined alternative to the stress classification route through offering scope to increase the design space and minimizing the conservatisms that are inherent in the design rules contained in other Codes and Standards.

The second objective of the DDC-IC is to align the design rules formulated as above to the requirements of DEMO in-vessel components by considering specific boundary conditions based on the constraints emerging from breeding blanket/ divertor concept design studies. This would be achieved through progressively refinement of the "basic" design rules targeted specifically towards DEMO IVCs with contextualised 'design margins' being introduced to address operability/ maintenance constraints/expectations. This is done from the viewpoint of structural integrity, of the DEMO "in-vessel" systems, structures, components, and associated interfaces through demonstration of suitable level of tolerance to the structural, mechanical, thermal, electromagnetic, and nuclear loads anticipated under normal operation, fault and accident scenarios.

As stated before, the DDC-IC is expected to provide a potential route to evaluate proposed concept designs from a 'limit state' perspective. Hence, as part of the design assessment, the DDC-IC would not only consider the assurance of structural integrity of the in-vessel components in the foreseen operational environment, but also the suitability of the IVCs to fulfil the intended functions in congruence with the overall plant availability/ reliability requirements. The scope of the DDC-IC initiative broadly encompasses the following aspects

1. Development of dedicated material models.

   This would be crucial to characterize the constitutive behaviour of candidate materials in monotonic/ cyclic loading conditions which would be a key point for the inelastic design by analysis assessment procedure. The material models may require targeted qualification to assess applicability in forecasted conditions considering aspects such as strain rate and radiation.

2. Development of advanced inelastic structural integrity design rules and FE based assessment procedures specifically for the assessment of design concepts for fusion in-vessel components and systems.

   This would entail a rigorous scrutiny and reformulation of the theoretical basis and assumptions underpinning each design rule. The increased refinement in the simulation/visualization of the component response in the inelastic loading regime made possible by advanced non-linear FE assessment methods would be used to introduce provisions to extend the design space through modification of existing rules.

3. Development of a targeted design philosophy for DEMO IVCs.

   This would be achieved through augmentation of the basic definition of damage taking into consideration the specificities inherent in fusion in-vessel environment (including irradiation induced damage) and concept design features. The overall target would be to establish design margins specific to components/ operational regimes through a reasoned approach.

4. Establishment of terminology to provide granularity in the relative significance of different failure mechanisms for each individual component.

   Assigning the same damage class for two different failure mechanisms may lead to ambiguity since physically, the damage development may have different ramifications for failure mechanisms. This would be addressed through introducing an abstract definition for each damage class in terms of the proximity to the onset of failure criterion as defined for each failure mechanism.

   Since the criterion for onset of failure would be defined differently for each failure mechanism, the damage class indicated against a specific failure mechanism would only indicate the margin built into the design against the onset of failure specific to that failure mechanism. This may be further complemented by considering the influence of the respective onset of failure criterion on the component functionality to identify the "critical" damage class corresponding to each failure mechanism for a given component.

   The normalising benchmark criterion being used to the identify the damage classes (i.e. the "onset of failure") will allow easier comprehension of what an assigned damage class actually means for each failure mechanism. The proposed classification approach would also make it relatively easier to understand the significance of the margins built against the different failure mechanisms.

5. Consideration of the synergistic effects between incremental damage and fast fracture inferred from established defect tolerance assessment procedures.

   This would be help to establish an approach to impose conservative limits on the incurred "accumulative" damage at an overall component level considering the influence of all applicable failure mechanisms.

6. Concretization of a suitable quality class identification methodology based on criteria specific to fusion in-vessel components by adapting the framework developed in ITER [3].

   This would be done taking into consideration the constraints imposed by foreseen challenges in maintenance and the impact of the component(s) on the overall plant performance and investment protection expectations.

While the main priority of the DDC-IC would be to provide rules to carry out design assessments via inelastic design by analysis route, the DDC-IC would also provide consolidated links to selected 'elastic' design rules and analysis methods in other design codes (where needed) detailing the scope of applicability and applicable caveats. There are two main reasons for including this provision. Firstly, although the failure mechanisms covered within the DDC-IC are considered to be the most significant ones for DEMO in-vessel components, it is adjudged that the designers must ideally have the option to assess designs using 'elastic' design by analysis rules from other Codes and Standards against selected failure mechanisms that are not covered within the DDC-IC. Secondly, for failure mechanisms that are already covered within the DDC-IC, the corresponding 'elastic' design rules from other Codes and Standards may still be used to (selectively) carry out an "initial check" (if needed) prior to carrying out more detailed assessments using the DDC-IC approach should the former yield overly conservative results which may invalidate potentially viable design concepts. Alternatively, carrying out design assessments through two independent approaches would also help to bolster the arguments made in support of any design concepts.

Section 3- IVC Safe life assessment considerations

Safe life assessment requires a demonstration that a component or system is designed and assessed against applicable failure mechanisms to function safely for a certain defined operational period before the limiting condition (as applicable based on the expected functionality of the component) is reached. As per the current position held within EUROfusion [4], DEMO in-vessel SSCs are not designated as Safety Important Components (SIC) given the great criticality in checking and testing the components inside the vessel once they are in operation. However, since failures and subsequent replacements of IVCs would result in prolonged maintenance downtimes, significantly impacting reactor availability and potentially limiting continued reactor operability, the expectation would be to design the IVCs according to the highest quality standards and the greatest strength constraints. Thus, ascribing sufficiently conservative design margins (within practical constraints) to DEMO IVCs appears to be the most likely option as part of the design assessment and validation studies.

Reference [5] identifies the key considerations from the viewpoint of safety and reliability in the design, construction, operation and maintenance of any installation, storage facility, equipment and infrastructure connected with the establishment's operation, which are linked to major accident hazards inside the establishment. Among other aspects, this would require evaluation of proposed component design(s) against various (foreseen) failure modes (considering the environment in which the equipment is to be utilized), the respective implications and implementation of measures to prevent, control or mitigate the consequences of SSC failure through appropriate selection of materials.

To address this, the DDC-IC is underpinned by design by analysis rules that provide routes for deterministic assessments for targeted IVCs based on fusion-specific design criteria through establishing clear guidelines on:

- Selective assessment against different failure mechanisms depending upon the nature of imposed loads and component quality classification.
- Correspondence between the damage classification approach and the design criteria associated with different failure mechanisms and corresponding margins for a design assessment.
- A comprehensive methodology for assessment by integrating all applicable failure mechanisms.
- Provision of material allowables, design curves and material behaviour laws for each failure mechanism under consideration.

Assessment against different failure mechanisms would then require an indication of the applicable validity limits of the associated design rule (considering factors such as the strain rate, temperature and irradiation to ensure accuracy of the design assessment) and the conservative margin built into the design against selected failure mechanisms taking into account the limit state requirements specific to each component (which would indicate the criterion for failure).

Additionally, the margins to be built into the design would be influenced by the significance of the component from a safety or operability perspective as identified through the quality class assigned to the component. The assignment of quality class to a component, in turn, would require consideration of a multitude of constraints that could influence the overall design life/performance requirements of the component. These would include (but not be limited to) aspects such as

- Assumed accumulative radiation dose to end of operational life.
- Key functional/ structural requirements assigned to the component.
- Inspection/ maintenance restrictions applicable to the component.

Furthermore, considerations underpinning the defence-in-depth principle for the safety design of DEMO to prevent or reduce the occurrence of accident situations resulting from system and equipment failures, human errors and internal or external hazards may also require attention as these may have relevance from the viewpoint of the design margin considerations within the DDC-IC.

Section 4- Overview of design rules and material models.

4.1 Introduction

Structural integrity assessment of fusion in-vessel components warrants consideration of several types of failure mechanisms associated with both ductile as well as brittle failure modes given the forecasted propensity of the loads conducive to these to act upon the in-vessel components in an alternating or synergistic fashion. In part, this also warrants the need for augmentation of the definition of "load" in the context of DEMO design criteria. Typically, the term "load" is applicable to agents that lead to mechanical effects which negates the consideration of "nuclear loads" as a valid category in the conventional terminology. However, for fusion IVCs, nuclear load warrants a separate consideration given the significance of the combined effect of nuclear fluence and temperature on component damage via mechanisms such as swelling and sputtering or alterations in mechanical properties.

The damage mechanisms that are likely to come into effect within the in-vessel environment would include ductile damage modes such as immediate plastic collapse, immediate plastic instability and time dependent plastic instability and brittle damage modes such as immediate plastic flow localisation, immediate local fracture due to exhaustion of ductility and fast fracture. The reason for brittle damage modes assuming equal prevalence within a fusion in-vessel environment is mainly due to the high energy neutron irradiation environment which increases the propensity for embrittlement/loss of ductility, swelling, increase in DBTT and time dependant material property changes (such as reduction in strain-hardening capability, irradiation induced creep) within the plasma facing components.

Furthermore, the inherent novelty of the candidate materials for in-vessel components given the lack of sufficient empirical experience of their usage (not least in the fusion in-vessel environment) also exacts the need for targeted material models to simulate the candidate material responses in post-yield loading regime.

The sections to follow will provide an overview of the key considerations relating to the material models and the design rules under development within the DDC-IC corresponding to selected damage mechanisms of interest.

4.2 Material models

A key input required for the successful implementation of the "direct" design by analysis approach is the analytical material models that accurately describe the constitutive behaviour of the candidate materials under monotonic and cyclic loading conditions. These models in turn need to be calibrated or validated for different temperatures, strain rates and strain ranges to ensure their accuracy in predicting the material response over the full operational regime that a component is likely to experience over the course of the design life.

To describe the monotonic plasticity, the DDC-IC prescribes the use of Voce nonlinear isotropic hardening law [6] for which the variables and the corresponding material property values are defined for CuCrZr and EUROFER97. Additionally, it is proposed that for simulating monotonic loads up to instability/UTS, an elasto-plastic (or visco-plastic) model with multiple kinematic variables can also be adopted and calibrated using data from material curves for the preferred temperature range. Accordingly, the model parameters for EUROFER97 for a selected temperature range is provided within the DDC-IC.

Additionally, since load reversal is likely to be the case in most shear dominated loading cases (shear-tension or shear-compression) it is recommended that a combined kinematic isotropic hardening model should be used to characterize the evolution of the yield surface for assessment against exhaustion of ductility.

The constitutive material model proposed within the DDC-IC for cyclic behaviour of EUROFER97 is a combined kinematic isotropic hardening model which is based upon the classical cyclic hardening model by Chaboche [7]. This combines the Voce law for isotropic hardening and the Armstrong–Frederick law for kinematic hardening.

The combined kinematic-isotropic model being an elasto-plastic model is incapable of describing time or rate dependent effects like linear cyclic softening seen in experiments after stabilization, strain-rate sensitivity, creep and hold time relaxation. To address this, a viscoplastic extension is necessary. Hence, the Chaboche model has been modified to include the complex cyclic softening behaviour of EUROFER through a specially designed formulation to describe the strain-memory effects and the stress relaxation during the creep hold time. The model parameters have been derived for quasi-static strain rate and the model has been validated for different temperatures and strain ranges. The model's applicability is limited to strain rates of the same order at high temperatures, where viscous effects sensitive to strain-rate are more prominent. At lower temperatures, the applicability of a quasi-static regime is considered valid. This model has also been adapted for CuCrZr in solution annealed cold worked and aged condition (which shows cyclic softening behaviour) through modification of the model parameters to suitably describe the cyclic deformation.

Furthermore, creep models have also been included to describe creep deformation behaviour of EUROFER97 using the modified time hardening equation (for primary creep) and the combined time hardening equation (for primary plus secondary creep). The coefficients for the chosen creep models of Modified Time Hardening and Combined Time Hardening were deduced from the available material creep data.

Section 4.3 Design rules overview

Section 4.3.1 Introduction

The selection of the failure mechanisms for development within the DDC-IC initiative was based on preliminary studies carried out at the pre-concept design phase which identified the life-limiting failure mechanisms of interest for the in-vessel components. For instance, references [8] and [9] indicate that the coolant pressure, thermal loads, electromagnetic loads and inertial loads (component dead weight) are of key relevance from the viewpoint of Breeding Blanket structural design assessment. The coolant pressure results in primary stresses in all cooled components of the blanket which is further exacerbated by electromagnetic loads in most parts of the structure. Additionally, due to the nonhomogeneous temperature fields, secondary stresses are induced which are exacerbated at geometrical discontinuities. In pulsed operation, the temperature fields in the different components and hence the secondary stresses are cycled which would result in cyclic thermo-mechanical loading superimposed to the primary loading.

For the divertor, it was identified that thermal loads, coolant pressure, inertial loads and electromagnetic loads would be of key relevance. The thermal loads would be introduced in the form of surface heat flux and thermal cycling while the coolant pressure would be imposed on the CuCrZr cooling system pipes. Additionally, residual stresses originating from manufacturing processes must also be carefully considered, as they significantly influence the overall stress and strain distribution experienced by the components during thermal cycling. As with the breeding blanket, electromagnetic loads such as disruptions and VDEs would further exacerbate the imposed damage due to the other loads.

These loadings effectively determine the life-limiting failure modes corresponding to different sections within with the BB and DIV components which hence need to be designed considering the relevance and level of each loading type.

On this basis, it was proposed that thermomechanical failure mechanisms such as plastic instability, local fracture due to exhaustion of ductility, creep-fatigue and fast fracture would need to be given prominence from the viewpoint of development of inelastic design rules as part of the DDC-IC initiative. Fast fracture, in particular, requires consideration since it is controlled by presence of defects which may either exist in the numerous welds foreseen for the fabrication of the blanket or may arise due to creep-fatigue damage interaction. Furthermore, given the potential dynamic interplay between the thermal, mechanical and irradiation loads, the ductile and brittle conditions imposed on the IVCs may alternate over the course of the design life. Thus, occurrence of fast fracture may be preceded by a stable crack growth under fatigue loading (up until a limiting defect size is reached) which would, by implication, necessitate the evaluation of crack growth due to fatigue over the component design life.

A brief overview of all the design rules specifically under development within the DDC-IC initiative is presented below. The design rule development activities have involved targeted experimental validation studies considering a range of applicable temperatures, strain rates/ ranges and manufacturing (heat treatment) process among other aspects.

Section 4.3.2 Design rules summary

The DDC-IC design rule for exhaustion of ductility is based on triaxiality at failure. The limit imposed on the maximum plastic strain limit is the minimum of two functions; namely the dilatational limit, which defines failure dominated by void growth and the distortional limit which defines failure dominated by void distortion. Furthermore, the DDC-IC criterion used the accumulated equivalent plastic strain as opposed to the equivalent plastic strain since it is deemed to better represent ductile damage especially when deviatoric stress is dominant (stress triaxiality < 1/3). However, these limits are only valid when triaxiality is greater than zero since positive hydrostatic stress is required to drive void growth and nucleation.

The exhaustion of ductility criterion in the DDC-IC is similar to the corresponding rules in the ITER SDC-IC [1] and the ASME BPVC [10] in that it is a local equivalent plastic strain limit that varies with stress triaxiality. However, investigations revealed that both of those rules do not accurately represent ductile failure over the full range of stress triaxiality. This is attributed to two main reasons.

Firstly, the failure strain values for the rules in SDC-IC and ASME BPVC are based on testing tensile specimens to failure. The triaxiality recorded for that failure strain is that at the beginning of loading (e.g. 1/3 for plane uniaxial specimens). However, the tensile specimens neck during failure causing increased triaxiality at fracture (usually around 1 for plane uniaxial specimens). This causes the failure curve produced to be shifted to lower triaxiality, effectively underestimating strain to failure. In other words, the failure strain applies to a different triaxiality than what it is assumed to be applicable to.

Secondly, the accumulated plastic strain- stress triaxiality curves are extrapolated from high triaxiality failures to low triaxiality failure even though the underlying phenomenological aspects between the two are quite different. In high triaxiality failures, the hydrostatic stress and void growth dominate whereas in the low triaxiality failure, the equivalent stress and void distortion dominate. This was also verified experimentally as part of the rule development. Hence it is argued in the DDC-IC that the extrapolation tends to overestimate strain to failure at lower triaxialities, which can be lower in some materials [11], or at least not follow the trend of the high triaxiality tensile specimens [12].

The modified creep-fatigue crack initiation rule prescribed within the DDC-IC for cyclically softening RAFMs is an extension of rules in RCC-MRx [13] and ASME [14] to ascertain the component life through an assessment of incurred creep and fatigue damage leading to crack initiation. The rule prescribed within the DDC-IC takes into account cyclic softening effects which reduces the tensile and creep strengths of certain materials (such as EUROFER97) under cyclic loading. The basic assessment approach involves a damage accumulation rule based on ASME-BPVC and RCC-MRx whereby the fatigue and creep usage fractions are first separately estimated (including hold time and strain rate effects) and the aggregate damage is then compared against an allowable total creep-fatigue damage limit derived from a creep-fatigue interaction diagram specific to the material.

The proposed approach allows the non-linear accumulation of the separately calculated fatigue and creep usages by varying the allowable sum of the fatigue and creep usages according to the creep-fatigue interaction diagram. Due to the nonlinear creep-fatigue interaction, the allowable total creep-fatigue damage is not specified as constant but as a variable dependent on the creep and fatigue damage usages, respectively.

The creep and fatigue usages at end of life are calculated considering experimentally determined creep rupture time and number of cycles to failure. As part of the fatigue damage assessment approach, provision is made for consideration of a number of different cycle types required to define the cyclic strain history for the specified service life with each cycle type uniquely defined by its equivalent mechanical strain range and the maximum material temperature occurring during the cycle. Likewise, for assessing creep damage the proposed approach provision is made for consideration of a number of time intervals each with a unique stress-temperature combination needed to represent the specified elevated temperature service life at the point of interest for the creep damage calculation.

To account for the fact that creep damage of cyclic softened material is typically underestimated by the usual damage accumulation rule, selected modifications are introduced to the creep-fatigue rules for cyclic softening ferritic martensitic steels. Specifically, the modified rule requires calculation of creep usage in the creep fatigue accumulation rule in first 10% of the lifetime using the initial stress from monotonic stress strain curves and design creep curves of as received material. The creep usage in the remaining 90% of the lifetime is then proposed to be estimated using the initial stress from cyclic stress strain curves and design creep curves of cyclic softened material.

The multi-axial fatigue crack initiation (MFCI) assessment criterion within the DDC-IC is based on the strain energy density method developed by Lagoda-Macha-Sakane (LMS) [15] which is used as the basis for assessment against Low Cycle Fatigue. This method stipulates that the number of cycles required to cause fatigue crack initiation in a material with a known fatigue strength and fatigue ductility properties, is governed by the strain energy density amplitude acting in the direction normal to a critical plane. The strain energy density is approximately the area under the material (cyclic) stress strain curve up until the point of interest corresponding to an applied strain. The assessment approach stipulates that the plane experiencing the maximum strain energy density (acting normal to it) would be the "weakest spot" for initiation of a crack in response to the applied (cyclic) load. By estimating the applied strain energy density corresponding to this critical plane for a given loading condition, the number of cycles to crack initiation can be subsequently estimated.

While the plane normal to the maximum principal stress can be calculated analytically for simple uniaxial loading, the LMS principle provides a route to identify this critical plane for other more complicated loading configurations (such as combined tension-torsion loading). Hence in assessing a component design against multi-axial fatigue loading, an FE simulation with the actual component geometry and the applied loading is used to identify the critical plane and deduce a predicted number of cycles to crack initiation. The maximum strain energy density amplitude and the critical plane orientation is determined from the inelastic stress and the strain amplitudes acting in the same normal direction. The determination of the maximum value of the strain energy density amplitude corresponding to the critical plane implies the consideration of all possible orientations of planes in a given point of the sample to determine the orientation corresponding to the highest value of strain energy density amplitude.

Conventionally, fatigue curves provide the number of cycles to failure based on applied strain or strain range which are typically derived from uniaxial tests. For uniaxial loading scenarios, these can be readily used for assessing a component design by monitoring just the applied principal strain (or strain range). However, for assessment against multi-axial fatigue, the maximum strain energy density is chosen as the governing (limiting) criterion. This is based on the premise that for "non-proportional" loading conditions (such as out of phase tension combined with torsion), the applied strain energy would serve as a better parameter for assessment since it would be independent of the loading configuration. The LMS principle states that for uniaxial tension tests, the strain amplitude-failure cycle relationship can be re-written with the strain energy density-failure cycles relationship. Thus, the conventional fatigue curves that are derived from uniaxial tests can be used to assess other loading scenarios.

Furthermore, the stress–strain curve, described with Ramberg–Osgood equation, and the strain–life curve, described with Manson–Coffin–Basquin equation present the total strain and strain amplitude respectively as a sum of elastic and plastic components. The assumption of equivalence of the respective elastic and plastic components in the two equations leads to the so-called “compatibility condition” which can be used to determine the coefficient and exponent in the stress–strain curve directly from the strain–life curve [16]. However, conventional fatigue tests often require estimating the model parameters under constant amplitude loading corresponding to the stabilized state which negate the possibility of variation of the constants with loading cycles due to hardening or softening effects. Hence the assumption underpinning the evaluation of the constants (that the material is stable during the fatigue loading) may not necessarily be physically valid if the material was to undergo hardening or softening. Hence, in cases where the "equivalence" of elastic and plastic strain components between Ramberg-Osgood equation and the Manson–Coffin–Basquin equation may break down (such as for materials that harden or soften), the MFCI approach can help to avoid the uncertainty of compatibility in the experimental coefficients.

Assessment of components containing defects is addressed within the DDC-IC through two routes.

To assess stable crack growth through fatigue, the DDC-IC provides a novel route to estimate the instantaneous J integral value directly from FE. This is achieved by modelling a defect in the component and estimating the instantaneous strain energy release due to crack growth by varying the defect size for a given load. This results in a direct estimation of the J integral. This can then be used to predict the crack growth using the Dowling and Begley equation [17] provided the crack growth law constants are known for applicable conditions. Provisions are also under consideration to accurately evaluate the instantaneous state of the component containing the defect under complex loading conditions. Such conditions are foreseen due to the forecasted interplay of temperature and irradiation and the ensuing alternation between ductile and brittle behaviour over the design life and variable amplitude cyclic loading due to plasma sweeping.

Within the DDC-IC, a dedicated assessment methodology for crack tolerance in irradiated/ embrittled component is also currently under development. This involves development of damage models taking into account steep gradients of fracture toughness and transition from brittle to ductile behaviour and implementation of Finite Element models to simulate crack behaviour in components. This methodology considers the fracture toughness and ductile to brittle transition temperature as field variables whose values are influenced by the irradiation dose, operating temperature and He exposure. The approach adopts the cohesive zone modelling strategy which models the damage and failure by considering a damage-free solid material (bulk) and an interface consisting of so-called cohesive elements. A cohesive force is considered to act on the cohesive element ahead of a crack tip preventing the crack from propagating. The cohesive element, located directly at the crack tip has a finite stress (the cohesive stress) and the material behaviour of the cohesive element is defined based on temperature and irradiation state. Once the stress in a cohesive element reaches the cohesive strength, the damage initiation criterion is met and the element starts to fail. In the context of this approach, failure implies that the cohesive element releases all its cohesive energy (which represents the work needed to create a unit area of fracture surface) until a critical separation reached. In case of linear-elastic behaviour, the cohesive energy can be related to the Griffith's critical energy release rate which in turn is a function of the mode-I fracture toughness, Poisson's ratio and Young's modulus. Combining the CZM approach with digital image correlation would help to assess the IVCs from the viewpoint of acceptability of crack size/ depth considering the variations in fracture toughness and fracture toughness gradients in the DBTT regime.

Section 5- Damage classification methodology.

Section 5.1 Damage classification rationale

Traditionally, the term damage is often ascribed to the structural deterioration of a material after being subject to different degradation mechanisms such as fatigue, creep etc. However, within the context of fusion IVCs, this definition of damage needs to be augmented due to two key reasons.

Firstly, given that investment protection priorities warrant a strong level of consideration due to the relatively novel and unproven nature of commercial fusion technology, the limit state of in-vessel components requires a consideration of both structural as well as functional aspects of component failure. The margins specified in other Codes and Standards against different failure mechanisms may lead to assurance of structural integrity but that may not necessarily imply assurance of the intended functionality of the component over the design life. Hence, they may need to be ratified prior to adoption considering the limiting criteria unique to each fusion IVC for DEMO conditions by considering all applicable constraints associated with structural integrity (such as strain) as well as functionality (such as heat transfer requirements) which may be influenced by the structural deterioration of the component.

A potential way to address this could be through a comparison of the state of a component when the criterion for onset of failure has been reached for each failure mechanism with an ultimate/ serviceability limit state serving as a benchmark using a target parameter (e.g. maximum allowable strain considering dimensional stability, material ductility limit or intercomponent spacing, critical crack depth considering structural integrity or functional constraints) which is specific to each failure mechanism. The margin between these values would then dictate the target upper limit for actual damage specific to each failure mechanism over the design life and allow assignment of a target damage class. This approach would serve to provide two indications simultaneously. 1). The imposed margin from the onset applied to each (applicable) failure mechanism for a given component 2). The relative significance of each failure mechanism in relation to its impact on the limit state of the component.

Secondly, the potential for synergistic effects between plastic damage accumulation and elastic fracture coming into play (which is to be expected in the case of fusion IVCs) merits the need for a strategic approach considering the overall impact on the component performance of all applicable failure mechanisms that would come into play over the component's design life in order to quantify the damage in a more pragmatic fashion.

The R6 failure assessment procedure [18], [19] indicates that the plastic damage accumulation has an influence on the margin against fast fracture and hence provides a suitable path for design assessment where both crack growth and plastic strain accumulation (in the remaining ligament) can be expected to occur simultaneously in the component over the course of the intended minimum design life. Such an approach would lead to more conservative estimates for the allowable margins corresponding to the two failure modes in comparison to what may transpire if they were to be treated in isolation. This would be particularly significant if there were to be constraints on component inspectability/ maintainability especially given the prospect of interplay between high temperature and high radiation effects.

From a design perspective, one may consider the possibility of a defect originating at any time during the operational life of the component and gradually growing under fatigue. Using a presupposition that protection against fast fracture warrants a stronger consideration (given the possibility of imminent catastrophic failure of the component in the event of the limiting condition being breached), an acceptable upper "design" limit can be fixed on the normalised stress intensity factor (through adopting a suitable margin) such that the corresponding limit imposed on the reference stress allows loading well past the yield point as per the R6 failure assessment diagram. Using a basic material constitutive model that adequately captures the monotonic or cyclic stress-strain behaviour of the material (such as the Ramberg-Osgood model), this can subsequently be translated into a corresponding limit on the allowable accumulated strain.

By using the limits so formulated against both the incremental damage (in the remaining ligament) and fast fracture, a design check would then involve a systematic assessment of the component performance corresponding to an applied load case considering crack growth as well as damage development in the remaining ligament apropos to the design life considerations. The parameters that need to be controlled through the imposition of these limits (e.g. defect size, accumulated strain) can be imparted with an additional layer of conservatism (beyond what the R6 failure assessment diagram would impose) through considering the component specific constraints that would transpire from the concept design considerations (such as geometric spacing constraints, material ductility limit etc). This forms the premise of damage classification rationale within the DDC-IC.

Based on this approach, the margins to be set against different (applicable) failure mechanisms can then be evaluated congruent to the overall component-level damage limit as mandated by the quality class assigned to the component. Thus, the proposed approach allows sufficient flexibility in the evaluation of different concept designs as opposed to applying pre-fixed margins to protect against different failure mechanisms for assessment of all concept designs which will likely provide a highly granular structural integrity assessment procedure for DEMO in-vessel components.

Conceptually, this approach would be preferable over qualifying a proposed design against the onset of each failure mechanism considered in isolation which may be non-conservative. This may be the case if the actual limit state of the component (as per the structural/ functional design constraints) may have well been exceeded prior to the onset criterion for any particular failure mechanism being reached or the aggregation of partial damage contributions from the incremental failure mechanisms and fast fracture could lead to the component reaching its limit state even if the onset criteria for individual failure mechanisms are not reached over the design life. Alternatively, if the component is assessed against only one particular incremental failure mechanism, then disqualifying a proposed design for exceeding the criterion for onset of failure for that specific failure mechanism may prove to be overly conservative if the final state component would be well within the requirements based on limit state considerations.

Section 5.2 Damage classification approach

The DDC-IC provides rules for design assessment against selected failure mechanisms which may have differing degrees of relevance depending on the extent to which the onset of a particular failure mechanism would impact the component-level requirements associated with the chosen damage limit. The damage classification scheme proposed in the DDC-IC encourages consideration of the ultimate limit state of the component going beyond the usual understanding for damage limit criteria levels (A-D) as mandated by the IAEA guidelines [2]. In part, this is to be achieved by apportioning selective weighting to the different failure mechanisms that a component being designed may likely be susceptible to. In addition, the proposed damage classification rationale proposes a route for establishing the acceptable maximum component-level damage limit for different criteria levels. This can be selectively assigned to a component dependent upon the quality class and operating condition using “conservative” limits that can be inferred from the R6 failure assessment diagram considering the combined effect of proximity to elastic fracture and plastic deterioration.

To implement this, the DDC-IC recommends identification of sub-levels or classes for the damage limits corresponding to each failure mechanism with the boundary for each class being set using the criterion for onset of failure specific to each failure mechanism as a baseline. This permits a clear indication of the differing degrees of relevance being apportioned to different failure mechanisms and provides a simple scheme to clearly indicate the safety margins being built into the design against different failure mechanisms through a normalizing benchmark criterion which will allow cross comparison (through a clear interpretation of the significance of the assigned damage class corresponding to different failure mechanisms).

The approach proposed within the DDC-IC involves the following major steps

1. Identification of the appropriate damage limit using the categorization approach prescribed in [2] giving due consideration to the operating condition and safety significance of the component.

2. Corresponding to the damage limit adopted, apportioning the appropriate target damage class specific to each failure mechanism to align the expected assessment outcome to be congruent to the requirements of the chosen damage limit.

As prescribed in [20], designing a component so that it resists the event met without suffering damage or by admitting the component can undergo a certain level of gross damage while guaranteeing the safety requirement may be approached by setting the acceptable damage limits and tailoring the safety margins considering the frequency of the event and the safety function. This may be further extrapolated by considering the relative significance of the different failure mechanisms coming into play. For example, a component which cannot be easily repaired assessed against fatigue crack growth and ratchetting may be required to show different margins of protection against the onset of each of these failure mechanisms. This would depend upon the extent to which the physical state of the component when the criterion for onset of failure corresponding to these mechanisms is reached would impact the susceptibility of the component to exceed the gross damage limit assigned to it.

On this basis, the DDC-IC recommends implementation of a four-level damage categorization scheme as summarised below

1. A combination of component and failure mechanism indicating conformance to D-0 (low damage) criterion (over the design life) implies that the estimated damage is less than 30% (currently set as the design limit) of the value corresponding to the criterion for onset of failure for that particular failure mechanism.

2. A combination of component and failure mechanism indicating conformance to D-1 (subcritical damage) criterion (over the design life) implies that the estimated damage is greater than 30% but less than 100% of the value corresponding to the criterion for onset of failure for that particular failure mechanism.

3. A combination of component and failure mechanism indicating conformance to D-10 (critical damage) criterion (over the design life) implies that the criterion for onset of failure is met but not exceeded at the end of the design life.

4. A combination of component and failure mechanism that can be assigned D-100 (excessive damage) criterion" would imply that a state of damage (at the end of the design life) being well past the criterion for onset of failure (for that particular failure mechanism) would still be acceptable. Assignment of the D-100 class would imply that the component design did not require assessment against that specific failure mechanism (for a specific operating condition).

   The D-100 class will likely be assigned to "non-critical" failure mechanisms under accident scenarios. Hence, while a component design may not be assessed against the failure mechanism which is assigned D-100 class (for a specific operating condition), this would not imply that the proposed component design would fail the overall structural integrity assessment for a given load case. It may well be possible for the proposed design to meet the limit state requirements after consideration of all other applicable failure mechanisms.

The above categories would identify the damage class against different failure mechanisms to which a component has been designed for each operating condition.

Furthermore, since the assessment against different load cases for the same component may involve consideration of a separate set of failure mechanisms (with acceptable damage limit also being effected by the component location to some extent), it stands to reason that separating the nomenclature to identify the margins set against different damage mechanisms from that used to identify the overall component level damage limit will provide a high level of granularity and clarity in the presentation of the design assessment outcomes. Also, since the criterion for onset of different failure mechanisms involves different parameters (e.g. limiting total damage based on number of cycles, limiting strain/ strain energy, fracture toughness), the proposed approach provides a route to easily identify the margins built into the design against different failure mechanisms through a consistent terminology.

Section 6- Near term challenges and key areas of focus for DDC-IC

The immediate challenge towards finalisation of the DDC-IC as a fully-integrated design guideline for DEMO IVCs involves concretization of the estimates associated with pertinent service loads and finalisation of candidate material properties and allowables to cover the full operational regime (considering steady operating conditions as well as "accident" scenarios) foreseen in the DEMO IVC environment.

Another key area of focus in the near term is to harmonize the structural integrity design by analysis rules under development within the DDC-IC with the corresponding rules from other sources to address any inconsistencies between the different sources and provide clear guidelines with the choice of the design rule (or the recommended rules from other sources presented in order of priority) to be used where multiple options are available for any particular failure mechanism. In order to address this, investigation of the following key areas are underway:

- Sufficiency of the design rule validation considering anticipated operating temperature, durations and irradiation dose (targeting DEMO IVC requirements).
- Sufficiency of the design rule validation through (physical) testing.
- Sufficiency of the load cases considered as part of design rule validation.
- Adequacy of the material models and material properties used as part of the design rule validation.
- Clarity of theoretical basis/ approximations underpinning each design rule and the corresponding limits of applicability.
- Sufficiency of the sensitivity analysis carried out in respect to mesh refinement, analysis set up (e.g. load step size increment) and applied boundary conditions.
- Sufficiency of the benchmarking studies carried out.

Selected challenges would need to be confronted and harmonized within the DDC-IC assessment philosophy in order to achieve the above targets. Among other aspects, this would involve assessment of component designs using load cases involving irradiation as a priority since it would likely expose critical considerations that may be missed otherwise. In the near term, assessment of the influence of radiation on material properties would need to be based on an extrapolation of the data from the fission irradiation database using theoretical assumptions. For instance, some studies from the past [21] indicate that the expected damage in fusion components is nearly 3-4 times that seen in fission reactor components while the expected production rate of transmutant Helium would be nearly 30-40 times that observed in fission reactors. Techniques such as isotope tailoring combined with intense mixed fission neutron spectrums are being explored as suitable approaches to realize the elevated Helium transmutation rates that would enable Helium induced irradiated bulk mechanical properties quantification.

Nevertheless, it would be difficult to validate the material properties for the target lifetime under “real” operating conditions due to lack of empirical knowledge and data. This hence necessitates modelling the effect of foreseen irradiation damage on the in-vessel material properties with sufficient accuracy which would, in turn, require a physical understanding of the effects of irradiation on the properties that would constitute the design resistance against the different failure mechanisms. For instance, it has been proposed [22] that pre-irradiation strains introduced in components (e.g. during manufacturing) can reduce the available ductility post irradiation by a level commensurate with the extent of damage incurred prior to irradiation. In other words, strain history effects would reduce the available ductility post irradiation as compared to an irradiated material with no prior loading history. Hence, establishing the relationship between the strain accumulated prior to the introduction of radiation and the cumulative strain to failure (considering partial loading in unirradiated condition followed by loading in irradiated condition) as a material property characteristic may be warranted from a design point of view. However, given that the strain to rupture is variable as a function of temperature and dose (with the dose itself evolving concomitantly with accumulated strain and temperature), the relationship between pre-irradiation damage and reduction in post-irradiation ductility may not necessarily be linear.

It has also been observed that at temperatures below 350°C (which may be of significance for water cooled concepts), irradiation of EUROFER may shift the DBTT in the affected regions. If the radiation damage does not impact the whole component uniformly, then it may be possible to have different levels of deformation (and allowable strains) in different sections of the material, when the material is cooled to room temperature for handling/ maintenance and subsequently reloaded during plant start-up. Such aspects may require close examination and consideration within the overall design philosophy.

Section 7- Conclusions

The DDC-IC initiative is primarily aimed towards optimisation of DEMO IVC structural integrity design assessments to support concept and detail design studies through addressing gaps in existing nuclear structural integrity design Codes and Standards. In particular, the DDC-IC addresses the need for design rules and analysis procedures to complement those in other Codes and Standards specifically targeting failure mechanisms that are not addressed adequately (at the time of writing this manuscript) in the other sources from the viewpoint of structural integrity design assessment. Equally, a closely related requirement is to formulate approaches to provide a higher level of granularity in the prevailing design assessment approaches against different failure mechanisms by harnessing the refinement in the visualization of the component response in the inelastic loading regime made possible by the advanced non-linear FE analysis tools.

As highlighted before, the DDC-IC initiative is unique in that it is supported by comprehensive and targeted validation testing and material qualification programs that would be pivotal for qualification of DEMO IVC concept designs in conditions well exceeding the limits of applicability of other Codes and Standards. It is hence anticipated that the DDC-IC will help to overcome the limits of applicability of other existing design Codes and Standards and increase the design space beyond what may be typically imposed by their usage. This is necessitated in part by the inherent peculiarities in the properties of the candidate materials that necessitate suitable trade-offs between design parameters and require a critical examination of the assumptions underpinning the design rules and methodology prescribed in the existing nuclear design Codes and Standards.

The inelastic DBA approach inherent to the DDC-IC supported by dedicated material models would allow monitoring (predicting) the structural response of the component to a high level of accuracy. Given the lack of evidence to substantiate the formulation of "empirically justified" load cases for DEMO operational conditions, a prudent measure would hence be to place emphasis on simulating and assessing the component response and imposing corresponding limits on the incurred damage. This flexibility would allow some relaxation in the stringency of the limits that would otherwise be imposed on the assumed loads if the allowable stress design philosophy was to be adopted as part of the concept design assessment studies. However, it would be counterbalanced by the imposition of limits on the component resistance parameters leading to a more refined assessment of the concept designs. This would be congruent to the limit state design philosophy which would permit the loading to exceed the material elastic limits (where warranted) and subsequently impose a requirement for (conservative) factors to be applied on both the applied load as well as resistance parameters considering the ultimate "limit state" of the component.

From the viewpoint of structural integrity assessment, it is also important to consider the complex interplay between ductile and brittle failure modes within a fusion IVC context especially considering the dynamic evolution of the material condition while a failure mechanism such as crack growth is underway. For instance, while ductile behaviour is typically expected in metals at high temperatures, it is quite possible for brittle failure mode to assume dominance under suitable conditions. This may include loss of ductility due to irradiation, imposition of plane strain conditions (either by the geometric factors such as component thickness or tri-tensile loading or a combination of these) and application of sufficiently high loading rate.

The DDC-IC would provide a design philosophy that would facilitate convergence of these considerations into a coherent engineering methodology through a careful examination of the fundamental concepts underlying different failure mechanisms and the respective significance and interplay of the key control variables such as the material properties and boundary conditions. Furthermore, the constraints imposed not only by the putative technical challenges inherent to fusion tokamak operations but also to the investment protection priorities that are expected to be on par with operational safety considerations will need to be taken in consideration. For instance, the EUROfusion Generic Site Safety Report [23] indicates that all in-vessel and in-port components of diagnostics and actuators on DEMO should achieve long component lifetime in order to minimize the number of control failures and to minimize maintenance needs and the resulting downtimes of DEMO. More quantitatively, the goal is to achieve maintenance-free operation of all in-vessel components over at least the blanket lifetime, i.e. 2 full power years for the starter blanket, which is designed for a maximum neutron fluence of 20 displacements per atom (dpa) in the structural material, and 5 full power years for the second blanket (50 dpa). It is anticipated that the DDC-IC would serve to facilitate not only the demonstration of the structural integrity of the in-vessel components in the foreseen operational environment, but also the suitability of the IVCs to fulfil the intended functions in congruence with the overall plant availability/ reliability requirements. Although this would be a stringent expectation to set at the design stage (attributable mainly to investment protection considerations), it would not however preclude the requirement for targeted in-service monitoring/inspections during plant operation. Should a key in-vessel component fail prematurely partway through the intended design life, then unplanned plant shutdowns may inevitably be required which may affect the intended maintenance-free operation period. However, sufficient optimization of maintenance activities and schedules (which could reduce the plant downtime during maintenance) may allow commensurate relaxation in the minimum maintenance-free operation expectation. This would likely evolve with empirical experience gained from plant operations.

It is also envisioned that the methodology developed as part of the DDC-IC initiative can be suitably leveraged for evolving requirements with suitable adaptation of the methodology through dialectic reasoning and supporting empirical adjustments considering the significance and interplay of the different failure mechanisms. These adjustments may include for example, using the correct constitutive model for the chosen materials (if distinct from the candidate materials considered as part of validation studies within the DDC-IC) and carrying out validation experiments to refine the design rule constants for the target materials using representative material data and targeted testing campaigns. This, along with the relevant material property data for the chosen materials in the representative operational conditions, would hopefully allow the basic methodology to be tailored for other cases. However, some judgement may need to be exercised as part of this to ensure that any material specific/ boundary condition related cliff edge effects (e.g. pertaining to ductile to brittle transition) are duly addressed.

Hence, while the short term objective of the DDC-IC initiative is to establish the DDC-IC as a viable single point of entry for DEMO in-vessel component design rules to ensure consistency and coherence in DEMO in-vessel component concept design assessment activities, it is also anticipated that over the longer-term, the DDC-IC methodology will serve as a generic guideline for structural integrity qualification of fusion systems and component designs.

Nevertheless, use of DDC-IC would not preclude the usage of other Codes and Standards especially given that there are selected failure mechanisms for which rules have not been explicitly developed as part of the DDC-IC initiative. In such instances, using other design codes for different aspects of design may be warranted. However, it may need to be recognised that the design rules in other Codes and Standards may have been so formulated as to give assurance of integrity through appropriate trade-offs between competing requirements (e.g. apportionment of design margins for selected component classes with commensurate expectations levied on aspects such as manufacturing, testing, maintenance and quality control requirements). Hence the adoption of other Codes and Standards should be done only after the ensuing implications and applicable caveats that are inherent to the overall design philosophy are clearly studied and understood.

Acknowledgements

The work reported in this paper was carried out with the framework of the EUROfusion consortium specifically to support Mission 6 of the European Research Roadmap to the realization of Fusion Energy for integrated DEMO design and system development. The preparation of this manuscript has been part funded by UK Atomic Energy Authority. The authors also wish to acknowledge the following researchers whose works in support of this initiative have been summarised in this manuscript.

J Aktaa (Creep-fatigue crack initiation assessment rule), P Cooper (Exhaustion of ductility assessment rule), N Gupta (Fatigue crack growth assessment rule), M Jetter (Fast fracture assessment rule), R Sharma/ R Spencer/ V Ambikadevi (Multi-axial fatigue crack initiation assessment rule).

Credit authorship contribution statement

S Madabusi: Writing – Original draft.
G Aiello : Writing – Review, editing and supporting contribution.
D Terentyev : Writing - Review, editing and supporting contribution.
G Pintsuk : Writing - Review, editing and supporting contribution.

Declaration of competing interest

The authors declare that all supporting activities associated with this work were conducted within the precincts of the EUROfusion collaboration and in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. International Thermonuclear Experimental Reactor (ITER), Structural Design Criteria for ITER In-vessel Components (SDC-IC), ITER, 2012.

2. International Atomic Energy Agency, "Integrated Approach to Safety Classification of Mechanical Components for Fusion Applications," 2018. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/TE1851web.pdf.

3. J. Ilves, "SOP-01.29 Quality Classification Determination and Implementation (QA-010)," F4E (IDM UID 22MD99), 2020.

4. EUROfusion deliverable report SAE-1.6.2-T002 D003 "Safety classification of Systems Structures and Components: Identification of SSCs safety relevance", OCT 2020, IDM reference EFDA_D_2P689S.

5. Health and Safety Executive, "Process safety aspects of safety report assessment", Health and Safety Executive, UK, https://www.hse.gov.uk/comah/sram/docs/s12c.pdf.

6. P. Cooper, " Report on Exhaustion of ductility", EUROfusion internal report (IDM - EFDA_D_2R3CJJ), 2023.

7. R. Rajakrishnan, "Report on FE materials models", EUROfusion internal report (IDM - EFDA_D_2R3M2Q), 2023.

8. J. Aktaa, W. Timmis, M. Porton, "Report for WP12-DTM-03-T02 – Identification of DEMO Failure Modes", EUROfusion internal report (IDM - EFDA_D_2M8CL5), 2012.

9. G. A. Spagnuolo, "Breeding Blanket Load Specifications Document", EUROfusion internal report (IDM - EFDA_D_2NLL6N), 2019.

10. The American Society of Mechanical Engineers, ASME BPVC Section VIII, Division 2, Part 5 - Design by Analysis requirements, The American Society of Mechanical Engineers, 2017.

11. T. Wierzbicki, Y. Bao, Y.-W. Lee and Y. Bai, "Calibration and evaluation of seven fracture models," International Journal of Mechanical Sciences, no. 47, pp. 719-743, 2005.

12. G. R. Johnson and W. H. Cook, "FRACTURE CHARACTERISTICS OF THREE METALS SUBJECTED TO VARIOUS STRAINS, STRAIN RATES, TEMPERATURES AND PRESSURES," Engineering Fracture Mechanics, vol. 21, pp. 31-48, 1985.

13. Afcen, RCC-MRx Design and Construction Rules for mechanical components of nuclear installations: high temperature, research and fusion reactors, Afcen, 2018.

14. The American Society of Mechanical Engineers, ASME BPVC Section III, The American Society of Mechanical Engineers, 2021.

15. T. Lagoda, E. Macha and M. Sakane, "Estimation of High Temperature Fatigue Lifetime of SUS304 Steel with an Energy Parameter in the Critical Plane.," Journal of Theoretical and Applied Mechanics, vol. 41, no. 1, pp. 55-73, 2003.

16. A. Niesłony et al, "New method for evaluation of the Manson–Coffin–Basquin and Ramberg–Osgood equations with respect to compatibility," International Journal of Fatigue, vol. 30, no. 10-11, pp. 1967-1977, 2008.

17. Ž Božić, S Schmauder and Marijo Mlikota, "Application of the ΔK, ΔJ and ΔCTOD parameters in fatigue crack growth modelling," Tehnicki vjesnik - Technical Gazette, Vol 18(3), p459-466, 2011.

18. P. J. Budden and J. K. Sharples, "THE R6 DEFECT ASSESSMENT PROCEDURE: STATUS AND KEY RECENT DEVELOPMENTS," in Transactions, SMiRT-23 - 23rd Conference on Structural Mechanics in Reactor Technology, Manchester, UK, 2015.

19. P. J. Budden and J. K. Sharples, "Practical Failure Assessment Methods," in Comprehensive Structural Integrity, ScienceDirect, 2003, p. Section 7.07.6.1.

20. S.M. Gonzalez de Vicente et al, "Safety classification of mechanical components for fusion application", Fusion Engineering and Design, Volume 136 (B), pp 1237-1241, 2018.

21. P.J. Karditsas, "Design Issues and Implications for Structural Integrity of Fusion Power Plant Components", Fusion Engineering and Design, Volume 84 (12), pp 2104-2108, 2009.

22. M. Fursdon, J.-H. You, M. Li, "Towards reliable design-by-analysis for divertor plasma facing components – Guidelines for inelastic assessment (part 1: Unirradiated)", Fusion Engineering and Design, Volume 147, 2019.

23. J. Johnston, "Final report on Generic Site Safety Report Volume 2 - Overview of Design and Safety Features", EUROfusion internal report (IDM - EFDA_D_2MRF7Z v2.0), 2020.