Fusion Engineering and Design xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Structural integrity for DEMO: An opportunity to close the gap from materials science to engineering needs

M. Porton[a,*], B.P. Wynne[a,b], R. Bamber[a], C.D. Hardie[a], M. Kalsey[a]

[a] *CCFE, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK*
[b] *University of Sheffield, Sheffield, South Yorkshire S10 2TN, UK*

HIGHLIGHTS

- Key shortfalls in the current approaches to verification of structural integrity are outlined.
- Case studies for high integrity applications in other demanding environments are examined.
- Relevant lessons are drawn from fission and space for the design stage and through service life.
- Future efforts are suggested to align materials and engineering for DEMO structural integrity.

ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form
17 December 2015
Accepted 21 December 2015
Available online xxx

Keywords:
Structural
Design
Criteria
DEMO
Materials

ABSTRACT

It is clear that fusion demonstration devices offer unique challenges due to the myriad, interacting material degradation effects and the numerous, conflicting requirements that must be addressed in order for in-vessel components to deliver satisfactory performance over the required lifetime. The link between mechanical engineering and materials science is pivotal to assure the timely realisation and exploitation of successful fusion power. A key aspect of this link is the verification of structural integrity, achieved at the design stage via structural design criteria against which designs are judged to be sufficiently resilient (or not) to failure, for a given set of loading conditions and desired lifetime. As various demonstration power plant designs progress through their current conceptual design phases, this paper seeks to highlight key shortfalls in this vital link between engineering needs and materials science, offering a perspective on where future attention can be prioritised to maximise impact.

Firstly, issues in applying existing structural design criteria to demonstration power plant designs are identified. Whilst fusion offers particular challenges, there are significant insights to be gained from attempts to address such issues for high performance, high integrity applications in other demanding environments. Therefore case studies from beyond fusion are discussed. These offer examples where similar shortfalls have been successfully addressed, via approaches at the design stage and through service lifetime in order to deliver significant insight for structural materials and improved design solutions for first-of-a-kind engineering endeavours where the consequences of failure were of similar concern.

Finally, drawing inspiration from these case studies, the current state-of-the-art is explored to propose how both materials science and engineering should be aligned in order to address the issues we face in realizing effective fusion demonstration power plants.

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1. Introduction

In parallel to the final realisation of ITER, several participating parties are pursuing the conceptual design of their own demonstration fusion power plants (e.g. [1–3] and referred to nominally as DEMO for the purposes of this paper). At this early stage outline plant configurations, safety case rationale and indicative component loads are under development in order to inform design studies for the in-vessel components, as typified by ongoing European activities [4].

A key aspect of such studies is the engineering analysis, undertaken to allow derivation of in-service temperature and stress distributions within candidate component designs. These distributions are post-processed to form metrics for various prospective failure modes, which are in turn compared against allowable values for the relevant structural materials. This collection of metrics

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[*] Corresponding author.
E-mail address: michael.porton@ccfe.ac.uk (M. Porton).

http://dx.doi.org/10.1016/j.fusengdes.2015.12.050
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Please cite this article in press as: M. Porton, et al., Structural integrity for DEMO: An opportunity to close the gap from materials science to engineering needs, Fusion Eng. Des. (2016), http://dx.doi.org/10.1016/j.fusengdes.2015.12.050

and allowables, against which structural integrity of designs can be assessed, is referred to as the structural design criteria. These criteria represent the intersection of materials science and engineering; material science culminates in the provision of material allowables for a range of operational conditions, loading scenarios and failure modes whilst the engineer seeks compliance for their design via demonstration (either by experiment or modelling) that these values are not exceeded in the anticipated life cycle of the component.

However, in assessing DEMO designs the engineer and materials scientist are presented with an unprecedented environment for which the current criteria were never intended. Existing structural design criteria originated: (i) to describe other operating environments; (ii) for technologies wherein high levels of conservatism were sought due to their hazards and associated safety case considerations; (iii) for systems wherein high levels of conservatism were permissible due to the substantial margins available in candidate designs when compared against the requirements placed upon them. This raises concern that consideration of designs against existing structural design criteria will provide misleading conclusions resulting in either non-conservative estimations that encourage the progression of designs with insufficient margin, or excessive conservatism and the unnecessary rejection of viable design solutions.

In turn this paper seeks to: (i) interrogate current practice in order to highlight some shortfalls of existing nuclear structural design criteria; (ii) discuss the freedom available to formulate an alternative approach in light of safety case considerations; (iii) identify applicable lessons from other world-leading engineering endeavours within new operational environments; (iv) draw attention to modern opportunities and aids that can contribute to this issue; (v) summarise the key findings.

2. What are the issues?

It is not possible, via the commonly applied tools of the fusion community, to verify whether the structural materials, and the designs in which they are embodied, are sufficient to withstand the challenges of the DEMO environment for the required operational lifetime and performance requirements. As first discussed elsewhere by the author [5] and elaborated below, the application of existing structural design criteria[1] for nuclear environments (e.g. ASME BPVC III [6], RCC-MRx [7], SDC-IC [8]) to exemplar DEMO in-vessel components highlights key shortfalls at the interface of materials and engineering: (i) existing metrics fail to adequately describe component and material performance; (ii) a comprehensive library of materials data in relevant conditions does not yet exist; (iii) the current approach to material allowables restricts the available design space for the development of acceptable conceptual solutions.

2.1. Describing component and material performance

Alongside the option of design by experiment, which is often eschewed due to its inherent expense, the current structural design criteria offer two analytical routes to permit the verification of a given design – elastic or inelastic/elasto-plastic. In applying design by analysis, the engineer will typically seek to verify the design by the simplest, quickest route available before progressing to increasing levels of analytical complexity and associated sophistication in the structural design criteria. Thus, the elastic analysis route is usually explored first, relying on the concept of stress linearisation to separate the stress field though the component thickness into components (membrane, bending, peak), allowing limits to be placed on their combinations, in addition to removal of fictitious and irrelevant stress concentrations as required. However, this is only applicable to situations with thin shells and is a link to the past; the geometries and components to which these techniques were originally applied did not necessitate, nor did the computational infrastructure of the time support, the application of intensive elasto-plastic analysis and targeted sub-modelling that is today a straightforward undertaking by comparison. Indeed, the simplifications made in applying elastic rules can be inherently misleading both in the metric created from the engineering analysis and the allowable against which it is measured.

For example, in the case of ratchetting, the Bree diagram visually defines limits for combinations of primary (e.g. pressure driven) and secondary (e.g. thermally driven) stresses extracted from elastic analyses in an attempt to ensure cyclic shakedown of the material and to prevent the runaway accumulation of plastic strain. However, the Bree diagram is geometry and load dependent, can only be constructed analytically for very simple cases that are remote from discontinuities and therefore can present wholly unrepresentative allowables in the context of complex 3-D fusion components [9].

The current structural design criteria do offer alternative inelastic analysis routes. However, for example in the case of ratchetting, in the absence of material models (e.g. Chaboche) that simulate strain softening and other complex material behaviours, an indirect measure of failure is used via path linearisations rather than attempting the more direct calculation of absolute cycle by cycle development of deformation. This results in arguably conservative limits that seek to completely prevent rather than precisely manage the accumulation of progressive deformation over the lifetime of the component.

Beyond these fundamentals of the analytical approach, another significant shortfall of the currently available design criteria is their inability to effectively describe the material phenomenological behaviour of DEMO candidate designs. For example, the current treatments of the key failure mechanism creep-fatigue are unable to describe or therefore to verify the effects of cyclic softening (an inherent behaviour of reduced-activation ferritic martensitic steels such as EUROFER97) upon component integrity [10].

Key challenges also remain for the verification of embrittled components due to the unique attributes of fusion structural materials and the environment in which they must perform; the intense thermal gradients within many in-vessel components will result in localised embrittlement and large variations in material performance within small regions, further invalidating the stress linearisation approach [11].

Though examples of preliminary rules for the assessment of heterogeneous multi-layer structures exist [8], verification of jointed or armoured structures by analysis is not possible with current criteria due to a lack of established practices for interface stress singularities such as those in the dissimilar joints foreseen for the DEMO divertor and first wall. Indeed, application of existing structural design criteria for monolithic structures to dissimilar joints is shown to be invalid due to the effects of residual stress and the change in yield observed on accumulation of plastic strain through the lifecycle, e.g. as can be often seen in manufacture of dissimilar joints (i.e. the Bauschinger effect) [12]. Due to the lack

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[1] For clarification, consider the following basic definitions:
Code is a set of rules and recommendations to assist demonstration of regulatory compliance. The rules typically cover design and analysis, material procurement, fabrication, inspection through operation and asset management, giving consistency to ensure the structural integrity of components through life and are subject to continuous improvement based upon feedback from industrial experience.
Structural design criteria are the body of rules offering a framework for design validation, supported by relevant material specifications and properties; may be found within the broader body of a code or in isolation.
Standards are a set of technical definitions and guidelines that function as instructions for designers, manufacturers, operators, or users of equipment.

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