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Design substantiation of ceramic materials on fusion reactor confinement boundaries

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HIGHLIGHTS

- Review of issues in design of ceramic components to established rules.
- Discussion of failure criteria for brittle materials.
- Discussion of potential solution for issues identified.

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ABSTRACT

Ceramic components will be used for electrical insulation and optical transparency on the heating and diagnostic systems of fusion reactors. As these form the boundary for the radioactive confinement, a defined procedure is required to demonstrate structural integrity. The established design codes are incompatible with ceramic materials for various reasons, predominantly the brittle nature of ceramics. CCFE and others have started to develop an in-house design code for the use of brittle materials in pressure vessels, this paper discusses the rationale behind the rules. The difficulty of reconciling the statistical nature of failure in ceramics with the deterministic nature in codes is addressed and it is suggested that the only way to achieve this is by a proof testing approach. The inherent weakness of the proof testing methodology, quantifying the strength loss during the qualification test is discussed. Further work is required to determine the validity of the rules experimentally.

1. Introduction

Ceramic insulators are critical parts to any fusion reactor heating system and will form part of the vacuum boundary and radioactive inventory confinement [1]. As radioactive inventories rise through the ITER and DEMO experimental reactors there is anticipated to be increased regulatory interest in ceramic structural integrity. In order to utilise these materials in a nuclear confinement application, such as the windows envisaged for the ITER or DEMO reactors, a rigorous demonstration of structural integrity though-out the anticipated lifetime is required. It is felt that an agreed set of formal design rules may be the most efficient vehicle for regulatory approval. The assumptions inherent in the design by analysis sections of conventional pressure vessel codes (RCC-MR [2], ASME BPVC [3] etc) are invalid for brittle materials, therefore it is unacceptable to use these codes to demonstrate structural integrity of such materials. The parts of the nuclear codes concerned with electrical penetrations [4,5] also fail to adequately address these issues (this is confirmed by the use of maximum shear stress theory in stress analysis). This may be acceptable for small insulators subjected to low stress levels, but in fusion reactor design larger window assemblies require explicit attention. In addition to these issues, the current industrial practice for hermetically joining ceramics to metals in high vacuum is limited to either brazing or diffusion bonding utilising interlayers, compounding the difficulties of applying the established pressure vessel design codes to ceramic components. Co-ordinated by the Culham Centre for Fusion Energy (CCFE), Waldon et al. [6] have developed a provisional design code for ceramic windows in fusion environments (WINCOD). This paper discusses the rationale behind the design by analysis rules used by Waldon et al. [6]. It should be noted that at the time of writing, this work is still very much in a preliminary stage and many further refinements and discussions between stakeholders would be necessary to create an autonomous set of design rules. Particularly,

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at present this work lacks consideration of the additional effects of irradiation on the ceramic material. In addition to the material property changes, it will be necessary to consider the effects of radiation induced growth on lattice strain and any effect that this has on subcritical crack growth (SCCG) and therefore lifetime. Further work is required to experimentally validate the prediction of failure provided by these rules against simple pressure vessels subjected to changing load cases.

2. Previous work in this area

Although ceramic materials have been utilised in construction for many centuries, it is only the relatively recent advent of advanced technical ceramics that have allowed them to be used with significant tensile stresses. A literature survey has failed to find accepted design rules for use in the aerospace and automotive industries. Whilst of the pressure vessel design codes surveyed, only the German AD 2000 code [7] has been found to address these issues, although this is written for specific materials e.g. glass and carbon. Some work was found regarding submarine hulls for deep sea diving, although this is thought to be irrelevant due to the strongly compressive stress state caused by the high external service pressures. With respect to nuclear fusion, Hopkins and Price published a review of design with ceramic materials in 1985 [8]. Although their work did not go as far as to express design rules, it did discuss many design issues, including subcritical crack growth. This work suggested that proof testing is the optimum way to achieve the extremely low probabilities of failure demanded in these applications. A NASA standard for ceramic windows on human spaceflight craft [9] was considered to be the most representative document found. This standard enshrined both factorial design and proof testing of ceramic windows. Although many authors have attempted to provide such rules for components in service, see for example [8], these almost always resort to probabilistic methods. The issue with probabilistic methods in the nuclear industry is the required failure probabilities (of for example 10^{-6}) require significant extrapolations from even large populations of test specimens (of perhaps few 100's of samples). This work intends to build on previous work in this area and develop a methodology for demonstrating the structural integrity of a given ceramic component.

3. Key differences between ceramics and metals

Five key differences between metallic and ceramic materials affecting the manner in which they should be treated in design have been identified and are described below.

1) **Brittleness of Material**

Ceramics are brittle materials, typically with ultimate failure at rather less than 0.2% strain. The established nuclear design codes [2,3] typically guard against immediate plastic collapse by comparing linearised primary stresses to allowable strengths. However, the practices of linearising stress and limiting only primary stress carry the assumptions, clearly invalid for ceramics, that the material is ductile enough to allow for both stress redistribution through the thickness and stress relief by thermal strain respectively [10].

2) **Statistical Strength of Ceramics**

Due the brittle nature of ceramic materials, it is impossible to redistribute stress through plastic deformation, therefore their strength is limited by the combination of the largest flaw in the highest tensile stress field in the component [11]. This has two implications for the design of safety critical structural components;

- The distribution of strengths displayed in a population of nominally identical ceramic components is difficult to reconcile with the deterministic approach to failure found in the established design codes. Although many safety cases are written with probabilistic methods, in order to maintain similarities with the current design codes and avoid large extrapolations to low probabilities of failure, it is desirable to use a deterministic approach. The only way to demonstrate ceramic integrity in a deterministic manner is to use proof testing [12].
- As parts get larger from test bar specimens to actual components, the probability of encountering a flaw large enough to limit strength increases. The implication of this is that large parts exhibit lower strength than smaller parts of the same material [12]. This must be accounted for when converting test specimen strength into allowable stresses for components.

Weibull statistics are used by many in the ceramic community to predict probabilities of failure at various levels of applied stress. However care must be taken when using these techniques as it is implicitly assumed that the types of strength limiting defects are similar between test pieces and components. If this is not the case, the extrapolations from test piece data required for predictive design can lead to large errors [12]. Typically in ceramic materials, the mechanical properties are more sensitive to processing and handling procedures than for metallic materials.

3) **Unequal Tensile and Compressive Strengths**

Ceramic materials have different uniaxial tensile and compressive strengths, for example, aluminium oxide typically has a flexural strength (i.e. the tensile surface stress) of approximately 300 MPa yet the compressive strength is often larger than 1500 MPa [13]. The established design codes use either Tresca or Von-Mises equivalent stresses which are inappropriate for use with materials where the stress state influences strength [10]. Using these equivalent stresses is appropriate for ductile (metallic) materials because failure occurs via shear movement of dislocations, which cannot be caused by hydrostatic stress. However, in the majority of strong ceramic materials fracture occurs via the propagation of cracks under tension or shear without the slip of dislocations. A range of multiaxial failure criteria for ceramics has been discussed in the literature.

4) **Time Dependent (Long Term) Strength**

It has been shown by numerous researchers that ceramics can suffer from delayed failure under tensile loads significantly lower than their short term strength [11,14,15]; indeed this effect is addressed explicitly for glass pressure vessels in the AD 2000 Merkblatt N4 [7]. Delayed failures of a ceramic support on the A2 antenna of the JET tokamak were attributed to this failure mechanism [16]. The failures are the result of subcritical cracks growing in a process similar (but not identical) to stress corrosion cracking in metals [12]. The failure mechanism is called "subcritical crack growth" (SCCG) or "static fatigue" and is stress, time and environment dependent, creating practical issues for a design by experiment approach. This has large implications for safety critical structures because structural integrity must be assessed at the end of life condition. It has been proposed in the literature to employ a proof test ratio diagram to determine the required proof test to applied load ratio to ensure adequate lifetime [15]. However, this model has been simplified and accounts for only one loading level, leading to overly conservative results when considering the differing normal and upset conditions found in most pressure vessel service histories.

5) **Minimum Yield Strength of Adjacent Components**

The design by analysis sections in typical pressure vessel codes use elastic – perfectly-plastic material models with minimum yield strengths for elasto-plastic and collapse type analyses. As an example, for a typical stainless steel this is 200 MPa, although actual components (particularly those with large amounts of cold work) can have yield strengths >350 MPa. This has implications for an

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