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A hybrid analysis procedure enabling elastic design rule assessment of monoblock-type divertor components

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ABSTRACT

This paper presents a simplified rule-based elastic analysis procedure (and its rationale) for the structural integrity assessment of the structural pipe component within monoblock divertor plasma facing components (components constructed from a tungsten block with through cooling pipe and copper interlayer). It is first demonstrated that the conventional fully elastic finite element analysis method used in an elastic code rule assessment must be modified when applied to monoblocks to overcome the problems caused by the assembly of multiple materials (with different yield strengths and different coefficients of thermal expansion causing residual stress). This is done by comparing the result of a fully elastic model with a more representative elasto-plastic model incorporating residual stress simulation. The results show that due to the expected high levels of residual stress, the desired elastic modelling of the structural pipe component can only be used to determine cyclic stress range (but not absolute stress), and even then, only if accompanied by elasto-plastic simulation of the non-structural interlayer (to apply the correct levels of differential expansion loads from the tungsten). This mixed elastic-elasto-plastic method is used in the proposed procedure, and applies the elastic code rules employing cyclic stress range, i.e. rules for ratchetting and fatigue. Additional rules for critical heat flux and allowable material temperatures are added. Example results of an assessment using the procedure are also presented for an ITER-like monoblock divertor target component.

1. Introduction

The plasma facing component (PFC) used in the ITER divertor is based on the "monoblock" construction (Fig. 1) comprising tungsten armour block with through CuCrZr cooling pipe separated by a copper interlayer [6]. The CuCrZr pipe provides both the structural support and the means for cooling the armour layer. This type of PFC is also being considered for the divertor in DEMO (the demonstration fusion power plant), but because loading conditions are expected to be more onerous (with high levels of irradiation and particle flux) new monoblock designs are being investigated [1] (as part of the EUROfusion power plant physics and technology programme).

Preferably, before undergoing physical testing, new designs would be assessed using Design by Analysis (DBA) methods following a design code. This is usually achieved by subjecting the results of an elastic Finite Element Analysis (FEA) to a set of "elastic" code rules defining allowable stress for each anticipated failure mechanism. However even the most appropriate current code as used by ITER (SDC-IC [2]) is not ideally suited for assessing PFCs (such as monoblocks) as highlighted in [5] because it is based largely on existing codes for pressure vessels (e.g. ASME [3]) or conventional nuclear installations (RCCMR [4]). Such codes are aimed mainly at thin-walled single material structures, and so are not well suited to the analysis of the multi-material thick-walled construction of the monoblock. Furthermore, monoblock (and most PFC) materials have different coefficients of thermal expansion (CTEs) which cause considerable residual stress following manufacturing joining processes (e.g. when cooling from brazing temperatures). As will be shown in this paper, these stresses are through-thickness stresses and, as such, are not factored into existing elastic design-code methods.

ITER currently use both DBA and "design by experiment" methods to overcome the DBA shortfall in their divertor monoblock design assessments [6]. For DEMO, a new (DBA) assessment code is being created to be called the "DEMO Design Criterion" (DDC) based on elasto-plastic FEA methods tailored to PFCs [7]. However, this is not expected to be released in time for the new concepts currently being developed by EUROfusion [8]. To overcome the immediate shortfall, EUROfusion are supporting the development of a "preliminary" analysis procedure specifically for monoblocks (aspects of this procedure are expected to

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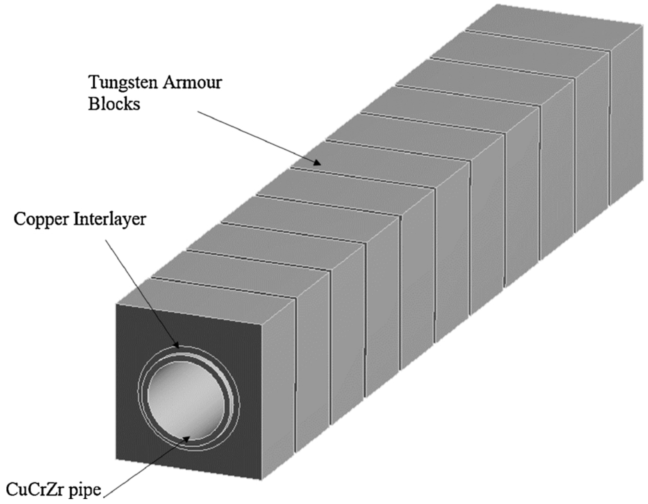

Fig. 1. Section from typical divertor plasma facing component comprising a series of individual tungsten armour blocks surrounding a CuCrZr cooling pipe with copper interlayer.

be integrated into the final DDC). This will not only give a design "performance" measure to use in design optimisation, but also create a common assessment approach to assess the relative performance of the various design concepts being developed.

This paper describes the first stage of this process in which a simplified monoblock elastic analysis procedure (MEAP) has been created. This procedure aims to give a simple but accurate assessment under steady state normal operating conditions and is based on the existing "elastic" code rules (rules to be used with elastic FE analysis), but in a revised form to suit the monoblock construction. The advantage of elastic rules is that they are simple to apply, are well proven and have considerable status. The disadvantage is that there is no explicit method in the associated elastic FE analysis to incorporate residual stress effects - potentially invalidating the resulting code assessment. In this paper, the validity of the elastic code rule methodology is assessed by making comparisons between an elastic code assessment FE model, and a more accurate full elasto-plastic model of the type devised by Li and You [22,23]. The latter allows residual stress to be calculated (approximately) which is then carried forward into the analysis of normal operating load steps to give the improved accuracy. From this comparison, a revised set of rules have been formed to create the MEAP.

2. Scope of assessment

2.1. Load cases

The divertor in both ITER and the proposed European DEMO fusion power plant, is required to withstand nominal steady state heat loads of the order of 10 MW/m^2 during plasma pulses and 20 MW/m^2 during occasional "slow transient" events (estimated to last several seconds) [30,31]. In both scenarios steady state heat distribution is achieved. Higher instantaneous heat loads are possible during fast transient major disruption events lasting a few milliseconds [30], but these events tend to affect only the first few mm of the tungsten [29], and are considered outside the scope of this paper. In the following, an assessment is made under the most prevalent operating case of 10 MW/m^2. The relevance of the conclusions drawn from this load case to other heat load conditions is discussed in section 4.4 and 7.0. A standby (isothermal) load condition is also considered which, for relevance to DEMO, is set by the anticipated coolant temperature of 150 °C.

2.2. SDC-IC elastic code assessment

The rules considered for the MEAP are taken from SDC-IC [2] low temperature rules (section IC3100). The failure mechanisms covered by these rules are plastic collapse, excessive strain (exhaustion ductility, flow localisation), immediate fracture, progressive deformation (ratcheting), and fatigue. The rules within the code are split into those relevant to the first application of the load – the monotonic rules (plastic collapse, excessive-strain, and fracture) – and those relevant to cyclic loading (ratcheting and fatigue). In most cases it is necessary to determine averaged section (membrane) stress or averaged membrane-plus-bending stress (using stress "linearisation") when comparing with allowable stress levels.

There are also rules in SDC-IC that deal with both elasto-plastic methods and joints (and by implication the effect of joining process). The joint rules are provided primarily for assessing joint strength using knock-down factors (joint coefficients). These rules have not been incorporated into the MEAP, primarily because of a lack of relevant empirical data. The elasto-plastic rules detailed in SDC-IC are also not included in the current work, partly because their appropriateness to PFCs is still being scrutinised as part of the longer DDC development, and partly because they are to be used (in revised form) in the proposed next stage of the "preliminary" monoblock analysis procedure.

For this first stage of procedure development, strict SDC-IC structural rules are only applied to the component deemed as the load supporting component of the monoblock, i.e. the pipe. This is acknowledged to be a simplification; since it can be argued that if the armour or interlayer fail significantly, then this may also cause a failure of the pipe. Recent studies [10,32] suggest that armour failure (such as deep cracking) can be anticipated by analysis of plastic and creep strains in the recrystalised surface layers (if any) of the Tungsten. However, the more complex modelling methods required for such analysis are beyond the scope of the proposed procedure. It is the intention that this limitation will be overcome in the second stage of this work when elasto-plastic methods are used.

2.3. Thermal rules

Where it is not possible to apply elastic rules in their full form (due to problems created by residual stress) a simpler temperature rule has been created, for example to avoid temperatures where CuCrZr is known to be brittle after irradiation. A thermal rule is also created to ensure the heat flux applied to the coolant does not cause film boiling (the critical heat flux rule).

3. FEA models

Two types of model are used initially in this work: an elastic code assessment model, and a full elasto- plastic model with residual stress simulation. From these a hybrid model is created combining both elastic and elastoplastic methods as described below.

3.1. Monoblock geometry, mesh, boundary conditions and materials

The example design of monoblock used for this work is based on the ITER-like design shown in Fig. 2 (similar to that shown in [9] Two planes of symmetry are utilised to enable the use of a quarter model as shown in Fig. 3, together with a coupled constraint on the pipe end face to simulate a no bending constraint but allowing axial expansion. To be consistent with elastic code assessment methodology, material properties for both elastic and elasto-plastic models were taken from SDC-IC App. A [17] and are summarised in Table 1. A Chaboche plasticity model was used in the elasto-plastic models, with coefficients (as shown in Table 2) set so that the uniaxial response matches the monotonic and cyclic stress-strain curves provided by the SDC-IC App. A Figure A.S30.3.1-1 and Figure A.S31.5.8-2 (see example in the Appendix of