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Implications of toroidal field coil stress limits on power plant design using PROCESS

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HIGHLIGHTS

- We describe the superconducting TF coil stress model in PROCESS.
- We show results of validation against FEA analysis.
- Run the model for both DEMO 1 and DEMO 2 over an allowable stress range of 440–720 MPa.
- Outline the implications of changing the allowable stress and the impacts on plant design.

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ABSTRACT

Power plant studies using systems codes allow the optimisation of designs to maximise or minimise some figure of merit: fusion power gain or cost of electricity, for example. The code should trade off between parameters to find the optimum whilst producing a solution consistent with physics and technology limitations. This paper describes the recently updated superconducting toroidal field coil (TFC) stress model in the systems code PROCESS. The TFC structure is critical in determining the reactor design as it influences key parameters, in particular the radial build and toroidal field. The model was validated with FEA and used to investigate how TF stress influences DEMO concept design in both pulsed (DEMO1) and steady-state (DEMO2) devices. The allowable stress in the TFC structural components was scanned between 440–720 MPa for runs in which PROCESS was minimising the major radius, R_0, and produced a variation in R_0 of ~1 m for fixed aspect ratio. The capital cost varied by \$2–3 bn over the same range. Understanding how some parameters limit the design is essential for exploring new DEMO concepts and guiding future research.

1. Introduction

The purpose of a systems code is to model all systems in a fusion power plant – given a set of inputs, requirements and constraints – and trade off parameters to optimise a solution to meet a criterion (such as cost of electricity or net electric power). The models for each system are not exhaustive but try to represent all relevant information to a suitable level of accuracy. Systems codes are necessary when investigating interactions between subsystems during conceptual design.

PROCESS is the systems code used at CCFE and is under continuous development for improvements and incorporating new results [1]. This paper describes the recently updated stress model for the superconducting TFC in PROCESS and examines how the stress in the coil limits the plant design. The current EUROfusion DEMO reference designs were used for the PROCESS runs in this paper with only the allowable stress being changed.

2. PROCESS stress model

The superconducting TFC stress model in PROCESS only considers the stress in the inboard TFC leg and treats it as a wedge of a toroidally continuous ring. The current EUROfusion DEMO designs have 16 TF coils so the toroidal thickness is just $\frac{2\pi}{16} \times r$ where r is a given radial position. The previous model had 5 layers of coil: three layers of steel case and two layers of winding pack.

The model has since been simplified and now consists of two regions: one steel layer and one winding pack layer (Fig. 1). The 5-layer model treated the steel layers as equal and splitting the region into three instead of a single layer was an unnecessary complication

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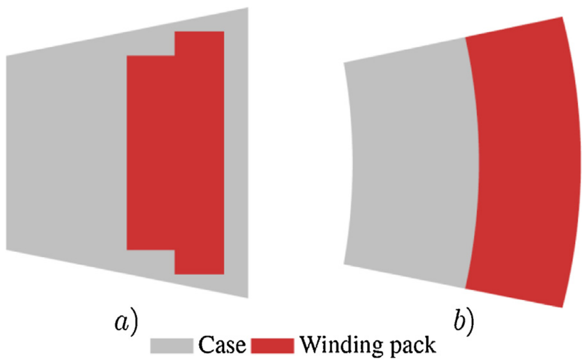

Fig. 1. PROCESS superconducting inboard TFC geometry: (a) is the geometry used for calculating the TFC properties, such as the number of turns, area of winding pack and (b) is the simplified geometry used in the stress model (which neglects the plasma facing and side-wall casing).

as for each layer there was $2n$ boundary conditions. For a given current density, j, in the conductor in region 2 the field is:

$$B = \mu_0 j \frac{r^2 - r_i^2}{2r} \quad (1)$$

where r is the radial position and r_i is the inner radius of the winding. As a result, region 2 has an electromagnetic force per unit volume acting on it in the radially inward direction, F_r.

$$F_r = jB = \frac{\mu_0 j^2}{2}\left(r - \frac{r_i^2}{r}\right) \quad (2)$$

In equilibrium:

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r}{r} - \frac{\sigma_t}{r} = -F_r \quad (3)$$

where σ_r is the radial stress and σ_t is the tangential stress. The code, using simultaneous equations and assuming zero radial stress at the inner and outer edges of the inboard TFC, solves for the deflection, radial and tangential stresses using a smeared (averaged) Young's modulus for the winding pack. The Young's modulus calculation assumes that only certain parts of the winding pack area provide stiffness for the stress calculation and takes this into account when calculating the smeared Young's modulus. The winding pack is made up of cable-in-conduit (CIC) turns. Using the calculated stresses one is able to calculate the von Mises stress for the coil which is given by:

$$\sigma_{vm} = \sqrt{\left(\frac{(\sigma_r - \sigma_t)^2 + (\sigma_t - \sigma_z)^2 + (\sigma_r - \sigma_z)^2}{2}\right)} \quad (4)$$

where σ_z is the vertical stress due to the hoop force (bursting force) in the coil. This is calculated from the cross-sectional area of the winding pack and the total Lorentz force on the upper and lower halves of the coil. The von Mises stress is compared to the input allowable stress limit. In the model there are no shear stresses due to the nature of the geometry in use (Fig. 1). In PROCESS there is currently no calculation for the effect of the out-of-plane stresses on the TFC due to the poloidal field and there is no calculation of the fatigue caused by this [2]. The code neglects the steel casing on the side of the wedge and on the plasma facing side of the coil; this makes the model more conservative as the plasma facing casing provides some support via the sidewall casing.

3. Validation

The data produced by the two-layer model was validated against axisymmetric finite element analysis (FEA) using Abaqus. The calculated stresses agree to <0.4% which is more than suitable for systems code analysis (Fig. 2). The Abaqus analysis also looked at a more detailed 2D model which included the plasma facing and side-wall casing. The results of the detailed 2D model were 6–9% lower than those of the two-layer model. This is due to the extra steel in the outer casing which supports the inner case via the side-wall steel. Table 1 shows the comparison between the 2-layer and 5-layer models for 3 common radial points. The results mostly are in agreement to within a few percent, this is not unexpected given the changes to the model but is sufficiently small for systems code analysis.

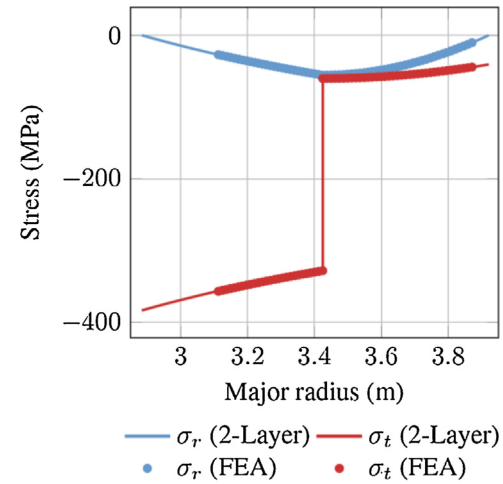

Fig. 2. Stress vs. radius for the two-layer model and finite element analysis for DEMO 1. σ_r is the radial stress and σ_t is the tangential stress.

Table 1
Validation results from comparison of 2-layer and 5-layer stress models for 3 common radial positions (inside edge of steel case, inside edge of winding pack and outside edge of winding pack).

Radius		σ_r	σ_t	σ_{vm}
r_1	2-layer	0	−372	567
	5-layer	0	−373	544
r_2	2-layer	−90	−68	334
	5-layer	−84	−64	325
r_3	2-layer	−46	−54	
	5-layer	−45	−53	

4. Influence on machine design

The results presented in this section come from a scan of the allowable stress in the inboard TFC structural components across the range 440–720 MPa for both the DEMO 1 (pulsed) and DEMO 2 (steady-state) machines whilst minimising the plasma major radius and fixing the aspect ratio at 3.5 for DEMO 1 and 2.8 for DEMO 2. The allowable stress limit in PROCESS is enforced if the von Mises stress (Eq. (4)) in either the case or winding pack reaches the limit. The allowable stress for ITER (class 1) strengthened austenitic steel is 667 MPa [3,4] and the allowable stress value of the weakest ITER TF inboard leg weld (class 1) is 530 MPa. The range chosen for the study was made to include all of these points and an extra margin at either end. If the limit is exceeded PROCESS can alter the make-up of the TF coil, such as increase the case fraction, to lower the estimated stress. There are materials with ultimate tensile stress limits higher than the limits chosen but once safety factors are included the actual allowable stress is lower. It is worth noting that for the DEMO 1 reference design created using PROCESS the TF stress was restricted to only be able to reach 88% of the total allowable limit to take into account the cyclic stresses mentioned at the end of Section 2 and [2].

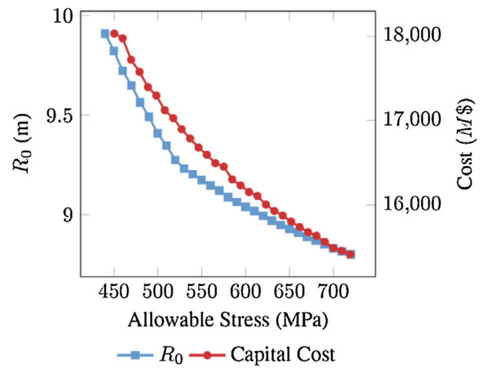

Fig. 3. Major radius and total capital cost (in 2014 USD) vs. allowable stress for DEMO 1 (pulsed).

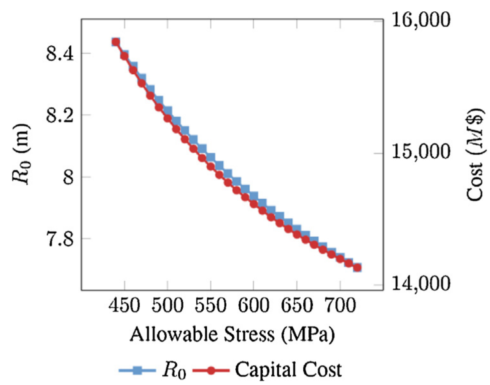

Fig. 4. Major radius and total capital cost (in 2014 USD) vs. allowable stress for DEMO 2 (steady-state).

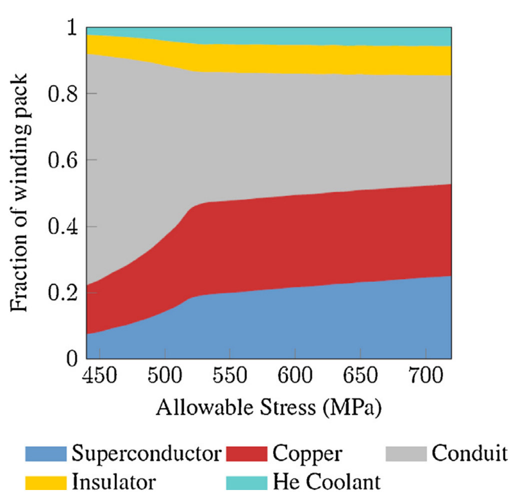

Fig. 5. Composition of the TF coil winding pack by cross-sectional area vs. allowable stress for DEMO 1 (pulsed).

As seen in Figs. 3 and 4 the major radius increases when the allowable stress is reduced. This is due to PROCESS increasing the thickness of the TFC case and the case fraction of the winding pack at lower allowable stresses (Figs. 5 and 6). The capital cost consequently increases and varies by more than \$2–3 bn over the allowable stress range.

The increase in cost is primarily due to the increase in major radius as the allowable stress decreases; this increases the size of most machine components. Capital costs in PROCESS are in 1990 USD but for this study they were converted into 2014 USD using the CPI inflation rate between 1990 and 2014 (1.85). However power plant costs vary with market conditions and an inflation rate of

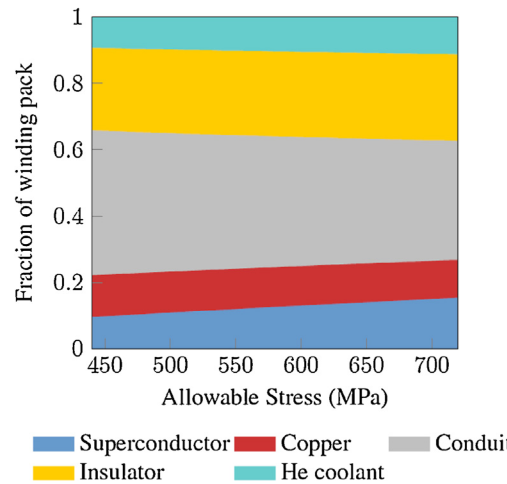

Fig. 6. Composition of the TF coil winding pack by cross-sectional area vs. allowable stress for DEMO 2 (steady-state).

2.29, between 2000 and 2014 was calculated. Using the current power plant inflation rate would increase the cost estimate in PROCESS. The higher rate is not used as market conditions when DEMO will be built are unknown. The magnets make up roughly 1/3 of the total capital costs in PROCESS therefore minimising the magnet contribution is desirable.

In Fig. 5 at low allowable stress, <∼525 MPa, the change in case thickness is much steeper for DEMO 1 because the case thickness reaches its limit of 1 m and PROCESS therefore increases the case fraction in the winding pack instead to provide stiffness. The inner case thickness (Fig. 1) varies from 1.00 to 0.71 m for DEMO 1 and from 0.97 to 0.62 m for DEMO 2. The current density for DEMO 1 increases sharply up to ∼525 MPa and above this value shows a linear increase. The DEMO 2 case shows a linear increase in winding pack current density across the whole range. This is consistent with the different increases in case fraction. The current density is not allowed to exceed 50% of the critical current density (ITER scaling, [5]) and is also limited by the estimated temperature change during a quench. Other considerations enter into the PROCESS calculation such as Psep = R (Psep is power over the separatrix) approaching 20 MW/m or a minimum shield and blanket thickness required on the inboard side both of which will limit gains made by increasing the allowable stress.

5. Summary and conclusions

The TF coil stress model in PROCESS has been updated and agrees with the FEA calculations. The model in PROCESS does not include out of plane stresses or cyclic loads expected in a pulsed machine; using data from more detailed models one might be able to compensate for this by altering the allowable stress accordingly. The model now in PROCESS adequately models the expected stresses in the structural components of the TF coils; at least to the level of accuracy suitable for a systems code. The allowable stress for the TFC structure strongly influences the machine and in particular the major radius and total capital cost. The magnets typically make up around a 30% of the machine cost in PROCESS so minimising the magnet costs is essential to making the plant as economically attractive as possible.

Acknowledgments

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