RATCHETING MODELS FOR FUSION COMPONENT DESIGN

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One of the primary failure mechanisms addressed by structural design rules for fusion components is ratcheting, the accumulation of strain with cyclic loads. If a component is loaded such that ratcheting occurs, failure can be expected in relatively short order, so design rules must ensure that the behavior is avoided. In this paper, we present finite element models for cyclic loading of typical fusion structures and compare the results to analytical models for simple geometries and design rules intended for more complex geometries. Both material and structural ratcheting is considered. For structural ratcheting, the 3Sm rule employed in the ITER Structural Design Criteria is found to be unduly conservative and the accompanying Bree rules are found, in some cases, to be non-conservative. Significant advantage can be gained from using fully plastic models to avoid ratcheting.

I. INTRODUCTION

One of the failure modes one must consider in designing a fusion component is ratcheting, which is an accumulation of strain with cyclic loadings. Shakedown occurs when the accumulation ceases and the strain saturates. Ratcheting cannot occur in a strain-controlled situation. There are two types of ratcheting. Material ratcheting occurs in the absence of structural effects, but only in some materials. It can occur in situations involving uniaxial stress which is uniform over a surface. Structural ratcheting can occur for any metal, but requires an inhomogeneous stress distribution.

In this paper we will explore the ability of finite element codes to model ratcheting in fusion structures. We provide benchmark results for simple geometries experiencing both material and structural ratcheting. Having validated the commercial finite element code, we use it to explore several issues of interest to fusion designs. These issues include: the effect of using full stress strain curves, rather than perfectly plastic models; the effect of using design rules developed from simple cylindrical models to address ratcheting in other geometries, such as beams and typical fusion structures; and the degree of conservatism inherent in elastic design rules and elastic-plastic design rules.

II. MATERIAL RATCHETING

As described earlier, material ratcheting is strain accumulation resulting purely from material effects. It can occur under conditions of uniform tensile stress and can be modeled using appropriate constitutive models that go beyond the typical stress-strain curve derived from a monotonic tensile test. It can be expected in several situations[1]:

1. In the case of an isotropically hardening material, ratcheting can occur if the strain increment under tension is not balanced by an equal compressive strain as the stress is cycled.
2. If a static mean stress is applied, if unloading does not completely offset the plastic strains developed during the initial load application
3. If the material properties are temperature dependent, rapid load changes can prevent material properties from responding instantaneously.
4. If the yield strength in tension differs from that in compression, then the direction of the strain vectors can differ between loading and unloading conditions, so they will not offset.
5. A similar effect occurs if the material is anisotropic.

To model material ratcheting in a finite element code, one must employ a constitutive model that permits the phenomenon. The commercial code ANSYS includes a nonlinear kinematic hardening model called the Chaboche[2] model. The key feature of this model is a back stress term in the yield function.

To test the ability of ANSYS to model material ratcheting, we ran a tensile test in an Alloy 4130 with a cyclic load ranging from -446 to 574 MPa.[3] The strain history for three different stress-strain curves is shown in Fig. 1. As can be seen in this figure, the strain saturates immediately for the typical kinematic and isotropic hardening curves, but for the Chaboche model, the plastic strain continues indefinitely as the cycles accumulate. This is evidence of material ratcheting. The Chaboche curve shows evidence of saturation, but running the simulation for additional cycles indicates that the strain increases linearly with the number of cycles indefinitely.

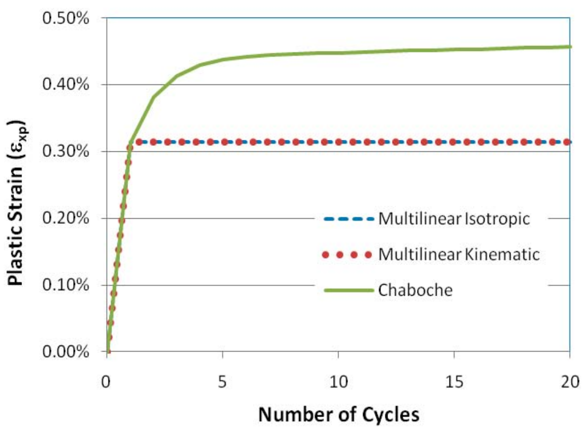


Fig. 1. Displacement history in a tensile bar for three different hardening models.

III. STRUCTURAL RATCHETING IN CYLINDERS

Bree[4] provides a theoretical model for ratcheting in a thin walled cylinder with constant internal pressure and a cyclic thermal gradient. According to this model, combinations of pressure and thermal gradient fall into one of six deformation regimes, as shown in Fig. 2. In this figure, E represents elastic deformation, S_1 and S_2 represent shakedown regimes, P represents plastic deformation without strain accumulation, and R_1 and R_2 represent ratcheting regimes. The stresses on the axes of this figure are the elastic hoop stresses that one would calculate in a model without plasticity. The curve separating the ratcheting and non-ratcheting regimes is represented by

$$\begin{aligned} &\sigma_p \sigma_t < \sigma_y^2 \quad for \quad \sigma_p < 0.5\sigma_y \\ &\sigma_p + 0.25\sigma_t > \sigma_y \quad for \quad \sigma_p > 0.5\sigma_y \end{aligned} \qquad \textbf{(1)}$$

The subscripts *p* and *t* represent primary and secondary stresses, respectively and *y* represents the yield stress. This result is the basis of design rules intended to prevent ratcheting in engineering structures.

IV. ANSYS BENCHMARK FOR STRUCTURAL RATCHETING IN BEAMS

To validate ANSYS in modeling structural ratcheting, we investigated a beam with a rectangular cross section, identical to that used previously to address issues of ratcheting in ITER.[5] The beam is assumed to be fixed at both ends and loaded with a uniform lateral pressure and a linear temperature distribution through the thickness. The pressure is assumed to be constant, while the temperature gradient is cycled. The commercial finite element code ANSYS was used for the calculations, employing plane stress, quadrilateral elements and a perfectly-plastic constitutive model. The pressure was varied and, for each pressure, the thermal gradient necessary to produce ratcheting was determined. To identify the boundary between a ratcheting region and a shakedown region, one must define a criterion from which the finite element results can be interpreted. For this study, ratcheting was assumed to be present when the maximum and minimum stresses within a loading cycle were increasing in magnitude as the number of cycles increased.[6] This boundary is presented in Fig. 3, with the finite element results compared to theoretical calculations.[3] The stresses in this plot are those which would be calculated if an equivalent elastic analysis were carried out. As can be seen, the comparison is favorable.

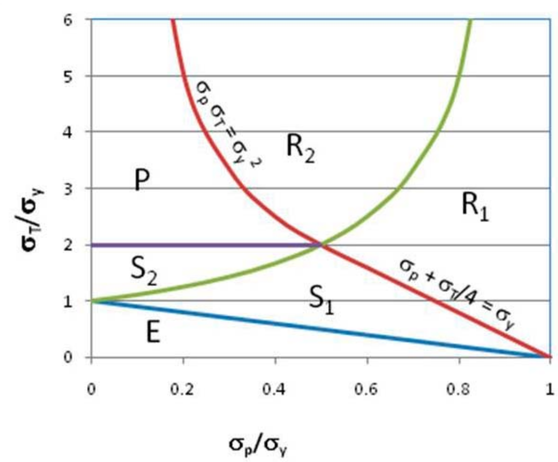


Fig. 2. Bree diagram for a pressurized cylinder with a cyclic thermal gradient through the wall.

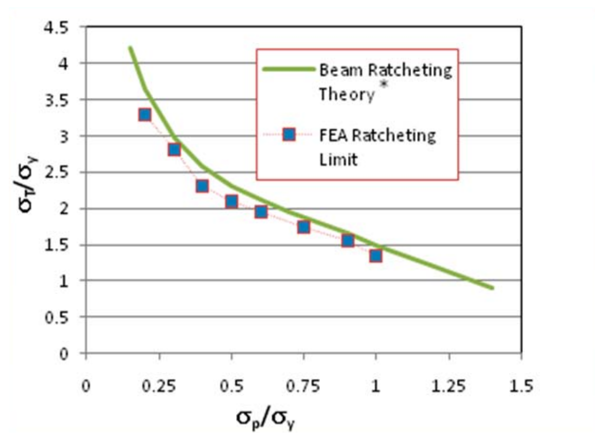


Fig. 3. Thermal stress to cause ratcheting as a function of pressure stress for a double cantilever beam. The stresses are normalized to the yield stress.

V. ITER DESIGN RULES FOR RATCHETING

The ITER Design Rules[7] invoke two rules to address ratcheting. The first is the $3S_m$ rule, which invokes an elastic stress analysis and considers combinations of primary (pressure) and secondary (thermal) stresses that will cause ratcheting. In a simplified case, where the allowable stress is governed by the yield stress and where time dependent effects are not considered, this rule simplifies to

$$\sigma_p + \sigma_t \le 2S_y \tag{2}$$

Where σ_p is the primary stress, σ_t is the secondary (thermal) stress, and S_y is the yield strength

The second rule is the Bree rule, which is a modified version of the result for cylinders. The rule is modified to allow consideration of other geometries by adding in a bending shape factor K. The model represents the primary stresses as

$$X = \frac{P_L + \frac{P_b}{K}}{S_y} \tag{3}$$

Where P_L is the primary local membrane stress and P_b is the primary bending stress. The fluctuating stresses are represented as

$$Y = \frac{\Delta\left(\overline{P} + \overline{Q}\right)}{S_y} \tag{4}$$

Where Δ(P+Q) is the maximum in the thickness stress intensity range, and P and Q represent primary and secondary stresses, respectively. Using these definitions, the ratcheting boundary can be defined as

$$\begin{aligned} Y &< \frac{1}{X} \quad for \quad 0 < X < 0.5 \\ Y &< 4(1 - X) \quad for \quad 0.5 < X < 1.0 \end{aligned} \tag{5}$$

We compared these rules for a double cantilever beam, using K=1.5, the value specified by the ITER Design Rules for a solid cross section.[7] The results are shown in Fig. 4, along with the theoretical results. As shown here, the $3S_m$ rule is the most conservative, while the Bree rule tends to under-predict the thermal stress needed to cause ratcheting.

This figure indicates poor agreement between the ratcheting model for a beam and the Bree model, which is based on cylindrical models. This result indicates that the Bree models must be modified to properly accommodate geometries and loading conditions other than those used to derive the initial Bree results.[8]

Finally, to assess the impact of these rules on a typical component design, we used ANSYS to simulate the primary and secondary stresses in a plate with rectangular cooling channels (with filleted corners), as shown in Fig. 5.

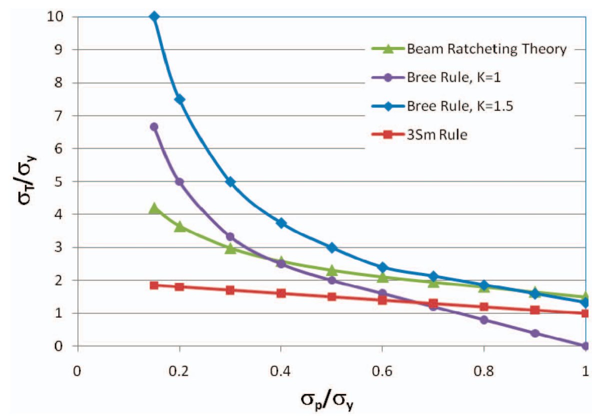


Fig. 4. Comparison of ratcheting limits for the 3Sm rule, the Bree rule, and a theoretical model for a double-cantilever beam.

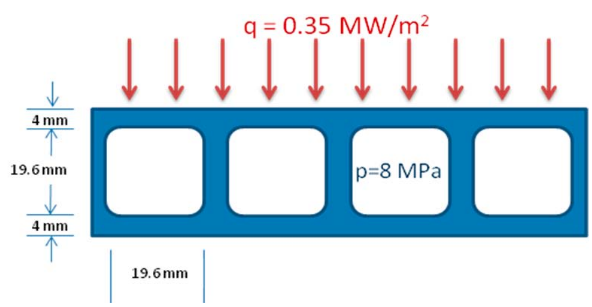
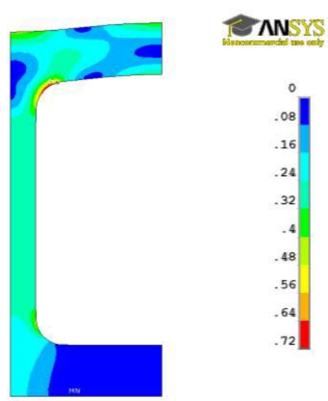


Fig. 5. Model used to study ratcheting in a fusion first wall.

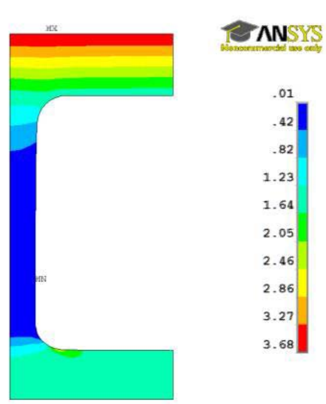
The pressure in this model was fixed, while the heat flux was cycled. The model employed constant thermal properties (independent of temperature), with values consistent with 316 stainless steel at a temperature of 250 C. The stress-strain curve was modeled using the same material and employing a multi-linear material model in ANSYS. The bottom surface of this 2-D, plane strain model was fixed, assuming that the component would be affixed to a blanket module. The sides of the model were coupled, allowing lateral expansion, but preventing rotation.

For reference, the elastic stress contours (with stresses normalized to the yield stress) are presented in Fig 6. These are equivalent stress contours.

Most simplified ratcheting models incorporate perfectly-plastic material models, largely to simplify the model. To investigate the effect of using a hardening model in place of one which is perfectly-plastic, we ran the model from Fig. 4 using both a perfectly plastic model and the 316 SS model with hardening included. To assess the impact on ratcheting, we plotted the displacement of the center of the channel as a function of number of cycles. These results are shown in Fig 7. The displacement plotted is the displacement of the top of the structure, at a point aligned with the center of a cooling channel (the upper right corner of the models in Fig. 6). As is clearly shown, the hardening model leads to saturation of the displacements (shakedown) after approximately 10 cycles, while the perfectly-plastic model increases quasi-linearly through 40 cycles. Hence, the perfectly plastic models may be overly conservative for some situations.



(a)



(b)

Fig. 6. (a) Elastic pressure and (b) thermal stress contours from the analysis of the model in fig 3. All stresses are dimensionless (normalized by the yield stress).

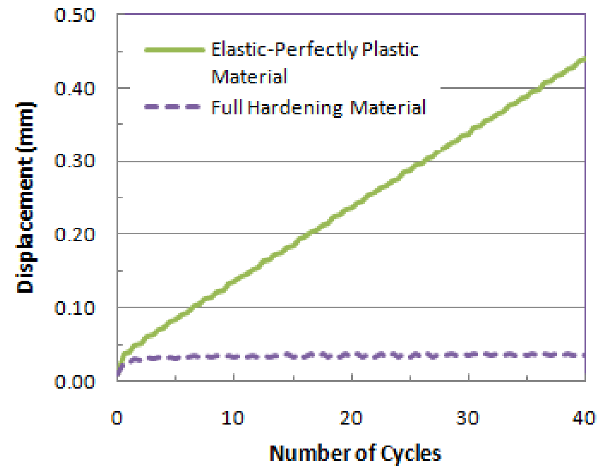


Fig 7. Maximum displacement in channel as a function of number of cycles using a perfectly plastic stress-strain curve and a fully hardening model. The maximum displacement occurs at the top of the structure, at a point aligned with the center of a cooling channel. This point is the upper right corner of the models shown in Fig. 6.

This same model (Fig. 5) was used to assess the relative predictions of a typical fusion structure. For this assessment, the primary stresses were fixed and the various rules were used to predict the secondary thermal stress level where ratcheting would begin. For the 3Sm and Bree Rules, the maximum von Mises equivalent stress on the outside of the heated wall was selected as the maximum primary stress. For the beam ratcheting theory analysis, the ligament above a coolant channel was treated as a beam clamped on both ends. For comparison to previous analyses, the stress from the center of the ligament (aligned above the center of the coolant channel) was used to carry out the ratcheting analysis. This allows us to ignore any stress concentrations at the corner of a coolant channel. The ratcheting limit was investigated through a trial and error finite element analysis where the thermal load was decreased until the ratcheting limit was reached. Again, the ratcheting limit was defined as the point where the stresses from one cycle to the next do not change. The results are shown in Table I. As can be seen in the data, the beam ratcheting theory agrees very well with the FEA results, while the 3Sm rule is conservative. The Bree rule overestimates the thermal stress required to initiate ratcheting for both cases.

TABLE I. Allowable thermal stress ratio for the model in Fig. 4, as predicted by several ratcheting models.

Design Rule	σ_t / σ_y
Beam ratcheting	*1.92*
3S$_m$ rule	*1.58*
Bree rule (k=1.0)	*2.38*
Bree rule (k=1.5)	*3.57*
FEA Limit	*1.93*

VI. STRAIN LIMITS

The ITER Structural Design Criteria[7] also include strain limits, which must be considered when one carries out an elastic-plastic analysis of a component. Those that are relevant to ratcheting include limits on the effective mean plastic strain

$$\left(\tilde{\varepsilon}_m^*\right)_{plastic} < 0.5\lambda_1\left(\varepsilon_u^*\right)_{\min} \tag{6}$$

and the significant local plastic strain,

$$\left(\tilde{\varepsilon}\right) < \min\left(5\%,\ \lambda_2\left(\varepsilon_{tr}\right)_{\min}\right) \tag{7}$$

In these equations, λ_1 and λ_2 are safety factors, ε_u is the uniform elongation and ε_{tr} is the true rupture strain. These would have to be satisfied along with the ratcheting limits described previously. The subscript *min* represents the minimum of a property such that that value is not likely to be reached during operation.[7] The degree to which this value falls below the nominal value depends on scatter in the available experimental data. It also varies from one material to another. These strain limits were not addressed in the current analysis.

VII. CONCLUSIONS

Though not addressed in the ITER Structural Design Criteria, material ratcheting can lead to failure in fusion-relevant structural alloys. Any material to be qualified for fusion components should be evaluated with respect to this potential failure mode.

To address structural ratcheting, the 3Sm limit is often used to design fusion components. However, this criterion can be overly-conservative. The Bree criterion for ratcheting that is provided in the ITER Structural Design Criteria is based on cylindrical geometry and thus provides suspect results for typical fusion component geometries. In fact, there are cases in which the Bree criteria are non-conservative. Hence, it is recommended that elastic-plastic analysis be employed for optimal component design.

ACKNOWLEDGMENTS

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