Designing Cladded Components for High Temperature Nuclear Service: Part II—Design Rules

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The challenge of using existing ASME Section III, Division 5, class A metallic materials for the construction of structural components of advanced reactors with corrosive coolants could be mitigated by allowing designers to use cladding to protect the base material from corrosion. However, the existing Section III, Division 5 rules provide no guidance on the evaluation of strain accumulation and creep-fatigue damage in cladded components. The availability of design rules for cladded components that do not require long-term clad material testing could promote the application of the cladding approach to accelerate the deployment schedule of these advanced reactor systems. To avoid long-term properties for the clad materials Part I of this work proposes two approximate design analysis methods for two types of clad materials—soft clads that creep much faster and have lower yield stress than the class A base material, and hard clads that creep much slower and have higher yield stress than the class A base material. The proposed analysis methods approximate the response of a soft clad by treating it as perfectly compliant and of a hard clad by treating it as linear elastic. Based on these approximate design analysis strategies this Part II develops a complete set of design rules for class A components cladded with either soft or hard clad materials. Part II discusses the reasoning behind the proposed design rules and uses example finite element analyses of representative reactor components to illustrate the use of these design methods.
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Introduction

The existing rules for high temperature nuclear service in Section III, Division 5 of the ASME Boiler and Pressure Vessel Code [1] allow the use of noncode-qualified materials as cladding if the clad thickness is 10% or less of the thickness of the base. However, the code does not provide complete guidance, especially for assessing the design limits on deformation controlled quantities, including ratcheting strain accumulation and creep-fatigue, in the cladded structure. This work aims to fill this gap by developing a set of design rules that ensures both clad and base material integrity under long term, high temperature service. The proposed design rules include an added constraint of avoiding long term testing of the clad material. The constraint of using only short term properties of the clad material in the design calculations limits the combination of clad/class A material systems that can be used.

Based on the relative mechanical properties of the clad and base materials, Messner et al. [2,3] identified three categories of clad materials: (1) soft clad materials that creep much faster and have lower yield stress than the class A base material, (2) hard clad materials that creep much slower and have higher yield stress than the class A base material, and (3) intermediate cases that exhibit mechanical properties similar to the class A materials. To avoid long-term properties in the design analysis, Part I develops approximate analysis approaches for the soft and hard categories of clad materials. The approach treats a soft clad material as perfectly compliant and a hard clad as linear elastic in the design analysis. For both types of analysis methods, the only required clad material properties are elastic modulus and coefficient of thermal expansion, which are available from short term tests. Sample finite element analyses of representative reactor components, as presented in Part I, show that the compliant clad approximation bounds the design quantities of interest in the soft clad while adequately representing the behavior of the base material and the elastic clad approximation of the hard clad material adequately represent the behavior of both the base and hard clad in the component. Based on these approximate analysis methods this Part II develops a complete set of draft proposal design rules for class A components cladded with either soft or hard clad materials that guard both the base and clad against the ASME Section III, Division 5 design limits.

Existing Section III, Division 5 Rules for Cladded Components

Per paragraph HBB-2121(c) of Section III, Division 5, the code allows the use of any metallic materials as cladding if its thickness is 10% or less than that of the base. In HBB-3227.8 the code contains three relevant provisions for clad design:

(1) when assessing a cladded component for primary load ignore the clad—do not take credit on the added strength due to the clad;
(2) ignore the clad when assessing buckling failure
(3) designers must consider the clad, and the interaction between the clad and base materials, when satisfying the limits on ratcheting and creep-fatigue.

The third provision is the most important as it requires designing the clad/class A system to meet the code ratcheting strain and creep-fatigue limits. However, the code does not provide any design rules for assessing these design limits for cladded components. The section Development of Design Rules addresses this gap for class A components cladded with either soft or hard clad material.

Development of Design Rules

Successful design rules should provide a reasonable assurance of protection against likely failure modes. The structural failure

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Table 1 Structural failure modes and corresponding design checks for class A components

Group	Failure modes	Design checks
Load controlled	Time-independent plastic instability Time-dependent creep-rupture	Primary load checks
Strain and deformation controlled	Time-dependent cyclic excessive deformation	Ratcheting limits
	Creep-fatigue damage	Creep-fatigue
	Time-independent buckling Time-dependent buckling	Buckling criteria

modes at elevated temperature considered in Division 5 are those caused by loads applied to and temperature transients experienced by components during the operation [4]. As summarized in Table 1, the failure modes can be grouped into (1) load controlled, and (2) strain and deformation controlled failure modes. The Division 5 rules guard a class A structure against load controlled failure modes by primary load checks while preventing strain and deformation controlled failure modes by ratcheting limits, creep-fatigue, and buckling criteria. Design rules for cladded class A components should guard both bases and clad against all these structural failure modes.

Section III, Division 5 design methodologies are based on a design-by-analysis approach which has two components: a method of analysis and design rules on the analysis results. Section III, Division 5 and associated nuclear code cases (N-861 [5] and N-862 [6]) describe three methods of design analysis—design by elastic analysis, design by elastic perfectly plastic (EPP) analysis, and design by inelastic analysis—for class A components. However, as discussed above, the constraint of using only short-term properties of the clad materials in the design calculations limits the type of analysis that could be employed for the clad material. Part I, therefore, proposes compliant clad analysis method for soft clad/class A base material systems and elastic clad analysis method for hard clad/class A base material systems. In both cases, the class A base material constitutive response is the standard representation of the underlying design method—elastic, elastic-perfectly plastic, or inelastic. The following describes approaches for developing rules for different design checks for both the soft clad/class A base and hard clad/class A base material systems.

Soft Clad/Class A Base Material Systems

Primary Load and Buckling. The compliant clad approximation does not attribute any strength to the soft clad material. Therefore, the clad can be ignored when conducting the primary load design and analysis, i.e., stress in the structure is calculated based on the base material thickness only. This approach is essentially what the current Division 5 rules require for cladded components. This approximation is always conservative for the base material primary load design checks because it completely neglects any strength of the clad material. Neglecting the clad material is also conservative for buckling design checks provided that the clad material remains fully bonded to the base material, i.e., neglecting clad debonding buckling modes.

Our proposed design approach also assumes that the clad material will not fail by plastic collapse or creep rupture under long-term, steady loading condition. This is a reasonable assumption considering the soft clad material creeps much faster than the class A base material. The soft clad material will quickly redistribute stresses onto the base material. This means the soft clad material will be at low stress level for most of the component life and should not rupture under steady load. We, therefore, do not propose checking the soft clad material against the primary load and buckling limits.

The base material then can be checked for primary load design and buckling using the current code rules, ignoring soft clad material in the analysis.

Creep-Fatigue in the Clad Material. The soft clad material may fail under cyclic load. As class A design primarily concerns high temperatures, design rules are required to evaluate creep-fatigue damage in the soft clad material. The existing design methods in the code require creep-fatigue and long-term creep-rupture test data for creep-fatigue evaluation. Therefore, implementation of current Section III, Division 5 design rules for creep-fatigue evaluation of the soft clad material would require a substantial test program.

The authors and others [7–12] have recently developed an alternate creep-fatigue design method based on an integrated EPP analysis and simplified model test (SMT) approach. The EPP-SMT concept is to incorporate the SMT creep-fatigue test data-based approach into the EPP methodology to avoid evaluating creep and fatigue damage separately. The method greatly simplifies the evaluation procedure for elevated temperature cyclic service. The SMT-based approach no longer requires the damage interaction or damage diagram, and the combined effects of creep and fatigue are accounted for in the SMT test data. The SMT specimens are designed to replicate or bound the stress and strain redistribution that occurs in actual components when loaded in the creep regime. Since creep damage is not evaluated separately, no creep rupture data are required. The creep-fatigue evaluation method that we recommend for soft clad materials is motivated by the EPP-SMT concept. However, the response of the soft clad allows many simplifying assumptions to be made that the challenges associated with the general creep-fatigue evaluations that are addressed by the EPP-SMT method are no longer present. For instance, SMT test data is not required for the soft clad material because the requirement of SMT test data in EPP-SMT method is basically to capture the effect of elastic follow-up. However, there is negligible elastic follow-up in a soft clad material which can be explained by considering a simple two bar model—an elastic bar in parallel with a perfectly compliant bar representing the soft clad material. Under the application of creep-fatigue loading, the elastic bar will always be infinitely rigid relative to the perfectly compliant bar and not redistribute stored strain energy into the clad. Thus, the creep-fatigue evaluation method that we recommend for the soft clad corresponds to a special method, and not a general method as is the case for EPP-SMT. We call the creep-fatigue design method the "design by EPP cyclic creep analysis" and the required design charts for the soft clad materials the "EPP cyclic creep design curves." In this method, the soft clad is modeled as elastic-perfectly plastic with a near zero yield stress as required by the compliant clad analysis method developed in Part I. The base material is modeled as elastic-perfectly plastic with a pseudo-yield stress determined from the code isochronous curves for a 0.2% offset in strain from the elastic slope at a given temperature and for a time equal to the cycle period.

As outlined in Part I, the compliant clad analysis will produce a conservative estimation for the strain range in the soft clad material. This strain range can be used to determine the allowable number of cycles from the EPP cyclic creep design curves for a representative hold time equal to the design cycle period. Note design cycle period is the time duration between the start and the end of a design loading cycle. The EPP cyclic creep design curves are essentially the hold time-dependent fatigue design curves plotting an effective strain range versus the expected number of cycles to failure, for a nominal life estimation, or an allowable number of design cycles. These curves can be generated from standard fatigue and creep-fatigue tests. However, creep-fatigue tests with only short hold time is required for the soft clad materials. The stress in soft clad materials will relax quickly to a point that the continued accumulation of creep damage will be negligible. This means the shift in the EPP cyclic creep curves to account for creep damage will saturate quickly, as illustrated in Fig. 1.

The discussion above implements a new method, motivated by the EPP-SMT concept, for creep-fatigue evaluation of the clad in class A components cladded with soft clad material. The new method does not require creep rupture test data and only

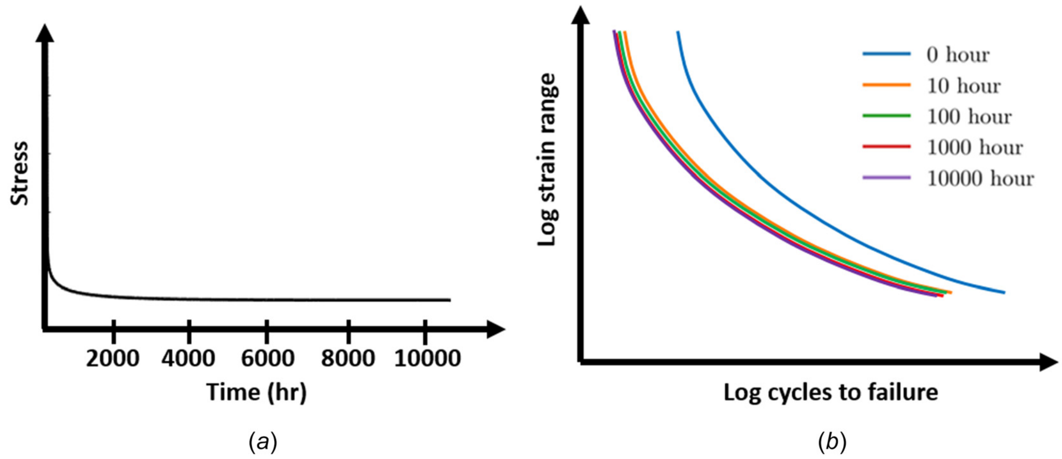


Fig. 1 Schematics showing (*a*) typical stress relaxation in a typical soft clad material and (*b*) the corresponding effect on the time-dependent fatigue (EPP cyclic creep) curves. Stress in a soft clad material will relax quickly to a point that the accumulation of creep damage will be negligible and therefore negligible shift in the time-dependent fatigue curves for longer hold times.

short hold time creep-fatigue are required for the soft clad material.

We performed a comparative analysis of a bent tube with and without cladding to assess the applicability of the EPP cyclic creep design approach for creep-fatigue evaluation in the soft clad material. Figure 2 illustrates the analysis problem. This model represents a single tube of a fuel salt primary heat exchanger in a molten salt reactor for elevated temperature service. The applied axial boundary conditions allow free expansion of the net section but prevent warping deformation. The tube is 1 mm thick, with an inner and outer 0.05 mm thick layer of cladding.

We considered 316H stainless steel, a Section III, Division 5 class A material, as the base material, and nickel (Ni), a soft clad material relative to 316H [13,14], as the cladding for the tube. We performed finite element analysis of the tube using an elastic-perfectly plastic material model for both the base and clad materials. The base material yield stress was adjusted to a pseudo-yield stress determined according to the method discussed above. The clad material yield stress was set to a value near zero, as required by the compliant clad analysis method. Analyses were run for multiple repetitions of the cyclic loading until the strain range over the cycle became constant for all the points in the structure.

Note the design by EPP cyclic creep analysis method does not require establishing elastic or plastic shakedown in the analysis. This is a significant change from current design by EPP analysis approach which requires the designer to demonstrate plastic shakedown in code case N-861 and elastic shakedown in code case N-862. The stabilized cyclic solution is sufficient purely for the sake of finding a strain range for use in the design method, which is all the design by EPP cyclic creep analysis method requires. While the Frederick–Armstrong theorem [15] guarantees that this type of EPP cyclic analysis will eventually reach a stable strain range everywhere in the component, this stabilized cycle may have nonzero ratcheting. This type of solution is sufficient

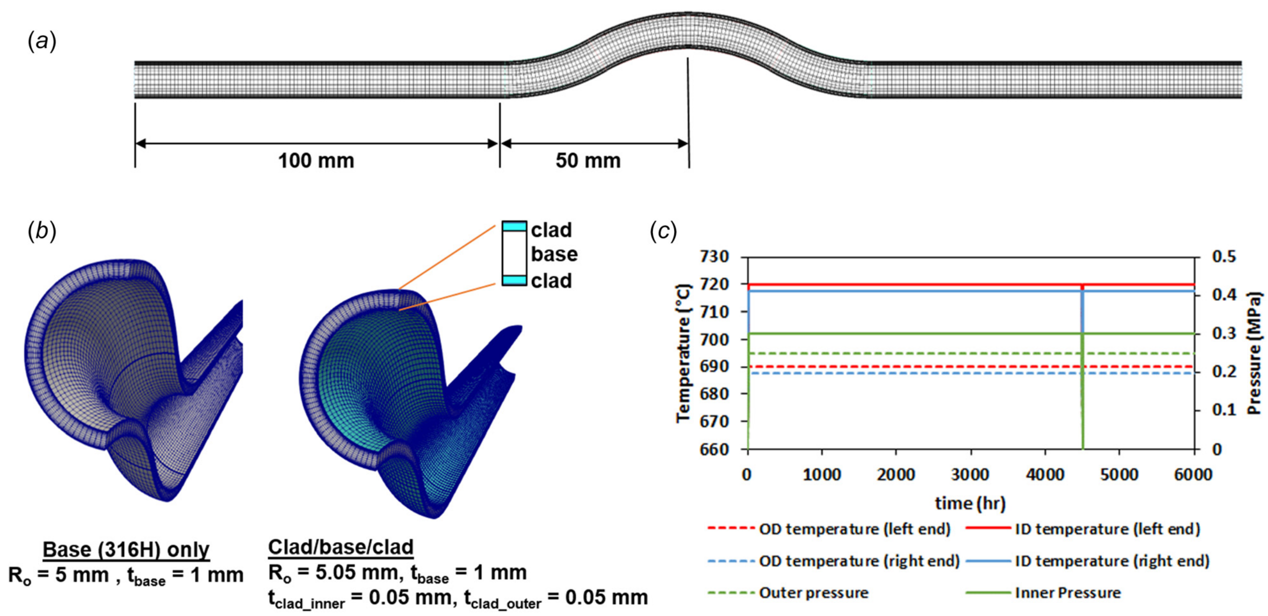
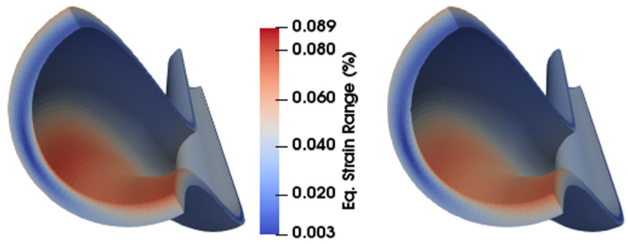


Fig. 2 (*a*) Geometry of the heat exchanger bent tube; (*b*) symmetric finite element models (element type = HEX8) of the tube without and with soft clad material, and (*c*) applied pressure and thermal loading profiles (heat up and cool down time = 10 h, hold time = 4480 h, cycle period = 4500 h)



(*a*) (*b*)

Fig. 3 Equivalent strain range in the base material of the bent tube computed using EPP cyclic creep analysis: (*a*) Tube without clad and (*b*) cladded tube

for a strain-range-based creep-fatigue assessment like the design by EPP cyclic creep analysis method but not to bound creep damage or strain accumulation in the existing code cases.

Figure 3 shows contour plots comparing the stabilized cyclic strain ranges in the base material between the tube with and without clad. The strain ranges closely match. As the clad material is modeled as perfectly compliant, it does not affect the strain range in the base material significantly. Therefore, the design by EPP cyclic creep analysis method can be used for creep-fatigue evaluation of the soft clad material. Figure 4 shows the equivalent strain ranges in the clad of the cladded bent tube, computed from the analysis results. These strain range values can be used to evaluate the clad for creep-fatigue damage using the EPP cyclic creep design curves.

Given an appropriate inelastic model for the base material, design by inelastic analysis method could also be used to check the soft clad material for creep-fatigue damage. In this approach, the base material constitutive response is modeled as inelastic while the soft clad material is modeled as perfectly compliant. Part I verifies this approach by comparing the clad material response from a full inelastic analysis with that from a compliant clad analysis for several representative cladded reactor components. Note that the full inelastic analysis uses inelastic material model for both the clad and base materials. The strain ranges in the clad material from a compliant clad analysis always bounds those from a full inelastic analysis. Again the cyclic strain ranges in the clad material, computed from the analysis, can be compared with the EPP cyclic creep design curves for creep-fatigue evaluation in the soft clad.

Since the soft clad material is modeled as perfectly compliant in both design by EPP cyclic creep analysis and design by inelastic analysis methods, we propose to use $\nu^* = 0.5$ when calculating maximum equivalent strain range in the clad using methods provided in Section III, Division 5, HBB-T-1413, or HBB-T-1414. Note the selection of $\nu^* = 0.5$ is based on the recommendation in Section III, Division 5 rules for design by inelastic analysis. For design by elastic analysis, the code recommends $\nu^* = 0.3$.

Creep-Fatigue in the Base Material. For creep-fatigue damage check in the base material, we propose to entirely neglect the clad in design analysis. This will provide a conservative estimation of the creep-fatigue damage in the base material. Since the clad is neglected in analysis, the base material can be evaluated for creep-fatigue using any of the existing design methods.

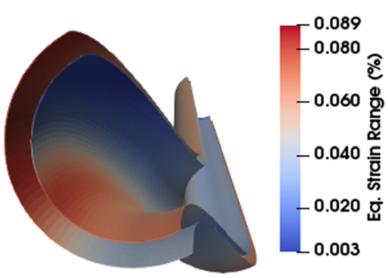


Fig. 4 Equivalent strain range in the clad of the cladded bent tube

Ratcheting in Clad and Base Materials. A soft clad material will essentially deform by following the deformation of the base material. Therefore, satisfaction with strain limit in the base material, completely neglecting the clad material, will safeguard both the base and clad materials from excessive strain accumulation. The clad material strain may exceed the code strain limits for cases where the base material strain marginally passes the code strain limits. The differences in the coefficient of thermal expansion between the clad and base materials could result in a strain increase at the interface. Moreover, a bending strain distribution could result in an increased maximum strain in the clad versus the strain at the material fiber at the interface of the clad and base. However, the extent the clad material strain exceeds the base material strain is limited by thermal bending strains induced over the clad thickness—which is, by the 10% thickness criteria, quite thin. This potential for some small amount of accumulated strain over the Division 5 limits is not a concern for soft clad material due to its high ductility. We, therefore, propose to not explicitly check the soft clad material for ratcheting. The base material ratcheting check can be performed using any of the existing design methods by neglecting the clad in design analysis.

Hard Clad/Class A Base Material Systems

Primary Load and Buckling. For the primary load and buckling design of the hard clad/class A base material systems, the proposed analysis method assumes that the hard clad remains elastic and can only fail under short-term failure modes such as time-independent plastic collapse and time-independent buckling. To evaluate these design checks from analysis results, only short-term material properties of the clad material are required—notably yield strength and ultimate tensile strength. However, as typical hard clad materials have high yield and tensile strengths compared to the class A base material, the time-independent failure of the hard clad is unlikely to control the design of the component.

Hard clad materials do not creep significantly under reactor operating conditions. Therefore, creep rupture failure is not a concern for the hard clad material. However, this raises a potential concern of stress redistribution over time from the base to the clad. The stress relaxation of the base material due to creep deformation will result in increase of stress in the clad material over the initial stress distribution. This requires determining if stress redistribution could significantly increase the stress in the clad over the lifetime of the base material, eventually causing the clad stress to exceed the code "time-independent" allowable stress S_m.

We created a two bar model—an elastic bar representing the hard clad material and a creeping bar representing the class A base material—to investigate the amount of load transfer from the base to the clad. Figure 5 shows the model. If both bars are pulled equally by a constant load, $F = \sigma(a_{\text{base}} + a_{\text{clad}})$, stresses in base, σ_{base} and clad, σ_{clad} at time, t can be determined from the following expressions:

$$\sigma_{\text{base}} = \sqrt[(-n+1)]{\left((-A)(-\text{n}+1)mE_{\text{clad}}tW + (\sigma W)^{(-n+1)}\right)};\ \text{n} \neq 1 \tag{1}$$

$$\sigma_{\text{clad}} = \frac{\sigma - (1-m)\sigma_{\text{base}}}{m} \tag{2}$$

where $W = \frac{E_{\text{base}}}{mE_{\text{clad}} + (1-m)E_{\text{base}}}$; E_{base} and E_{clad} are the elastic modulus of the base and clad materials, respectively; A and n are, respectively, the power law creep prefactor and creep rate exponent of

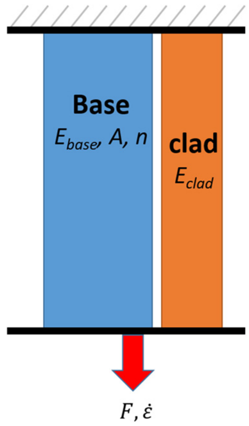


Fig. 5 A two bar model comprising an elastic bar and a creep bar, representing a hard clad/class A base system under primary load

the base material considering its behavior can be represented by a power law creep model; and m is the ratio between the cross-sectional area of the clad bar and the total cross-sectional area of both bars, i.e., $m = \frac{a_{\text{clad}}}{a_{\text{base}}+a_{\text{clad}}}$.

Using the two bar model we examined several hard clad/class A base material systems at different temperatures and for various clad thicknesses. Results indicate that stress relaxation of the base causes a negligible increase in stress in the clad at the end of the base material design life. Tables 2 and 3 show some example results for titanium-zirconium-molybdenum/316H clad/base systems using ASME Section III, Division 5 allowable stress, S_{mt} values of 316H. TZM, a molybdenum-based refractory alloy, is a hard clad material for 316H base material according to the hard clad selection criteria provided in Ref. [13]. The tables list stresses in the TZM clad at the end of the S_{mt} design life of 316H base for 1% and 10% clad thicknesses. Note the values are listed in percentage of initial stress values. For these calculations, elastic moduli of TZM come from Ref. [16], elastic moduli of 316H are from Section II, Part D of ASME boiler and pressure vessel code, and power law creep constants of 316H are calculated using relevant equations and parameters given in Ref. [17]. The tables indicate negligible stress increase in TZM clad at the end of design life due to the stress relaxation of 316H base under elevated temperature operation. Stress redistribution is limited by the amount of load initially carried by the clad (in turn based on the clad thickness) and the rate of creep in the base metal (limited by the ASME load-controlled stress limits). Based on these results, we propose to neglect the primary load stress redistribution between the base and clad in the clad material design rules.

The base material then can be conservatively checked for primary load design and buckling by entirely ignoring the clad in the design analysis. This also agrees with the current code rules, requiring the designer to neglect the strength of the clad in the load controlled stress limits criteria.

Table 2 Percent of initial stress in TZM clad (thickness: 1% of the base thickness) at the end of the design life of 316H base

	Design life (h)					
Temp (°C)	1000	3000	10,000	30,000	100,000	300,000
600	101.7%	105.2%	107.9%	106.3%	105.6%	104.4%
625	102.6%	104.2%	104.1%	103.1%	102.5%	102.2%
650	101.0%	101.4%	102.0%	101.9%	101.2%	100.9%
675	100.5%	100.7%	100.8%	100.9%	100.6%	100.4%
700	100.2%	100.3%	100.3%	100.2%	100.2%	100.1%
725	100.1%	100.1%	100.1%	100.1%	100.0%	100.0%
750	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3 Percent of initial stress in TZM clad (thickness: 10% of the base thickness) at the end of the design life of 316H base

	Design life (h)					
Temp (°C)	1000	3000	10,000	30,000	100,000	300,000
600	101.1%	103.3%	104.9%	103.9%	103.5%	102.7%
625	101.6%	102.6%	102.6%	102.0%	101.6%	101.3%
650	100.6%	100.9%	101.3%	101.2%	100.8%	100.6%
675	100.3%	100.4%	100.5%	100.5%	100.4%	100.2%
700	100.1%	100.2%	100.2%	100.1%	100.1%	100.1%
725	100.1%	100.1%	100.0%	100.0%	100.0%	100.0%
750	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Creep-Fatigue and Ratcheting Limits. Ratcheting is not a concern for hard clad materials. The high yield stress of the clad will prevent classical, rate-independent ratcheting and the low creep rate in the clad material prevents creep strain accumulation. However, the hard clad material will significantly slow the ratcheting of the base/clad system. Being relatively stiff, the clad will tend to restrain deformation that can accumulate in the creeping base material. Similarly, due to their negligible creep rate, the creep-fatigue interaction can be neglected for the hard clad materials. However, a hard clad must be checked for pure fatigue damage. The required design information for this check is design fatigue curves which can be generated in relatively short time frame with strain controlled fatigue tests at reactor operating temperatures. As discussed in Part I, the elastic clad analysis approach should provide a reasonable strain range in the hard clad which can be used for fatigue damage evaluation. To assess the applicability of this approach we performed a comparative design study of a bent tube—with and without cladding. Details of the assessment and findings are discussed below.

Figure 2 illustrates the design problem. We considered 316H stainless steel, a Section III, Division 5 class A material, as the base material, and TZM, a hard clad material relative to 316H [13], as the cladding for the tube. Analyses for this comparative design study are performed by using an elastic perfectly plastic analysis approach for the base material and modeling the clad as an elastic material. We used code case N-861 design by EPP analysis [5] and code case N-862 design by EPP analysis [6], respectively, for ratcheting and creep-fatigue design checks in the base

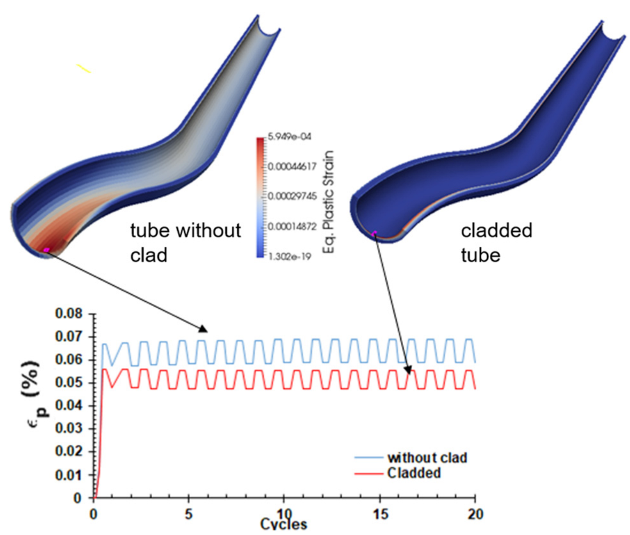


Fig. 6 Example results showing plastic shakedown of the bent tubes

material. Design data as provided in the code are used for 316H, while elastic modulus of TZM comes from Ref. [16].

The code case N-861, ratcheting design by EPP analysis method uses a finite element simulation to establish nonratcheting deformation, i.e., plastic shakedown, of the overall structure. Finite element calculations are performed using an elastic perfectly plastic model for 316H base material with a pseudo-yield stress selected to bound accumulated inelastic strain, per the code case rules. The pseudo-yield stress is determined from code isochronous stress–strain curves at a target inelastic strain, x, where $0 < x < 0.01$ but not higher than the yield strength. Note that, for the cladded tube simulation, the TZM clad is treated as linear elastic and therefore a pseudo-yield stress is not required for clad. Criteria for a design to be acceptable per code case N-861 are $x + \varepsilon_p \leq 0.01$ for at least at one point for all through-thickness locations and $x + \varepsilon_p \leq 0.05$ at all points in the structure. Here, ε_p is the code defined scalar measure of the plastic strain components. Figure 6 shows examples of plastic shakedown in the base material. Table 4 compares the ratcheting design life of the 316H base material in tubes with and without clad. These maximal design lives were obtained by iteratively increasing the design life in the EPP check until it fails for any value of target strain. This iterative method converts the pass/fail EPP check into a calculation of maximum design life.

The code case N-862, creep-fatigue design by the EPP analysis method bounds the creep damage directly with a pseudo-yield stress combined with establishing a rapid cycle solution by achieving elastic shakedown in the finite element simulation. In this code case, the pseudo-yield stress refers to a temperature-dependent minimum stress-to-rupture value based on a selected trial time duration, limited to not exceed the material's yield strength. Again, the definition of the pseudo-yield stress is required to conduct the EPP analysis of the base material, while clad material is modeled as linear elastic. Once elastic shakedown is established in the base, creep damage is determined by dividing the total time by the trial time. Figure 7 shows examples of results of elastic shakedown in the finite element simulations. Fatigue damage is then calculated by extracting a representative maximum strain range from the simulation results and converting it into an allowable number of cycles using design fatigue curves. Figure 8 shows the computed maximum strain range in the base and clad of the cladded bent tube. Finally, the creep and fatigue damages in the base material are compared to the Code creep-fatigue interaction diagram to determine if the design passes the creep-fatigue design check for the base material. Table 4 compares the creep-fatigue design life of the 316H base material in tubes with and without TZM clad. The maximum equivalent strain range, as shown in Fig. 8, in the clad material can be used to evaluate the clad material against fatigue failure. However, as a fatigue design curve is not available for TZM at the temperature considered in this problem, fatigue life of the clad could not be computed.

Table 4 indicates that the ratcheting life of the base material is much longer for the cladded tube than the tube without clad. This is expected as the hard TZM clad serves as a stiff constraint for the 316H base and therefore restrains the deformation that can be accumulated in the creeping 316H base material. Therefore, ignoring the hard clad in the analysis will be a conservative evaluation of ratcheting in the base material. This allows the use of any of the existing design methods for ratcheting check in the base.

Table 4 Creep-fatigue and ratcheting design life of the 316H base in tubes with and without TZM clad

	Ratcheting design life (cycles)	Creep-fatigue design life (cycles)
Tube without clad	~21	~4
Cladded tube	>66	~5

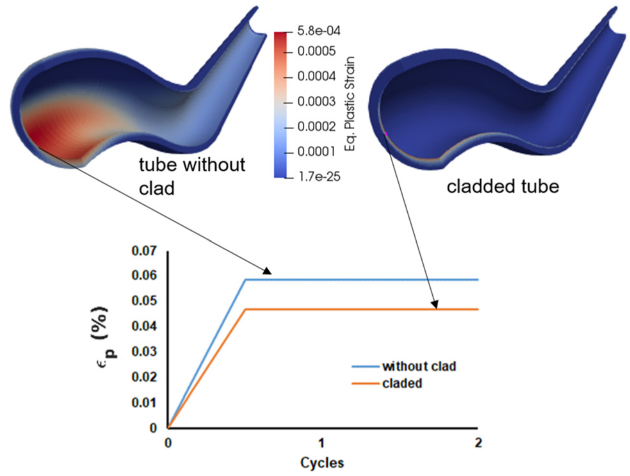


Fig. 7 Example results showing elastic shakedown of the bent tubes

For creep-fatigue evaluation of the base material, however, the interaction between the hard clad and base materials must be considered in design analysis as the clad will generally affect the stresses and strains experienced by the base material during cyclic operation. We propose to use design by EPP analysis, as used for the example cladded bent tube problem, and design by inelastic analysis for creep-fatigue evaluation of the base material. A design by elastic analysis method cannot be used as it requires stress classification and linearization which cannot be performed when the clad is included in the design analysis.

For design by inelastic analysis, the base material is modeled with an appropriate inelastic model and the clad is again modeled as linear elastic. Part I verifies the design by inelastic analysis approach by comparing the clad material response from a full inelastic analysis with that from an elastic clad analysis for representative reactor components. Note that the full inelastic analysis uses inelastic material model for both the hard clad and base materials. The design quantities of interest from an elastic clad analysis adequately represent those from a full inelastic analysis.

The maximum equivalent strain range in the hard clad material from any of the design by EPP analysis and inelastic analysis methods described above can be used for the fatigue evaluation of the clad. Since the hard clad material is modeled as linear elastic in both analysis methods, we propose to use $\nu^* = 0.3$ when calculating the maximum equivalent strain range in the clad using methods provided in Section III, Division 5, HBB-T-1413, or HBB-T-1414.

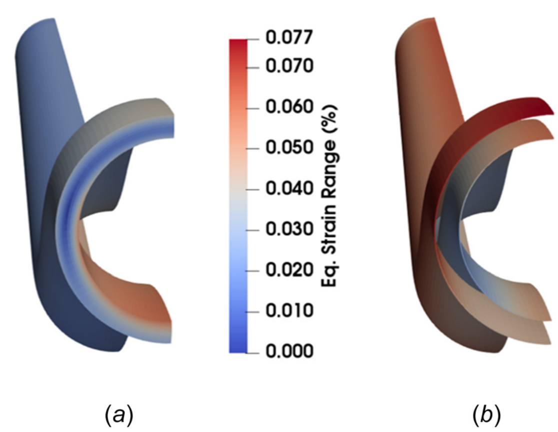


Fig. 8 Maximum equivalent strain range in (*a*) 316H base and (*b*) TZM clad of the cladded bent tube

Brittle Failure of the Hard Clad. Brittle failure could be a concern for hard clad materials, particularly for refractory metals and their alloys. Refractories such as molybdenum, TZM, and tungsten have relatively low ductile-to-brittle transition temperatures. These materials will be susceptible to brittle failure if the temperature under any Service Level loading condition descends below the ductile-to-brittle transition temperature. We, therefore, include a limitation for the use of hard clad material under the General Requirements section in the proposed design rules provided below.

Summary of the Design Rules. Based on the discussion above, design rules for Class A components cladded with either a soft or a hard clad material are provided in the next section. Figure 9 provides a summary of all the design evaluations. As indicated in the flowchart in Fig. 9, the clad is not included in the primary load, buckling, and ratcheting design checks. The base material can be checked for primary load, buckling, and ratcheting design by ignoring the clad in the design analysis. The design rules refer to the rules in Section III, Division 5 for checking the base material for primary load and buckling design. For ratcheting check of the base material, there are three options—design by elastic analysis, design by inelastic analysis, and design by EPP analysis. The rules then refer to Section III, Division 5 rules for first two options and code case N-861 for the design by EPP analysis option.

For soft clad/class A base material systems the flowchart in Fig. 9 indicates the clad can be ignored when the base material is evaluated for creep-fatigue damage using the current rules. Again there are three options – design by elastic analysis, design by inelastic analysis, and design by EPP analysis methods. Section III, Division 5 rules are again referred for the first two options, while code case N-862 is for the design by EPP analysis option. Creep-fatigue design check of the soft clad material can be performed using two options—design by EPP cyclic creep analysis and design by inelastic analysis. In both cases, the soft clad material is modeled as perfectly compliant while the base material constitutive response conforms to the underlying design method. For creep-fatigue damage evaluation of the soft clad material the maximum equivalent strain range in the clad from the analysis is compared with EPP cyclic creep design curves to determine the number of allowable design cycles for each cycle type. Then the total creep-fatigue damage fraction computed using Miner's rule must be less than or equal to 1 for a design to pass the creep-fatigue damage check in the soft clad

$$\sum_{i=1}^{p} \left(\frac{n}{N_d}\right)_i \leq 1 \quad (3)$$

where $(n)_i$ is the number of repetition and $(N_d)_i$ is the number design allowable cycles for cycle type i and p is the total number of cycle types.

Unlike other design checks, the clad must be included in creep-fatigue evaluation of the base material in hard clad/class A base material systems. There are two options for this check—design by EPP analysis and design by inelastic analysis. In both cases, the hard clad material is modeled as linear elastic while the base material constitutive response conforms to the underlying design method. Again, the rules refer to Section III, Division 5 for design by inelastic analysis and code case N-862 for design by EPP analysis. Results from this analysis should be used for creep-fatigue design check of the hard clad material which is basically a strain-based fatigue damage evaluation, comparing the maximum equivalent strain ranges with the design fatigue curves to determine the number of allowable design cycles for each cycle type. Again the total fatigue damage fraction computed using Miner's rule (Eq. (3)) must be less than or equal to 1 for a design to pass the fatigue damage check in the hard clad.

Note the clad is ignored in analysis for some of the design checks of the base material. In such cases calculating the pressure load on the base surface could be difficult for complex geometry. A conservative way to resolve this issue is to directly apply the internal pressure load at inner face and the external pressure load at the outer face of the base material. This approach also avoids complication in applying the pressure load in finite element analysis when the clad is not included.

Draft Proposal of Design Rules for Class A Components Cladded With Either Soft or Hard Clad Materials

General Requirements

- In these rules, the term "base" refers to the class A base material and its associated weldments in the cladded component under evaluation.
- The clad thickness should be limited to 10% of the base material thickness as required by Section III, Division 5, HBB-2121(c).
- To ensure accurate calculation of the temperature field and resulting thermal stresses, the clad must be included in the

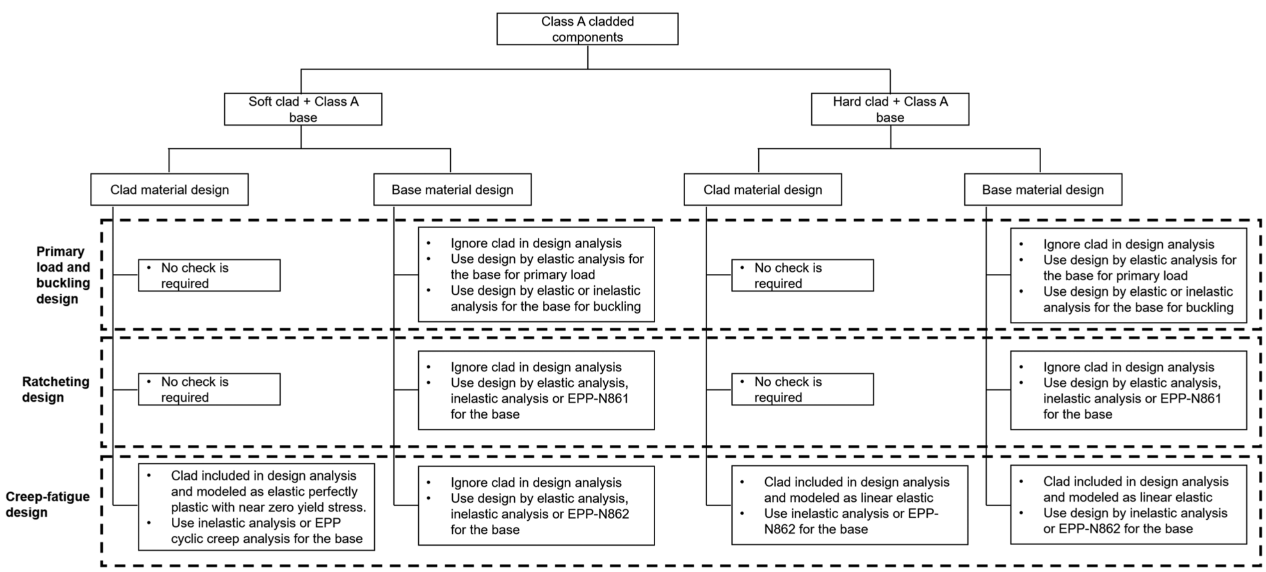


Fig. 9 Summary of design evaluations for class A components cladded with either soft or hard clad materials

thermal analysis even if it is ignored in the structural analysis.

- For hard clad/class A base material systems the minimum clad temperature for any service level loading must not descend below the hard clad material's ductile-to-brittle transition temperature.

Primary Load and Buckling Design

Design of the Base

- Do not include clad in the design analysis.
- Check the base against the load controlled stress limits described in Section III, Division 5, HBB-3200 and -3300, -3400, -3500, or -3600.
- Check the base against the buckling and instability limits described in Section III, Division 5, HBB-3252, and nonmandatory Appendix HBB-T.

Design of the Clad

- No check is required.

Ratcheting Design

Design of the Base

- Do not include clad in the design analysis.
- Check the base against the strain and deformation limits described in Section III, Division 5, HBB-3252, and nonmandatory Appendix HBB-T using any of the existing methods as listed below.

  (i) Design by elastic analysis in Section III, Division 5, HBB-T-1320 or HBB-T-1330.
  (ii) Design by inelastic analysis in Section III, Division 5, HBB-T-1310.
  (iii) Design by elastic-perfectly plastic (EPP) analysis in code case N-861.

Design of the Clad

- The clad is not required to satisfy the strain and deformation limits.

Creep-Fatigue Design of Components Cladded With Soft Clad

Design of the Base

- Do not include clad in the design analysis.
- Check the base against creep-fatigue limits described in HBB-3252 and nonmandatory Appendix HBB-T using any of the existing methods as listed below.

  (i) Design by elastic analysis in Section III, Division 5, HBB-T-1430.
  (ii) Design by inelastic analysis in Section III, Division 5, HBB-T-1420.
  (iii) Design by elastic-perfectly plastic (EPP) analysis in code case N-862.

Design of the Soft Clad

- Include clad in the design analysis.
- Use either method (i) or (ii) below to determine cyclic strain history in the clad.
  (i) Design by inelastic analysis: Model the clad as elastic-perfectly plastic with a near zero yield stress and the base as inelastic.
  (ii) Design by EPP cyclic creep analysis:
    (a) Develop a composite cycle for the analysis. The definition of the composite cycle can be found in code cases N-861 and N-862.
    (b) Model the clad as elastic-perfectly plastic with a near zero yield stress and the base as elastic-perfectly plastic with a pseudo-yield stress determined from the isochronous stress-strain curves for a 0.2% offset in strain from the elastic slope at a given temperature and for a time equal to the composite cycle period.
    (c) Run multiple repetitions of the cyclic loading defined by the composite cycle until the strain range over cycles becomes constant for all points in the structure.
- Determine a representative maximum equivalent strain range for each point in the clad for each cycle type in accordance with Section III, Division 5, HBB-T-1413, or HBB-T-1414 when applicable, with $\nu^* = 0.5$.
- Determine the creep-fatigue damage fraction for each point in the clad for each cycle type as the ratio between number of applied repetitions and number of allowed cycles determined from the EPP cyclic creep design curves of the clad corresponding to the cycle period and the maximum temperature during the cycle.
- The acceptance criteria is $\sum D \leq 1.0$, where D is the creep-fatigue damage fraction for each cycle type computed above. The acceptance criteria must be met at all points in the clad.

Creep-Fatigue Design of Components Cladded With Hard Clad

Design of the Base

- Include clad in the design analysis and model it as linear elastic.
- Check the base against creep-fatigue limits described in HBB-3252 and nonmandatory Appendix HBB-T using either method (i) or (ii) below.

  (i) Design by inelastic analysis in Section III, Division 5, HBB-T-1420.
  (ii) Design by elastic-perfectly plastic (EPP) analysis in code case N-862.

Design of the Hard Clad

- The analysis results from creep-fatigue evaluation of the base shall be used for fatigue evaluation of the clad. Determine the cyclic strain history in the clad from these analysis results.
- Determine a representative maximum equivalent strain range for each point in the clad for each cycle type in accordance with Section III, Division 5, HBB-T-1413, or HBB-T-1414 when applicable, with $\nu^* = 0.3$.
- Determine the fatigue damage fraction for each point in the clad for each cycle type from the ratio between number of applied repetitions and number of allowed cycles determined from the fatigue design curves of the clad corresponding to the maximum temperature during the cycle.
- The acceptance criteria is $\sum D \leq 1.0$, where D is the fatigue damage fraction for each cycle type computed in *(c)*. The acceptance criteria must be met at all points in the clad.

Conclusion

This work develops a complete set of draft proposal of design rules for designing class A components cladded with either soft or hard clad materials for elevated temperature service in advanced reactors. Long term creep test data for the clad material are not required in applying these design rules to guard against the ASME Section III, Division 5 failure modes in the clad.

The design rules do not require evaluating the clad material against the ASME Section III, Division 5 primary load, buckling, and ratcheting design criteria. For creep-fatigue evaluation in the soft clad material, the rules use either a design by EPP cyclic creep analysis or a design by inelastic analysis approach, modeling the soft clad material as perfectly compliant. For creep-fatigue evaluation in the hard clad material, the rules use either a design by EPP analysis or a design by inelastic analysis approach, modeling the hard clad material as linear elastic in the design analysis. In all these cases, the base material constitutive response is the standard representation of the underlying design approach. To avoid brittle failure of the hard clad in hard clad/class A base material systems, the rules limit the minimum clad temperature to be higher than the ductile-to-brittle transition temperature of the hard clad material.

The rules use the existing design methods for primary load, buckling, and ratcheting checks in the base, ignoring the clad in the design analysis. The rules also use the existing design methods for base material creep-fatigue checks for soft clad/class A base material systems by ignoring the clad in design analysis. The rules, however, require including the hard clad in the design analysis for creep-fatigue evaluation of the base material in hard clad/class A base material systems and provides two options for creep-fatigue design—design by EPP analysis and design by inelastic analysis.

Finally, the design rules developed here assume perfect bonding between clad and base and do not guard against the clad/base interface failure. This failure mode is a potential concern. Instead of addressing this problem via a design-by-analysis method, in Ref. [18], we proposed an acceptance test for ensuring the structural integrity of the clad/base metal interface under the operating cyclic loads.

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