ANL-ART-53

FY16 Status Report on Development of Integrated EPP and SMT Design Methods

Nuclear Engineering Division

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Argonne National Laboratory

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ABSTRACT

The goal of the Elastic-Perfectly Plastic (EPP) combined integrated creep-fatigue damage evaluation approach is to incorporate a Simplified Model Test (SMT) data based approach for creep-fatigue damage evaluation into the EPP methodology to avoid the separate evaluation of creep and fatigue damage and eliminate the requirement for stress classification in current methods; thus greatly simplifying evaluation of elevated temperature cyclic service.

The EPP methodology is based on the idea that creep damage and strain accumulation can be bounded by a properly chosen "pseudo" yield strength used in an elastic-perfectly plastic analysis, thus avoiding the need for stress classification. The original SMT approach is based on the use of elastic analysis. The experimental data, cycles to failure, is correlated using the elastically calculated strain range in the test specimen and the corresponding component strain is also calculated elastically. The advantage of this approach is that it is no longer necessary to use the damage interaction, or D-diagram, because the damage due to the combined effects of creep and fatigue are accounted in the test data by means of a specimen that is designed to replicate or bound the stress and strain redistribution that occurs in actual components when loaded in the creep regime.

The reference approach to combining the two methodologies and the corresponding uncertainties and validation plans are presented. Results from recent key feature tests are discussed to illustrate the applicability of the EPP methodology and the behavior of materials at elevated temperature when undergoing stress and strain redistribution due to plasticity and creep.

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1 Introduction

There are two approaches of interest to the proposed integrated evaluation of cyclic service life that have received attention over the last several years. One of these approaches is identified as the Elastic-Perfectly Plastic (EPP) methodology and the other is identified as the Simplified Model Test (SMT) methodology.

There are several applications of the EPP methodology that have been developed (Carter et. al., 2016) and two of the applications are ASME Code Cases related to cyclic service that have recently been approved by the ASME Committee on Construction of Nuclear Facility Components (BPV III). The two EPP Code Cases address strain limits and creep-fatigue damage evaluation. A driving motivation for these code cases was the evolving interest in high temperature nuclear reactors, specifically the Very High Temperature Gas Cooled Reactor (VHTR) with a potential nominal operating temperature of 950^{o}C (1753^{o}F). Alloy 617 is the reference high temperature material for the VHTR. The current evaluation methods based on elastic and simplified inelastic analysis in Section III, Div 5, Appendix HBB-T (formerly Appendix T of Subsection NH) were deemed inapplicable to Alloy 617 above 650^{o}C (1200^{o}F). Since the full inelastic analysis option was not, and still is not, supported by defined material models, there was a gap in approved methods. There was also a long time goal of the Subgroup on Elevated Temperature Design to find a way to simplify the elevated design procedure.

The EPP cyclic service code cases address both of those objectives in that they are applicable at very high temperatures and greatly simplify the design evaluation procedure by eliminating the need for stress classification that is the basis of the current rules. However, the EPP Code Case for evaluation of creep-fatigue damage still requires the separate evaluation of creep damage and fatigue damage by placing a limit on the allowable combined damage, the “D” diagram based on the calculated individual damages. The difficulties and approximations in the D diagram approach are what led to the second approach of interest, the Simplified Model Test or SMT methodology.

The original SMT approach is based on the use of elastic analysis. The experimental data, cycles to failure, is correlated using the elastically calculated strain range in the test specimen and the corresponding component strain is also calculated elastically. The advantage of this approach is that it is no longer necessary to use the damage interaction, or D, diagram because the damage due to the combined effects of creep and fatigue are accounted in the test data by means of a specimen that is designed to replicate or bound the stress and strain redistribution that occurs in actual components when loaded in the creep regime. However, as originally proposed, there is still a requirement for stress classification into primary, P, primary plus secondary, P + Q, and primary plus secondary plus peak, P + Q + F, for the overall design procedure.

The goal of the EPP-SMT approach is to incorporate a SMT data based approach for creep-fatigue damage evaluation into the EPP methodology to avoid the use of the D diagram and to minimize over-conservatism while properly accounting for localized defects and stress risers. Below the creep regime this approach is already accommodated in Subsection NB through plastic analysis per NB-3228.4 for primary plus secondary stress limits and cumulative fatigue damage based on the strain ranges from the EPP analysis. The challenge is to extend the concept to the creep regime through appropriately chosen pseudo stress values and shakedown analyses.

In the following sections, the rationale and application of the EPP and SMT approaches and relevant data will be reviewed. Based on that, the reference approach to combining the advantage of the EPP methodology, e.g. no stress classification, with the advantage of the SMT methodology, e.g. no damage diagram to separately evaluate creep and fatigue, will be presented with a discussion of the proposed path forward.

2 EPP Methodology

2.1 EPP Methodology

The EPP strain limit methodology is based on the idea that strain accumulation can be bounded by a properly chosen “pseudo” yield strength used in an elastic-perfectly plastic analysis, thus avoiding the need for stress classification. The EPP method exploits the fact that elastic-plastic methods naturally handle the stress redistribution which is the key to stress classification schemes The accumulated strain is bounded by a pseudo yield stress given by the stress to accumulate 1% inelastic strain over the design life plus the local inelastic strain from the EPP analysis. The total accumulated inelastic strain at any point is also limited to 5%. These limits are consistent with the current limits in Section III, Div 5, Appendix HBB-T.

The use of bounding simplified solutions to characterize complex structural creep problems is well established (Goodall et al., 1979). In order to guarantee creep strain limits based on elastic-plastic analysis, the conservatism of the rapid cycle solution may be exploited. (Carter et al., 2016). (Note: rapid cycle is in the sense that no stress relaxation is modeled in the analysis) The physical principle here is that any stress history resulting from an elastic analysis, or from an elastic-plastic analysis that shakes down provides an upper bound to the creep deformation over time. For a given load and temperature cycle, a number of solutions may be defined and calculated. From each of these, the temperature and respective stress histories may be used to calculate creep strain rates, work done by boundary forces and energy dissipation rates over the volume. These may be compared and ranked. From this, a bounding cyclic solution associated with a simplified elastic-plastic analysis method may be identified. The proposed method for evaluation of strain limits makes use of a cyclic plastic solution which will provide an upper bound to energy, work, strains and displacements. For the most general case of thermal-mechanical loading on a creep-plasticity material, the bound is justified using the qualitative argument below. More detail is available in Carter (2005a; 2005b).

The argument used for the general case of thermal-mechanical loading and creep-plasticity is based on the self-evident assumption for a structure under general loading: *Reducing the perfectly plastic yield stress does not reduce the deformation.* Applied to the plastic rapid cycle solution, this statement means that the cyclic increment in deformation of a structure is not reduced if the yield stress is reduced, all other factors being unchanged. Therefore, if the yield stress is reduced to the point where ratcheting in a cyclic problem is imminent, then the cyclic incremental deformation is not less than for the original yield stress. Therefore, the energy dissipation and deflection for the reduced yield stress case provides an upper bound of the energy dissipation and deflection in the original cases.

The strain limits code case exploits the rapid cycle concept to define a temperature dependent “pseudo” yield stress incorporating the desired strain limit.

The strain limit code case is intended as an alternative to the rules in HBB-T-1320, Satisfaction of Strain Limits Using Elastic Analysis, and in HBB-T-1330, Satisfaction of Strain Limits Using Simplified Inelastic Analysis. It also includes provisions from HBB-T-1710, Special Strain Requirements at Welds. These requirements are met by using an average, or reference, limit of 1% to define a general ratcheting stress limit. For the case of pure bending in a uniform section, this implies a 2% limit on the extreme fiber strain. A procedure to determine follow-up effects is used in conjunction with a local strain limit, including follow-up effects, of 5%.

The pseudo yield stress is obtained from the lower of the yield strength or the stress from the applicable Isochronous Stress Strain Curve (ISCC). The time duration for entering the ISCC is the total design life. The temperature is the local instantaneous temperature as determined from the transient thermal analysis. The strain used to determine the pseudo yield strength from the ISSC at a given time and temperature is an iterative procedure governed the relationship that $0<x<\varepsilon_{avg}$ where x is the target inelastic strain used to define the pseudo yield stress and ε_{avg} is the strain limit, 0.01 for base metal and 0.005 for weldments.

The next step is a cyclic elastic-perfectly plastic (EPP) analysis using the above determined pseudo yield strengths that vary spatially and temporally. Shakedown for the strain limits code case is defined as the absence of incremental plasticity or deformation. Note that this permits stable hysteresis loops with plasticity. If the analysis shakes down, then the next step is to determine the local plastic strain, ε_p, from the EPP analysis, and add it to the target strain, x. The local plastic strain from the EPP shakedown analysis is added to the target inelastic to account for strain redistribution due to elastic follow up, redundancy, etc. The sum $(x+\varepsilon_p)$ must satisfy the following constraints: $(x+\varepsilon_p)\le\varepsilon_{avg}$ at least at one point for all through thickness locations and $(x+\varepsilon_p)\le\varepsilon_{local}$ at all points. The value of ε_{local} is equal to 0.05 for base metal and 0.025 for weldments.

There have been a series of steps taken to verify this approach; more fully discussed in Sham et al. (2015). There was a representative example problem defined with sustained and transient loading on a nozzle to sphere joint. There were simplified examples evaluated to compare the results of the EPP strain limit code case which showed the results to be approximately equivalent. There were also a series of tests on two cylindrical specimens loaded in parallel with superimposed sustained and cyclic loading which identified an anomaly in the applicability of the strain limit code case which was resolved though inelastic analysis.

2.1.1 Stovepipe Anomaly

When the two-bar in parallel ratcheting test results were compared to strain limit code case predictions based on the allowable load combinations that would result in 1% strain, there was an anomalous result which is shown in Figure 1. Both the code case and experiment predicted a "stovepipe" or narrow region of primary load application where the elongation due to sustained load was offset by ratcheting due to cyclic thermal loading. Thus, inside the stovepipe, much larger cyclic thermal loads did not lead to excessive strain accumulation. The anomaly was that the experimental stovepipe occurred at a significantly greater sustained load than the code case prediction. That raised the possibility that the code case could significantly under predict strain accumulation for some configurations and loading conditions. A subsequent simplified inelastic analysis showed acceptable agreement with the experimental results.

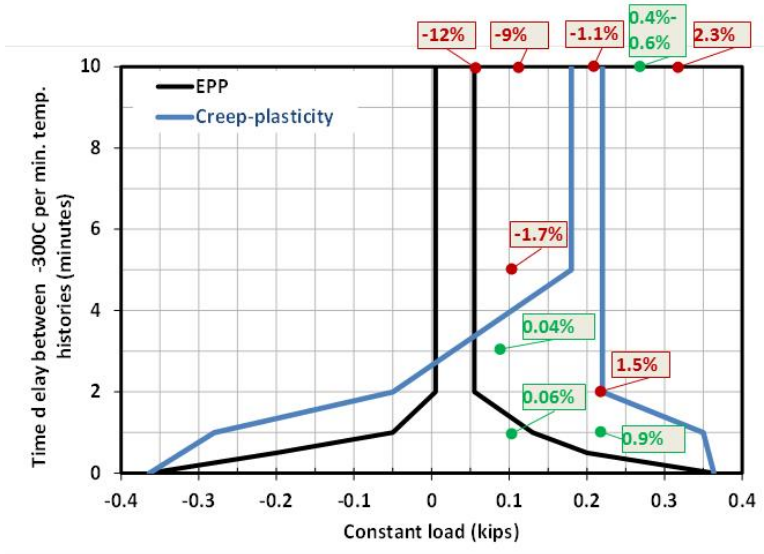


Figure 1. Two bar test data with 1% design envelope predictions from the strain limits code case and inelastic analysis

It was postulated that this anomaly would only show up in configurations with uniform stress and temperature throughout the structural element, e.g. skeletal structures. This was confirmed by comparing the results of inelastic analyses of Bree cylinder problems, using the same simplified model as for the two bar experiment, to code case predictions. Figure 2 illustrates the Bree cylinder solution. The analytical points inside the ratcheting boundary illustrate the applicability of the strain limit code case to distributed structures.

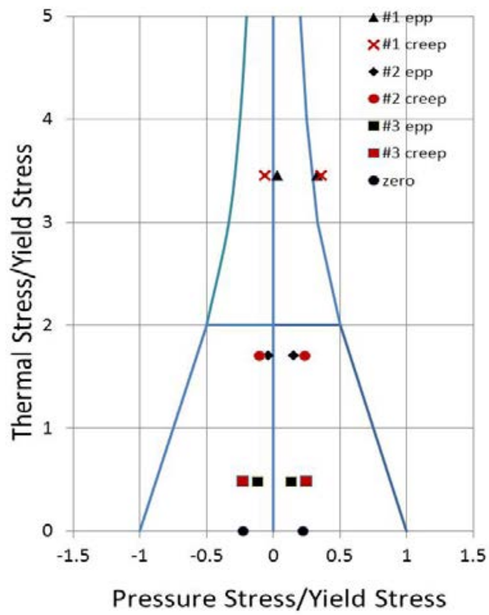


Figure 2. Summary of EPP and Creep Analysis Load Cases on Bree Plot of Normalized Primary and Thermal Stress

3 SMT

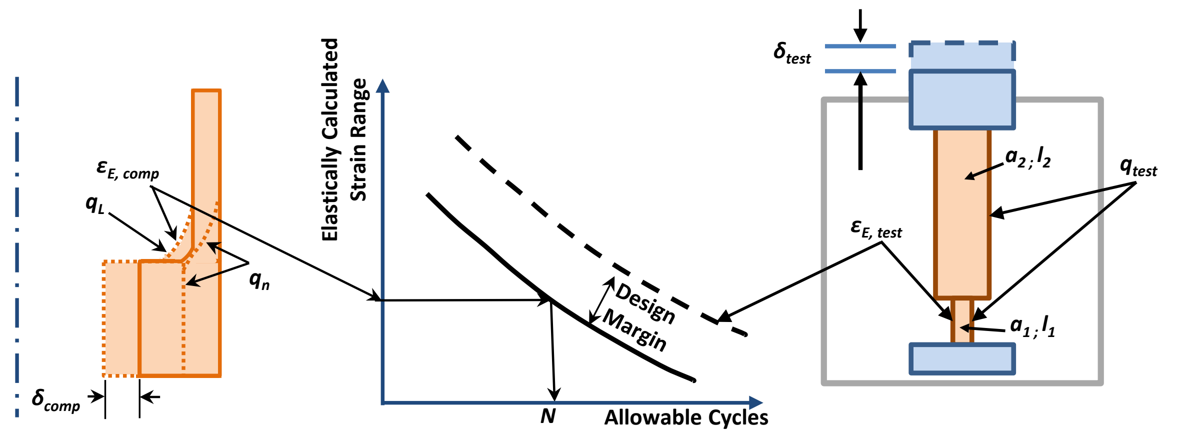
The SMT design methodology is not part of the EPP creep-fatigue code case. However, SMT specimen tests, conceptually two bars in series subjected cyclic displacement controlled loading, were used to verify the acceptability of the EPP approach. Briefly, the EPP creep-fatigue code case is based on similar rational and supporting example problems as discussed above. Creep-fatigue damage is evaluated using a pseudo yield based on the minimum creep-rupture stress. Using the D diagram, the trial life is iterated to result in an acceptable combined creep and fatigue damage. The local strain range used to calculate fatigue damage is determined from the local total strain from the EPP analysis. The advantage of the EPP creep-fatigue method is that it avoids the difficult and contentious process of stress classification. The disadvantage is that it still requires the use of the D diagram and the separate evaluation of creep and fatigue damage. Also, the creep damage evaluation is based on the bounding nature of the rapid cycle, characteristic of EPP methods, which can be quite conservative, particularly at very high temperatures. Further details of the EPP creep-fatigue methodology can be found in Sham et al. (2015).

3.1 SMT Design Methodology

3.1.1 Conceptual basis of the SMT approach

The basic concept of the SMT methodology is shown Figure 3. The component design is represented by a stepped cylinder with a stress concentration at the shoulder fillet radius. The component has a global elastic follow-up, q_n, which is due to the interaction between the two cylindrical sections, and a local follow-up, q_L, which is due to the local stress concentration.

Figure 3(a) illustrates the damage from a strain, $\varepsilon_{E,comp}$, that is applied, held, and then cycled back to zero and reapplied. The damage is evaluated from a design curve, Figure 3(b), based on data from the simplified model test, Figure 3(c). The evaluation procedure is essentially the same as that used in Subsection NB, where the damage fraction is determined as the ratio of actual number of cycles, n, to the allowed number of cycles, N. The design curve envelopes the effects of hold time duration and follow-up magnitude without being excessively conservative. It is developed from SMT data that is plotted as elastically calculated strain vs. observed cycles to failure, Figure 3(b).



(a) Shell structure with stress concentration and elastic follow-up

(b) Design curve

(c) Hold time creep-fatigue test with elastic follow-up

Figure 3. SMT methodology.

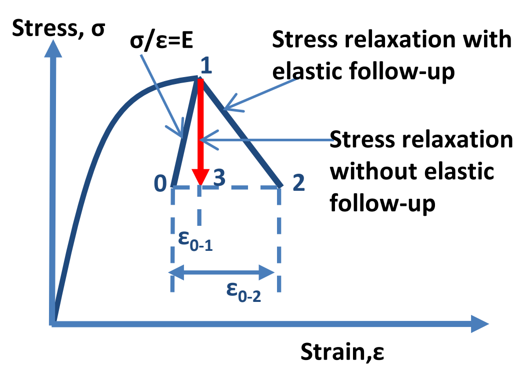


Figure 4. Definition of elastic follow-up.

A key point in the basic SMT approach is the use of elastically calculated strain in the test specimen to correlate the test results. The idea is that if, for the same elastically calculated strain, the effects of plasticity, creep and strain redistribution in the SMT specimen result in a stress-strain hysteresis loop that envelopes the hysteresis loop in the component, then the SMT results can be used to assess the cyclic damage in the component. A design margin must be applied to the test data to account for factors such as data scatter and extrapolation to longer hold times.

3.1.2 SMT Specimen characteristics

In order to be effective, the SMT specimen must be sized to provide a stress-strain hysteresis loop under cyclic loading which envelopes the hysteresis loop of components of interest. Unfortunately, there is apparently no rigorous way to demonstrate that a two-bar model, Figure 3(c), can bound the response under all circumstances. However, there are approaches based on a four-bar model representation of the stepped cylinder shown in Figure 3(a) that can be used to demonstrate the bounding strategy is applicable to a range of practical circumstances.

There are two types of geometric limitations. The first is the allowable value of local stress concentration when combined with the effects of global elastic follow-up. By requiring that the stress at the local stress concentration relax and using an expression for the relaxation rate developed by Kasahara et al. (1995), Jetter (1998) developed the following restriction on elastic stress concentration, *K*, as a function of global follow-up q_n:

$$K \le \frac{q_n}{q_n - 1} \tag{1}$$

There are two important reasons to avoid the regime where the stress in the local stress concentration is not relaxing. First, a high stress concentration in an area where there is a structural discontinuity with large global elastic follow-up can result in a nonlinear increase in localized strain range and accelerated creep damage. The second reason is that when the global follow-up becomes very large, it is not possible to bound the response with a reasonably sized SMT specimen. In earlier Finite Element Analysis (FEA) (Sham et al., 2012), K is defined as the ratio of the maximum principle stress at the stress concentration location to the average stress at the necked test section. The second issue on geometric limitations is the magnitude of global follow-up, q_n, in the representative structure and the requirement that places on the follow-up of an SMT specimen in order to bound the response of representative structures of interest. As discussed by Jetter (1998), there have been numerous investigations reported in the literature. In summary, it appears that the value of global follow-up is conservatively represented by $q_n = 2$ and certainly bounded by a value of three (3), provided that the stress range is suitably limited.

Based on the relaxation rate expression of Kasahara et al. (1995), Jetter (1998) developed an expression for the peak combined follow-up, q_p, in the four-bar structure given by:

$$q_p \le K q_n \tag{2}$$

for a range of practical values of K and q_n. This expression for peak elastic follow-up was also recommended by Takahura et al. (1995), based on thermal transient testing of a cylindrical shell using a notch model and a stepped cylinder model.

Combining Eqs. (1) and (2) with the global follow-up of representative structures results in the following requirement for the follow-up of an SMT specimen in order to bound the response of representative structures of interest;

$$q_p \leq 4.0 \text{ to } 4.5 \tag{3}$$

This follow-up value is a target value for developing a SMT design curve. However, there are practical difficulties with specimen design, instrumentation and control, and supporting test frame design that are discussed in more detail in by Wang et.al. (2013). Several specimen geometries under varying loading conditions and materials have been tested. The results from 15 tests are reported in Wang et al. (2015) Most of the test data was obtained on a Type 1 geometry.

The Type 1 geometry was based on a maximum isothermal specimen length and a test or necked test section diameter-sized to provide protection against a buckling failure mode. The driver section diameter was sized to provide an area ratio of 0.5 to maximize the follow-up factor within a given specimen length. The transition radius of 0.25 in was selected based on elastic analysis of the stress concentration to provide the lowest stress concentration consistent with the overall length constraint and the necked test section length required for the extensometer. The hope was that the specimen failure would occur in the gage section and not at the transition radius, although this turned out not to be the case. Figure 5 shows the Type 1 test geometry and Table 1 summarizes the some of the relevant test parameters. Not shown is the Type 2 geometry that has a much sharper transition radius 0.085in to model the combined effects of global follow-up and a local stress concentration.

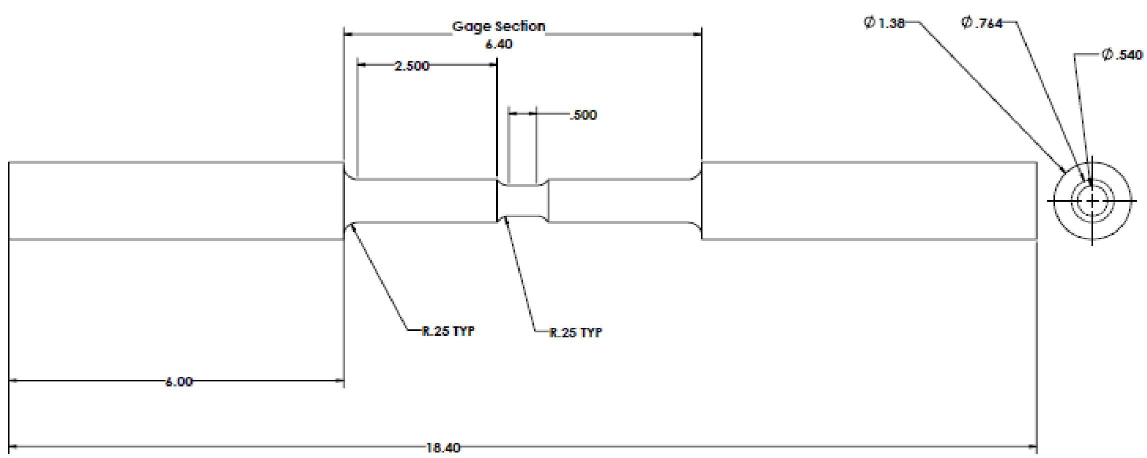


Figure 5. Type 1 SMT geometry for Alloy 617

There are two key test results that illustrate the role of strain redistribution in elevated temperature structures that is modeled by the SMT results. The first is the magnification of the elastically calculated strain range due to plasticity and creep. This is illustrated by Figure 6 which shows the measured strain in the test section of a Type 1, Alloy 617 specimen tested at 950^{o}C with a tensile hold time of 10min. Identified on the figure is the elastically calculated strain for the same test parameters. There is seen to be about a factor of two increase in strain range.

Table 1. SMT testing specimen geometry

	Necked test section length, in	Transition radius, in	SCF	Transition length, in	Driver section length, in	Total testing length, in	Target Elastic follow up value	Material Tested
Type 1	0.5	0.25	1.37	0.208	4.08	5	3.5	Alloy 617, 304H, 316H

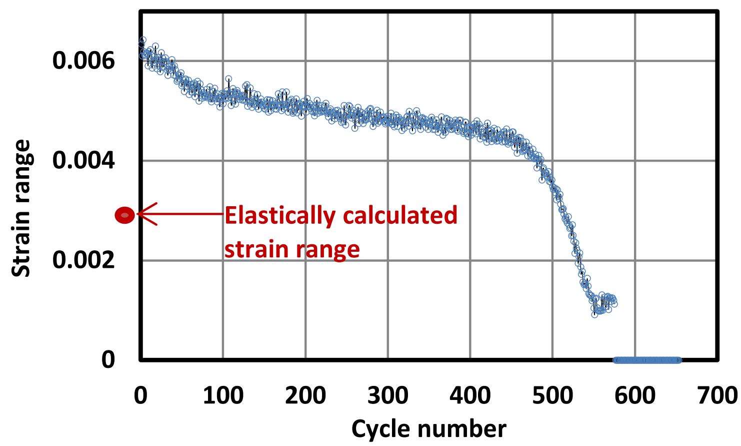


Figure 6. Strain range history

The second key illustrative result is the retardation of stress relaxation due to follow-up effects. This is shown in Figure 7 that compares the measured stress history for an SMT specimen with the same initial measured strain as in a conventional strain controlled creep fatigue test. It is seen that the creep damage, and resultant cycles to failure, will be underestimated as compared to the damage accrued in a structure with significant elastic follow-up.

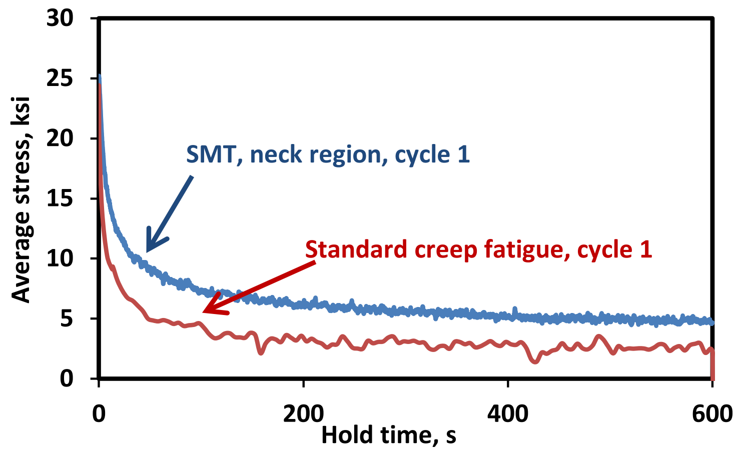


Figure 7. Stress relaxation during the hold period for SMT neck region and standard creep-fatigue specimen, Carroll (2012).

4 Incorporation Plan for Integrated EPP-SMT Evaluation of Cyclic Elevated Temperature Loading

As stated above, the goal is to incorporate an SMT data based approach for creep-fatigue damage evaluation into the EPP methodology to avoid the use of the D diagram and to minimize over-conservatism while properly accounting for localized defects and stress risers. Figure 8 is an updated flow chart that identifies key issues, original assumptions (Sham et al., 2016), findings from the investigations so far and their impact on the flow chart logic for resolution and verification of the EPP-SMT approach. Shown are the initial three key assumptions that have been made to move forward, the near term test and evaluation actions required to validate these assumptions including recent results, and the long term test and analytical development required depending upon the outcome of the near term validation efforts.

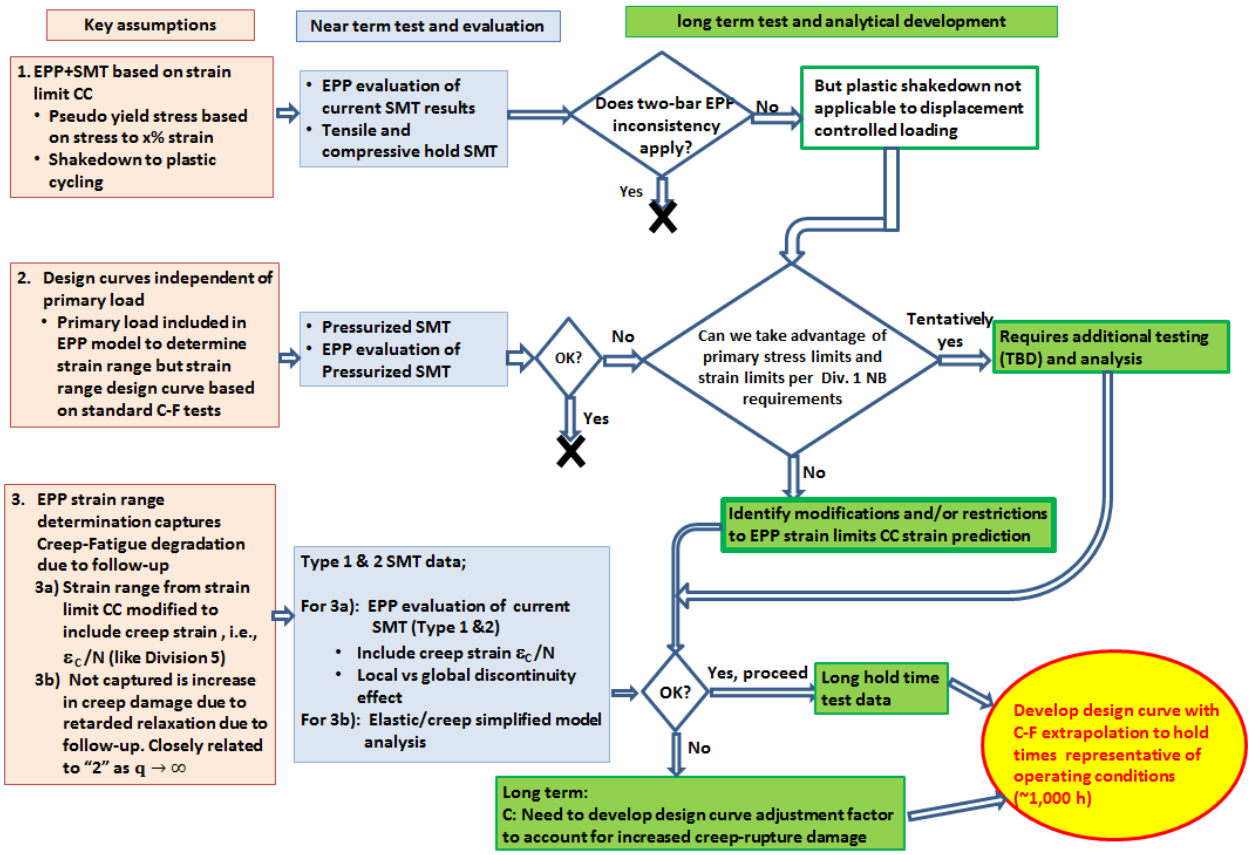


Figure 8. Path to resolution and verification of the EPP-SMT approach

4.1 Assumptions

EPP/SMT approach will be based on the EPP/Strain limit code case with the pseudo yield stress based on the stress to x% strain and shakedown to plastic cycling

The rationale is that the strain limit code case provides an upper bound to creep strain that can be used to approximate the creep strain per cycle by dividing by the number of cycles similar to the cyclic creep strain adjustment in Subsection HBB (formerly NH). (Note: it would be advantageous to be able to calculate a local creep strain instead of a bounding strain. Also, in the current methodology, the actual length of time in an over temperature transient isn't taken into account, thus overweighting the effect of short time over temperature transients.)

An important initial consideration is whether the use of the SMT data for validation of the strain range methodology will be subject to the same limitations as the two bar test results. As described above, the two bar results were not in agreement with the EPP strain limit code case predictions. The so-called "stovepipe" plot of allowable temperature difference vs. applied mean load was predicted at much lower mean loads than the test data. This was postulated to be caused by uniform temperature and stress fields in the EPP model and it was demonstrated by inelastic analysis of a distributed load example, a Bree type cylinder, that the EPP strain limit methodology worked for representative distributed load geometries and temperatures. The concern was that if there was, unexpectedly, a similar situation with the EPP strain limit application to the SMT data, it would not clear how to proceed using that data as a basis for validation.

A subsequent evaluation of some of the SMT data was carried out which demonstrated that the above discussed two bar inconsistency did not apply. This evaluation was based on modeling the SMT test as two bars in series using truss elements. (Note that this is consistent with the initial formulation of the SMT approach based on two idealized cylinders in series.) However, as a result of this evaluation it was shown that the EPP shakedown concept did not apply to pure displacement controlled cyclic loading without a sustained primary load. Under these conditions the idealized cylinder model shows an immediate stabilized plastic strain in the smaller test section that is proportional to the applied displacement. This finding has relevance to the use of strain range determination from the EPP Code Case and requires further evaluation.

Also shown under the category of “near term test and evaluation”, is a comparison of tensile hold data with data from tests with alternating tension and compression hold times. The reason for this is twofold. First, it would be desirable to base the validation on the more conservative data. However, perhaps the more important reason is to minimize the barreling effect that clouds the interpretation of the tensile hold only test data.

Also noted here, is the proposal to use standard creep-fatigue data as the basis for generation of the SMT type design curve.

4.1.1 The design curves will be independent of primary load

Part of the rationale for this is that the primary load is included in the EPP model to determine strain range. Also, as described in the original SMT paper (Jetter, 1998), the stress level associated with primary loading will be small compared with the secondary and peak stress levels and shouldn’t have a significant effect on the total life. However, it is important to confirm this point, hence the need for near term pressurized SMT tests. Conceptually, taking credit for limitations on primary loading and strain limits is analogous to the NB hopper diagram philosophy where, for example, the use of strain controlled fatigue data is predicated on the stress field surrounding a local stress riser shaking down to elastic action in accordance with the primary plus secondary stress range limits. Similarly, elastic shake down of primary plus secondary stresses is predicated on the primary stress being less than yield.

4.1.1.1 Pressurized SMT

Pressurized SMT capsule tests are being used to assess the second assumption that the effects of stress levels associated with primary bending will be small compared to the secondary and peak levels and should not have a significant effect on the total allowable design life. Figure 9 shows the configuration of the pressurized SMT. The effective length of the pressurized SMT specimen is 5in with a 0.5in necked test section. Figure 10 and Table 2 show the results of recent pressurized testing. Further details of the pressurized SMT can be found in Wang et al. (2016a, 2016b). Initially, tests were run at a negligible level and at 200psi. From these results it was concluded that the effect of pressure would be not have a significant impact but subsequent test at 500 and 700 psi showed that there was an effect of pressure. However, rough calculations for allowable design life at the tested pressures yielded approximately 30,000hr at 200psi and 300 and 100hr at 500 and 700 psi respectively. For a usual design situation, the design life would be longer than 30,000. This tends to confirm the original hypothesis that relatively small primary loading would not impact the allowable cyclic life. However, additional testing and evaluation with longer hold times and lower levels of cyclic loading are required for confirmation.

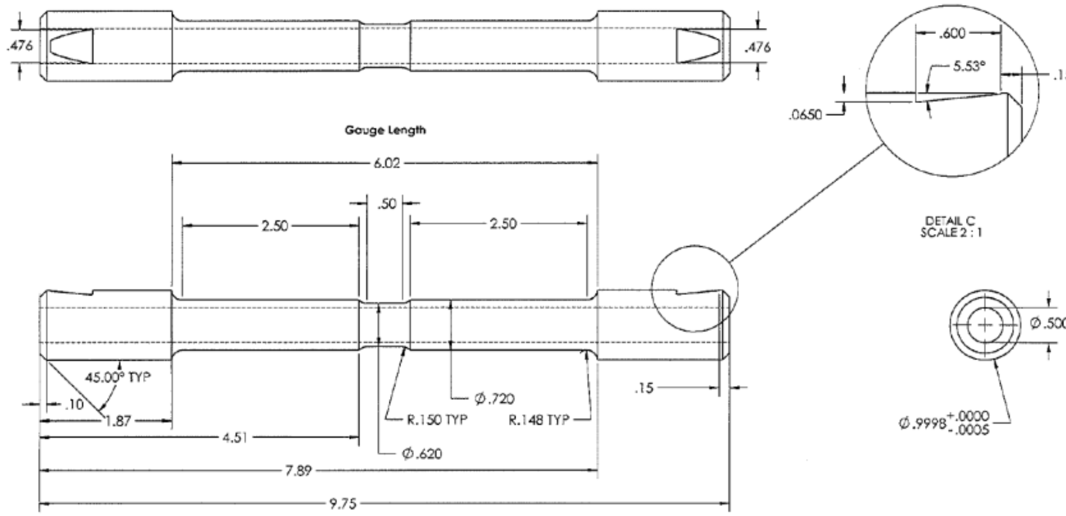


Figure 9. Center section of the tubular SMT pressruziation specimen for Alloy 617. Units are in inches.

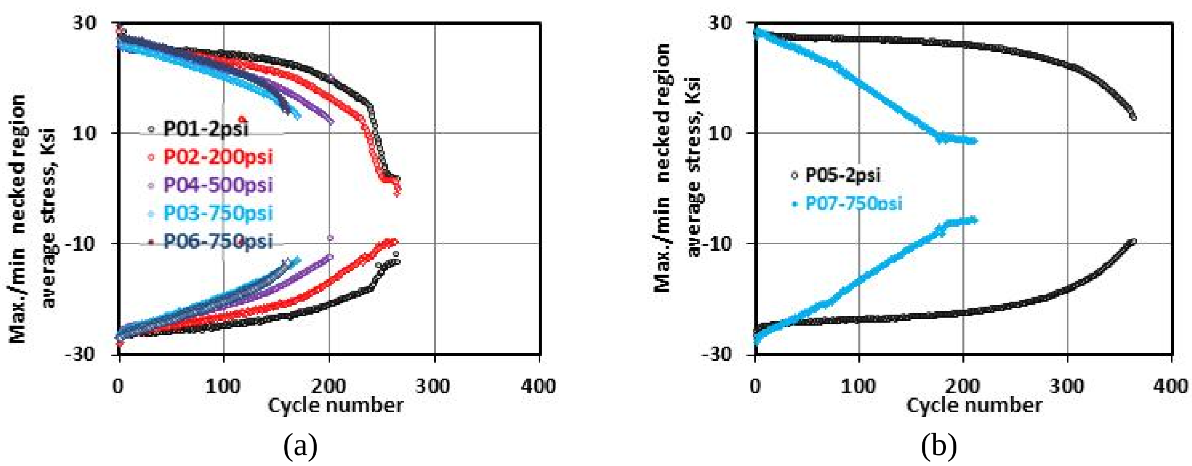


Figure 10. Comparison of the maximum and minimum stresses for tension hold (a) or combined tension and compression hold (b) pressurization SMT tests on Alloy 617

Table 2. Tubular SMT pressurization for Alloy 617 with elastic calculated strain range of 0.3%

Spec. ID	Amplitude, δ value, mil	Disp. hold[(1)]	Hold time, sec	Initial strain range, %	Test temp., °C	Internal pressure, psi	Life time, hr	Cycles to failure
INC617-P01	4.5	T	600	0.8	950	2	37.4	220
INC617-P02	4.5	T	600	0.8	959	200	37.4	220
INC617-P04	4.5	T	600	0.8	957	500	34	200
INC617-P03	4.5	T	600	0.75	958	750	25.5	150
INC617-P06	4.5	T	600	0.8	950	750	23.8	140
INC617-P05	4.5	T&C	600	1.0	955	2	107.7	320
INC617-P07	4.5	T&C	600	1.05	950	750	60.6	180

[(1)] T – tensile displacement hold, T&C – both tensile and compressive displacement holds

4.1.1.2 Modified Two-bar configuration and loading profile

In addition to the pressurized SMT data, the modified two bar test shown conceptually in Figure 11 will provide valuable data for verification of the effects of superimposed primary loading. In this modification, the SMT Bar 1 configuration is held constant elevated temperature while the uniform diameter Bar 2 is thermally cycled with hold times. The test sections of Bar 1 and 2 are constrained to have equal elongations. There is a constant load applied to both bars in parallel. The advantage of this two bar modified configuration is that all the relevant test parameters can be measured directly

If it turns out that the effect of primary loading is significant, then the proposed solution, as shown under the long term test and analytic development column, is to develop mean stress type design curves analogous to the mean stress correction curves for the fatigue evaluation of some materials below the creep regime.

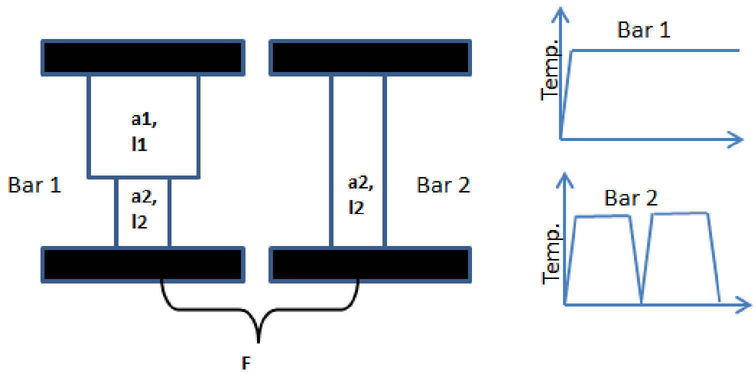


Figure 11. Modified two-bar test configuration and loading profile

4.1.2 The EPP strain range determination captures the creep-fatigue degradation due to follow-up

In this assumption, the strain range from the strain limit code case will be modified to include creep strain, ε_c , divided by the number of cycles N, to estimate the additional strain per cycle due to creep. This is similar to current Div. 5 approach in HBB-T-1432(h).

As currently envisioned, the plastic strain from the EPP strain limit code case will capture the enhanced strain redistribution at both gross and local structural discontinuities. Further, the use of a pseudo stress in the elastic-perfectly plastic analysis will account for creep as well as plastic redistribution and the use of the elastic-perfectly plastic material model will also contribute to the bounding nature of the solution. However, what is not addressed directly due to the use of standard creep-fatigue test data to develop the SMT design curves is the retardation of stress relaxation due to follow-up effects. For local structural discontinuities the surrounding stress field will tend to limit localized stress and strain redistribution and approach the pure relaxation mode characteristic of stain controlled creep-fatigue tests. If, based on test data and analysis, additional modifications are required, then a combination of restrictions on follow-up and stress concentration factor limits per the Jetter paper (Jetter, 1998) and a creep damage enhancement factor based on nominal follow-up characteristics may be required. If required, the use of these factors and other potential considerations as discussed above will need to be factored into the creep-fatigue correlation equations required to develop the design curves as shown under the long term test and analytical development column heading.

As shown under the near term test and evaluation heading, the results from both the Type 1 and 2 SMT test specimens will be evaluated to determine which of the factors discussed above will be required. Interpretation of the test results will be complemented with elastic/creep simplified analytic models analogous to those used in the two bar evaluations.

4.2 Long term tests

Longer term tests support the SMT design curve development shown in Figure 8 and provide a partial validation of the hold time extrapolation procedures developed for application to the design curves. The modification of the two bar test configuration is discussed above in section 4.1.1.2.

5 Summary

The concept of Elastic-Perfectly Plastic (EPP) combined integrated creep-fatigue damage evaluation approach is presented. The goal of the proposed approach is to combine the advantage of the EPP strain limit methodology, that avoids stress classification, with the advantage of the Simplified Model Test (SMT) method for evaluating creep-fatigue damage without deconstructing the cyclic history into separate fatigue and creep damage evaluations. The EPP methodology for strain is based on the use of a pseudo yield stress that limits creep and plastic strain accumulation and intrinsically reflects the stress and strain redistribution currently based on the use of stress classification procedures. The resulting strain ranges are then assessed for combined creep and fatigue damage using the SMT approach. In this approach, the enhanced damage resulting from strain redistribution and slowed stress relaxation due to follow up effects is accommodated in the design of the test specimen, sized to bound redistribution effects in typical components. A path forward to merge these methodologies was identified along with the anticipated problems, facilitating assumptions, and required steps and test data needed to verify their applicability.

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