DEVELOPMENT OF A CREEP/FATIGUE CRACK GROWTH TESTING CODE OF PRACTICE FOR COMPONENTS

K M Nikbin
Mechanical Engineering Department,
Imperial College,
Lonndon SW7 2BX.
UK

ABSTRACT

In fossil, nuclear power generation, chemical and aerospace industries there is a need to assess the significance of defects which may exist in high temperature equipment operating in the creep and creep/fatigue range [1-6]. Creep and creep/fatigue crack growth models as well as residual defect assessment codes need reliable and verifiable material properties data and validated fracture mechanics parameters for use in their predictive methodologies. VAMAS TWA25 has incorporated in a draft Code of Practice the results from the research to develop an overall methodology for deriving acceptable data and validated parameters for life assessment analysis. The results have been compared to the Creep Crack Growth ASTM E1457 [7] standard. The Draft Code of Practice (CoP) identifies methods of testing and presents validated fracture mechanics parameter used for analyzing laboratory creep crack growth data derived from non-standard feature test components.

INTRODUCTION

VAMAS has been active in the field of standardisation of testing and analysis of elevated temperatures fracture mechanics specimens since 1987. Between 1987-1992 a new working group, TWA 11, was setup to develop and formulate a standard for a high temperature test method. This involved making recommendations for measuring the creep crack growth properties of materials and using the creep fracture mechanics parameter C^* in the analysis of the data. The method was restricted to creep ductile situations. The findings were incorporated into ASTM test procedure [7] that was the first standard to deal with crack growth testing at elevated temperatures. This methodology was extended under TWA 19 (1993-1998) to conditions where only limited creep deformation or otherwise creep brittle conditions were observed. It has been clear for some time that Industry needs additional justifications both in testing and analysis methods, in order to accept with further confidence the results derived in defect assessment codes. A number of European Community funded collaborative projects since 1995 have produced sizable amount of data and analysis to show the importance of testing different geometries. VAMAS TWA 25 committee, established in 1999, which has had the broad aim of recommending testing, analysis and life prediction methods for assessing elevated temperature creep and creep/fatigue crack growth in metallic specimens, and 'Feature components' containing defects.

BACKGROUD TO LIFE ASSESSMENT CODES

Components in the power generation and petro-chemical industry operating at high temperatures are almost invariably submitted to static and/or combined cycle loading. They may fail by net section rupture, crack growth or a combination of both. The development of codes in different countries has moved in similar direction and in many cases the methodology has been borrowed from a previously available code in another country. Early approaches to high temperature life assessment, show methodologies that were based on defect-free assessment codes. For example ASME Code Case N-47 [1] and the French RCC-MR [2], which have many similarities, are based on lifetime assessment of un-cracked structures. More recent methods make life assessments based on the presence of defects in the component. The more advanced codes dealing with defects over the range of creep and creep/fatigue interaction in initiation and growth of defects are the British R5/R6 [4,5], BS 7910 [3] and the French A16 [6] which have clear similarities in terms of methodology. It is also obvious from these assessment methods that the correct evaluation of the relevant fracture mechanics parameters, for which the lifetime prediction times are dependent upon, are extremely important.

It is also evident that the detailed calculation steps, which are proposed in these documents, do not in themselves improve the accuracy of the life prediction results. In any event as these procedures have been validated for limited sets of geometries and material data, their use in other operating conditions will need careful judgment. The CoP from VAMAS TWA25 will present validated fracture mechanics parameters for this purpose. The CoP will assist by highlighting improvements in the test methods so that verifiable material properties are collected in order that modelling methods using standard laboratory and feature component tests can be used with increased confidence in life estimation codes. The work would be of interest to ASTM, ISO, ASME, API (American Petroleum Institute) and PVRC (Pressure Vessels Research Council (USA)) as well as to further improving available life assessment CoP such as R5, BS7910 and A16. Clearly the recommendations resulting from this CoP will be useful for increasing confidence in defect assessment codes. In addition the similarities of the approaches in the various codes do not necessarily imply that calculations by the different methods will give the same predictions. It may be possible that under certain controlled and validated circumstance the predictions can be optimised. It is clear that a critical comparison is only possible when the same method is used on another material and condition or the same test cases are examined by the different codes.

OBJECTIVES

The main objective has been to establish accurate and reliable testing methods and a unified procedure for assessing creep crack growth at elevated temperatures in industrial specimens, which contain defects. Determination of procedures for analysing the test data using fracture mechanics concepts is important and therefore the validated correlating parameters will be made available in the CoP. Validation of results against measurements on standard Compact Tension laboratory specimens using ASTM E1457 [7] has been also carried out as it indicates the effects of constraint on specimen geometry and size. There are a number of parameters such as K [7] linear elastic fracture mechanics, Q^* [8] based on the thermally activated process and K_{cmat} [9] based on creep toughness properties that will be included in the Draft CoP, once they are validated with experimental data. In this paper an outline of geometries that have been validated will be identified and the differences in method of analysis using the fracture mechanics parameter C^* in laboratory and components will be highlighted and compared for a pipe component.

STEADY STATE CRACK GROWTH ANALYSIS

Creep crack growth rate under steady state for a creep ductile material is usually analysed using the fracture mechanics parameter C^* [7]. Once a steady-state distribution of stress and creep damage has been developed ahead of a crack tip, it is usually found that creep crack growth rate $\dot{a}$ can be described by an expression of form (e.g. [7,10,11]):

$$\dot{a} = D \cdot C^{*\phi} \tag{1}$$

where D and ϕ are material constants.

For fatigue the linear fracture mechanics solution is used [2-4, 10] to correlate the crack extension per cycle da/dN in the form

$$da / dN = C \cdot K^{m} \tag{2}$$

This paper will not go into detail in describing fatigue testing and analysis as methods for time independent fatigue process are available and their use in life assessment is well established [2-4].

With respect to situations where creep dominates most often the constants in Eqn. (1) are obtained from tests that are carried out on compact tension (CT) specimens based on the recommendations of ASTM E 1457-01 [7] and hence, C^* is estimated experimentally from measurements of creep load-line displacement according to the experimentally determined value of C^* given by

$$C^*_{\exp} = \frac{P\dot{\Delta}^c}{B_n(W-a)} \frac{n}{n+1}\eta \tag{3}$$

where $\dot{\Delta}^c$ is the load line displacement rate due to creep alone, B_n, W and a are the specimen net thickness (accounting for side-grooves), width and crack length, respectively, n is the creep stress exponent. The geometry function η from [1] is given as

$$\eta = -\frac{1}{m}\frac{dm}{d(a/W)}. \tag{4}$$

Where m is a function of collapse load. Solutions for the geometry function η, in the alternative geometries, based on analytical solutions (limit load analyses) and finite element calculations will be presented in the draft CoP.

The data obtained from CT from Eq.(3) usually considered as 'benchmark' for creep crack growth properties of the materials in the same way as creep strain rate and rupture for uniaxial creep tests. These data are, then, employed directly in crack initiation and growth models described in the different codes [1-5] to estimate residual lives in components. For components such as pipes and plates, on the other hand, C^* must be determined from finite element analysis or reference stress methods. In the CoP, the reference stress procedure is adopted in line with that used in the defect assessment codes [1-5]. With this approach C^* is expressed approximately as [11-12]:

$$C^*_{ref} = \sigma_{ref} \cdot \dot{\varepsilon}_{ref} \cdot \left(\frac{K}{\sigma_{ref}}\right)^2 \tag{5}$$

where $\dot{\varepsilon}_{ref}$ is the creep strain rate at the appropriate σ_{ref} for the component and K is the stress intensity factor corresponding to the applied loading. When the creep strain rate $\dot{\varepsilon}$ at an applied stress σ can be described in terms of the Norton creep law [12]:

$$\dot{\varepsilon} = A \cdot \sigma^n \tag{6}$$

where A and n are material constants at constant temperature. Thus, Eq. (5) can be rewritten as:

$$C^*_{ref} = A \cdot \sigma_{ref}^{n-1} \cdot K^2 \tag{7}$$

The typical value for n is between 5 and 12 for most metals. In addition, the concept of the average creep rate, $\dot{\varepsilon}_{Ave}$, obtained directly from rupture data, has been used 12] to account for all three stages of creep as an approximate method for estimating the average creep rate $\dot{\varepsilon}_{Ave}$ as shown and defined by

$$\dot{\varepsilon}_{Ave} = \frac{\varepsilon_f}{t_R} = \dot{\varepsilon}_o \cdot \left(\frac{\sigma}{\sigma_0}\right)^{n_{Ave}} = A_{Ave} \cdot \sigma^{n_{Ave}} \tag{8}$$

where σ is the applied stress, ε_f is the uniaxial failure strain, t_R is the time-to-rupture and A_{Ave}, n_{Ave}, σ_o and $\dot{\varepsilon}_0$ are material constants.

CRACK INITIATION ANALYSIS

When a structure containing a defect is first loaded the stress distribution is given by the elastic K-field or the elastic-plastic J-field. Therefore, time is required for the stresses to redistribute to the steady-state creep stress distribution controlled by C^*. During this period, transient conditions exist which are not uniquely defined by C^*. In addition, a period of time is needed for creep damage to develop around the crack tip [11]. Furthermore due to the practical limitations of crack detection equipment, the initiation of crack growth is difficult to determine precisely. Typically, this ranges between an extension Δa of between about 0.1 and 0.5 mm depending on component and crack dimensions. For laboratory specimen such as CT, ASTM E1457-00 [7] identifies an extension of 0.2 mm to cover the entire transition time to steady state conditions and this distance also takes into account the resolution of crack monitoring equipment. However, in order to increase the confidence in the crack measurement of the different components, it has been determined, in this present work, that Δa = 0.5 mm was the best value to choose to compare both the CT data and the semi-elliptical defects in the pipes and plates.

From Eq. (1) it may be expected that the time, t_i, to initiate a crack extension of Δa can be expressed by:

$$t_i = D_i \cdot C^{*\phi_i} \tag{9}$$

where D_i and ϕ_i are material constants. For steady-state cracking D_i is expected to be given approximately by Δa /D with ϕ_i = -ϕ and hence Eq. (9) can be re-written as follows [12]:

$$t_i = \frac{\Delta a}{D} \cdot C^{*-\phi_i} \tag{10}$$

This equation assumes that the entire initiation period is governed by steady-state C^*. This cannot be expected to be true during at least part of the initiation period t_i. The applicability of the equation will be examined for the pipes and plates.

GEOMETRY DEFINITIONS FOR LABORATORY SPECIMENS

The draft CoP will identify seven specimen geometries that have been verified for the purpose of creep and creep/fatigue crack growth and initiation testing. This does not mean that other geometries are invalid but that they would need validation before their inclusion in the CoP. This section presents the geometries. Detailed dimensions, machining instructions methods of setting up and limits of testing accuracies will be available in the draft CoP. For the geometries listed below more detail will be available in the document as these have been validated by various round robin and collaborative programmes. The abbreviations which are to be used to denote the specimen geometries to be examined are given in Table1.

Table 1: Specimen Abbreviations

C(T)	Compact Tension
CS(T)	C-Shaped Tension
SEN(T)	Single Edge Notched Tension geometry
SEN(B)	Single Edged Notched Bending geometry
DEN(T)	Double Edge Notched Tension geometry
M(T) or CC(T)	Middle Tension or Centre (through) Cracked Panel in Tension
CNB(T)	Circular Notch Bar in Tension

GEOMETRY DEFINITIONS FOR FEATURE COMPONENTS (Pipe and Plates)

Componet or feature component testing is an important part of the draft CoP. It has been shown previously that although different codes employ Eqns. (5-7), often different formulae are used to evaluate K and σ_{ref}. Greater sensitivity of C^* and cracking rate to reference stress than to K is expected from Eq. (5) since ϕ in Eq. (1) is close to one, and typically n>>1 and evidence of this has been demonstrated previously [11,12]. It has also been previously demonstrated that 'global' collapse solution represent best the cracking behavior in pipe components [11]. Consequently, in the present work, solutions for K due to Raju and Newman [13] and the 'global' collapse solution for the reference stress have been used to estimate C^* in the analysis. 'Global' solutions of reference stress are based on the collapse of the entire cross-section at the site of a defect. For a semi-elliptical axial defect in a pipe subjected to an internal pressure p, R6 [11] gives the reference stress as:

$$\sigma_{ref\ Pipe} = \frac{p}{\frac{1}{R_e - a} \cdot bate(a,c) + \ln\left(\frac{R_e - a}{R_i}\right)} \tag{11}$$

where *bate(a, c)* is given by :

$$bate(a,c) = \frac{a}{\sqrt{1 + 1.61 \cdot \frac{c^2}{[(R_e - a) \cdot a]}}} \tag{12}$$

Where *bate*(*a, c*) function of dimensions, *a* is crack depth, *c* is half crack length at the surface and R_i and R_e are the internal and external radii of the pipe, respectively.

REFERENCE STRESS SOLUTIONS FOR PLATES

Similar to the pipes, there exist several reference stress solutions. It has been shown previously that for small partially penetrating defects in plates subjected to combined tension and bending loading, these reference stresses can significantly over-estimate creep crack growth rates [4]. In the draft CoP, a reference stress, which is based on a global collapse mechanism [14] used and is expressed as follows:

$$\sigma_{ref\ Plate} = \frac{(\sigma_b + 3 \cdot \gamma \cdot \sigma_m) + \left\{(\sigma_b + 3 \cdot \gamma \cdot \sigma_m) + 9 \cdot \sigma_m^2 \cdot \left[(1-\gamma)^2 + 2 \cdot \gamma \cdot (\alpha - \gamma)\right]\right\}^{1/2}}{3 \cdot \left\{(1-\gamma)^2 + 2 \cdot \gamma \cdot (\alpha - \gamma)\right\}} \tag{13}$$

where $\gamma = (a \cdot c) / (W \cdot l)$ and $\alpha = a / W$. In these equations, *a* is crack depth, *c* is half crack length at the surface, *W* is the thickness of the plate and *l* is the half-width of the plate, respectively.

It will be shown in the [11] that there is no absolute correct solution for reference stress in components and that in order to get an overall agreed definition compromises have to b made. Eventually by using detailed FE analysis of the geometry in 3D and the right boundary conditions it may be possible to improve the solutions. But for the present it is more important to be able to compare inter-laboratory data and reach definitive comparison with the results.

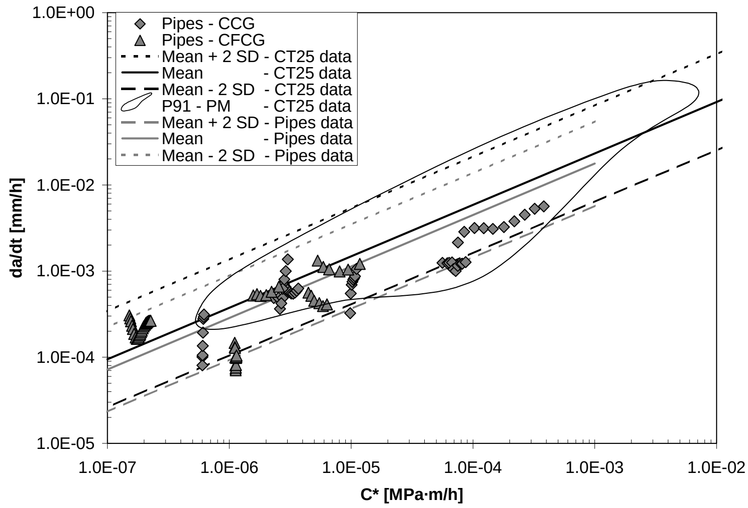

Figure 1: Effect of static and cyclic loading on crack growth rate, for P91 at 625°C for both CT and pipe specimens [11].

As an example Figure 1 highlights the comparison for cracking rate between CT and pipe geometry for P91 under static and cyclic loading. The trend follows Eq. 1 but has a large scatter. This information can be used as a basis to assess residual life of components employing for example the R5 or BS7910 and/or by using probabilistic methods.

CONCLUSIONS

Creep and fatigue crack growth models as well as residual defect assessment codes need reliable and verifiable material properties data and validated fracture mechanics parameters for use in their predictive methodologies. VAMAS TWA 25 has incorporated the results from the research to develop an overall methodology for deriving acceptable data and validated parameters for life assessment analysis. The results have been compared to ASTM E1457 [7] standard for testing CT specimens. The present collaborative study has developed a draft Code of Practice for testing non-standard geometries and components. It presents validated results for testing and analysis used for laboratory creep crack growth data and considers their relevance to long term crack initiation and growth of cracks in components.

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