DAMAGE ANALYSIS OF PRESSURE PIPES UNDER HIGH TEMPERATURE AND VARIABLE PRESSURE CONDITIONS

P. Arsenos, K. Zafiris, E. Kartsonaki, M. Kouskouti, K. Kyriakos, D. Papassalouros, D. Pavlou, N.V. Vlachakis

TEI Halkidas, Mechanical Engineerning Dept., 34400 Psahna, Halkida Evoia, Greece, email: dpavlou@teihal.gr

Absract. The problem of non-linear stress analysis of creeping reinforced pipes under constant pressure has been treated in a recent work [1]. In the present work, a damage accumulation analysis of the above problem is attempted taking into account the non-linear distribution of the stresses as well as non-linear damage accumulation under variable pressure and/or temperature conditions. For the stress analysis a non-linear differential equation is used to derive the stress concentration in critical locations of power pipes reinforced by rigid rings which are distributed along their axis. Due to step-wised temperature and internal pressure of the pipe, the damage accumulation is predicted by using a damage function specified with respect to damage parameter derived by the stress versus Larson-Miller coefficient curve. Advantages of the proposed methodology are:

(a) the 2-D creep stress analysis incorporates mechanical behaviours of material derived by uniaxial tests,

(b) the predicted damage accumulation due to the variable pressure takes into account the previous damage history as well as the loading order effect.

1. Introduction

The service conditions of pressure pipes in power plants often incorporate high temperature and step-wised variable pressure. To perform life-time prediction due to these creep-fatigue interaction phenomena two stages should be followed: (a) non-linear (due to creep) stress analysis of the pressure pipes, and (b) non-linear damage accumulation prediction. Concerning the first stage, to perform stress analysis for biaxial loading of the creeping walls of a pressure pipe, a non-linear bending theory will be used. Due to a non-linearity in the material behaviour the corresponding boundary-value problem results in a sixth-order no-linear differential equation which - after phenomenological simplifications and mathematical treatment -is reduced to a fourth order non-linear one. Because of the lack of analytical solution, this non-linear ODE is solved using the finite differences method (F.D.M). The derived stress field is associated by the dependency of the internal pressure by the time. Due to the superposition of high temperature with the variable step-wised stress conditions, creep-fatigue interaction phenomena are taking place. The total damage can be considered to be equal to the sum of the damage increments corresponding to each individual loading step. Failure occurs when the total accumulated damage reaches a critical value. The prediction of accumulated damage through above concept pre-assumes the selection of a suitable damage function. A large number [2-5] of damage accumulation models have been published, recognising as damage functions sensitive material properties or internal stress or inelastic strain parameters resulting in more or less successful life-time prediction. However, most of them are limited for constant uniaxial loading and temperature conditions. In the present work, the use of a recent non-linear creep-fatigue damage accumulation rule developed by Pavlou [6], incorporating parameters of constant stress and temperature creep tests, is attempted for the prediction of the remaining life of a step-wised loaded reinforced pipe under high temperature.

2. Formulation of the problem

An axisymetric thin-walled pipe reinforced by rigid rings (Fig. 1) is considered to be loaded with step-wised internal pressure under high temperature. The rigid rings are considered to be periodically distributed along the pipe while the distance between the rings is L. The boundary conditions of the problem can be summarised as follows:

$$w(0)=0 \tag{1}$$

$$w(L)=0 \tag{2}$$

$$w'(0)=0 \tag{3}$$

$$w'(L)=0 \tag{4}$$

$$w'(L/2)=0 \tag{5}$$

$$w(\alpha)=w(L-\alpha), \qquad 0 \le \alpha \le L \tag{6}$$

$$w'(\alpha)=-w'(L-\alpha), \qquad 0 \le \alpha \le L \tag{7}$$

In above equations the magnitudes *w* and *w’* denote the radial displacement and its derivative with respect to *x*.

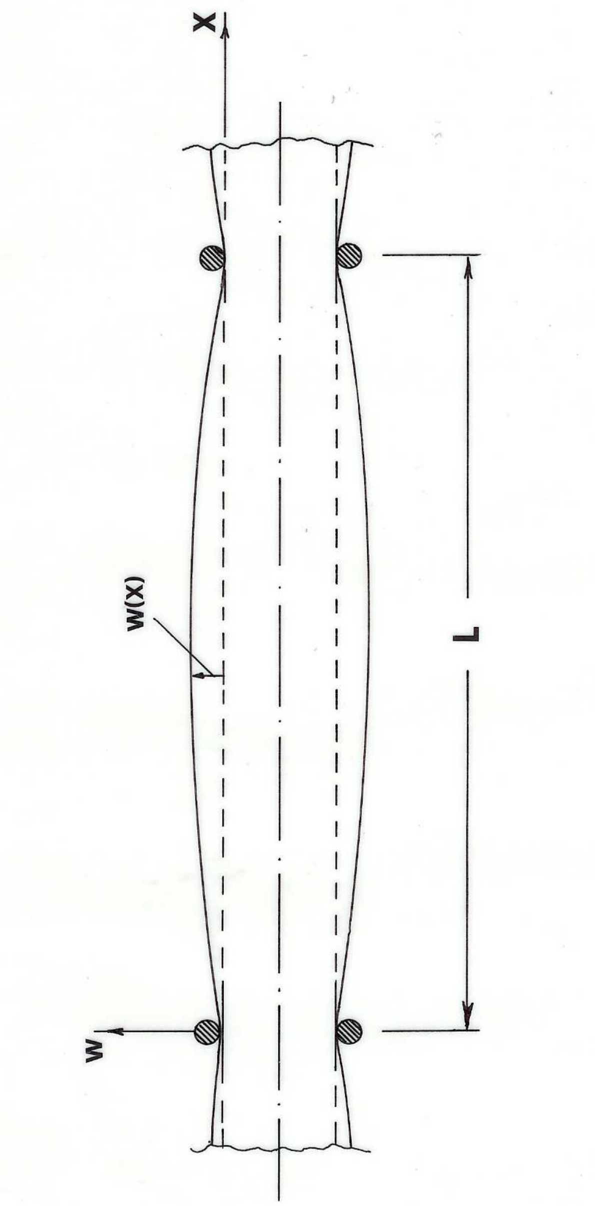

Figure 1: Geometry and coordination system of the pipe

3. Material behaviour

Due to the high temperature condition the relation between the stress and strain can be described by a creep law. Because of the short period of the primary and tertiary creep, the stress analysis will be performed with the aid of the well known Norton-Bailey steady state creep rule:

$$\frac{d\varepsilon}{dt} = Ae^{-Q_c / R_g T} \sigma^n \tag{8}$$

Where ε is the strain, σ is the stress, T is the temperature, Q_c is the activation energy for creep (J/mole), R_g is the universal gas constant (8.31 J/mole K) and A, n are material constants derived by uniaxial creep tests.

4. Stress analysis

To perform stress analysis of the pressure pipe shown in Fig. 1, the equilibrium of a longitudinal strip of length L and unit width is considered (Fig. 2). It is well known [7] that

$$\varepsilon = yw'' \tag{9}$$

Considering the Norton-Bailey rule given by the Eq. (8), the above equation can be written:

$$Ae^{-Q_c / R_g T} \sigma^n t = yw'' \tag{10}$$

Let

$$Ae^{-Q_c / R_g T} = B \tag{11}$$

Then Eq.(10) can be written:

$$\sigma = \left(\frac{w''}{Bt} \right)^{1/n} y^{1/n} \tag{12}$$

Combination of the above equation with the following equilibrium condition for the bending moment M

$$M = \int_F y \sigma dF \tag{13}$$

results to the equation:

$$M = \frac{J}{(Bt)^{1/n}} (w'')^{1/n} \tag{14}$$

Where J is given by:

$$J = \int_F y^{\frac{1}{n}+1} dF \tag{15}$$

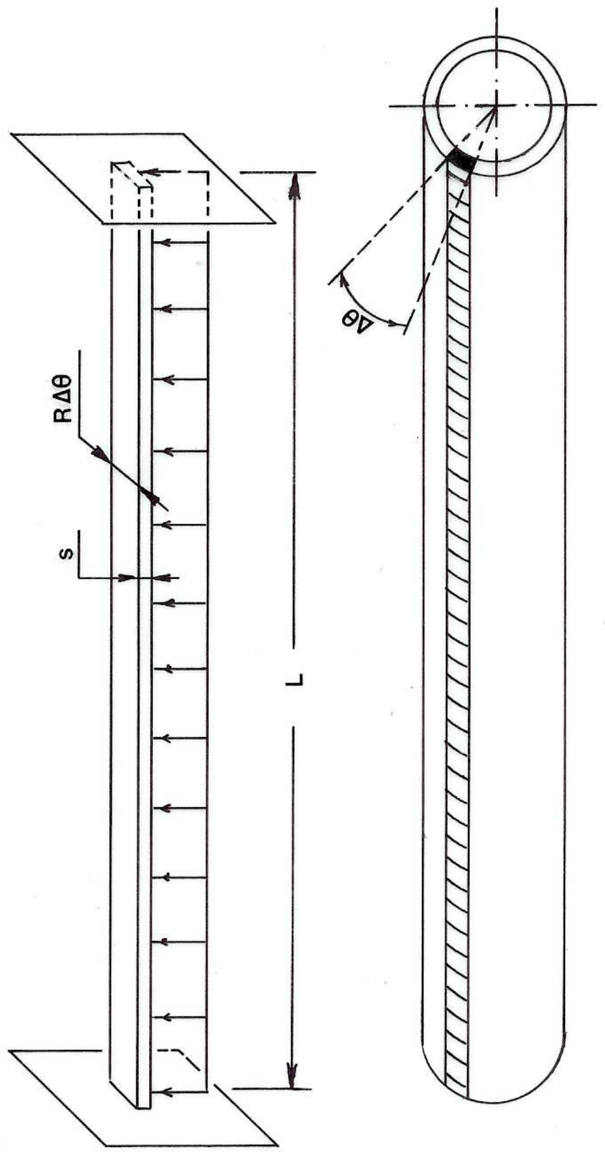

Figure 2: Equilibrium of a wall's material strip

With the aid of Eq. (14), the following equilibrium equation

$$q = \frac{d^2 M}{dx^2} \tag{16}$$

can be written:

$$\frac{J/n}{(Bt)^{1/n}} \left((w'')^{\frac{1}{n}-1} w''' \right)' = q \tag{17}$$

where q is the distributed load due to the action of the internal pressure q^{**} and the reaction q^{*} of the wall resistance:

$$q = q^{**} - q^{*} \tag{18}$$

It has been proved [1] that

$$q^{**} = 2\pi R P(t) \tag{19}$$

and

$$q^* = \frac{2\pi s}{(BRt)^{1/n}} w^{1/n} \tag{20}$$

where P(t) is the internal pressure and s the wall thickness.

Combining the Eqs. (17)–(20) the following non-linear differential equation is resulted:

$$(J/n)\left(w''^{\frac{1}{n}-1} w''' \right)' + \left(2\pi s R^{-1/n}\right) w^{1/n} = 2\pi R P_o (Bt)^{1/n} \tag{21}$$

Linearizing the non-linear reaction q^* by the simulation of the real wall strip with a substitute one that accumulates the same strain energy [1] the following simplification of the Eq. (21) can be achieved:

$$g'''' + \beta\, g^n = 0 \tag{22}$$

where

$$g = (w'')^{1/n} \tag{23}$$

and

$$\beta = \frac{n}{n+1} \frac{4\pi s}{RJ} \varepsilon_f^{\frac{1-n}{n}} \tag{24}$$

In Eq. (24), ε_f denotes the material's tensile ductility. Taking into account the Eq. (23), the boundary conditions given by the Eqs. (1) – (7), can be written:

$$g''(0) = m \tag{25}$$

$$g''(L) = m \tag{26}$$

$$g'''(0) = 0 \tag{27}$$

$$g'''(L) = 0 \tag{28}$$

$$g'''(L/2) = 0 \tag{29}$$

$$g'''(\alpha) = -g'''(L-\alpha), \qquad 0 \le \alpha \le L \tag{30}$$

where

$$m = \frac{2\pi R P(t)(Bt)^{1/n}}{J} \tag{31}$$

5. Damage accumulation

The damage accumulation of a metal subjected to constant stress can be described with an experimental curve relating the loading parameters σ, T with the life through the Larson – Miller parameter [8]:

$$P_f = T(C + \log t_f) \tag{32}$$

where C is a constant coefficient independent from σ and T for a wide variety of metals. The above curve can be approximated by a straight line (Fig. 3). At each point along the log(σ)-P_f curve, creep failure occurs after loading time t_f. Therefore, the log(σ)-P_f curve is an isodamage line corresponding to damage state 100%. It can be postulated [6] that the accumulated damage of a material subjected to loading conditions σ, T for time $t < t_f$ should be defined as:

$$D = \frac{\tan\theta_i}{\tan\theta_f} \tag{33}$$

where θ_i is the slope of an isodamage line and θ_f is the slope of the log(σ)–P_f line (Fig. 4). Then, the damage function D has two end values: D=0 when θ_i=0 (undamaged state) and D=1 when θi=θ_f (creep failure). Following above concept it has been proved [6] that the corresponding damage accumulation rule has the following form:

$$\left(\cdots\left(\left(\left(\left(\frac{t_1}{t_{f_1}}\right)^{q_{1,2}}+\frac{t_2}{t_{f_2}}\right)^{q_{2,3}}+\frac{t_3}{t_{f_3}}\right)^{q_{3,4}}+\cdots+\frac{t_{k-1}}{t_{f_{k-1}}}\right)^{q_{k-1,k}}+\frac{t_k}{t_{f_k}}=1\right. \tag{34}$$

where

$$q_{k-1,k} = \frac{T_{k-1}\log(\sigma_k/\sigma_e)}{T_k \log(\sigma_{k-1}/\sigma_e)} \tag{35}$$

and σ_e is a fitting parameter derived by short two-stage creep-fatigue tests.

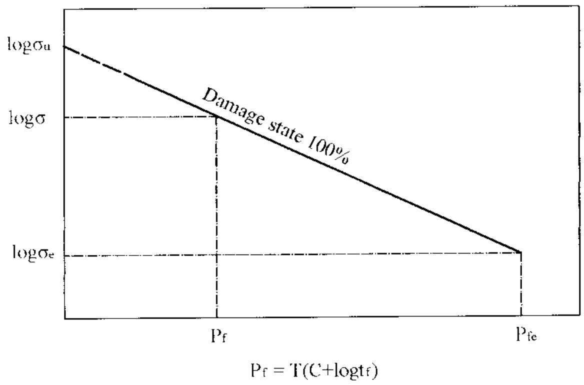

Figure 3: Stress versus Larson Miller parameter schematic diagram

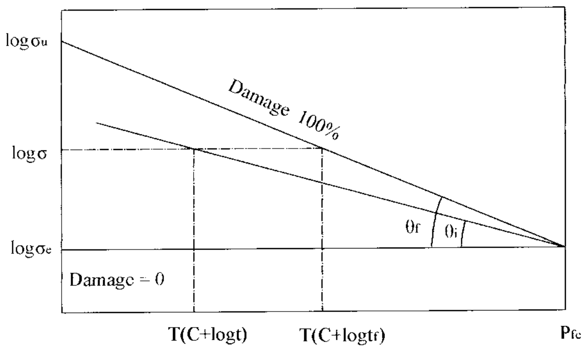

Figure 4.

6. Numerical example

A pipe with geometrical parameters L=9.5m, R=0.26m and s=7mm can be considered to be loaded by the two stage loading. The used material for the pipe is the steel X8CrNiMoNb1616. For this material the Norton – Bailey parameters have been obtained by the ref. [9] and take the values n=6.43 and B=$3.85\text{x}10^{-33}$ (for A=$3.5\text{x}10^{-19}$ h^{-1}, Q_c=260 KJ/mole, R_g=8.314 J/mole.grad, T=973 K). In table 1 are summarized the two types of stress histories of the external surface of the section x=L/2: (a) H-L type where the stress of the first loading stage is grater than the stress of the second one (i.e. $\sigma_1>\sigma_2$), and (b) L-H type with the opposite load sequence (i.e. $\sigma_2>\sigma_1$). According to the ref. [6] the corresponding damage accumulation rule have the following form:

$$\left(\frac{t_1}{t_{f1}}\right)^{\frac{T_1 Log(\sigma_2/p)}{T_2 Log(\sigma_1/p)}} + \frac{t_2}{t_{f2}} = 1 \tag{36}$$

where p=184.93 MPa and T_1=T_2=973 K.

Table 1: Two-stage loading data

	H-L		L-H	
	σ_1 (MPa)	σ_2 (MPa)	σ_1 (MPa)	σ_2 (MPa)
Case 1	170	150	150	170
Case 2	150	130	130	150
Case 3	130	110	110	130

Let the consumed life t_1/t_{f1} for each case is t_1/t_{f1}=0.2, 0.4, 0.6, 0.8. Then, with the aid of the Table 1 and the Eq. (36), the results shown in Fig. 5(a),(b),(c) can be obtained. This figure demonstrates that the damage is accumulated non-linearly. In contrast with the well known Robinson's rule which assumes that

$$\frac{t_1}{t_{f1}} + \frac{t_2}{t_{f2}} = 1 \tag{37}$$

above results indicated that

$$\frac{t_1}{t_{f1}} + \frac{t_2}{t_{f2}} < 1 \tag{38}$$

for the L-H loading types, while

$$\frac{t_1}{t_{f1}} + \frac{t_2}{t_{f2}} > 1 \tag{39}$$

for H-L. This means that a linear consideration of damage accumulation (Eq. (37)) overestimates the remaining life for the L-H type while provides conservative predictions with the H-L. This conclusion is in accordance with the non-linear evolution of creep mechanisms. Especially, the deviation by the linear evolution is increased when the ratio $\sigma 1/\sigma 2$ decreased for the H-L loading type and increased for the L-H.

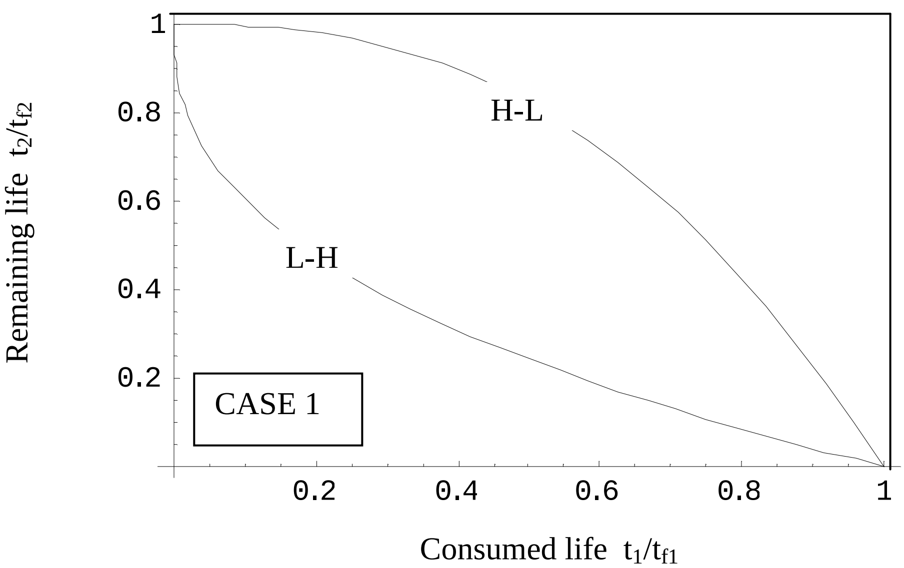

Fig. 5(a)

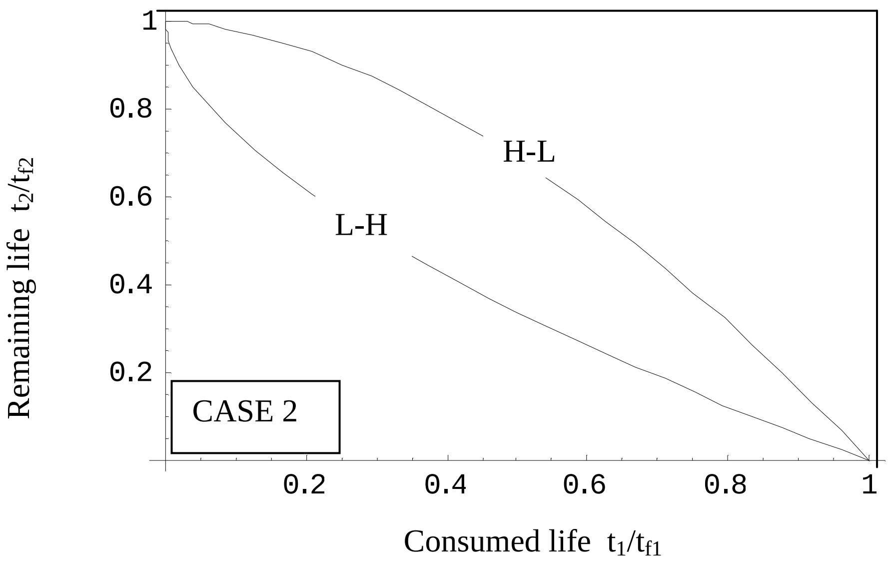

Fig. 5(b)

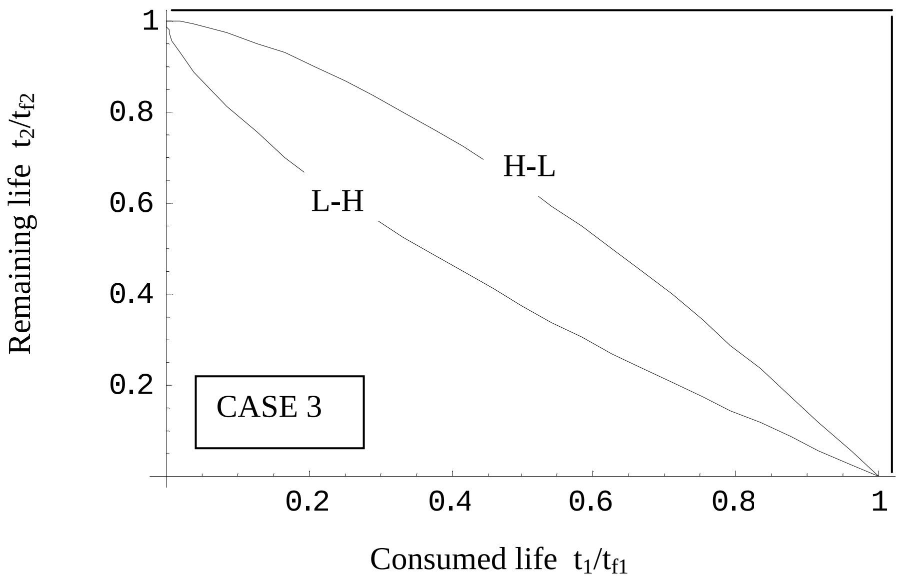

Fig. 5(c)

Figure 5: Presentation of isodamage lines

7. Conclusions

1. A non-linear stress analysis have been performed for the description of the stress/displacement field of a reinforced pipe under constant creep conditions.
2. A non-linear damage accumulation model have been used for creep-life prediction of a pipe under variable creep conditions.
3. An example of remaining life prediction for a specific point of a pipe subjected in two-stage loading have been treated. To this end, two loading types has been examined: (a) the L-H loading type where the stress level of the first stage is lower than the stress stage of the second level, and (b) the H-L loading type with opposite sequence.
4. The predictions for the L-H type indicated that the sum of the consumed and the remaining normalized life $t_1/t_{f1}+t_2/t_{f2}$ is lower than the unity while for the H-L type the corresponding sum is greater than unity. Furthermore, the deviation of the predicted

damage accumulation by the linear evolution is increased when the ration σ_1/σ_2 is decreased for the H-L loading type and increased for the L-H.

References

[1] D.G. Pavlou, N.V. Vlachakis, Ch. Tsitouras, M.G. Pavlou, A. Fatsis, Creep sagging analysis of pressure pipes, Computational Materials Science, 36 (2006) 303-309.
[2] J. Pamin, Gradient plasticity and damage models: a short comparison, Computational Materials Science, 32 (2005) 472-479.
[3] J. Lemaitre, R. Desmorat, Engineering damage mechanics, Berlin: Springer, 2005.
[4] J. Betten, Creep mechanics, Berlin: Springer, 2002.
[5] J. Lemaitre, Handbook of materials behaviour models, N.Y.: Academic press, 2001.
[6] D.G. Pavlou, Creep life prediction under stepwise constant uniaxial stress and temperature conditions, Engineering Structures, 23 (2001) 656-662.
[7] A.P. Boresi, O.M. Sidebottom, Advanced Mechanics of Materials, Wiley, 1985.
[8] F.H. Norton, Creep of steel at high temperatures, Mc Graw Hill, N.Y., 1929.
[9] S.G. Pantelakis, Kriechverhalten metalliscer Werkstoffe bei zeitveraenderlicher Spannung, Ph.D Thesis, RWTH-Aachen, 1983.