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A Test Concept for Lifetime Prediction of Polyethylene Pressure Pipes

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Summary. The present paper describes the main elements of a novel concept for lifetime and safety assessment of polyethylene pressure pipes for arbitrary installation conditions based on modern methods of fracture mechanics. At the core of the proposed concept is the accelerated generation of so-called synthetic crack growth curves and corresponding material laws for crack growth initiation and slow crack growth for service-near temperature conditions without the use of stress cracking liquids.

Keywords. Fracture mechanics; Slow crack growth; Fatigue.

Introduction

Depending on the material generation, pipes made from polyethylene (*PE*) have been in use for up to about five decades with overwhelmingly positive operational outcomes [1, 2]. Assessments of findings and evaluation of damage statistics demonstrate that pipe damage predominantly arises because of additional local loading caused by laying and installation faults, and only after the pipe has been in service for an extended period. Frequently they are a consequence of slowly occurring processes of damage connected with the initiation and growth of quasi-brittle cracks within zones of the wall of the pipe, which are subject to additional local loading [2–4].

There are theoretical investigations based on structural mechanics [3, 4] and an experimental body of knowledge interpreted from the polymer physics point of view [5, 6], all of which account for the practical suitability of *PE* pressure pipes subject to local loadings on the pipe surface, e.g. due to installation without sand embedding, or other point or linear loads conditioned by their installation. The former works are based on computational simulation using methods, which were developed and applied by the authors cited, among other things, for the identification of causes of pipe damage taking into account practical findings, measurements and experimental investigations. They come to the conclusion that as a consequence of e.g. point support conditions in *PE* pressure pipes approved according to engineering guidelines, local irreversible damage and crack initiation in the pipe wall must be regarded as probable at operating pressures above four bar, so that at higher operating pressures, premature failure of *PE* pipes is possible [3, 4].

On the other hand, the investigations based on empirical and polymer physics evidence [5, 6] come to the conclusion that although the installability of point loaded *PE* pipes without sand embedding is naturally dependent on the pipe and/or material grade, an operational life of 100 years is entirely possible where there is an appropriate level of resistance to slow crack propagation in the type of *PE* used. These works are based on indirect qualification by correlation of results from a range of accelerated laboratory tests on internally pressurized pipe test specimens (experimental investigations at various temperatures with and without point loading, and also with and

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without additional media effects) with results from the full notch creep test (*FNCT*) assisted by theories of activation. The methodical approach raises a number of fundamental questions, however. Neither the conclusions drawn from the experimental results nor the argument concerning the quantitative transferability of the knowledge gained from the laboratory tests accelerated by media effects and elevated temperature to the actual installation and structural behavior of locally loaded pressure conduits over a period of 100 years can be directly followed. In professional circles the informational value and reproducibility of *FNCT* tests are also subjects of controversial debate [7–9].

These points of view, admittedly outlined in a highly condensed form, emphasize that the problem of *PE* pressure pipe installation without sand embedding has up until now been judged very differently in professional circles and that, at least for higher internal pressures (above four bar), cannot be regarded as even partially solved.

Fracture Mechanics Concept of Qualification

The following models concern the important elements of the proposed concept of fracture mechanics qualification for operational life and safety of *PE* pressure pipes. Starting with the fundamental principles of a fracture mechanics-based lifetime model without additional local loading, the individual subsections present descriptions of important aspects and elements of qualification with additional local loading and finally the generation of adequate crack growth characteristics for the description of crack growth failure kinetics in *PE* pipe materials under service-near conditions.

Fracture Mechanics Lifetime Model without Additional Local Loads

For creep stress behavior of internally pressurized *PE* pipes without additional local loadings, it is well known from literature that internal pressure-creep stress curves for this type of pipe can be divided into three (or in certain cases four) distinct regions (Fig. 1) [10]. After short periods at high internal pressures (high equivalent stress σ_{hoop}), region A is characterized by ductile deformation fractures with large plastic zones (so-called fish mouth ruptures). This part of the internal pressure creep-stress curve is chiefly influenced by the type, density, and strength (or yield stress) of the polymer material under investigation, as well as the testing temperature. Normally, failure occurs at the area of smallest wall thickness, which is determined by manufacturing factors along the length of the pipe section under investigation, or at points where defects are present. After longer periods and somewhat greater equivalent stresses, “ductile-brittle” mixed fractures or quasi-brittle fractures frequently occur (region B), which are determined by the failure processes of crack initiation (commencing at local defects) and the slow crack growth with only local plastic deformation at the crack front. The steeply falling curve

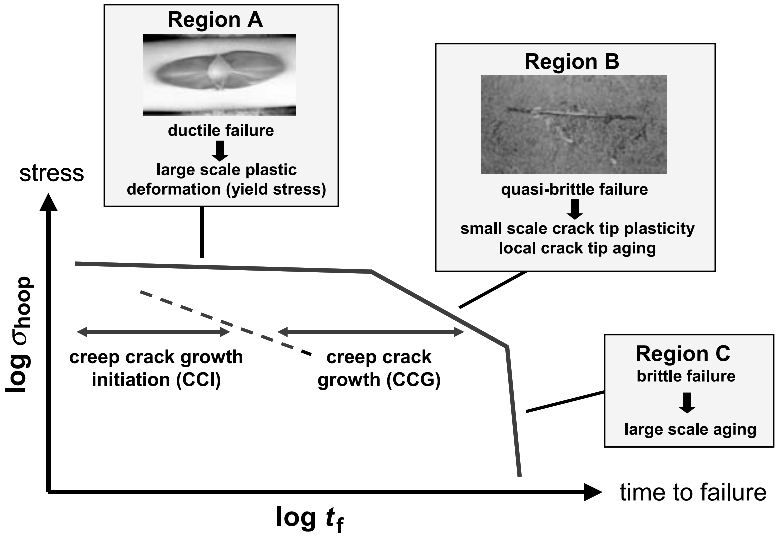


Fig. 1. Schematic illustration of the failure behavior of pressurized *PE* pipes

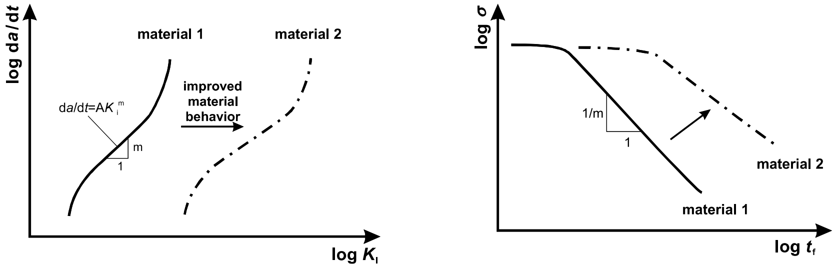
section in region C is reached after relatively long test periods, sometimes at very low internal pressures. The position of this section of the curve along the time axis is mainly determined by aging processes and polymer degradation, which implies that stabilization of the polymer material is of greater significance for this region of the creep stress curve in particular. Whether a polymer exhibits all three (or in certain cases four) regions of the curve or merely certain individual portions of the creep stress curve depends firstly on the type of polymer under investigation and secondly on the test conditions [10].

In order to account for the localized character of the failure phenomena "crack formation and slow crack growth", which shows up in region B of the internal pressure-creep stress curve but is more especially evident in practice, there has been increasing use in recent years of well-established methods of fracture mechanics traditionally used for metal materials but now transferred to *PE* pipes [10–13]. For this purpose notched specimens are placed under static loads with defined conditions (temperature, media action) and crack lengths measured as a function of time. From the shape of the specimens, the crack length a and the force acting on the specimen F, stress intensity factor K_I can be calculated (the index "I" denotes pure tensile load on the crack), which represents a measure of the stress distribution acting immediately at the crack tip. The crack growth rate da/dt calculated from the time under load t and the crack length a is then placed graphically in relation to K_I.

Frequently, but not always, materials exhibit crack growth curves with an S-shaped graph as illustrated schematically in Fig. 2. According to this, the crack growth behavior is divided into three regions:

- In region I, the so-called threshold region K_{th}, cracking rates fall sharply as values of K diminish, until the crack practically comes to a halt.
- In region II, the region of stable steady crack growth, the double logarithmic plot of data frequently exhibits a section corresponding to a straight line with the exponential relationship $da/dt = A \cdot K^m$.
- In region III the cracking rates frequently rise sharply with a rising value of K, since the stress intensity factor approaches the crack toughness K_{IC} of the material for unstable crack growth.

The relationship between crack growth curves of this type and results from internal pressure-creep stress rupture testing of pipes is also illustrated schematically in Fig. 2. In both diagrams it is indicated how a better material behavior shifts the curves to the right. The relationship for a quantitative lifetime model for the internal pressure-creep stress behavior according to concepts of fracture mechanics is also shown in Fig. 2. According to this, the slow crack growth phase as a proportion of the total time to failure depends on the effective stress σ acting on the component (*i.e.* in this case the hoop stress acting in the wall of the pipe), the starting length of crack (or starting size of defect) a_0, other parameters concerning shape which are combined in the shape factor Y and the material-specific parameters A and m



LEFM lifetime modeling

$$t_f = t_{tot} \approx t_{in} + \frac{2}{A \,.\, (m-2) \,.\, Y^m} \cdot a_0^{(2-m)/2} \cdot \sigma^{-m}$$

t_f = time to failure (= t_{tot})
t_{in} = time to crack initiation
σ = specimen, component stress
A, m = material parameters
a_0 = initial crack length
Y = shape factor

Fig. 2. Relationship between creep crack growth behavior and failure behavior of internally pressurized pipes and corresponding lifetime model

determined by fracture mechanical experimental investigations. Similarly the crack initiation phase section can be described by reference to the effective stress acting in the component and the shape parameters (a_0, Y) listed above, where further material-specific parameters B and n, to be determined by experimental investigation, are again required [10].

Based on these relationships and corresponding investigations, taking the example of a commercial polyethylene high density (*PE-HD*) grade *PE* 80 and test temperatures of 60 and 80°C, the authors' working group verified an extremely good quantitative correlation between pipe failure times modeled on a fracture mechanics basis and experimental results of internal pressure-creep stress rupture tests on pipes [10, 13]. It was also possible to demonstrate from numerous additional series of tests on a great variety of *PE-HD* formulations, that fracture mechanical crack growth curves and the times to failure determined by separate experiments on internally pressurized pipes in the region of the quasi-brittle failure also correlate outstandingly well concerning the influence of altered material (molecular) parameters, such as mean molecular mass and molecular mass distribution, concentration and length of short chain branches [11, 12] and also types of stabilizer and stabilizer concentration [13].

It is of some significance for a polymer physics-based, fracture mechanics lifetime model that the latter works could support the hypothesis originally put forward in Ref. [10] that local aging effects in the immediate crack tip area also occur in the failure region B in Fig. 1, and that these signs of local material aging can also be recognized in fracture mechanics modeling under accelerated short-term test conditions. These local aging mechanisms are induced and promoted by the combined action of the temperature, the locally elevated stresses, and simultaneous good media accessibility at the crack tip and in the surrounding region of plastic deformation. In regions remote from the crack tip no signs of global aging in the material can be detected (concept of local crack tip aging) [10, 13].

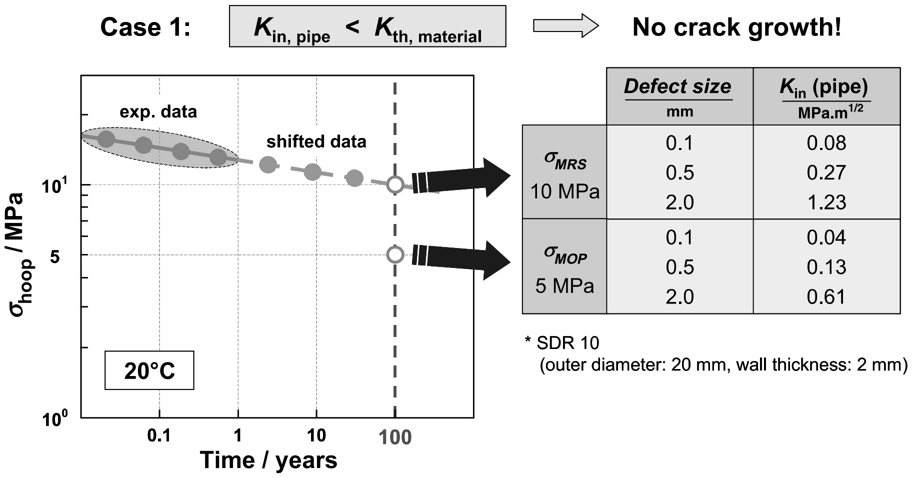
Fracture Mechanics Lifetime Model with Additional Local Loads

A characteristic of additional local loadings, such as point loads on internally pressurized pipes, is their extreme stress and deformation enhancing action in regions of the pipe wall that directly surround the additional load, and also the accompanying regionally and locally enhanced degree of multiaxiality of the stress condition with simultaneous reduction of the material's tolerance of deformation. With reference to the creep stress rupture behavior of internally pressurized and point loaded pipes, this means that pipe failure behavior in regions A and B of the creep stress rupture curves is controlled by the regionally acting enhanced stresses σ_{regional} (instead of the global stresses σ_{global}, which act on other regions of the pipe and result solely from internal pressure) and by accelerated crack initiation and accelerated crack growth in this zone. As far as the quasi-brittle failure region B is concerned, a portion of the curve that is relevant to the fracture mechanics lifetime model, there is a shift towards shorter times to failure due to the additional stress-concentrating action of the local and/or regional loading.

Qualification for region A (ductile pipe failure in the post yield region of the material due to the time-dependent yield limit being exceeded) can be carried out for arbitrary installation conditions using suitable numerical methods based on finite element analysis combined with time-dependent yield criteria for the specific grade of *PE-HD*. The material-specific yield criterion results from ductile pipe failure data according to normal internal pressure-creep stress rupture testing under EN ISO 9080 without additional loading, and where applicable taking into account a constraint factor for enhanced resistance to deformation for regions of the pipe with enhanced multiaxiality. This means that even under additional local and/or regional loadings, the failure region A can be described on the basis of data from direct experimental and time-temperature-shifted data according to EN ISO 9080, only incorporating ductile pipe failures into the analysis. The constraint factor discussed above can be estimated on the basis of short-term testing.

At the other end of the time spectrum, failure region C is almost independent of mechanical stress effect and therefore also of additional local loads. Thus the qualification of service life including sufficient safety can be carried out by using the kinetics of aging for the operating temperature of the pipes and using the characteristic activation energies for the polymer degradation.

In terms of the fracture mechanics qualification of service life for failure region B under additional



	Defect size mm	K_{in} (pipe) $\mathrm{MPa.m}^{1/2}$
σ_{MRS} 10 MPa	0.1 0.5 2.0	0.08 0.27 1.23
σ_{MOP} 5 MPa	0.1 0.5 2.0	0.04 0.13 0.61

* SDR 10
(outer diameter: 20 mm, wall thickness: 2 mm)

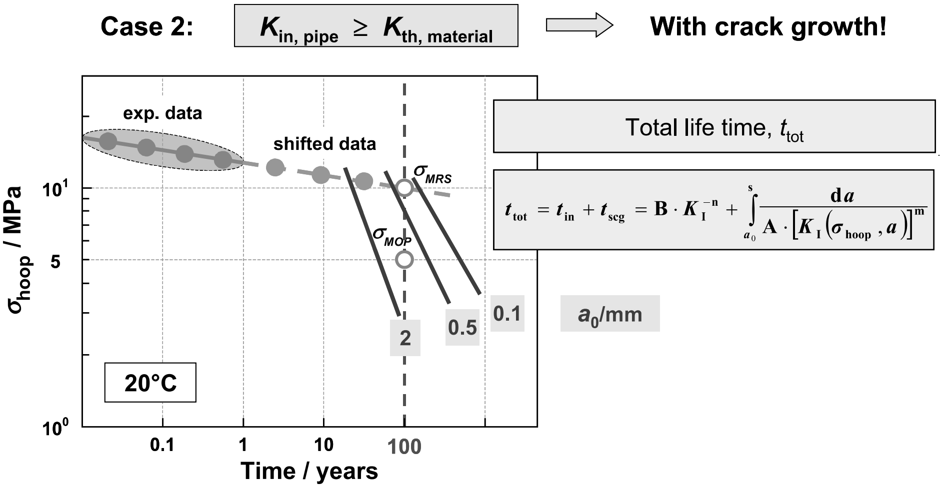
Fig. 3. Fracture mechanics procedure considering additional local loading for Case 1, for which creep crack growth during the pipe application period (100 years) is to be avoided

local loading, a distinction must be drawn between two cases:

- Case 1: Crack initiation and slow crack growth must be fundamentally avoided over the period of pipe service that is under definition (50 or 100 years).
- Case 2: Crack initiation and slow crack growth are permissible to a limited extent but only in so far as, during the period of pipe service that is under definition (50 or 100 years), no total failure occurs (crack propagation through the entire pipe wall).

Case 1 corresponds to a conservative criterion and is represented schematically in Fig. 3. According to this criterion, proof must be furnished that at the start of loading, the maximum stress intensity factors $K_{\mathrm{in,pipe}}$ in the pipe in highly-stressed regions remain below the threshold value for slow crack growth in the specific material $K_{\mathrm{th,material}}$. As long as the starting values for $K_{\mathrm{in,pipe}}$ are low enough to allow no crack growth, no failure should ensue. The figure shows example values for $K_{\mathrm{in,pipe}}$ for two levels of stress ($MRS = 10$ MPa corresponds to the extrapolated long-term yield stress; $MOP = 5$ MPa corresponds to the maximum operating stress due to internal pressure for *PE* 100 gas pipes) and varying sizes of defect (assumed semi-elliptical crack in the listed test pipe, size SDR 10).

Case 2 which permits a limited amount of crack growth is illustrated schematically in Fig. 4. In this



$$t_{\mathrm{tot}} = t_{\mathrm{in}} + t_{\mathrm{scg}} = \mathbf{B} \cdot K_{\mathrm{I}}^{-\mathrm{n}} + \int_{a_0}^{\mathrm{s}} \frac{\mathrm{d}a}{\mathbf{A} \cdot \left[K_{\mathrm{I}}\left(\sigma_{\mathrm{hoop}}, a\right)\right]^{\mathrm{m}}}$$

Fig. 4. Fracture mechanics procedure considering additional local loading for Case 2, for which creep crack initiation and growth during the pipe application period (100 years) may occur, however, without leading to total pipe failure

case the values for the stress intensity factor $K_{\mathrm{in,pipe}}$ at the start of the loading already lie above the threshold value $K_{\mathrm{th,material}}$. In order for no total failure to occur within the pipe's service life, it must be demonstrated by fracture mechanics simulation calculations for static internal pressure and local additional loadings, that the calculated overall life t_{tot} exceeds the service life to be defined for the pipe. Calculations being based on the kinetic crack growth data for the material and the specific size of pipe made from that material, and using a size and position of starting defect to be determined. The stress value that is relevant for global analysis is determined from the maximum operating pressure (*MOP*); the stress value that is used for additional locally/regionally acting loads may correspond to or reflect the material's *MRS* value, or it may be determined based on an FE analysis. The influence of the starting defect size a_0 on the overall time to failure is also illustrated schematically in this diagram. In this case there is again a more conservative and a less conservative approach; the analysis for the first would only take into account the slow crack growth phase t_{scg} and the second would also take into account the crack growth initiation phase t_{in}.

Fracture Mechanics Lifetime Model with Additional Local Loads

Two central sets of questions connected with the fracture mechanics approach outlined above are related on the one hand to the fundamental fracture mechanics concept being applied (linear elastic fracture mechanics (LEFM) or post-yield fracture mechanics (PYFM)), and on the other hand to the appropriate testing methodology for the generation of required crack growth data and material laws derived from them for initiation and growth of cracks under static load in the application temperature range without media action.

Regarding an accelerated testing methodology, which is relevant to practical pipe applications, that is in the temperature range of 5–20°C without the presence of stress crack promoting media, literature already contains a range of investigations on crack growth behavior in *PE-HD* under cyclical loading (fatigue loading) [14–19]. With regard to the concrete problem, the main consideration is to describe and approach the crack growth behavior under static load [14, 15] using cyclically generated data at differing R-ratios by extrapolation to $R = 1$. By definition, R represents the ratio of the minimum and maximum load in a loading cycle ($\sigma_{\mathrm{min}}/\sigma_{\mathrm{max}}$), and thereby the related ratio of the minimum and maximum stress intensity factor $K_{\mathrm{min}}/K_{\mathrm{max}}$ at the crack front.

Crack growth data from experimental investigations of the authors' working group with differing R-ratios are presented in Fig. 5 for *PE* 80 at three temperatures (23, 60, and 80°C) and for *PE* 100 at 23°C as a function of K_{max}. For both types of material clear influences of R can be recognized at 23°C, and for *PE* 80 this is also true at 60°C,which at least for *PE* 80 virtually disappear at 80°C. In the lower temperature range, the cracking rates $\mathrm{d}a/\mathrm{d}t$ and $\mathrm{d}a/\mathrm{d}N$ rise considerably as the R value diminishes, *i.e.* as the cyclic nature of the loading increases, which can be traced back to the crack accelerating action of the cyclical stress components. From the experimental point of view it is important to point out that at room temperature and below kinetic data

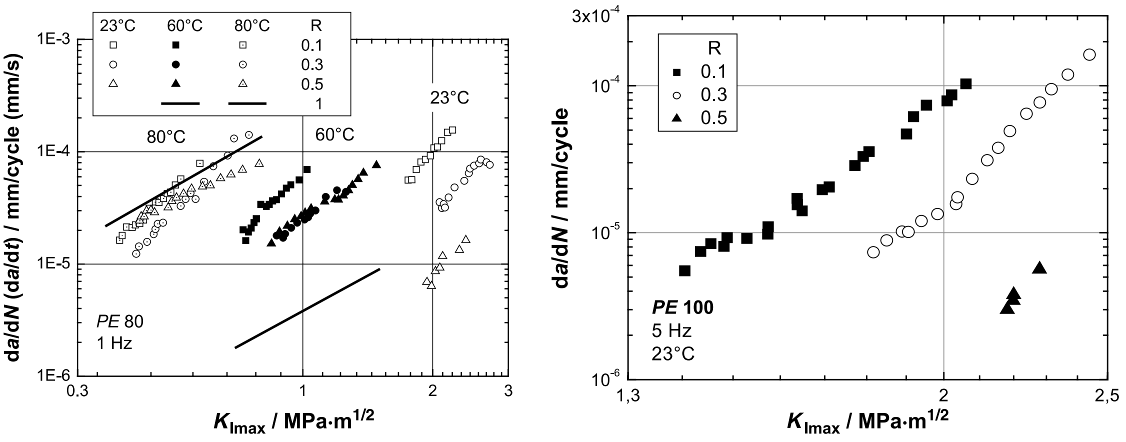


Fig. 5. Effect of R-ratio and temperature on crack growth behavior of *PE* 80 and *PE* 100 (CT specimens)

generation for quasi-brittle crack growth at varying R-ratios obviously works very well within reasonable testing timescales for ductile materials like *PE* 80 and *PE* 100. Whereas for purely static loads in this temperature range with no media action this is not possible within reasonable testing timescales.

Although in principle different types of specimen can be used for the generation of crack kinetic data according to fracture mechanical methods, and very often so-called compact type (CT) specimens are employed, it appears advisable for the qualification of service life and safety of *PE-HD* pipes to consider other specimen configurations. One specimen option is the cracked round bar (CRB) specimen [19]. There are some significant experimental and design advantages in favor of the use of CRB specimens. Among others these include:

- possibility of generating data in the region of low *K* values and cracking rates over short testing periods
- a loading condition that more closely approaches that of the pipe (high constraint) by avoiding or reducing zones of plane stress at the crack front with a simultaneous higher specimen cross-sectional stress with lower stress gradients in regions remote from the crack tip
- potential suitability for LEFM and PYFM experiments.

For the generation of crack growth curves for arbitrary forms of loading, especially for static long-term loading, the procedure outlined schematically in Fig. 6 can be applied. This procedure will result in the necessary material laws that are the basis for the computational approach outlined above for qualification and safety assessment of *PE* pressure pipes subject to arbitrary additional regional/local loading. The five key steps in this procedure are:

1. Execution of fatigue tests with CRB specimens at different stress levels and with different R-ratios (*e.g.* $R = 0.1$ to 0.7; test frequency 1 Hz if possible); evaluation of data in the form of R-specific *Wöhler* curves (S-N curves).
2. Transformation of the R-specific experimental data sets from Step 1 by curve-fitting using fracture mechanics computational methods into "synthetic" fatigue crack growth (FCG) curves log $\mathrm{d}a/\mathrm{d}t$ *vs.* log $K_{\max}$; extrapolation of the synthetic FCG curves in the direction of lower *K* values and cracking rates; depending on the approach selected, the crack initiation portion can be accounted for by integration in this step, or it can be excluded.
3. Transfer of data from Step 2 onto a log $K_{\max}$ *vs.* R diagram with individual curves for defined crack growth rates and extrapolation of these curves to $R = 1$ (corresponds to a static load).
4. Retransformation of the data set for $R = 1$ from Step 3 into the "synthetic" crack growth diagram from Step 2 in order to generate a "synthetic"

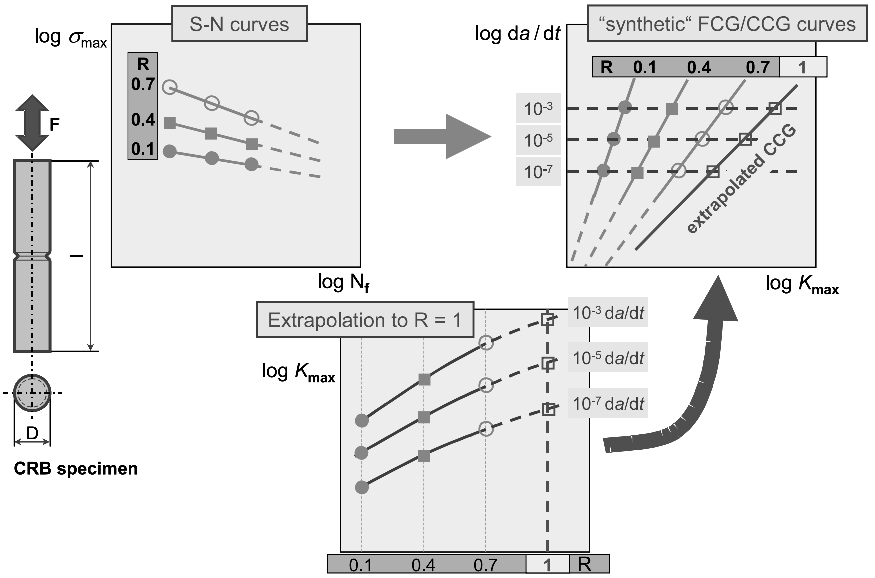


Fig. 6. Procedure to generate synthetic crack growth curves for static loading ($R = 1$) based on cyclic experiments with CRB-specimens

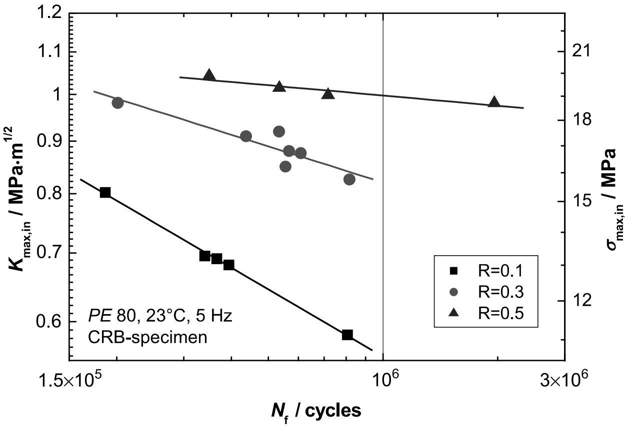


Fig. 7. R-specific *Wöhler* curves (S-N curves) for a *PE* 80 material

crack growth curve for static load (creep crack growth (CCG) curve).

5. Fixing of the threshold value K_{th} in the CCG curve, where the crack practically comes to a halt, by means of additional suitable experiments or by engineering-based assessment.

In order to verify the above described methodology tests were started with a *PE* 80 material. In Fig. 7 R-specific *Wöhler* curves from $R = 0.1$ to $R = 0.5$ are presented for this material and basically this is the first step in the procedure described above. In the diagram cycles to failure are shown as a function of the initial maximum stress $\sigma_{max,in}$ and initial maximum stress intensity factor $K_{max,in}$ in the fatigue tests. The initial loads were chosen in that way that the growth of a quasi brittle crack was responsible for the failure of the specimens. As expected it was found that with increasing R-ratio the number of cycles to failure increased. The scatter in the results (esp. for the tests at $R = 0.3$) is still in a tolerable magnitude. After completion of the test series (tests at $R = 0.7$, in order to come more close to static conditions) the next steps in the evaluation procedure will be done.

Conclusions and Prospects

The aim of this paper was to disseminate a proposal for a novel concept for qualification of service life and safety of *PE* pressure pipes under additional local loadings (*e.g.* point or linear loads) which, in its experimental and empirical portions, reflects the additional influences on pipes such as operating temperature and surrounding media as realistically as possible. The concept proposal is based on the application of fracture mechanics methods for the generation of suitable (near real-life) material laws for the kinetics of relevant micromechanical failure processes (crack initiation and crack growth) in *PE* pipe materials under long-term loads, and their integration into appropriate computational simulation models for the structural and failure behavior of *PE* pressure pipes with additional local loadings. As well as achieving near real-life loadings by experimental methods, an additional significant advantage of this fracture mechanics approach is that it is applicable in principle to arbitrary installation conditions with locally concentrated stresses in the pipe wall, which determine the service life through the potential formation and growth of quasi-brittle cracks, and is therefore not limited only to the case of non-sand embedded pipe laying. In principle it could also take into account residual stresses present in commercial pipes and their effects on crack growth, as well as the derivation of overall safety coefficients based on statistical methods and polymer physics contexts.

After the basic preliminary work is concluded on further development of the proposed concept, the testing time requirements per material (or material condition in the pipe) are estimated at a few weeks (up to a maximum of a few months) which appears reasonable in comparison with other long-term experiments (including accelerated tests). It must be noted, however, that this does not render obsolete the current requirements for qualification according to EN ISO 9080.

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