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Procedure of SPC data treatment for “uniaxial test correlation”

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Abstract: In order to determine creep properties from small punch creep (SPC) tests, several theoretical models and analytic methods are applied, such as the Chakrabarty’s membrane stretch model and reverse finite element method. However, because the problem is too complicated, differences are always found between the theoretical prediction and the uniaxial creep tests. In this paper, a concept of “Uniaxial test correlation” is proposed without any theoretical assumption and analytic calculation. By comparison of the rupture time in SPC with the uniaxial creep rupture data, the equivalent stress σ in SPC is determined. By using the obtained equivalent stress σ and the uniaxial creep strain rate data, the derived minimum strain rate in SPC can be found. A large experimental data pool is built up, containing 97 uniaxial creep tests and 159 SPC tests in total. From there, two empirical formulas are proposed to calculate the ratio of force *F* to stress σ, and the derived minimum strain rate $\dot{\varepsilon}_{min}$ in SPC. With these two important values known, the material creep properties can be determined accordingly.

Keywords: “Uniaxial test correlation”; small punch creep tests; creep properties; rupture time dependence; Norton creep law.

1. Background

In 1990s the SP test technique was introduced to Europe, and has been extended to the creep domain. In 1994, a Copernicus project entitled “Small Punch Test Method Assessment for the Determination of the Residual Creep Life of Service Exposure Components (Contract: ERB CIPA CT 94 0103)” has been set up and carried out in laboratories in different European countries [1-2]. From 2000 to 2003 a “Contribution In Kind” project was carried out within EPERC network, namely in the Technical Task Force 5 (TTF5, “Service Integrity during Operation”). The results of the Round Robin have been summarized in the EPERC Technical Reports [3].

Encouraged by the ASME standards F1248 and F2183 on small punch test for polyethylene pipe [4], further work for code acceptance for steels was organized by the European CEN workshop WS 21. Since 2006 the European Code of Practice (CoP) documents are available for both high and low temperature properties, which summarize documents in last 20 years and provide a guide line to perform small punch test for metallic materials [5]. At present, small punch testing is used for various applications to a broad range of materials [6-19]. Since 2015, a working group is engaged to upgrade the CoP to a European standard.

Let us re-call the progress of research on SPC in last 20 years. At beginning most of the work on the SPC test aimed to find the relation between SPC test load *F* and creep rupture time t_r [1-2]. Some of them introduced the Larson-Miller parameter for rupture time interpolation with stresses and temperatures [19]. Tettamanti and Crudeli put forward the equivalent stress concept: “What is the load value to use in the small punch test to obtain the same time to rupture as in a uni-axial test?” [20]. Chakrabarty’s membrane stretch model [21] was introduced to calculate stress and strain in SPC by Yang and Wang [22]. Based on the Chakrabarty’s model, CoP provides a formula for estimating the test load in SPC [5]. In order to derive creep properties from the SPC test, authors carried out a reverse algorithm to identify material parameters from the best match of the measured creep deflection curves [23-24]. Several reverse algorithm approaches were put forward by authors to determine the Norton creep law and rupture time dependence [25-26]. Abendroth introduced a neural network to identify the Norton creep properties automatically, and the optimization criterions were based on both the creep deflection curve and the rupture time. A neural network approach is useful to avoid the time-consuming finite element creep analysis [27]. Hyde and Sun pointed out that the stationary portion of the SPC curve is at the tertiary stage, rather than at the secondary stage, as the creep strain is already at a level of 10-15% in the stationary portion [28].

Interesting discussions have been taking place during the Nottingham and Petten symposia. David Allen questioned whether due to the excessive plastic deformation at initial loading, the creep behavior could be influenced. Authors pointed out that, due to large deformation, the stress and strains in SPC should be considered as true stress and true strain, in contrary to the uniaxial creep test, where these are engineering stress and engineering strain. Kristof Turba and Peter Hähner also pointed out that the effect of strain hardening should be also considered in creep analysis. Recently, experiments have been carried out to study an excessive plasticity during the initial loading and its influence on the creep behavior [29]. Actually, this phenomenon has been addressed in earlier literatures [30-31].

Although many efforts have been made to improve the interpreting approach for SPC and several conferences and symposia have been held to exchange ideas and experiences, up to now there is no generally accepted method to estimate uniaxial creep properties. This is because the complexity of the SPC consists in the inclusion of several non-linear problems: the geometrical non-linearity due to large deformation, the physical nonlinearity due to plasticity and creep and the contact nonlinearity due to the contact area between the punch and the specimen. Therefore, differences are always found between the theoretical prediction and the uniaxial creep tests, as some effects are still not taken into account in analysis.

2. Correlation using uniaxial creep test data

As the analytic approach is very complicated, let us turn on to an alternative approach. A concept of "Fracture-based correlation" was put forward by Dobeš and Dymáček [32, 33] in which, the equivalent stress is derived using the rupture time in SPC with the uniaxial rupture data. In this paper, the "Fracture-based correlation" is further improved, not only to estimate the rupture time, but also to estimate the minimum strain rate. This new methodology is called the "Uniaxial test correlation". This approach is fully based on experimental tests data, no model or assumption is adopted. Thus all the effects mentioned above are implicitly included. In addition, this approach delivers better prediction than the formula in CoP or the Chakrabarty model. Furthermore, it is very simple and user-friendly.

The basic idea of the correlation approach is to determine the relation between the uniaxial creep test and the small punch creep test. The uniaxial creep test is a one-dimensional test which has been historically the standard method for deriving creep material properties which are used in design- and remaining lifetime evaluation standards. Therefore, an analysis of a large number of experimental data to find the relation between the uniaxial tests and the small punch tests, is an effective way to solve the problem.

Purmenský and Matocha already applied a correlation approach to predict the yield strength and the ultimate tensile strength from small punch tests at constant deflection rate [34]. They build up a data pool that includes both small punch and uniaxial tensile tests data and found an optimal parameter to correlate between small punch test results and uniaxial tensile quantities.

A similar approach can be applied to SPC analysis. However, the SPC analysis is more complicated than the analysis of the constant deflection rate test. Because in SPC, both the creep rupture time and the minimum creep rate, or more specifically, its description in terms of Norton creep law should be dealt with.

The basic procedure of the "Uniaxial test correlation" is that, the equivalent stress σ in the SPC test can be estimated from the rupture time which is comparable with to the uniaxial rupture data, thus the ratio $\Psi=F/\sigma$ is obtained. Using the obtained equivalent stress σ, the minimum strain rate can be also derived from the uniaxial creep strain rate data. The resulting ratio Ψ and the minimum strain rate are summarized in a sufficiently large data pool, from which empirical formulas of the ratio Ψ and the minimum strain rate can be established with an optimal correlation parameter. The flowchart of the "Uniaxial test correlation" is shown in Fig. 1.

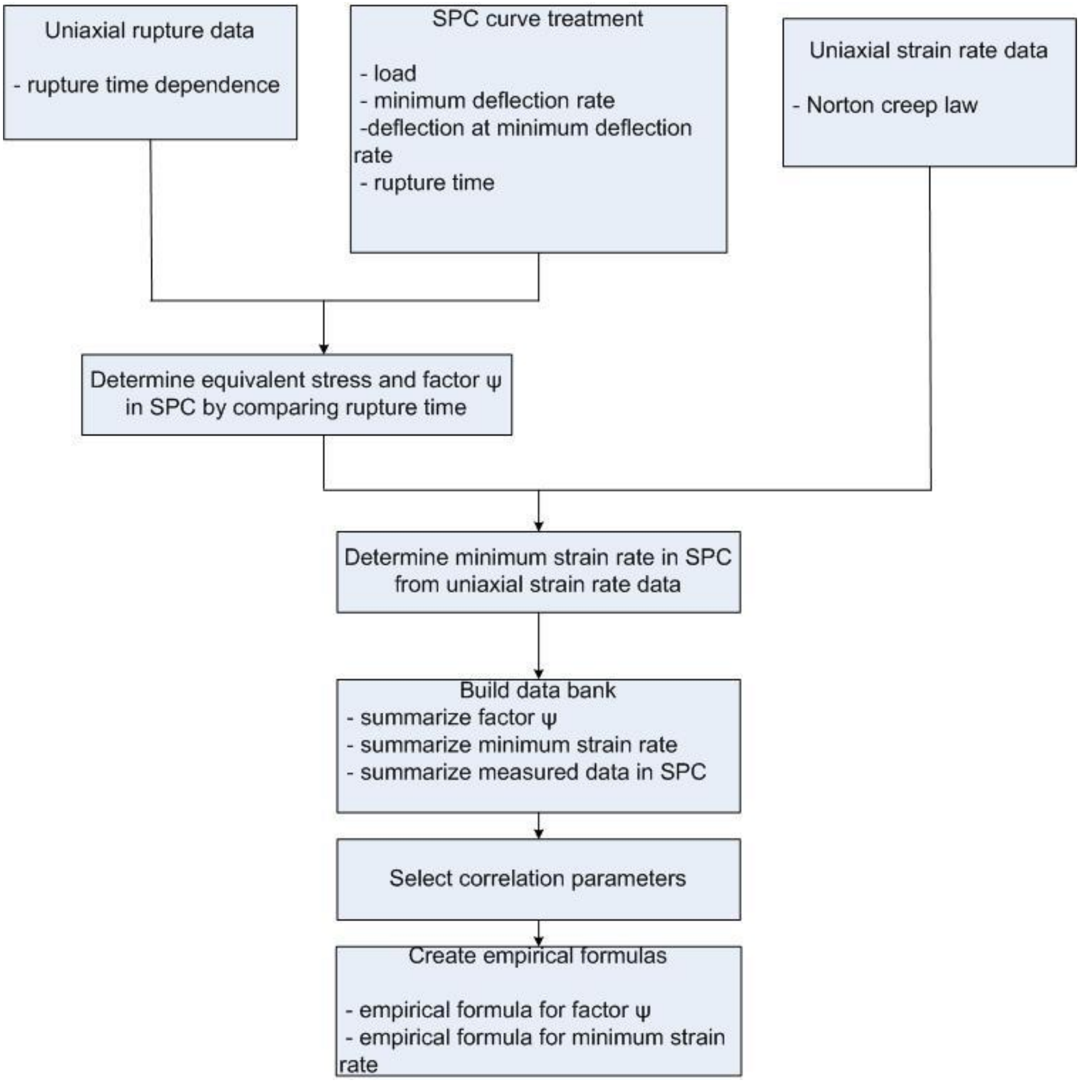


Figure 1. Flowchart of the “Uniaxial test correlation”.

3. Build up the data pool

The test data pool contains 97 uniaxial creep tests and 159 SPC tests, covering temperatures from 550 ^{0}C -700 ^{0}C, loads from 300 N to 900 N. The current materials, both new and exposed, are mainly low alloy steels and 9Cr steels, such as 14MoV63, X20CrMoV121, P91, P92 and Eurofer 97. Single example of austenite steels, namely 316 L steel, is also included in the data pool. All material names, test temperatures and data sources in the data pool are listed in the references [37-39].

All the materials tested are “creep ductile” materials, and all the SP tests for these materials were carried out using the same type of specimen/punch/support/loading configurations etc. specified in the CoP [5]. For all test data, the specimen with diameter of 8 mm and with thickness of 0.5 mm; the diameter of support hole is 4 mm; the punch diameter is 2.5 mm, and that with punch radius of 2.0 mm is excluded. Therefore, the data used for fitting belong to “the same family”, but under different temperatures.

4. Matlab code for data treatment

In order to deal with large data treatment for different materials with both uniaxial creep and SPC tests, a general Matlab code with name of Psi.m is compiled with Matlab version 2016a. As the data pool contains more than 20 materials, the material name is set as an input variable in the code Psi.m. The active command is Psi(*mat*). Here the *mat* is the material name in characters.

According to the input variable *mat*, the program Psi.m will identify the files “uniaxial_*mat*.txt” and “spt_*mat*.txt”. These two files contain the list locations of the test curves for uniaxial creep and SPC tests.

The program Psi.m consists of three parts: 1) uniaxial creep curve treatment, 2) SPC curve treatment and 3) comparison of measured and predicted with respect to rupture time dependence and the Norton creep law. After the uniaxial creep and SPC curve treatments are finished, the obtained data are summarized using another Matlab code summary.m. Regressions are carried out to derive the constants of two empirical relations: rupture time dependence and Norton creep law. The summary results are input to Psi.m as prediction results for the comparison in part 3.

The uniaxial creep curve treatment output are written in the file history_uni.txt, including applied stress, minimum strain rate $\dot{\varepsilon}_{min}$and rupture time tr. The SPC curve treatment output are written in the file history_spt.txt, including applied load F, equivalent stress σ, factor Ψ, derived minimum strain rate $\dot{\varepsilon}_{min}$, minimum deflection rate $\dot{u}_{min}$, deflection at minimum deflection rate u_{min} and rupture time t_r. The results derived from Chakrabarty's model are also included for comparison. The flow chart of the Matlab code Psi.m is shown in Fig. 2.

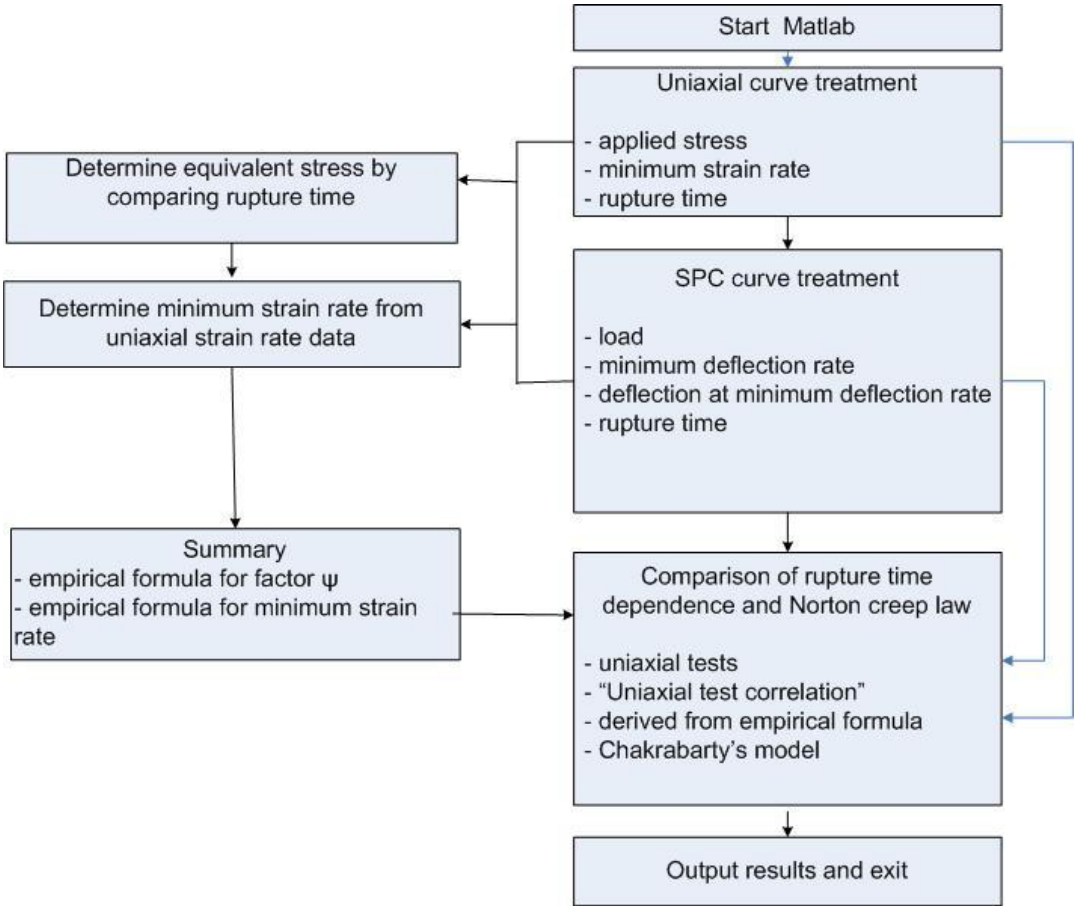


Figure 2. Flowchart of Matlab code Psi.m.

5. Parameters selection for factor Ψ and minimum strain rate

Actually, many factors could influence the value of factor Ψ, such as the temperature, the material, initial loading deflection and so on. All the factors will give influence on a deflection curve. In other words, the deflection curve reflects and represents all the influences. According to Chakrabarty's membrane stretch model, the factor Ψ=F/σ depends on the deflection u only. Although this is for an extreme membrane stage, it could be suitable for a large deformation status like the SPC test. Therefore the deflection u could be a candidate parameter for factor Ψ.

The code summary.m outputs not only the factor Ψ, but also the following items: the equivalent stress σ, the minimum strain rate $\dot{\varepsilon}_{min}$, the minimum deflection rate $\dot{u}_{min}$, the deflection at minimum deflection rate u_{min}, the Monkman Grant constant MGC, the rupture time t_r and a few others. In order to find an optimal correlation parameter to calculate factor Ψ, several regressions for different candidates are carried out and the coefficient of determination, R^2, of the regression are compared. It turns out that the deflection at the minimum deflection rate, u_{min}, is the optimal parameter for the ratio Ψ. The deflection rates are calculated by derivative of deflection curve, and the deflection u_{min}, is corresponding to the minimum deflection rate.

The coefficient of determination, R^2, of regression for different parameters are summarized in table 1.

Table 1. The R^2 of regression for different parameters.

No.	**Relation in logarithm**	R^2
1	Deflection at minimum deflection rate, u_{min} vs. factor Ψ□	0.5948
2	Average deflection at $1/3t_r$, $1/2t_r$, $2/3t_r$ vs. factor Ψ□	0.5600
3	Rupture time t_r vs. factor Ψ□	0.1332
4	Minimum strain rate $\dot{\varepsilon}_{min}$vs. factor Ψ□	0.2346
5	Minimum deflection rate $\dot{u}_{min}$vs. factor Ψ□	0.1436
6	Monkman-Grant constant MGC vs. factor Ψ□	0.4290
7	Ratio of $\dot{\varepsilon}_{min}/\dot{u}_{min}$vs. factor Ψ□	0.3137

The acquired data pairs (F/σ, u_{min}) are then fitted to the following empirical formula (Fig. 3)

$$\Psi = \frac{F}{\sigma} = A.u_{min}^{m} \quad (N/MPa) \tag{1}$$

The best fit is found at A = 1.9204 and m=0.6530.

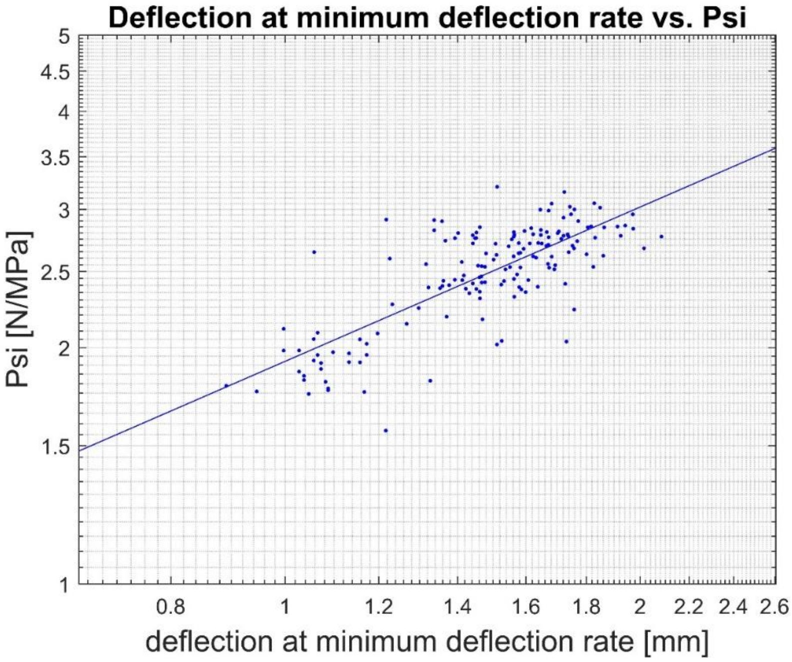


Figure 3. Relation between Ψ and the deflection at the minimum deflection rate, $u_{min.}$

The derived minimum strain rates are also output from summary.m. An empirical relation between the minimum deflection rate $\dot{u}_{min}$ and the minimum strain rate $\dot{\varepsilon}_{min}$ is established and expressed as follows (see Fig. 4).

$$\dot{\varepsilon}_{min} = 0.3922\dot{u}_{min}{}^{1.1907} \quad (1/h) \tag{2}$$

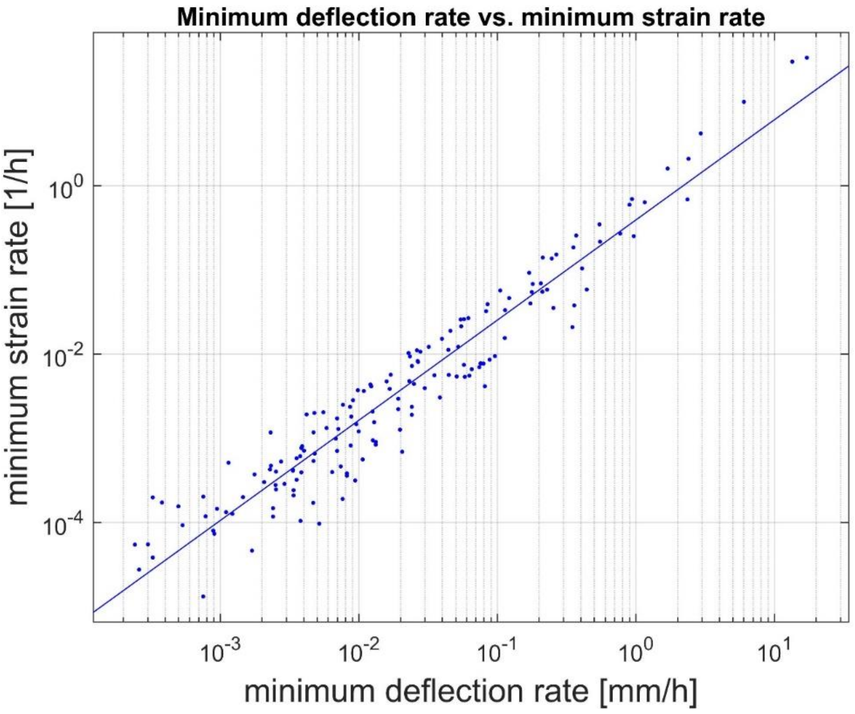


Figure 4. Relation between the minimum deflection rate $\dot{u}_{min}$ and the minimum strain rate $\dot{\varepsilon}_{min}$.

The correlation between the minimum deflection rate $\dot{u}_{min}$ and the minimum strain rate $\dot{\varepsilon}_{min}$is quite good. The coefficient of determination, R^2, of the regression is equal to 0.9218. No other parameters reach this level of correlation.

6. Procedure for the application of "Uniaxial test correlation"

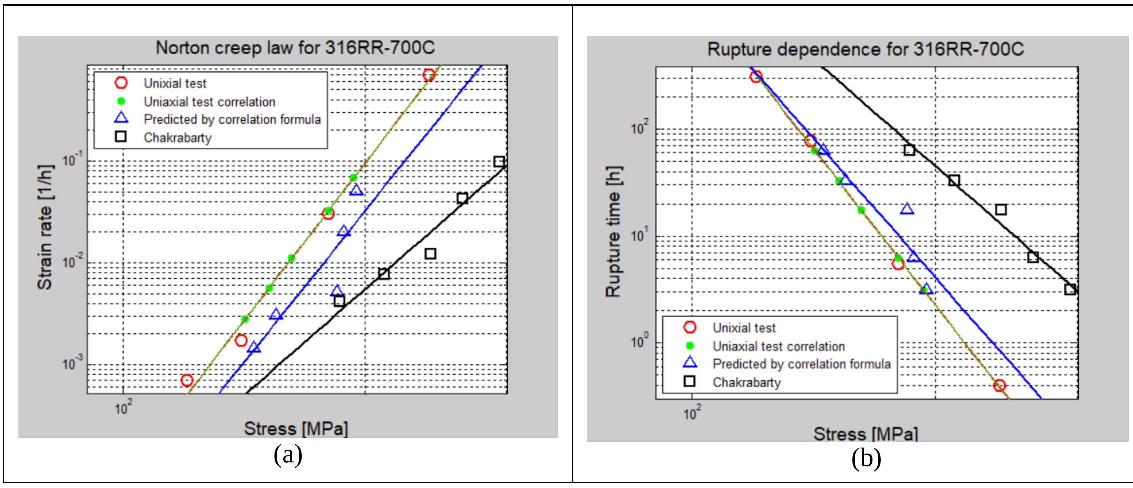
The procedure for application of the "Uniaxial test correlation" is described as follows:

1. Carry out multiple SPC tests at the equal temperature and follow the next steps for each test.
2. For a given load F, determine the rupture time t_r, the minimum deflection rate $\dot{u}_{min}$, and the deflection at the minimum deflection rate, u_{min}.
3. Using the deflection at the minimum deflection rate, u_{min}, determine the ratio $\Psi = F/\sigma$ from Eq. (1), and consequently the equivalent stress σ is also determined.
4. Using the minimum deflection rate $\dot{u}_{min}$, determine the minimum strain rate $\dot{\varepsilon}_{min}$ from Eq. (2).
5. With the equivalent stress σ, the rupture time t_r, and the minimum strain rate $\dot{\varepsilon}_{min}$ known, the rupture time dependence and the Norton creep law are determined by regression.

7. Verification

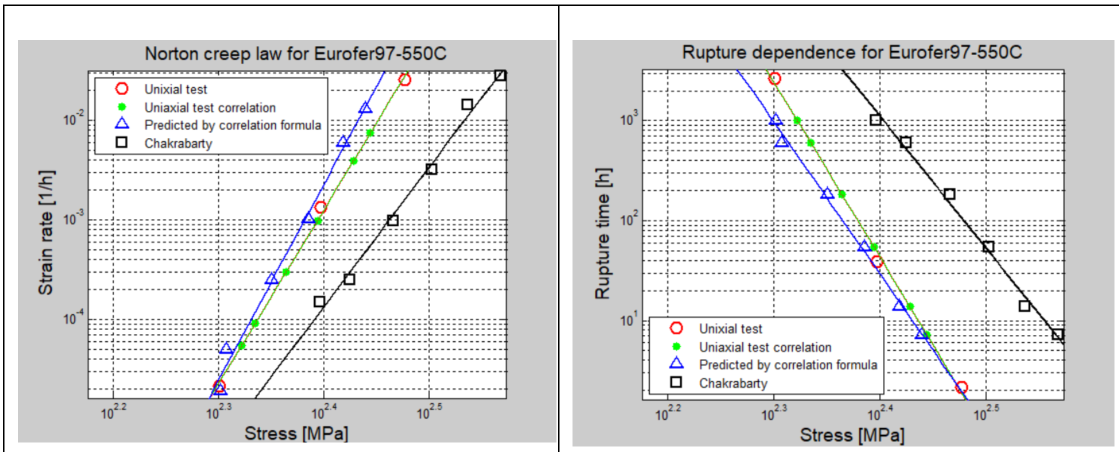
The best method for verification is to compare the prediction results directly with the uni-axial tests. The verification has been carried out for each test set during building up the data pool. Herewith some examples are shown below for predictions of the rupture time and the minimum strain rate. The prediction of the Chakrabarty model is also included. Obviously, the present approach gives better prediction than the Chakrabarty model.

In the following figures, the red points and the red lines are the uniaxial creep data. For the green points and green line, the equivalent stress σ is estimated using the rupture time in the SPC test to compare the uniaxial rupture data. Then using the obtained equivalent stress σ is used to calculate the minimum strain rate in SPC from the uniaxial creep strain rate data. Thus the red line and green line are always overlapping. The blue points and blue line are derived from the empirical formulae Eqs. (1) or (2) and represent the prediction by the "Uniaxial test correlation" approach. The black points and black line are derived from the prediction by the Chakrabarty model.



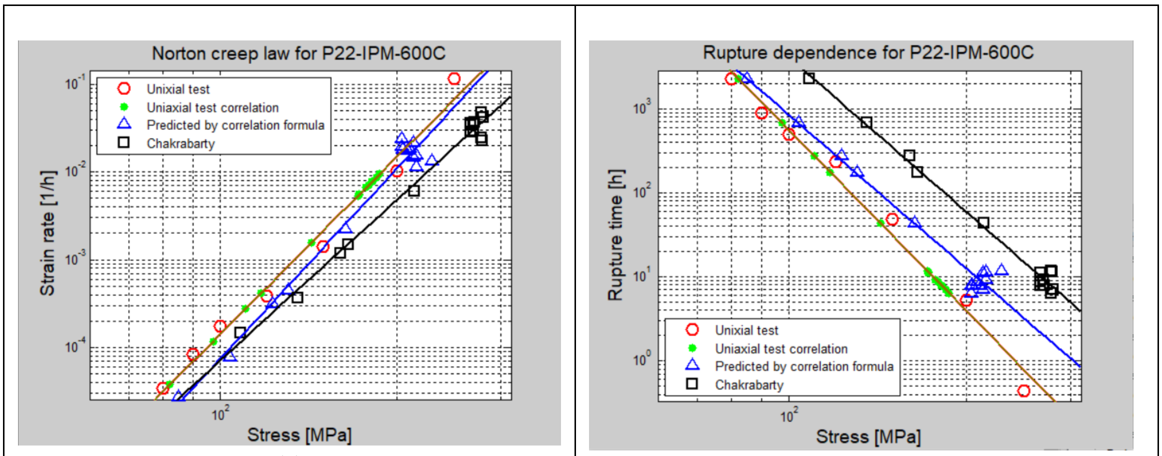
(a) (b)

Figure 5. Comparison of uniaxial creep data with prediction methods for 316RR at 700 ^{0}C (a) Norton creep law, (b) Rupture time.



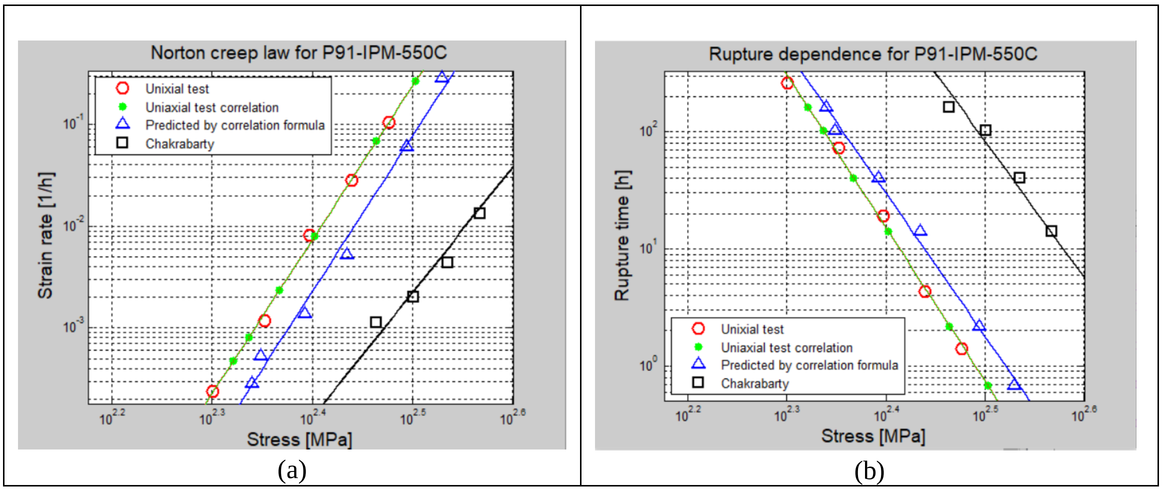
(a) (b)

Figure 6. Comparison of uniaxial creep data with prediction methods for Eurofer97 at 550 ^{0}C (a) Norton creep law, (b) Rupture time.



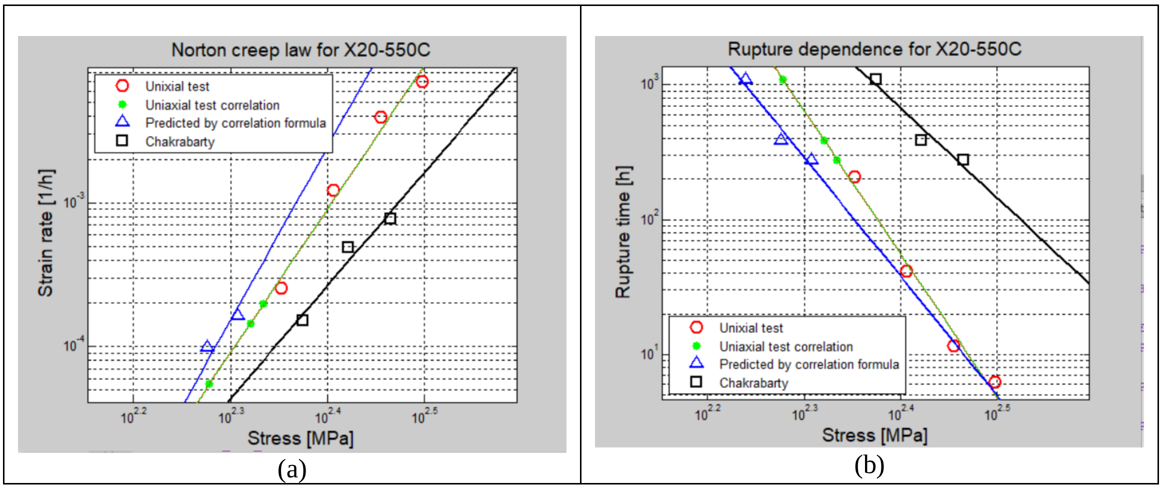
(a) (b)

Figure 7. Comparison of uniaxial creep data with prediction methods for P22 at 600 ^{0}C (a) Norton creep law, (b) Rupture time.



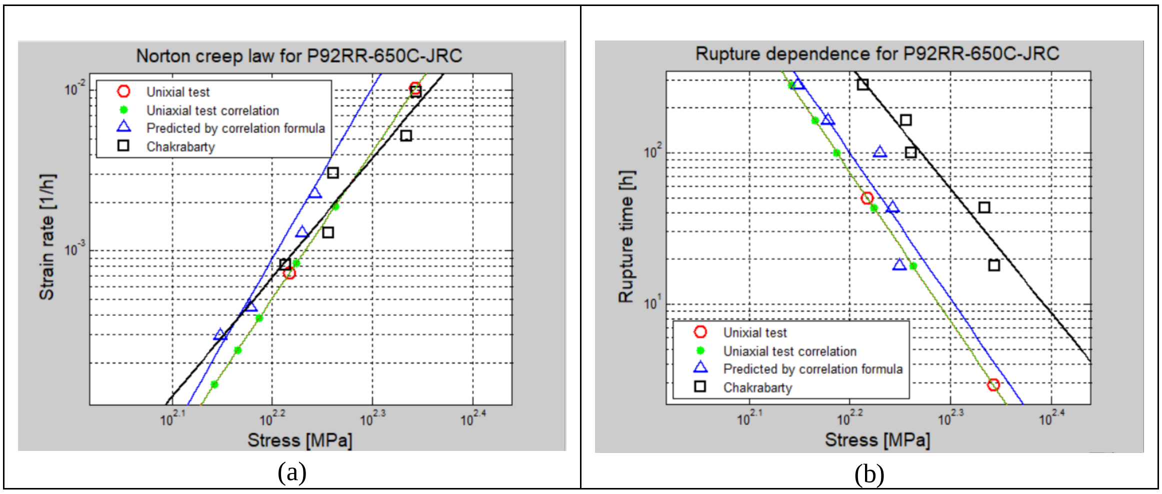
(a) (b)

Figure 8. Comparison of uniaxial creep data with prediction methods for P91 at 550 ^{0}C (a) Norton creep law, (b) Rupture time.



(a) (b)

Figure 9. Comparison of creep uniaxial data with prediction methods for X20 at 550 ^{0}C (a) Norton creep law, (b) Rupture time.



(a) (b)

Figure 10. Comparison of uniaxial creep data with prediction methods for P92RR at 650 ^{0}C (a) Norton creep law, (b) Rupture time.

8. Discussion and conclusion

The Chakrabarty model [23] has been introduced in European CoP to estimate the creep load setting. However, it is not sufficient for the prediction of creep properties from SPC tests. This is because the complexity of the SPC problem, as too many non-linearities are involved. Efforts have been made by considering several effects; however none of them is commonly accepted yet.

This paper puts forward a new methodology based on direct use of experimental data. Because the experimental data implicitly contain all effects, a theoretical analysis with unavoidable assumptions is not needed.

Empirical formulas are given to estimate the equivalent stress σ and the minimum strain rate $\dot{\varepsilon}_{min}$, thus creep properties can be predicted using the measured SPC data.

Verification has been carried out and shows that, the predictions by the empirical formulas are in good agreement with the uniaxial creep data, and are much better than predicted by Chakrabarty model. From Figs. 5-10, one can notice that the fitting quality for rupture life is better than that for minimum strain rate. That is understandable, as the equivalent stress σ is derived from the comparison of the rupture time, while the minimum strain rate is derived from further comparison. Someone may feel a bit unexpected about the very high fitting quality in rupture life in Figs. 5-10(b). Due to the factor that the values of factor Ψ for these examples are close to the fitting line and far from the scattering points. In addition, the test data for these examples are provided by IPM, IMT and JRC with high quality.

The accuracy of the empirical formulas should be improved further, especially for the factor Ψ. At this moment, the coefficient of determination, R^2, of the regression is about 0.59, and this value is quite low. The consequence of using the fitting (straight) line in Fig. 3 for any random tests indicates that the stress error could be > 50% in the worst cases, which will lead to a huge difference in minimum strain rate (n is large) if used. Therefore a study should be carried out case by case for these scattering points to find the influence factors. It may be necessary to distinguish low-alloy steel from austenitic steel or consider the temperature difference. A neural network approach is under developing for this purpose.

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