Compatibility and cyclic properties of linear flow splitted steel

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Abstract In this paper, the work is presented which is a part of research activities of the Collaborative Research Centre (CRC) 666, where the technology for integral sheet metal design with higher order bifurcations is elaborated. The results from constant amplitude fatigue tests are presented for steel in basic state and for the material state after new technique of linear flow splitting under room temperature, where a large plastic deformation occurs. Since manufactured products with the method of linear flow splitting will be a part of cyclic loaded structures it is important to outline the fatigue characteristics of used material before and after splitting technology exactly. It is observed, that the investigated steel has better fatigue resistance after linear flow splitting. For the estimation of fatigue parameters of material with high plastic deformation a new method is used, witch is taking mathematical connections into consideration between Ramberg-Osgood and Manson-Coffin-Basquin equations. In order to evaluate the 6 basic fatigue material parameters of these equations the presented method uses the projection of a 3-D line (ε_{ap}-σ_a-N_f). Compared with traditional methods for determining fatigue parameters similar fitting curves were received, however the new method assures the so called compatibility between stress-strain and strain-life curves.

1 INTRODUCTION

For the description of material fatigue resistance the strain-life curve is usually used [1]. One of the best know equation is the Manson-Coffin-Basquin proposition [2-4], where the total strain amplitude $\varepsilon_{a,t}$ is divided into elastic $\varepsilon_{a,e}$, and plastic $\varepsilon_{a,p}$ components as such:

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c . \tag{1}$$

The Young's modulus E is obtained either from a static tensile material test or from the first hysteresis loop recorded during the fatigue test. In order to determine the remaining four material constants, it is necessary to perform several fatigue tests under cyclic loading with constant amplitude and a load ratio of $R_\varepsilon = -1$ on unnotched specimens. Due to hardening or softening effects, materials subjected to cyclic loading are often unstable, producing stress amplitude changes during the tests [5, 6]. Thus, the stress amplitude corresponding to the stabilized state must be used, which occurs at the half of the number of cycles to crack initiation. With this stress amplitude, the Young's modulus and the total strain amplitude the plastic part of the strain amplitude can be calculated:

$$\varepsilon_{a,p} = \varepsilon_{a,t} - \varepsilon_{a,e} = \varepsilon_{a,t} - \frac{\sigma_a}{E} . \tag{2}$$

Ramberg and Osgood [1, 5, 7] proposed a method of describing stresses and strains in materials subjected to constant amplitude cyclic loading. This method is widely applied in fatigue analyses as an important source of information about the material behaviour [5, 8]. Like in the Manson-Coffin-Basquin equation (1), the total strain amplitude is divided into elastic and plastic components, but described as a function of stress amplitude σ_a and not fatigue life N_f

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} . \tag{3}$$

2 DELIBERATION ABOUT CONNECTION BETWEEN MANSON-COFFIN-BASQUIN AND RAMBERG-OSGOOD EQUATIONS

Eqs. (1) and (3) have similar structures in that both total strain amplitudes consist of the sum of plastic and elastic parts. By comparing the elastic components, the following equations can be derived:

$$\begin{gathered} \varepsilon_{a,e}^{MC} = \varepsilon_{a,e}^{RO} \\ \frac{\sigma'_f}{E}\left(2N_f\right)^b = \frac{\sigma_a}{E} \\ \log\left(\sigma'_f\right) + \log\left(2N_f\right)b = \log\left(\sigma_a\right) \end{gathered} \tag{4}$$

and for the plastic parts of Eqs. (1) and (3):

$$\begin{gathered} \varepsilon_{a,p}^{MC} = \varepsilon_{a,p}^{RO} \\ \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} = \varepsilon'_f\left(2N_f\right)^c \\ \left[\log\left(\sigma_a\right) - \log\left(K'\right)\right]\frac{1}{n'} = \log\left(\varepsilon'_f\right) + \log\left(2N_f\right)c \end{gathered} \quad . \tag{5}$$

Introducing the $\log(\sigma_a)$ part from Eq. (4) into (5) leads to the following expression

$$\left[\log\left(\sigma'_f\right) + \log\left(2N_f\right)b - \log\left(K'\right)\right]\frac{1}{n'} = \log\left(\varepsilon'_f\right) + \log\left(2N_f\right)c\,, \tag{6 a}$$

$$\log\left(\sigma'_f\right)\frac{1}{n'} + \log\left(2N_f\right)\left(b\frac{1}{n'} - c\right) - \log\left(K'\right)\frac{1}{n'} = \log\left(\varepsilon'_f\right). \tag{6 b}$$

Material parameters as well as number of cycles appear in Eq. (6 b). This equation shows three terms containing only material parameters which do not depend on the number of cycles. However, this equation should be valid for the entire range of cycles, which leads to:

$$\underbrace{\log\left(2N_f\right)}_{\neq 0}\left(b\frac{1}{n'} - c\right) = 0 \quad \text{if, and only if,} \quad b\frac{1}{n'} - c = 0\,, \tag{7}$$

$$n' = \frac{b}{c} = n'_{comp.} \tag{8}$$

Substitution of Eq. (8) into (6 b) leads to:

$$\begin{gathered} \log\left(\sigma'_f\right)\frac{c}{b} - \log\left(K'\right)\frac{c}{b} = \log\left(\varepsilon'_f\right) \\ \frac{\sigma'_f}{K'} = \left(\varepsilon'_f\right)^{\frac{b}{c}} \end{gathered} \tag{9}$$

$$K' = \frac{\sigma'_f}{\left(\varepsilon'_f\right)^{\frac{b}{c}}} = K'_{comp.}\,. \tag{10}$$

Eqs. (8) and (10) are the so-called compatibility equations and they couple the coefficients and exponents which appear in the Ramberg-Osgood and Manson-Coffin-Basquin formulations. This yields the possibility of determining the coefficient and exponent in the stress-strain curve (3) directly from the strain-life curve (1). It is assumed, that the number of cycles to failure does not influence the elastic-plastic properties of the material. Thus, it is supposed that the material is stable during fatigue tests and does not exhibit significant softening or hardening effects. Therefore, the constants E, K', n', ε'_f, σ'_f, b and c do not depend on the number of cycles N_f or on the values of strain ε_a or stress σ_a. This assumption may be invalid for some materials.

3 METHODS OF EVALUATING THE MATERIAL FATIGUE PROPERTIES

In order to calculating the material fatigue properties two methods were used. Detailed description of this methods can be found in following subsections.

3.1 Conventional method

In order to calculating the material fatigue properties the conventional method was used which is recommended by several institutions and described in norms [1, 5, 9, 10]. On the Fig. 1 the algorithm are show using during computation. To compute the material parameters in Eq. (1) from experimental data the least squares method for fitting the component curves can be applied [9]. Linearization of the plastic part of Eq. (1) leads to

$$Y = \log(\varepsilon'_f) + cX \,, \tag{11}$$

where $Y = \log(\varepsilon_{a,p})$ and $X = \log(2N_f)$. While fitting the line (11) only those points should be take into account where the value of the plastic strain is higher than the established limit ε_0. This limitation results from the measuring accuracy of the total strain and from the operations of subtraction in Eq. (2). For steels, the value $\varepsilon_0 = 0.01\%$ is recommended [11]. Many problems related to the strain limit ε_0 have been discussed in [12, 13]. Linearization of the elastic part of Eq. (1) can be done in the same manner:

$$Y = \log\left(\frac{\sigma'_f}{E}\right) + bX \,, \tag{12}$$

where $Y = \log(\varepsilon_{a,e})$, and $X = \log(2N_f)$.

The stress-strain curve is usually presented in a linear coordinate system, but in the double-logarithmic coordinate system, the terms of the equations, i.e. elastic and plastic part, are expressed by straight lines. Thus, in order to determine the material parameters K' and n', the plastic part of the Eq. (3) must be linearized. Linearization is performed by finding the logarithms of the equation

$$\sigma_a = K' \varepsilon_{a,p}^{n'} \,, \tag{13}$$

and thus obtaining

$$Y = \log(K') + n' X \,, \tag{14}$$

where $Y = \log(\sigma_a)$, and $X = \log(\varepsilon_{a,p})$.

For the fitting procedure test results used for determining the Manson-Coffin-Basquin curve are usually applied [11]. Since many materials stabilize after a relatively short time, it is possible to obtain the experimental points using a more efficient method that uses only one specimen. These methods are: Incremental Step Test, Multiple Steps with Increasing Strain, Multiple Steps with Decreasing Strain and a method using Random Cyclic Strain Amplitude Tests [14, 15]. The experimental results (pairs of amplitudes of total strain and stress) are considered in the same way as those obtained from constant-amplitude tests for stabilised hysteresis, and are fitted as described above. However, the results obtained for materials with unstable material behaviour can differ extensively depending on the used method [10, 14].

3.2 3-D method

The second method for evaluating material fatigue properties was new designed 3-D method. From Eqs. (1) and (3) it appears, that one value of the total strain amplitude, $\varepsilon_{a,t}$, corresponds to only one stress amplitude, σ_a, and to a single number of cycles, N_f. In such a case, it is possible to formulate the total characteristics expressed by the curve ($\varepsilon_{a,t}$-σ_a-N_f) in a three-dimensional space. Fig. 1(a) shows such characteristics also depicting curves for the parts of elastic strain ($\varepsilon_{a,e}$-σ_a-N_f) and plastic strain ($\varepsilon_{a,p}$-σ_a-N_f). By a projection of the three-dimensional characteristics, the following curves can be obtained: projection to the plane ($\varepsilon_{a,t}$-σ_a) gives the trajectory of the cyclic stress-strain curve (Ramberg-Osgood equation), projection to the plane ($\varepsilon_{a,t}$-N_f) gives the strain-life curve (Manson-Coffin-Basquin equation), and projection to the plane (σ_a-N_f) gives the stress-life curve, expressed with Eq. (15). Particular projections for 3-D characteristics are shown in Figs. 1(b) to 1(d).

In this new method, all six cyclic characteristics are determined through the approximation of the regression line in the 3-D space. It is proposed to define the position of the straight line ($\varepsilon_{a,p}$-σ_a-N_f) in 3-D space by coordinates of the point $P_1(x_1, y_1, z_1)$ located on this straight line and the directional vector $\mathbf{R}(l, m, n)$ to which the straight line is parallel [16]. The approximation of the points can be done with the least-square method, minimizing the sum of the squares of the distances of the points from the straight line. There are many efficient methods for such regressions in the 3-D space [16, 17]. The location of the straight line in 3-D space also determines the positions of its projections on the particular planes. Thus, the material parameters of interest can be determined directly from the following equations:

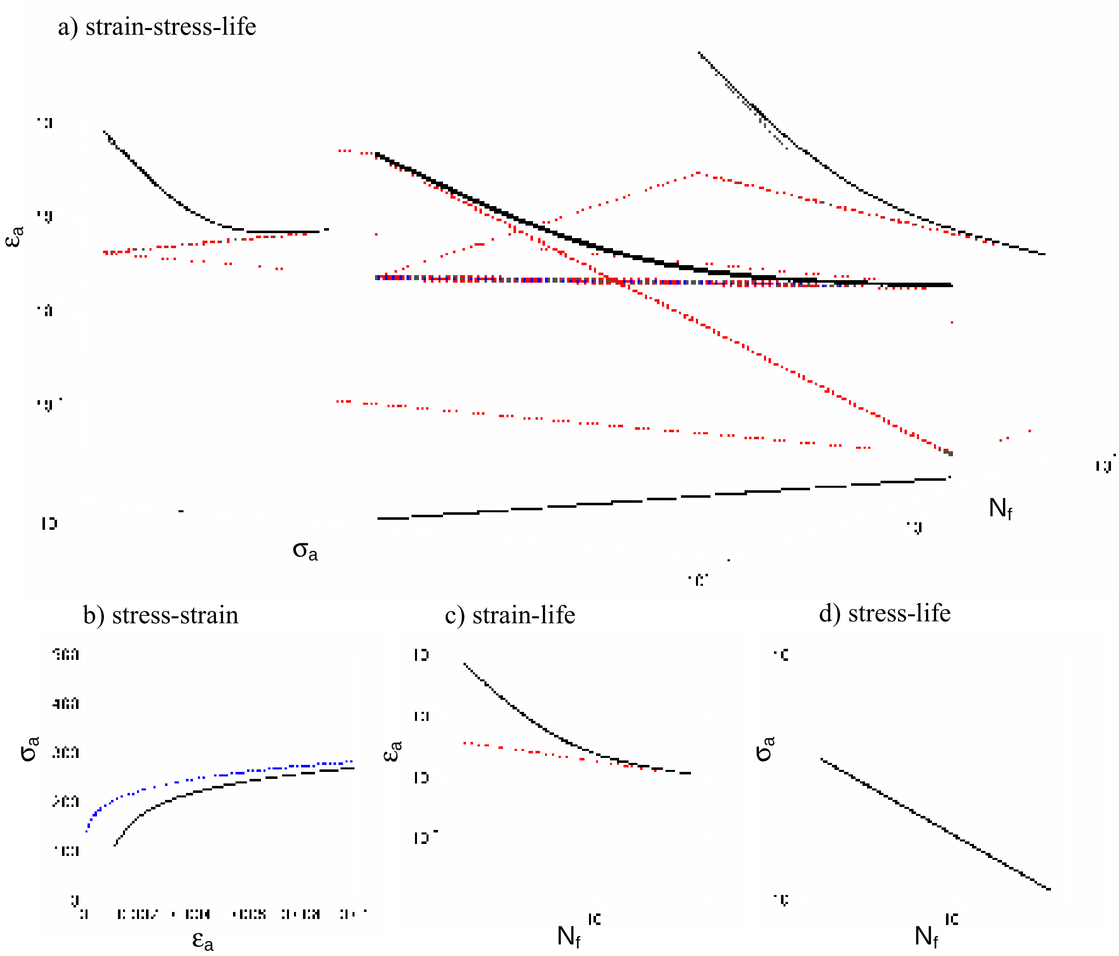

Figure 1 Three-dimensional space with the strain-stress-life curve (a) and its projections on stress-strain plane (b), strain-life plane (c), and stress-life plane (d)

$$n' = \frac{m}{l}, \qquad c = \frac{l}{n}, \qquad b = \frac{m}{n},$$
$$K' = 10^{(y_1 - x_1 n')}, \quad \varepsilon'_f = 10^{(x_1 - z_1 c)}, \quad \sigma'_f = 10^{(y_1 - z_1 b)}. \tag{15}$$

These equations have been derived according to the following assumptions:

$$x = \log(\varepsilon_{a,p}), \quad y = \log(\sigma_a), \quad z = \log(N_f). \tag{16}$$

As in the conventional method, the established limit ε_0 is considered in the 3-D method. While fitting the line, only those points were considered where the value of plastic strain is higher than ε_0. However, it is not recommended to do this directly since omission of such points can greatly influence the stress-life curve (σ_a-N_f), where the elastic part of the strain plays a significant role. Therefore, it is proposed to recalculate the plastic strain parts with $\varepsilon_0 < 0.01\%$ so that the new values do not change the strain-life curve (ε_a-N_f). These new values then lie directly on the line of the plastic part of the Ramberg-Osgood equation, which was determined without considering these points. However, the stress values which form the third plane of these tests are not corrected, and are subject to further scatter. Subsequently, a second regression is carried out in order to recalculate the location of the ($\varepsilon_{a,p}$-σ_a-N_f) line. The algorithm of the computations is shown in Fig. 2.

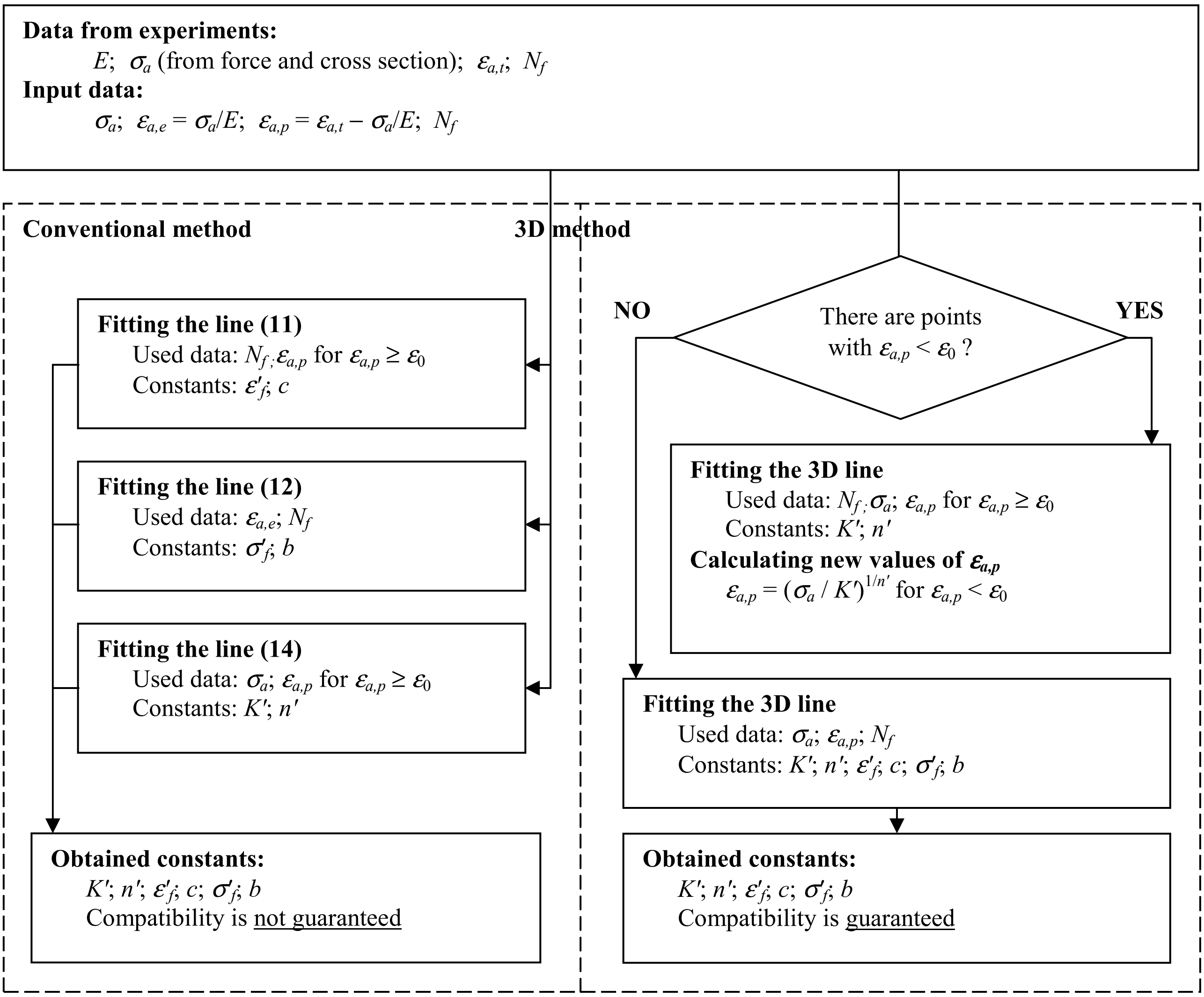

Figure 2. Algorithms for calculation of the material constants K', n'; ε'_f, c, σ'_f and b

4 EVALUATION OF THE FATIGUE PROPERTIES

The above described methods were used to evaluate the cyclic parameters for the steel ZStE500 in the unformed stage and after linear flow splitting process. Figure 3 and Figure 4 show the stress-strain curves and the strain-life curves for the tested steel before the linear flow splitting process. Three curves can be seen in Figure 3. One describes the stress-strain curve derived from the conventional method, and one from the 3D-method. The third one is derived by using the compatibility equations and the strain-life parameters from the conventional method. The stress-strain curve due to the conventional method differs from the two others curves. In Figure 4 the strain-life curves are shown for the conventional method and for the 3 D method. Both figures show that there are small differences in the curves, but probably with respectively small influences on the fatigue life assessment. Figure 5 and Figure 6 show the curves for the steel ZStE500 after the linear flow splitting process. These curves show almost no differences for the different methods.

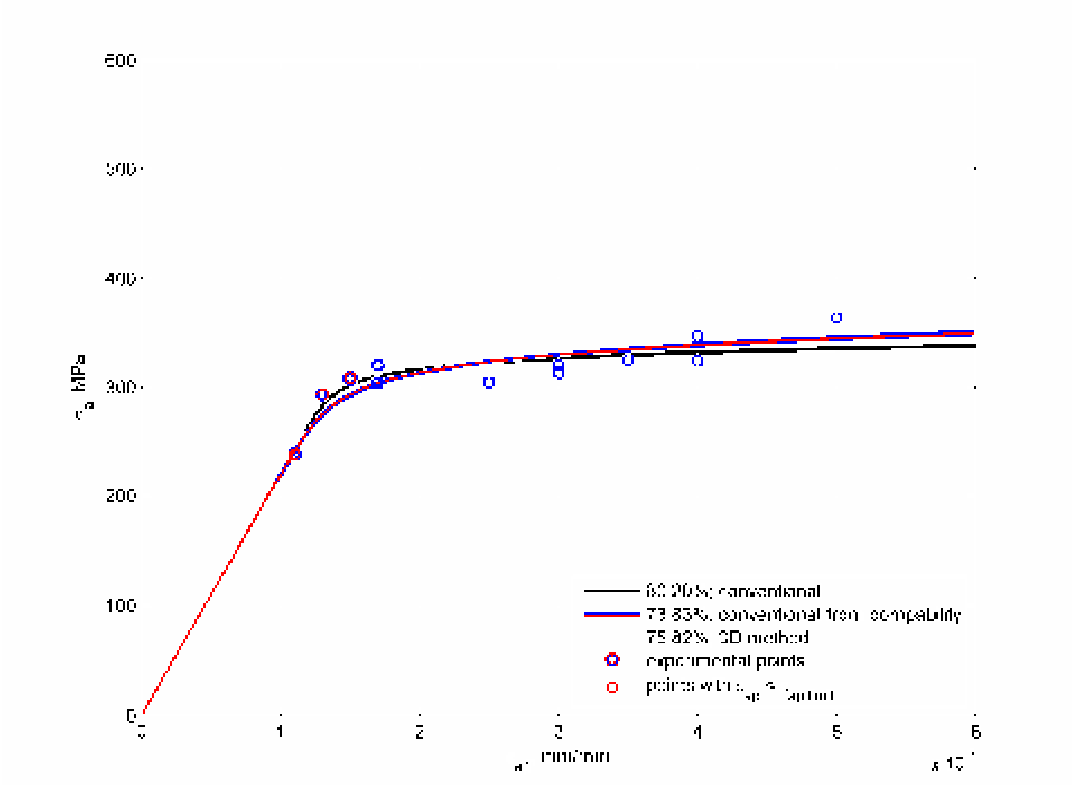

Figure 3. The stress-strain curves for ZStE500 steel before the linear flow splitting processes calculated with conventional and 3-D methods

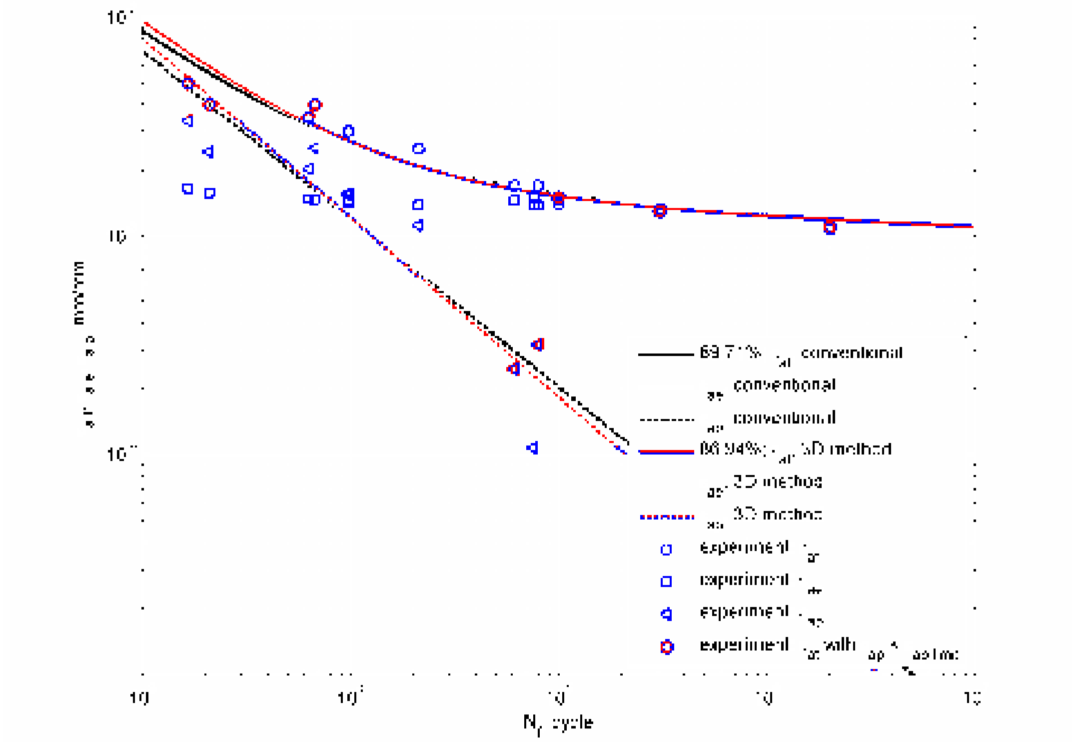

Figure 4. The strain-life curves for ZStE500 steel before the linear flow splitting processes calculated with conventional and 3-D methods

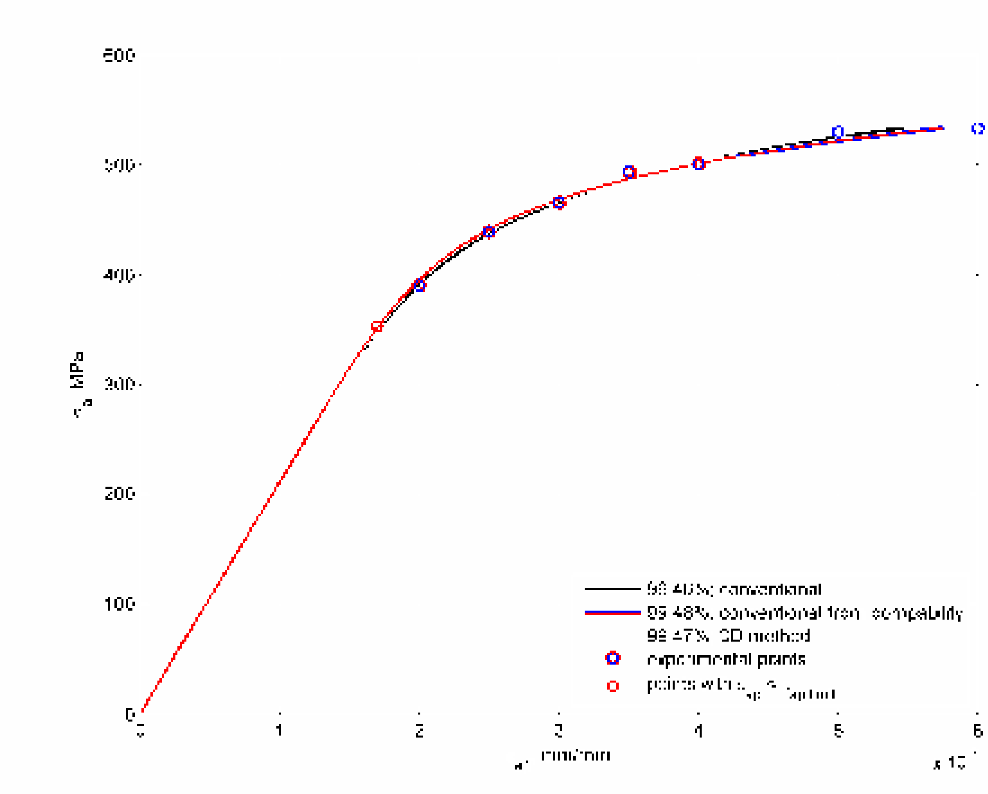

Figure 5. The stress-strain curves for ZStE500 steel after the linear flow splitting processes calculated with conventional and 3-D methods

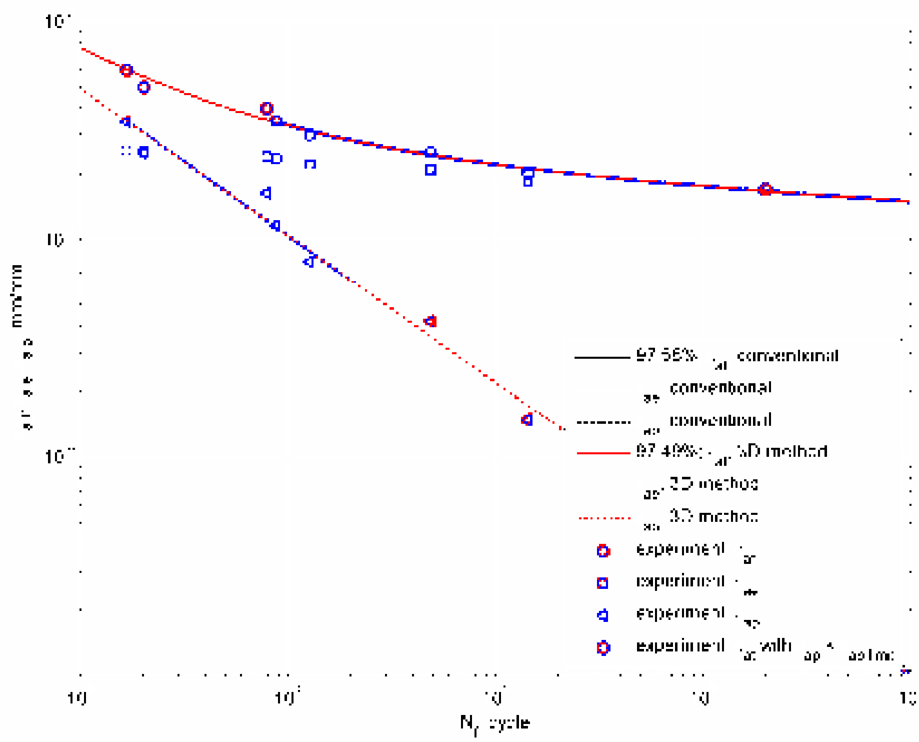

Figure 6. The strain-life curves for ZStE500 steel after the linear flow splitting processes calculated with conventional and 3-D methods

5 CONCLUSIONS AND REMARKS

Using the conventional method doesn't guarantee compatibility, but in the case of this material ZStE500 there is no significant difference in the curves from the different methods. Investigations with other materials like aluminium have shown higher differences between the methods [19]. In this case the fatigue life assessment has a dependency of the used method.

The conventional method calculates the material properties in three independent steps. This may be the reason for inaccuracy in calculating the material fatigue properties. However the stress-strain and strain-life curves are connected with the compatibility equations. Using the 3Dmethod guarantees always the compatibility, and has the advantage of having no dependency on the regression direction.

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