Further evaluation of the advanced prediction method EVICD for arbitrary multiaxial loading

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Abstract

EVICD, a fatigue prediction method for arbitrarily multiaxially loaded complex components, has reached a standard which is of interest for a more general engineering application. Comparisons of EVICD predictions to the results of our recently performed tests and to results as reported in the literature have shown that the differences between the predictions and the experimental results were typically less than a factor of 3. EVICD comprises an input section which is open to nearly all formats of loading data in engineering practice. Although the multi-surface material model after Mróz-Garud was originally introduced into EVICD, other elastic-plastic material models can also be used.

1 Introduction

EVICD represents a crack initiation life prediction tool for multiaxially loaded engineering components. The stresses can be proportional and non-proportional triaxial. Although fully triaxial stresses and strains are not always present at fatigue critical locations of engineering components they occur very often at components which are larger and expensive. Also under circumstances where the above mechanical loading as well as other influences, for example technological influences, become important at a component, the exact evaluation of the stresses and strains forms the basis for a qualified consideration of the other influence.
The development of EVICD started in the late 1980s [1] and has run through several stages until it reached its present format. The basics of EVICD have already been described in [2,3] such that they need to be mentioned only briefly here.

Recent work on EVICD dealt with the further evaluation of the prediction capability and the closer integration of EVICD into engineering design. The latter aspect led to the development of a powerful input section. This aspect forms the central idea of the present investigation. This investigation consisted of two parts. In the first part new experiments were run, the other part considers experimental investigations as reported in the literature.

2 EVICD

2.1 Theoretical background

As mentioned above, EVICD evaluates the stress-strain behaviour of the construction material completely three-dimensionally. The experience of the authors showed that at the fatigue critical location of engineering components no really strong cycle dependent changes of the cyclic material behaviour like cyclic creep, ratchetting and relaxation normally occur. Under such circumstances the elastic-plastic multi-yield-surface model after Mróz-Garud offers advantages. However, EVICD is also open to other multiaxial material models such as, for example, the Jiang model [4].

Regarding damage evaluation, EVICD takes the increments of plastic work as performed by the material at the fatigue critical location as the primary damage parameter. However, a special version of EVICD (EVICD-Δγ) also takes the elastic-plastic shear strains as the primary damage parameter according to the observation that micro-structural damage predominantly develops in connection with slip processes. But because EVICD-Δγ did not lead to really better predictions until now, the version of EVICD which is based on incremental plastic work as the primary damage parameter was applied in the present study.

Incremental plastic work is determined as indicated in Figure 1. Besides incremental plastic work as the primary damage parameter EVICD further uses a unique secondary damage parameter. This secondary damage parameter is the instantaneous normal stress either on the plane of maximum shear stress (EVICD-N) or on the octahedral planes (EVICD-J1). It accounts for the fact that fatigue damage develops predominantly in connection with microscopic slip processes. The instantaneous increment of plastic work and the normal stress either on the instantaneous maximum shear plane or on the octahedral planes determine the instantaneous amount of fatigue damage, ΔD:

\[ ΔD = ΔW_p \cdot d^* \]  

(1)

d*, in this equation, is the instantaneous specific damage which is a function of the instantaneous normal stress on the maximum shear stress plane or on the
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Figure 1: Evaluation of incremental plastic work.

octahedral planes. For each segment of the multi-yield-surface material model which is instantaneously passed through due to the action of the outer loading $d^+$ has to be specially determined. This is performed as indicated in Figure 2 for one range of the multi-yield-surface material model. In the figure, two situations are of importance. Under pure torsion loading the normal stress on the maximum shear stress plane and on the octahedral planes become zero. Under such circumstances $d^+$ can directly be derived from shear controlled pure torsional constant amplitude tests on unnotched specimens. Another well defined loading situation is uniaxial tension-compression loading on unnotched specimens. Under these circumstances well defined normal stresses are present on the plane of maximum shear or on the octahedral planes. Under arbitrary multiaxial stresses the instantaneous normal stress on the maximum shear plane or on the octahedral planes take a value which can be calculated after the equations as indicated at the top of Figure 2. The actual $d^+$ is determined on the basis of a linear interpolation between the condition with pure torsion and with pure tension-compression as indicated in the middle of Figure 2. As Figure 2 also shows for all normal stresses below zero $d^+$ is set equal to the $d^-$-value as caused by pure torsion. Although this assumption appears, at first glance, to some extent arbitrarily chosen, it turned out that quite satisfactory damage predictions were achieved by this approach. More details of the procedure have been described in [2,3].
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Figure 2: Evaluation of the specific damage \( d^* \) within one-element of a hysteresis loop (which is taken here as a simple example for one range of a multi-yield-surface material model).

At EVICD no special adjustment possibilities to real (experimental) results are foreseen. That is very important from the viewpoint of the practical application of EVICD.

2.2 Practical application of EVICD

For common engineering use EVICD has been subdivided into two sections (see Fig. 3). The first section, the input section, offers a link to different sources of (multiaxial) loading data in the engineering design stage. After the input section has been passed through the complete elastic-plastic stress-strain history at that location of the component which is presently considered has been determined. The stress-strain history is then transferred to the second section of EVICD, the fatigue damage evaluation section.

The input section comprises four main data input channels. One channel considers the situation where the complete multiaxial loading history as a function of time is available (e.g. from a preceding multi-body simulation). A fully elastic-plastic FEA of the stresses and strains as a function of the input data is then performed. However, because such FEA are rather time consuming and
Figure 3: Schematic overview of the new EVICD concept.

expensive it is normally preferred to perform a multiaxial Neuber type stress-strain analysis. For this type of analysis only a simple elastic FEA of the component is required. The Neuber type multiaxial stress-strain analysis itself has been described in detail in [5]. It is meanwhile available as part of a professional software system. Multiaxial Neuber type stress-strain analyses run fast and are numerically stable.
Another situation in engineering practice is that some elastic rosette gauge measurements are already available from prototype measurements. These data can be used to perform fatigue predictions for arbitrary loading histories that are assumed in the design stage using the multiaxial Neuber type method. Alternatively the complete elastic-plastic strain history at the fatigue critical location may be available from measurements. The recorded data can then serve as an input to the material model implemented in EVICD to obtain the conjugate stress-strain components.

3 Evaluation of EVICD

EVICD has already been applied to predict the fatigue life of cruciform specimens which were subjected to a variety of proportional and non-proportional (biaxial) loading histories. The materials investigated were the high-strength mean stress sensitive aluminium alloy Al-7475 and a common tube steel (C 0.12, Mn 1.6, Cr 0.05, V 0.05, Si 0.43 [weight-%]). Comparisons of the EVICD predictions and of the experimental results were published previously in [6,7] and turned out to be quite satisfactory.

3.1 New experimental data

For a further validation of EVICD further systematic experiments were performed. Figure 4 shows the tension-torsion load paths which were applied to unnotched tubular tube steel specimens. As already mentioned, in unnotched specimens extensive cycle dependent changes in the material behaviour can occur. For example, for the loading types according to Figures 4a) and 4b) the development of significantly different mean strain levels is predicted. At loadings corresponding to Figure 4c) the multi-yield-surface Mróz-Garud type material model predicts a strong ratchetting. At loadings corresponding to Figure 4d) a considerable elastic shake down of the strains is predicted.

3.2 Experimental data from the literature

In the past several experimental investigations with multiaxial loading histories have already been performed. In [8] a larger number of experimental data with normalized SAE 1045 steel specimens has been presented. The loading ranged from bending-torsion, to in-phase tension-torsion and to 90° out-of-phase tension torsion histories.

The cyclic material data required for an application of EVICD were also presented. That means that comparisons of the prediction after EVICD and of the tests results could be performed and, furthermore (because the authors also applied other multiaxial fatigue prediction methods), the EVICD predictions could be compared with the predictions after the other methods.
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Figure 4: Tension-torsion load paths as applied to tube steel tubular specimens in the present investigation.

Figure 5: EVICD predictions and experimental results for the loading histories as shown in Fig. 4 (tubular unnotched tube steel specimens).

3.3 Comparison of the EVICD predictions with the new experimental results

In Figure 5 the EVICD predictions for the new tests with the loading histories as shown in Figure 4 are compared with the experimental results. It can be seen that the predictions and the test data did not deviate more than by a factor of 2.5. This can be seen as satisfactory from an engineering viewpoint.

However, despite of the fact that the EVICD predictions were satisfactory some critical remarks have to be made. As mentioned before, the multi-yield-surface Mróz-Garud type material model predicted a strong ratchetting for the loading type according to Figure 4c). However, in the tests the ratchetting was much smaller. This indicates that for a better consideration of ratchetting effects (at unnotched specimens) another type of material model should probably be used. EVICD also is open to other types of material models like the Jiang model which explicitly accounts for ratchetting effects. Another possibility to consider extensive ratchetting effects has been proposed in [9] where a single yield surface model was used.
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Under the loading conditions according to Figures 4a) and 4b), where EVICD in connection with the multi-yield surface material model after Mróz-Garud had predicted the development of significantly different mean strains, the tests showed that the difference was actually considerably smaller.

For the loading type corresponding to Figure 4d) where EVICD predicted a strong elastic shake-down effect, a same behaviour was also observed in the tests.

3.4 Comparison of the EVICD predictions to the test results reported in the literature

In Figure 6 the comparisons of the EVICD predictions and the data from the experimental investigations as reported in the literature are shown. It can be seen that for the bending-torsion loading histories on notched specimens, for the in-phase tension-torsion loading histories under strain control on unnotched tubular specimens and for the 90° out-of-phase tension-torsion loading histories on unnotched tubular specimens under strain control, the differences between the EVICD predictions and the test results were again typically not larger than by a factor of 3. This means that here the EVICD predictions also turned out to be satisfactory. In Figure 7 the predictions after EVICD and after other prediction methods are shown. It can be seen that the EVICD predictions were also satisfactory in comparison to the predictions after other prediction methods.

Figure 6: EVICD predictions compared to experimental results from the literature [8] for SAE 1045 steel for various loading histories.
Figure 7: Comparison of the predictions after EVICD and after other prediction methods for the SAE 1045 steel experiments as shown in Fig. 6.

The investigation results presented in the present paper can, in summary, be seen as a further proof for that EVICD may be considered as some substantial help if a fatigue design of complicated multiaxially loaded components has to be performed. Meanwhile activities have been started to also offer EVICD on a convenient professional software platform.

References


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