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LOADING CYCLE ANALYSIS REGARDING MULTIAXIAL FATIGUE LIFE ASSESSMENT

ANALIZA CIKLUSA OPTEREĆENJA SA PROCENOM VEKA PRI VIŠEOSNOM ZAMORU

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Keywords
- multiaxial fatigue
- fatigue
- accumulated damage
- variable amplitude loading
- virtual cycle counting
- loading blocks

Ključne reči
- višeosni zamor
- zamor
- akumulacija oštećenja
- promenljivo amplitudno opterećenje
- virtualni broj ciklusa
- blok opterećenja

Abstract

The paper presents and discusses new concepts about multiaxial cycle counting under multiaxial variable amplitude loading using the SSF equivalent shear stress. The few multiaxial cycle counting methods presented in literature are based in the rainflow methodology. However, this work presents a non-rainflow methodology (virtual cycle counting) to characterize multiaxial loading cycles under variable amplitude conditions.

Izvod

U radu je predstavljena i data je diskusija novih koncepata višeosnog brojanja ciklusa pri višeosnom amplitudnom opterećenju primenom SSF ekvivalentnog napona smicanja. Mali broj metoda višeosnog brojanja ciklusa u literaturi se baziraju na „Rainflow" metodologiji. Međutim, u ovom radu je prikazana metodologija koja nije Rainflow (virtuelno brojanje ciklusa) za karakterizaciju ciklusa višeosnog opterećenja u uslovima promenljive amplitude.

INTRODUCTION

Multiaxial fatigue loading conditions are a key issue in several mechanical components. Studying the life of components subject to cyclic stresses is of utmost importance to avoid the unexpected failure of equipment, vehicles or structures. Among other parameters, a correct definition of a load cycle in multiaxial fatigue conditions appears to be crucial concerning the fatigue life issue, /1/.

Another critical aspect in multiaxial fatigue damage analysis is to identify the damage inherent to each loading cycle. That damage can be quite different, for the same stress level, by varying the loading paths type, /2/.

Under uniaxial loading conditions, that analysis is quite easy and intuitive because loading cycles can be identified by their load period.

The loading cycle's identification and frequency may change within a uniaxial loading spectrum, but the load cycle remains easy to perform in such loading conditions. Further, the loading path for each cycle aforementioned has only two damage regimes applied in the same direction (uniaxial direction), one at tension and the other at compression. It is well known that the tension loading regime is more damaging than compression.

Moreover, these two damaging regimes are different because the loading type (e.g. tension or compression in the uniaxial loading case) results in two different mechanical mechanisms in the material microstructure leading to different damages.

However, the damage inherent to each loading cycle is a summation of tension and compression damages, despite having different damage mechanisms; the uniaxial cycle total damage is composed by both damages. Therefore, the damage within a loading path may have different damage contributions from each part of the loading path. Though, under multiaxial loading conditions the material's damage response is activated in several directions increasing the damage interpretation complexity, /3/.

Macroscopically metals can be considered as isotropic in terms of monotonic mechanical properties, but in terms of cyclic properties that is not true. Materials tend to change cyclically their stress/strain response and that change is related with the load type and their inherent direction.

One example of that is the material hardening behaviour. In this case the material became harder due to cyclic loads i.e. it is necessary to apply higher stress levels to have the same strain amplitude verified at the beginning of the cyclic loads. This hardening behaviour is a material response to the loading type which in turn is strongly connected with the loading direction /3, 4/.

Therefore the material hardening has a direction equal to the loading one. For instance, a material that was cyclic hardened in axial direction and other that was not will have approximately the same stress/strain response in torsion.

Therefore, materials tend to adapt their response to the loads effect in the direction of those same loads. Similarly, as a consequence of the load type and load direction, the material fatigue damage is an anisotropic mechanical property, /4/. Material's fatigue damage is accumulated in the material in a non-uniform way, i.e. there are some material regions more damaged than others. These regions are strongly related with the loading type and loading direction and are independent of the stress level. The stress level is essentially related with the damage intensity and not with the damage distribution within the region of the damaged material.

This principle, that fatigue damage has direction, is the base stone of critical plane models /1, 5, 6/. In these models, a critical plane where the fatigue crack will start is pursuit in all material directions and that search is based in the loading path time evolution within the loading period.

The plane which has the maximum value of damage parameter is the one from each it is expected that the crack initiation starts to appear. From here, two damage variables can be gathered: the highest damage parameter and the inherent direction. Intuitively, critical plane models indicate that the fatigue damage has a direction.

One important damage evaluation tool is the damage parameter concept which can be found in multiaxial fatigue literature and is mainly represented in three types: equivalent stresses, equivalent strains or equivalent energetic parameters that are a combination of stresses and strains / 7/.

In multiaxial loading conditions, the multiaxial stress, strain or energetic state must be transformed into a uniaxial one (equivalent damage parameter) to be interpreted in terms of fatigue damage. That damage parameter (an equivalent stress for instance) must capture the fatigue damage inherent to the loading path having into account the material capability to resist to that loading. This is an important issue because the material's ability to resist a loading is not equal in all directions.

Usually, for multiaxial loading paths the equivalent stress approaches establish a stress value representative of that loading path damage. In order to do that it is considered the maximum stress value within a loading cycle, loading block or loading spectrum. In such way, the lower loading path branches' damage contribution to the total damage is not considered. For some simple cases this procedure works well, usually for reference ones, but for more complicated loading histories the results are not so good. Despite these results, loading blocks can be analysed in terms of damage, using equivalent stresses.

Loading blocks can be decomposed into simple loading cases were the fatigue life estimation can be handled as a cumulative damage issue.

This interpretation is not new, the Miner´s rule on uniaxial cases establishes material fatigue damage by identifying several stress levels and associating them with the inherent number of cycles on the loading block, /8/. However, Miner's rule principle considers that the stress level and loading path effect on material must be captured by the damage parameter. The critical aspect on loading block cumulative damage is centred on the equivalent stress or damage parameter used, and in the cycle counting method which in turn is related with the cycle definition. Over the years, cycle counting methods have not been so much a studied issue, especially in multiaxial fatigue. The most known multiaxial cycle counting methods have several years being the most used rainflow based methods /1, 9-12/.

These methods have acceptable results in uniaxial loading cases, but in multiaxial loading conditions they are not able to capture the damage associated to complex multiaxial loads. Even so, new approaches on cycle counting are very few, /1/. Despite that fatigue damage is strongly related with loading type and complexity it is also related with the stress level. To corroborate this, SN curves are usually made with the same loading path at different stress levels and for each level different fatigue lives are achieved. The stress level increase is experimentally related with a decrease on the amount of cycles at failure time, the cycle definition is the same but the damage inherent to each cycle is different, thus cycle damage is not only defined on the cycle definition but also on stress level, /5/. This has led to conclude that there is a fundamental importance in the equivalent stress definition to establish a representative damage cycle counting. Usually, in testing machinery the cycle counting is determined by block summation, the machine input establishes the loading trajectory which is repeated until the specimen test is totally separated. This cycle counting method considers the load block as one cycle but the cycle damage unit for the same stress level is different.

Thus if the stress level is the same and the fatigue life is quite different then the cycle definition must be analysed.

The aim of this work is to achieve a correct definition for a cycle in multiaxial loading conditions. A low alloy steel 42CrMo4 heat treated, quenched and tempered (500ºC) is used in this study. In order to establish a relation between the block damage and a loading cycle definition, three different loading blocks are studied in this paper.

Two equivalent stress approaches (von Mises and SSF equivalent stresses) are used as damage parameters and two cycle counting methods: the ASTM version of rainflow cycle counting method and the SSF virtual cycle counting (SSF vcc).

Based on achieved results a definition for a fatigue cycle in multiaxial fatigue loading conditions is proposed and some remarks are drawn.

MATERIALS AND METHODS

The 42CrMo4 quenched and tempered high strength steel is the material used in this work. Specimens used in the test series are machined from rods 25 mm in diameter, its dimensions are presented in Fig. 1.

Specimens are inspected and manually polished through sandpapers of decreasing grain size, from P200 to P1200. Fatigue tests are carried out through a multiaxial servo-hydraulic machine in order to study different sequential effects; the specimens are tested using 3 types of loading paths under axial and torsion combined loads shown in Fig. 2.

The loading sequence for each loading case is represented through the numbering sequence shown in the von Mises stress space, see Fig. 2.

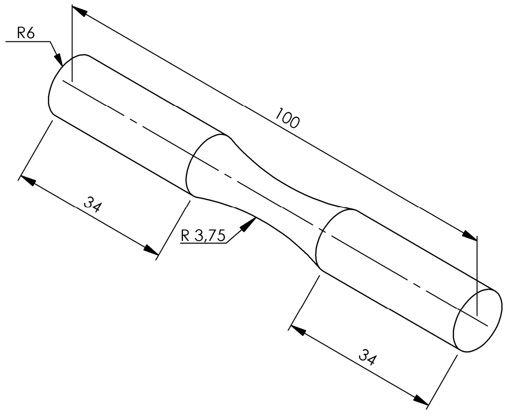

Figure 1. Specimen test geometry and dimensions (mm).
Slika 1. Geometrija epruvete sa dimenzijama (mm)

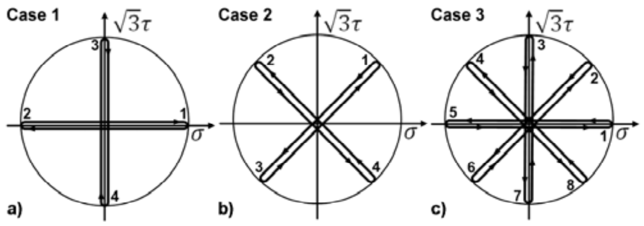

Figure 2. Selected multiaxial loading paths.
Slika 2. Izbor putanja višeosnog opterećenja

THEORETICAL ANALYSIS

In order to study the fatigue damage inherent to each loading case, selected are two multiaxial fatigue approaches i.e. the von Mises and the SSF equivalent stress developed by authors, /4/.

The von Mises equivalent stress approach

The von Mises criterion was firstly used as multiaxial fatigue damage parameter in the vessel code, /4/, where the criterion' strain version is used. Nevertheless, the von Mises' stress version, as presented in Eq.(1), has been widely used in multiaxial fatigue life evaluation for a high number of cycles. The von Mises criterion can be used, with acceptable results, under proportional loading conditions, but for non-proportional ones the results are not satisfactory. During a block loading period, the von Mises equivalent stress varies instantaneously in time. Thus, the damage parameter is determined by selecting the maximum value achieved within the loading block period. This damage parameter (equivalent stress) can be used to estimate fatigue life as follows, Eq.(1):

$$\max_{block}\left(\sqrt{\sigma^2+3\tau^2}\right)=A\left(N_f\right)^b \quad (1)$$

where A and b are power law regression variables obtained from pure tensile fatigue life results for the considered material. The σ and τ variables are maximum values of the axial and shear stress amplitudes of the loading path.

SSF equivalent stress approach

The SSF equivalent stress approach is proposed by the present authors, /4/, being a multiaxial fatigue damage parameter it is also an equivalent shear stress. The criterion considers that the stress ratio amplitude and stress loading level have a huge influence on the material fatigue strength response. These two aforementioned effects are accounted in this criterion through the SSF damage map, which transforms an axial damage into a shear one.

Basically, the SSF equivalent stress is obtained by adding two shear stresses. Considering the two stress components of a biaxial loading, axial and shear components, the SSF equivalent stress is obtained by adding the shear stress with the axial one, which must be previously transformed into an equivalent shear stress using the ssf map aforementioned. This transformation allows adding axial and shear stresses in order to account the combined damage of a multiaxial loading path.

Likewise as the von Mises case, the SSF equivalent stress is computed instantaneously within the loading path time evolution. With this equivalent stress it is also possible to estimate fatigue lives as follows, Eq.(2):

$$\max_{block}(\tau+ssf\cdot\sigma)=B\left(N_f\right)^c \quad (2)$$

where B and c are power low regression variables obtained from pure shear fatigue life results (SN curve) for the considered material. The *ssf* is a polynomial function that represents the material damage map and can be calculated using Eq.(3).

$$ssf(\sigma_a,\lambda)=a+b\sigma_a+c\sigma_a{}^2+d\sigma_a{}^3+ \\ +f\lambda^2+g\lambda^3+h\lambda^4+i\lambda^5 \quad (3)$$

where, σ_a is the axial component of the biaxial loading and λ is the stress amplitude ratio. The constants from 'a' to 'i' are determined through experimental tests. The σ_a variable aims to capture the stress level effect on the material's damage and the stress amplitude ratio, λ aims to capture the contribution of the loading path type to the overall damage.

Rainflow cycle counting method

The Rainflow method presented in ASTM E-1049 /13/ is selected to quantify the number cycles associated with the loading block inherent to each loading case. Despite this, the cycle counting method has been developed based on the stress/strain time variation in uniaxial loading conditions, here it is tested considering equivalent stress time evolution along each loading block, i.e. the number of cycles is established by Rainflow procedures applied to the equivalent stress time evolution.

SSF virtual cycle counting method

The SSF virtual cycle counting (VCC) is a multiaxial cycle counting method proposed by the authors, /14/, and is developed based on the SSF equivalent stress time evolution. This cycle counting method is a non-rainflow method that relates a reference damage yield by the maximum SSF value with the overall block damage. Virtual cycle counting is determined as follows, Eq.(4):

$$VCC=\frac{\sum abs(\tau)_{\text{peak,valley}}}{2\tau_{\max,block}} \quad (4)$$

where $\tau_{\text{peak,valley}}$ are the maximum or minimum SSF values between two consecutive zero stress points in the SSF time evolution and $\tau_{\text{max,block}}$ is the maximum SSF value within the block's SSF time evolution.

Experimental cycle counting

To quantify the damage associated with each loading block here are considered experimental and estimated fatigue lives, where the experimental results are compared with the multiaxial criteria estimations. As shown on previous subsections, the criterion to establish the damage parameter is usually the maximum value encountered along a loading block. However, that approach does not consider how many times that maximum value occurs and does not take into account the loading path trajectory. Therefore, it is expected that the fatigue life estimated using the maximum damage parameter within a loading path, to be greater than the experimental one in complex loading paths. In other words, the loading block causes more damage than the estimated by the maximum damage parameter within that same loading block. Thus, it remains to find out how many times lesser is the block fatigue life compared to the estimated by maximum equivalent stress verified on that same loading block.

In order to quantify this damage differential, the estimated fatigue life (determined using maximum equivalent stress within a loading block) is compared with the experimental one as follows, Eq.(5):

$$ecc = \frac{N_{f_{\text{estimated}}}}{N_{f_{\text{experimental}}}} \quad (5)$$

Equation (5) represents a kind of experimental cycle counting (*eec*) methodology where the damage reference (given by the maximum damage parameter within a loading block) is compared with the loading block damage yield from experiments.

Block's fatigue life estimation

In order to estimate the number of cycles within a loading block without falling back on experimental tests, the Rainflow cycle counting and the Virtual cycle counting accuracy when applied to multiaxial loading blocks using the equivalent stress time evolution, are investigated here. With the aforementioned cycle counting methods it is estimated how many times the estimated fatigue life must be reduced due to the block damage, see Eqs.(6) and (7). Using Eqs.(6) and (7) it is possible to estimate the block's fatigue life entering, in the fatigue damage estimation, with the loading history. Thus, with the stress level in this way it is possible to enter the loading path type and number of maximum equivalent stress occurrences during a block loading in order to account the overall damage. In Eq.(6), RF_{cycles} indicates the number of cycles encountered on the loading block determined using the Rainflow method. In Eq.(7), VCC_{cycles} indicates the number of cycles within a loading block determined using the virtual cycle counting method. $N_{f\,\text{estimated}}$ indicates the number of cycles determined with block equivalent stress and $N_{f\,\text{block}}$ is the block's estimated fatigue life.

$$N_{f_{\text{block}}} = \frac{N_{f_{\text{estimated}}}}{RF_{\text{cycles}}} \quad (6)$$

$$N_{f_{\text{block}}} = \frac{N_{f_{\text{estimated}}}}{VCC_{\text{cycles}}} \quad (7)$$

RESULTS AND DISCUSSION

Cycle counting results

In Figs. 3, 4 and 5 the equivalent stress time evolution along each loading case for the von Mises and SSF approaches is shown. The von Mises equivalent stress time evolution is always positive, in contrast with the SSF approach which has positive and negative values. The SSF equivalent stress criterion considers that the shear stress damage does not have a sign because the damage mechanisms are equal in both torsion directions. Thus, in the SSF equivalent stress criterion the shear stress assumes the sign of the axial stress. Contrary to the observed in the shear stress case, the axial damage does have direction because the tension damage is quite different from compression. However, the von Mises equivalent stress is always positive because the criterion is based on the norm principle.

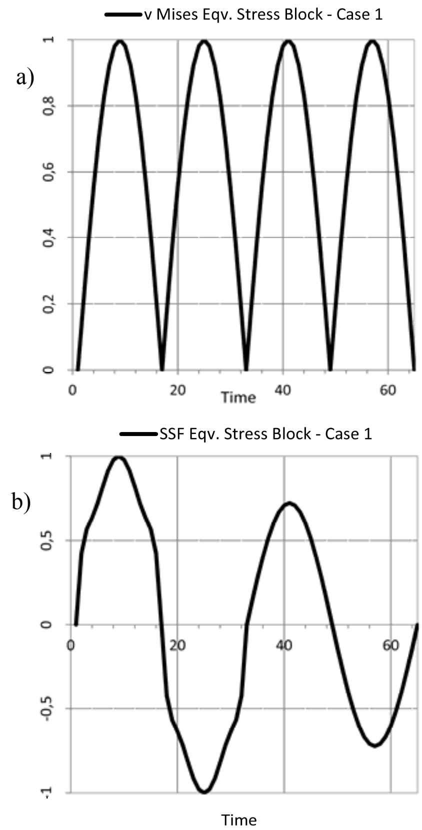

Figure 3. Equivalent stress evolution along loading block for case 1: a) von Mises equivalent stress; b) *ssf* equivalent stress.
Slika 3. Razvoj ekvivalentnog napona duž bloka opterećenja za 1. slučaj: a) fon Mizes ekvivalentni napon; b) *ssf* ekvivalentni napon

Table 1 presents the results for the experimental cycle counting considering fatigue life estimations and experimental tests, as presented in Eq.(6). In Table 1, a value greater than one indicates a greater damage than the one captured by maximum equivalent stress within a loading block. If it equals one, the block damage is equal to the one captured by the maximum equivalent stress. Finally, in cases where the value is less than one, this indicates that the block damage is inferior to the one captured by the maximum damage parameter.

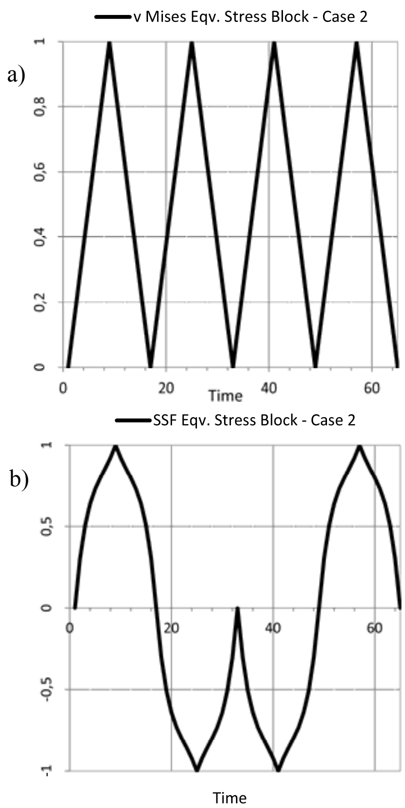

Figure 4. Equivalent stress evolution along loading block for case 2: a) von Mises equivalent stress; b) *ssf* equivalent stress.
Slika 4. Razvoj ekvivalentnog napona duž bloka opterećenja za 2. slučaj: a) fon Mizes ekvivalentnog napona; b) *ssf* ekvivalentni napon

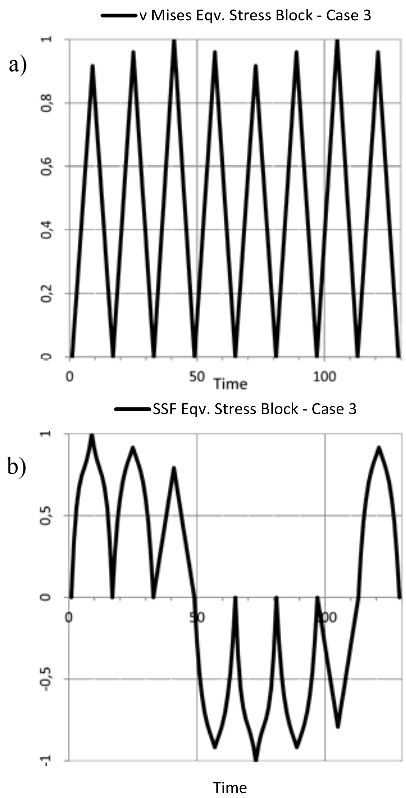

Figure 5. Equivalent stress evolution along loading block for case 3: a) von Mises equivalent stress; b) *ssf* equivalent stress.
Slika 5. Razvoj ekvivalentnog napona duž bloka opterećenja za 3. slučaj: a) fon Mizesovog napona; b) *ssf* ekvivalentnog napona

The second column of Table 1 presents the experimental damage captured using SSF equivalent stress. Here, all loading cases have an experimental cycle counting greater than one. These results indicate that the loading blocks cause more damage than the reference loading paths for the same stress level. However, the results for the von Mises equivalent in case 2 fail to capture the block damage because the experimental cycle counting is inferior to one. Thus, in case 2, the experimental von Mises equivalent stress indicates that the block damage is inferior to the one captured by the maximum von Mises equivalent stress within the loading block.

Table 1. Experimental cycle counting with von Mises and SSF equivalent stresses in cycles.
Tabela 1. Brojanje eksperimentalnih ciklusa sa fon Mizes i SSF ekvivalentnim naponima u ciklusima

	Exp. with v. Mises	Exp. with SSF
Case 1	1.19	1.8
Case 2	0.12	2.7
Case 3	1.9	3.2

Table 2 presents the cycle counting estimations for each loading path using the rainflow and SSF *vcc* criteria. The first two columns show the cycle counting results using the rainflow methodology applied to the time variation of the von Mises and SSF stresses.

Correlating the first columns of Table 1 and Table 2 can be concluded that the estimated cycle counting is far from the experimental ones. Thus, it can be concluded that using the rainflow method applied to the von Mises time evolution do not capture the unitary damage associated to a load cycle in the three loading cases considered here.

Nevertheless, the rainflow applied to the SSF time evolution yield acceptable results in loading cases 1 and 2 but in loading case 3 the result is not so acceptable, please see second columns of Tables 1 and 2.

In loading case 3 the rainflow method yields 7 cycles to the loading path 3, but using the reference SSF damage parameter, only 3.2 cycles are experimentally achieved. Thus, the rainflow method applied to SSF equivalent stress time evolution fails to capture the unitary cycle damage, in all loading cycle considered here. Despite the yield of good estimations in cases 1 and 2, it fails in case 3. Regarding the SSF *vcc*, the method yields very good results, where the unitary damage to each loading cycle is well captured by the SSF *vcc* as can be seen at columns 2 and 3 from Tables 1 and 2 respectively.

Table 2. Cycle counting estimations using the Rainflow and SSF *vcc* criteria in cycles.
Tabela 2. Procene brojanja ciklusa primenom *Rainflow* i SSF *vcc* kriterijuma u ciklusima

	RF with v. Mises	RF with SSF	SSF vcc
Case 1	4	2.5	1.7
Case 2	4	3	2
Case 3	8	7	3.4

Fatigue life correlation

Figures 6a and 7a present fatigue life correlation regarding the von Mises and SSF equivalents stresses without any correction resulting from rainflow cycle counting method. Instead, those figures represent the fatigue life correlation using the equivalent damage parameter obtained within each loading block, which are used to obtain the fatigue life estimation to each loading block.

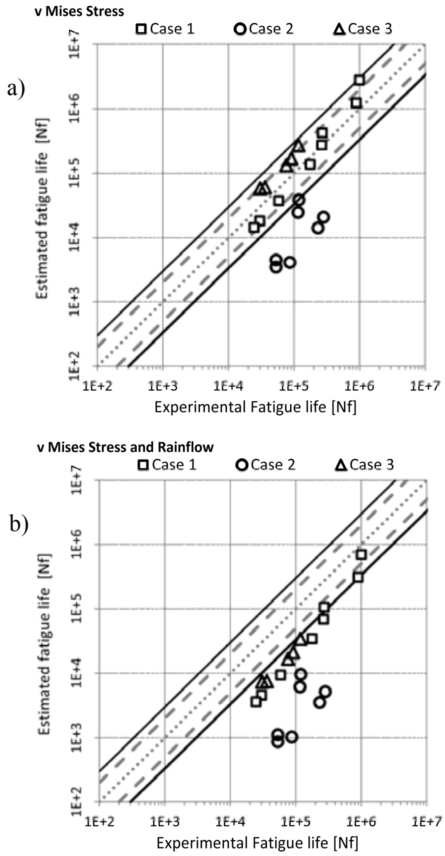

Figure 6. Fatigue life correlation for case 1: a) v. Mises approach; b) v. Mises approach affected with the rainflow cycle counting results.

Slika 6. Korelacija zamornog veka za 1. slučaj: a) pristup fon Mizesa; b) pristup fon Mizesa sa *Rainflow* brojanjem ciklusa

Further, Figs. 6b and 7b present the fatigue life correlation using the rainflow method applied to each criteria time evolution. The fatigue life correlation in von Mises approach in association with rainflow criterion is not improved comparatively to the results that yield uniquely by the von Mises equivalent stress.

Also, the SSF in association with rainflow methodology yields satisfactory results but with a scatter not centred within the life boundary. The loading block fatigue life correlation using the *ssf* approach and rainflow methodology have satisfactory results with few results outside boundaries.

Figure 8 presents the fatigue life correlation for the SSF criterion in association with the SSF vcc methodology. In accordance with the results presented in Table 2, the results indicate that the SSF vcc concept captures the unitary damage under the SSF equivalent stress paradigm. As a result the fatigue life correlation is centred between fatigue life boundaries, as can be seen in Figure 8.

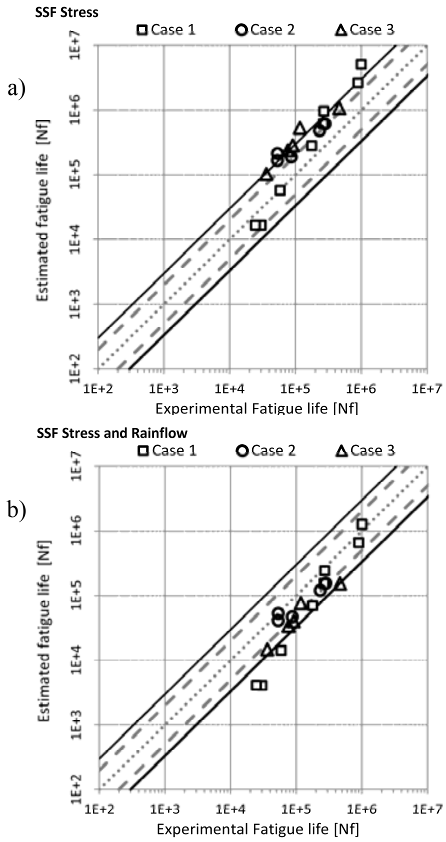

Figure 7. Fatigue life correlation for case 1: a) SSF approach; b) SSF approach affected with the rainflow cycle counting results.

Slika 7. Korelacija zamornog veka za 1. slučaj: a) pristup SSF; b) pristup SSF sa *Rainflow* brojanjem ciklusa

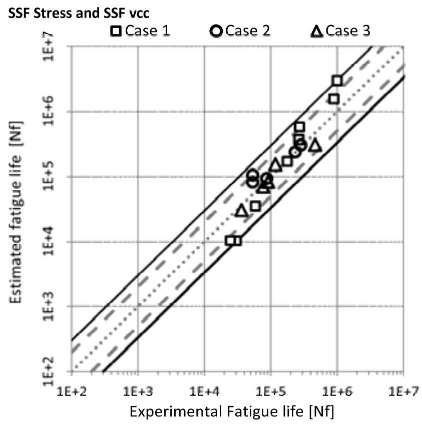

Figure 8. Fatigue life correlations using the SSF criterion and SSF *vcc* methodology.

Slika 8. Korelacije zamornog veka primenom kriterijuma SSF i metodologije SSF *vcc*

CONCLUSIONS

The paper presents a new approach on loading block damage interpretation based on high strength steel 42CrMo4 fatigue life results. Two equivalent stress approaches, the von Mises and the SSF equivalent stress are used, in association with the rainflow ASTM E-1049 cycle counting method. Moreover, the SSF vcc method is applied to the SSF equivalent stress time evolution to analyse block damages. Unlike the von Mises approach, the SSF equivalent stress in association with SSF vcc methodology has reached consistent results in block damage analysis with good fatigue life correlations.

Thus, SSF equivalent stress criterion in association with the SSF vcc methodology is a tool that is available and is advised to be used in fatigue life estimation regarding multiaxial loading blocks.

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ECF 22 ANNOUNCEMENT

The Society for Structural Integrity and Life (DIVK) from Serbia will organise the 22nd European Conference of Fracture (ECF22) in Belgrade, Serbia. The venue of the conference is the University of Belgrade, Faculty of Mechanical Engineering and Faculty of Technology and Metallurgy. An experienced DIVK Organizing Committee, consisting of highly experienced DIVK staff, will be responsible for ensuring a smooth process and provide logistical support throughout the conference.

Topic: Loading and Environmental Effects on Structural Integrity

The topics to be considered at the ECF 22 should be focused on experienced, possible and predictable fracture and failures, considering interrelation between external effects (loading, environment), structure characteristics, components strength and material properties.

Safety and reliability problems during operation life, including maintenance and repair, represent also items, very important for structural integrity. Specifically, applied stress-strain state in critical structural components, induced by acting loading at global level, and affected by stress concentration at the local level should be considered theoretically and applying convenient numerical modelling.

In addition to structures of macro to micro scales of commonly used metallic and non-metallic materials, attention will be paid to the new huge complex structures of civil engineering objects, well exceeding classical objects of macro size on one side, and structures of nano level on the other side. Structural integrity, functionality, reliability and safety of such structures and applied materials require special consideration.

Loading types
- static and quasi-static loading
- cyclic loading of variable amplitudes (high cycle-loading well below yield stress; low cycle loading after initial yielding)
- vibrations
- impact and earthquake loading
- combined loading

Environment
- corrosion
- stress corrosion
- high operating temperatures
- temperatures in the range of nil ductility transition (NDT) and below it
- combined environmental effects

Structures
- thermo electrical power
- hydro electrical power plants
- nuclear power plants
- process equipment and plants in petrochemical industry
- welded structures
- civil engineering objects
- transportation means

Materials
- steel
- metallic materials
- plastics
- nonmetallic materials
- composite materials
- nano materials
- bio materials

Proceedings and Publications

Two-page abstracts will be published in the form of ECF22 Proceedings Book. CD-ROM will be available during registration. Also on the ESIS website. Selected papers shall be published as special issues of 'Engineering Fracture Mechanics', 'Engineering Failure Analysis' or 'International Journal of Fatigue'.