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A LOW CYCLE FATIGUE DAMAGE ACCUMULATION APPROACH BASED ON ENERGY CRITERION AND ITS VERIFICATION FOR POLYVINYL CHLORIDE POLYMER

PRISTUP AKUMULACIJE OŠTEĆENJA NISKOCIKLIČNOG ZAMORA NA BAZI ENERGETSKOG KRITERIJUMA I NJEGOVA VERIFIKACIJA ZA POLIMER POLIVINIL HLORID

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Keywords
- low cycle fatigue
- damage accumulation
- energy criterion
- blocks loading
- polyvinyl chloride

Abstract

A new approach of low-cycle fatigue damage accumulation based on an applied energy criterion of the fatigue process is proposed. However, taken for granted is that the proportion of two or further successive stress levels are used to explain the phenomenon on damage expansion. This approach is introduced into a nonlinear fatigue model whose purpose is to predict the fatigue life under variable loading. Experimental data from polymer material as polyvinyl chloride are utilized to verify the effectuality of the proposed approach. It is found that the proposed approach shows a good estimation and its damage curve presents a characteristic nonlinear behaviour of damage growth.

Ključne reči
- niskociklični zamor
- akumulacija oštećenja
- energetski kriterijum
- blokovi opterećenja
- polivinil hlorid

Izvod

U radu je prikazan novi pristup akumulacije oštećenja niskocikličnog zamora na bazi primene energetskog kriterijuma procesa zamora. Međutim, pretpostavlja se da se veličine dva ili više uzastopnih nivoa napona mogu upotrebiti za objašnjenje fenomena rasta oštećenja. Ovaj pristup se uvodi u nelinearni model zamora sa ciljem predviđanja zamornog veka pri promenljivom opterećenju. Eksperimentalni podaci za polimerni materijal, kao što je polivinil hlorid, se koriste za verifikaciju ispravnosti predloženog pristupa. Pored toga, pokazuje se da predloženi pristup daje dobru procenu i njegova kriva oštećenja predstavlja karakteristično nelinearno ponašanje pri rastu oštećenja.

INTRODUCTION

Fatigue damage in materials or structures grows progressively in an accumulated manner which may cause unwanted accidents and economic casualties. Therefore, the fatigue life prediction is vital to structural design, safe use, and reliability assessment. Owing to the complex nature and significance of fatigue damage, estimating the damage evolution behaviour is still a critical and complex topic /1-2/. It is crucial to present fatigue damage mechanisms significantly and contribute to more precise life prediction.

A better comprehension of the micro material scale is fundamental to provide that certain types of failure mechanisms do not appear, like: low-cycle fatigue (LCF) crack initiation, ratchetting, cyclically enhanced creep. This includes the determination of plastic strain range for LCF assessment, /3/. It has become known that the LCF of material relevant to the plastic deformation has been a hot topic of research. Most of the research has covered the LCF behaviour, /4-5/, and others assess the microstructure evolution, /6-9/. Furthermore, there are researchers who turn their attention towards the damage mechanism and life prediction in the oligocyclic domain (LCF), /10-14/. Other researchers are interested in digital simulations of the fatigue phenomenon, /15/. The pattern of some surface cracks in polymer material after several years of use may be due to low cycle fatigue loads, /16/. This is what makes studying this kind of loads so important. Among scientific works that deal with LCF in polymer materials, the work of Yang et al. /17-18/ can be mentioned. Furthermore, visco-hyperelastic-damage models for high-cycle and low-cycle fatigue behaviour of styrene-butadiene rubber, are respectively proposed by Ayoub et al., /19-20/.

Methods for life calculation are based either on historical stress tensor and/or deformation, or on energy concepts. Generally, the approaches developed in deformation are used in LCF, while stress-based (S-N) criterion, and energy based criterion are usually used in HCF. Suggestions of such an approach (energy based criterion) can be found in the papers of Ellyin /21/, Gołoś /22/, Gołoś and Ellyin /23/, Łagoda /24/ and Smith et al. /25/. It proves to be correct for the high-cycle fatigue range in the loading program.

DAMAGE MODELLING

A damage parameter for uniaxial fatigue loading is introduced; it has been validated in the case of polycyclic fatigue in our previous research /26-27/. D is established as the ratio of the increment of energy due to stress damage beyond the difference between the energy due to ultimate stress and applied stress. Accordingly, this damage indicator is described by:

$$D=\frac{W_{edi}-W_i}{W_u-W_i}\,. \tag{1}$$

The oligocyclic fatigue domain corresponds to the largest stresses, above the elastic limit. The fracture is usually preceded by a noticeable plastic deformation. Nevertheless, the nonlinear behaviour of materials under cyclic uniaxial loading (hysteresis loop) can be represented by the Ramberg-Osgood /28/, this constitutive model is appropriate for categorizing the monotonic loading stress-strain relations of the semi-crystalline polymers presented by the equations, /29/:

$$\varepsilon_t=\varepsilon_e+\varepsilon_p=\frac{\sigma}{E}+\left(\frac{\sigma}{K}\right)^{1/n'}, \tag{2}$$

$$w_a=\frac{1}{2}\left[\frac{(\sigma_f)}{E}(2N_f)^{2b}+\sigma'_f\varepsilon^e_f(2N_f)^{b+c}\right]. \tag{3}$$

where: n' and K are constants of the material of the cyclic consolidation curve. If we consider Eq.(3), these constants can be calculated by equations, /30-31/:

$$n'=\frac{b}{c}\,, \tag{4}$$

$$K=\frac{\sigma_f}{(\varepsilon'_f)^n}\,. \tag{5}$$

Several methods are presented in literature to calculate the strain energy due to a stress greater than the elastic limit. We can cite the criterion proposed by Molski and Glinka /32-34/:

$$W_t=W_e+W_p=\frac{\sigma^2}{2E}+\frac{2\sigma}{n'+1}\left(\frac{\sigma}{K}\right)^{1/n'}. \tag{6}$$

The yields stress of a material is defined in engineering and materials science as the stress at which a material begins to deform plastically. If the material is loaded cyclically into the plastic range it can display hysteresis loops if the loads are high abundance leading to a plastic flow (stresses above yield stress). In this case, we speak about the plastic strain energy (W_p) termed the modulus of toughness which is the total area under the σ-ε curve up to fracture. Taking into account the plastic strain energy, this term can be added in the proposed approach by using the specimen momentary values of stress σ_i and strain ε_i. The energy W_p for individual loading cycle can be calculated from Eq.(7):

$$W_p=\left[\sum_{i=1}^{n-1}\frac{1}{2}(\sigma_{i+1}-\sigma_i)(\varepsilon_{i+1}-\varepsilon_i)\right]+(\sigma_n+\sigma_1)(\varepsilon_1-\varepsilon_n)\,, \tag{7}$$

where: n is records number of momentary values stress and strain taken during one loading cycle. In this paper, due to the difficulty of applying the Ramberg-Osgood model for this type of material (polyvinyl chloride), the Origin Pro software /35/ is selected to calculate the total strain energy via ‘integration tool’ performing numerical integration on the active data plot using the trapezoidal rule by selecting to calculate the mathematical area (algebraic sum of trapezoids) as represented in Fig. 1.

The study materials in this work are Polyvinyl chloride (PVC), belongs to a family of "industrial" polymers. This material is the world's third-most widely produced synthetic plastic polymer, after polyethylene and polypropylene. These

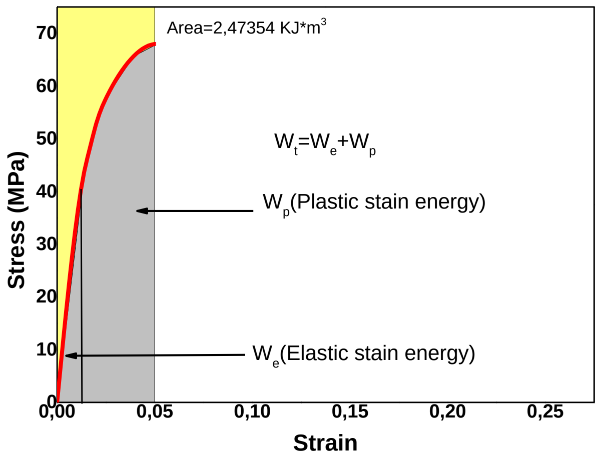

Figure 1. Total strain energy W_t using Origin Pro software.

are crystalline thermoplastic polymers obtained by polymerization of chloride; under optimized conditions of temperature and pressure in the presence of a super active catalyst, the tested specimens are taken from a pipe, 500 mm outer diameter, 12.6 mm thick, along the longitudinal direction using a digital milling machine (Emco Concept MILL 55). Engineers recommend this pipe in sanitary and rainwater canalization, manufactured according to German standards DIN 8061/8062.

Consequently, the scope of this study includes tensile tests and fatigue tests. Monotonic mechanical properties of PVC tubes and fatigue properties are determined using these tests. Specimen geometry corresponds to ASTM D638-14, /36/. Tests are carried out on an Inströn tension testing machine with a strain rate equal to 0.1 and at ambient temperature 23 °C. Moreover, the uniaxial fatigue tests are also conducted by Inströn tension testing machine. Therefore, the values of test parameters considered in fatigue tests e.g. load frequencies are equal to 2 Hz, according to ASTM D7791-10, /37/; a sinusoidal waveform loading is employed with this frequency. Consequently, the stress ratio ($R = 0$) is chosen to avoid the influence of the heating of specimens during loading, taking into account that this effect of the fatigue test frequency on polymers is much more marked than that on metals, /38/.

RESULTS AND DISCUSSION

Static properties

The mechanical properties for PVC based on stress-strain curve (Fig. 2) obtained from tension testing in longitudinal pipe direction, for $\dot{\varepsilon}$ = 0.1 s^{-1} are elasticity modulus E = 2978 MPa, Poisson coefficient ν = 0.4, yield stress σ_e = 43 MPa, and ultimate tensile stress σ_u = 65 MPa. This curve pursues the conduct of a characteristic viscoelastic polymer material, i.e. beginning with a linear rise, proportion limit, plastic point, neck formation, stress creating neck propagation, and finally the fracture point.

Fatigue properties

The relationship between total cyclic strain energy and number of cycles is represented in Fig. 3. It can be seen from this figure that the total strain energy increases with the number of cycles.

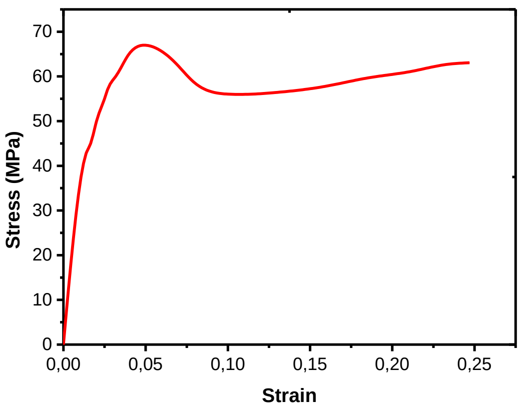

Figure 2. Stress-strain curve of polyvinyl chloride (PVC).

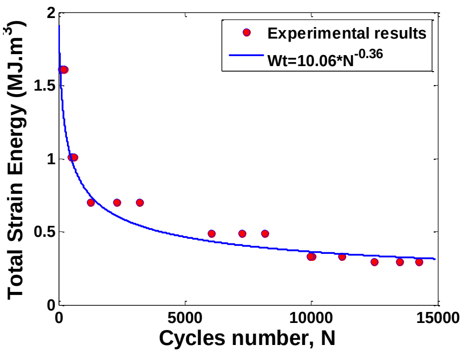

Figure 3. Cyclic strain energy release rate W_t vs. number of cycles.

Low cycle fatigue tests

- Two blocks loading

A series of uniaxial load tests for two blocks programs of low cycle fatigue for PVC are carried out over different stress amplitude. The various loading conditions and experimental results are grouped in Tables 1 and 2.

Table 1. Experimental results, Miner and EDM model predicted life (increasing loading amplitude).

Increasing load (low-high)						
Block test number	σ_1 = 45 MP	σ_2 = 55 MPa, n_2 (residual life)				
	n_1	experimental result	Miner's model		EDM	
			result	REP%	result	REP%
Block N1	500	4159	4199	-0.96	4216	-1.37
Block N2	1000	3925	4030	-2.68	4106	-4.61
Block N3	1500	4126	3860	6.45	3994	11.66

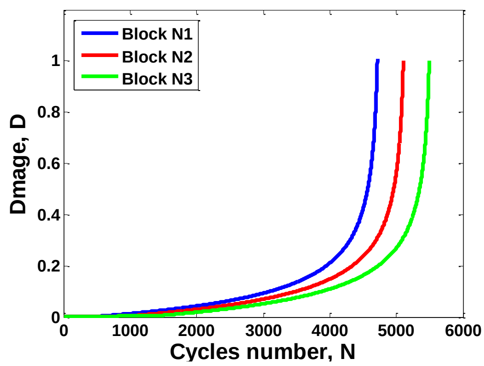

Figure 4. Fatigue damage evolution with number of cycles for increasing blocks loading for EDM model.

Table 2. Experimental results, Miner and EDM model predicted life (decreasing loading amplitude).

Decreasing loading (high-low)						
Block test number	σ_1 = 55 MPa	σ_2 = 45 MPa, n_2 (residual life)				
	n_1	experimental result	Miner's model		EDM	
			result	REP%	result	REP%
Block N1	500	9758	11430	-17.13	10618	-8.81
Block N2	1000	7748	9952	-28.45	8582	-10.76
Block N3	1500	6912	8475	-22.61	6745	2.42

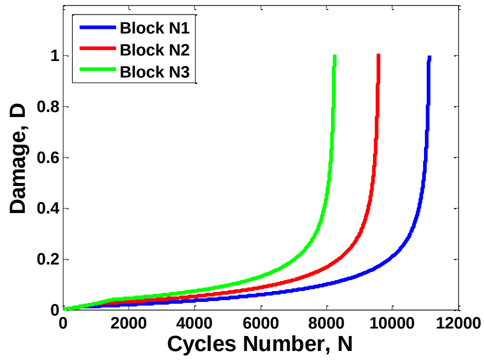

Figure 5. Fatigue damage evolution with number of cycles for decreasing blocks loading for EDM Model.

- Variable blocks loading

Five cyclic stress levels are considered and three different sequences are applied. The proposition of this set of tests is setting the influence of increasing or decreasing and random loading conditions on lifetime, and to estimate the fatigue life under random block loading. The experimental conditions and results for the blocks loading are listed in Table 3 and represented in Fig. 6.

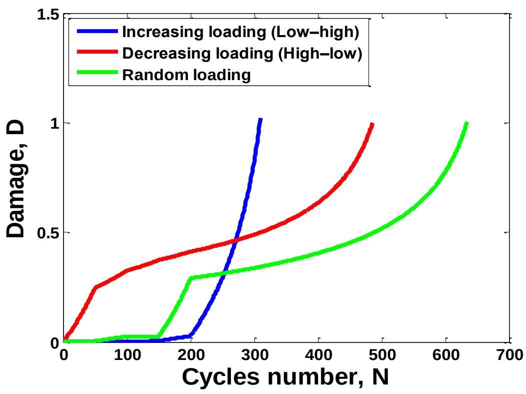

Fig. 6. Fatigue damage evolution with number of cycles for variable blocks loading for EDM Model.

Figures 4, 5 and 6 represent the fatigue damage evolution for three configurations (increasing, decreasing and variable block loading), they show the evolution of damage according to the number of cycles for EDM. We notice that the permutation between loading blocks does not have an influence of the lifetime, especially for the Miner's model. The curves of the cumulative damage determined by the proposed model have a concave form, i.e. the value of the damage is kept low during the totality of the loading, then quick growth until the rupture of the specimens.

Except the case of the increasing loading, where the proposed model gives a slight variation of lifetime from Miner's model (at the end of the lifetime of specimens), the decreasing and random block loading configuration shows that the proposed model presents a weak variation by comparison with Miner's model. In this investigation, the relative error of prediction represents the relative difference between experimental and calculated lives using the EDM model. The REP is defined by Eq.(7):

$$\text{REP}[\%]=\frac{N_{experimental}-N_{calculated}}{N_{experimental}}\,. \quad (7)$$

REP results for cumulative damage in different blocks of loading given in Tables 1, 2 and 3 are summarized in Fig. 10. The latter shows that predictions estimated by damage models presented in this study are acceptable, since most relative errors corresponding to this model are less than 20 % (more than seven loading cases). Figure 7 presents relative errors of prediction calculated by Eq.(7) for a DEM model for all loading configurations.

Table 3. Results carried out, for three configurations (increasing, decreasing and random block loading).

Increasing loading (low-high)						
σ_1 = 45 MPa	σ_2 = 50 MPa	σ_3 = 55 MPa	σ_4 = 60 MPa	σ_5= 65 MPa experimental results	EDM	Miner's model
n_1	n_2	n_3	n_4	n_5		
50	50	50	50	89	110	140
Decreasing loading (high-low)						
σ_1 = 65 MPa	σ_2 = 60 MPa	σ_3 = 55 MPa	σ_4 = 50 MPa	σ_5 = 45 MPa		
50	50	50	50	315	286	7262
Random loading						
σ_1 = 55 MPa	σ_2 = 60 MPa	σ_3 = 45 MPa	σ_4 = 65 MPa	σ_5 = 50 MPa		
50	50	50	50	489	434	2490

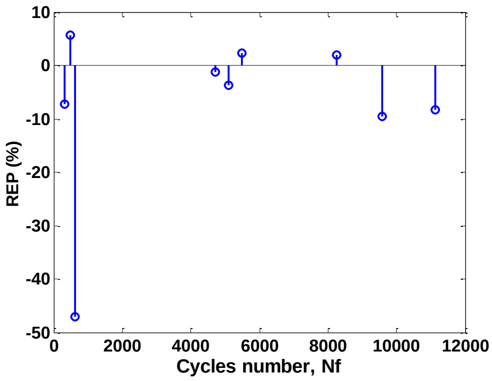

Figure 7. Relative errors of prediction for calculating fatigue lives using damage models under 2-, 3-, and 4-blocks.

It is clear from Fig. 8 that the DEM model presented in this study gives good results concerning random loading for 3 and 4-block loading, where REP's are close to 20 % except in case of random relative to 4-block loading.

Results obtained from the model are promising. Indeed, given the dispersed nature of fatigue, one can judge the relevance of predictions obtained by DEM model for polyvinyl chloride. Comparison between experimental results and model predicted lives under various loading configurations for the above conditions (Tables 1, 2 and 3) is shown in Fig. 8.

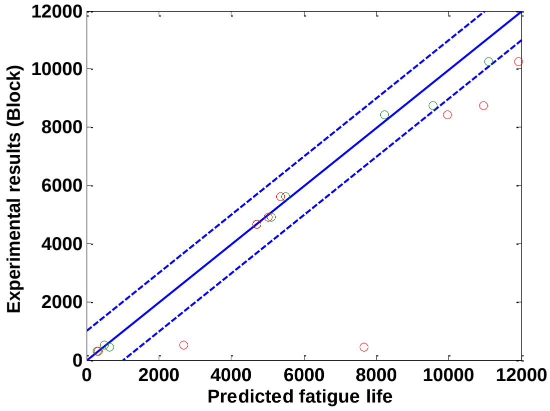

Figure 8. Predicted vs. experimental fatigue lives of polyvinyl chloride under various loading configuration based on energy-based (EDM) damage model and Miner's rule.

CONCLUSION AND PROSPECTS

The paper attempts to present a damage accumulation nonlinear model approach based on energy criterion which makes it possible to calculate fatigue life and estimate the state of polymer material, such as PVC, and structure elements operating in different cases of complex random loading.

The model calibration problem is solved for this model and no constants to determinate for, only the parameters of the Wöhler curve. Therefore, theoretical results are in good agreement with experimental data for material tested in this study. Future prospects of the model may be extended to complex multiaxial loading conditions with the use of Fatemi-Socie Dang Van, Crossland, or other multiaxial criteria. Likewise, other comparisons between model predictions and experimental data have to be carried out for other polymer materials to confirm promising results presented in this paper. Based on the comparison between the predicted results and experimental data in this paper, the main conclusions can be summarized as follows:

– based on nonlinear damage accumulation, the fatigue damage evolution behaviour under block loading and random block loading in low cycle fatigue is studied and a new approach to present the load interaction effect is proposed. The load ratio between consecutive stress levels is employed to characterize the effect. It offers a good understanding of fatigue damage phenomenon and its evolution;

– by introducing the energy approach to a nonlinear damage model, a modified model is formulated and verified using experimental results under increasing-, decreasing- and variable block loading conditions. Comparing with the Miner rule, this model gives satisfactory predictions and presents the efficiency of consolidated effects of load sequences and load interactions.

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