Modeling of the stress-strain relationship for specimens made of S355J0 steel subjected to bending block loading with mean load

R.Pawliczek, C.T Lachowicz
Opole University of Technology, Mikołajczyka 5, 45-271 Opole, Poland
r.pawliczek@po.opole.pl, c.lachowicz@po.opole.pl

ABSTRACT. The paper presents results of calculation for modelling of the stress-strain relationship in the case of block loads with mean load value. A model, based on the stable hysteresis loops, was assumed and modified to use for block loading analysis. For stress history calculation, the proposed model and two other constitutive models were used. Results of fatigue test of specimens made of S355J0 steel subjected to bending block loading with mean load value are presented and used to verify the proposed model. In the tests, the mean load was increased and decreased in subsequent blocks. The changes of strain recorded during the tests shown in the paper indicate a different behavior of the material. Damage accumulation degree for block sequence was used to compare the results of calculations. It was shown, that stress history parameters (stress amplitude and mean stress value in this case) are similar for all investigated models.

KEYWORDS. Stress-strain relationship; Block loading; Mean load.

OPEN ACCESS

Citation: Pawliczek R., Lachowicz C.T., Modeling of the stress-strain relationship for specimens made of S355J0 steel subjected to bending block loading with mean load, Frattura ed Integrità Strutturale, 42 (2017) 30-39.

Received: 31.05.2017
Accepted: 08.06.2017
Published: 01.10.2017

INTRODUCTION

Observation of the relation between strains of the structural materials and loading applied to the structure allow assessing the phenomena which occurs during fatigue of materials [1, 2]. For given material the value of load is a parameter which decides about strain-stress relationship. The area of the stress-strain hysteresis loop is identified with the plastic strain energy density. This energy parameter is widely used in so called energy based criteria to describe and predict the fatigue life of material, eg. [3, 4] as well for unnotched and notched components eg. [5].

In the case of complex load, during operation of the structures, some changes of the shape and location of the hysteresis loop are observed. It has to be considered in the algorithm of the fatigue life calculation, where the influence of the different load parameters on the strain-stress relationship is important. Using a proper combination of cyclic loading blocks it is possible to realize complex load histories as laboratory tests. Also the mean stress influence can be investigated – in this case, a constant component should be added to the generated blocks of variable amplitude loading. The load sequence can change the final fatigue life of materials and components, because damage accumulation is changed. The most important load sequences are these, which are strongly different with their parameters – amplitude and mean stress. Usually the Hi-Lo or Lo-Hi sequences are used [1]. Studying papers on that problem, we can find that there is no standard procedure for fatigue life calculation and some researchers obtained completely opposite results [6]. Most of those considerations were based on experimental results which were obtained for different materials, loading conditions, applied stress levels. It is possible to describe a proper damage accumulation rule for such cases only. Fatemi and Yang [7] present a wide number of different cumulative fatigue damage and life prediction theories. They conclude that none of them is widely accepted. Each damage model can only account for one or several phenomenological factors, such as load dependence, multiple damage stages, nonlinear damage evolution, load sequence and interaction effects, over load effects, small amplitude cycles below the fatigue limit and mean stress.

The tests presented by Chiou and Yip [8] shows the effect of the mean load based on the example of research on AISI 316 alloy steel subjected to uniaxial loads of constant amplitude and the saw-toothed waveform. Curve parameters of cyclic strengthening were determined for a fixed value of the mean strain of ε_m= 0.1%; 0; 0.2%; 0.4% resulting in the following values: K'=745.594; 722.571; 693.080; 587.699 MPa and n'=0.1572; 0.1507; 0.1424; 0.1170 [8], respectively. In the case of block loads involving different mean values in each load blocks, distinct changes of fatigue life are observed.

The authors Memon at al. [9] shows the results of fatigue tests under conditions of two-stage block loads in Lo-Hi and Hi-Lo sequences (Fig. 1) for different sequences of amplitude and the mean stressess.

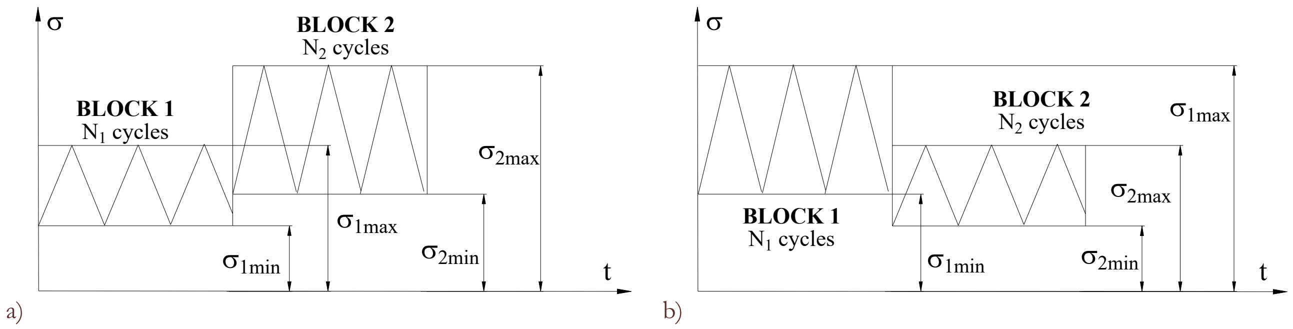


Figure 1: The sequence of blocks according to [8]: a) Lo-Hi, b) Hi-Lo.

The algorithm of fatigue life calculation, proposed by the authors, uses Lemaitre's model of kinematics hardening and also additional stress-strain analysis based on MES method. Final degree of damage accumulation was calculated with the use of linear Palmgren-Miner rule. The results present good agreement between calculations and tests in the cases, where amplitudes of the load in analyzed sequences were on similar level and maxi-mum stresses were near the yield limit. Bigger difference be-tween amplitudes of the loading in the block sequence strongly influences on the level of the degree of damage accumulation for Hi Lo and Lo-Hi cases.

The effect of block loads on the fatigue life is shown by Pawliczek and Lachowicz [10], which have involved bending of specimens from S355J0 steel to certain maximum stress levels. In the case of loads at yield point, a difference in fatigue life has been observed depending on the direction of increase of the mean load, and fatigue life was twice lower if the highest mean load value occurred in the beginning of the load sequence. Similar tests were performed by Pawliczek [11]. The paper describes the research on the relationship between stress and strain under bending block loads where the mean value of the load varied for each block segment. A significant impact of such a load on strains generated in the material, and consequently on the fatigue life, is shown.

It can be seen, that analyze of the stress-strain relation is an important part of block loading fatigue tests where mean load is applied. Such investigations allow considering that effect and verifying the influence of the mean load on it. The aim of this paper is to create an algorithm for stress history parameters definition and its application for calculations of accumulation damage degree.

MODEL FOR STRESS HISTORY PARAMETERS DEFINITION

The model for stress amplitude and mean stress value calculation bases on the model of the hysteresis loop presented by Chiou and Yip [8]. I was assumed that the shape of the stable hysteresis loop remains unchanged under the same strain amplitude and different mean strain level conditions. Additionally, the stable hysteresis loop shifts in accordance with the value of the mean strain. This results in symmetry of the hysteresis loop according to the point described by mean strain ε_m and mean stress σ_m (Fig. 2).

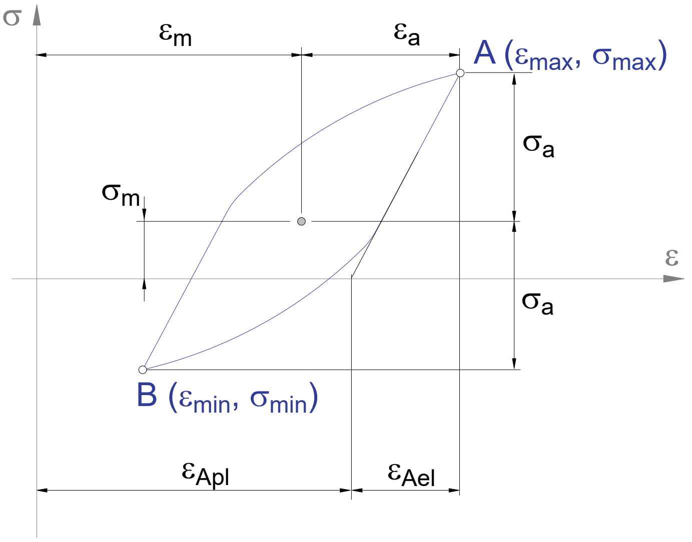


Figure 2: Description of the stable hysteresis loop [7].

The parameters on the Fig. 2 are as follow:
ε_{max}, σ_{max} – maximum strain and stress at point A respectively, ε_{min}, σ_{min} – minimum strain and stress at point B respectively, ε_m, σ_m – mean strain and stress in the point respectively, ε_a, σ_a – amplitude of strain and stress in the point respectively, ε_{Apl}, ε_{Ael} – plastic strain and elastic strain at point A respectively.

For situation presented in Fig. 2 the most conservative case exists. All calculations are performed for known strain history ε(t) registered during the test, so all strain parameters in Fig. 2 are available. Take into account geometry of the stress-strain relation based on the presented assumptions and using standard Ramberg-Osgood formula for its mathematical description, the strain amplitude ε_a can be expressed as:

$$\varepsilon_a = \frac{\sigma_{\max}}{E} + \left(\frac{\sigma_{\max}}{K'}\right)^{\frac{1}{n'}} \tag{1}$$

where: σ_{max} – maximum stress at point A, E – Young modulus, K' = K'(ε_m) - cyclic strength coefficient, n' = n'(ε_m) – cyclic fatigue exponent.
Assuming additionally, that cyclic strength coefficient and cyclic fatigue exponent values depend on the actual value of the mean strain, it should be noted, that coefficients K' and n' are defined for actual mean strain ε_m [8]. Eq. (1) allows calculating stress at point A.
Considering, that $\varepsilon_m+\varepsilon_a= \varepsilon_{Apl}+\varepsilon_{Ael}$ and $\sigma_{max}=\sigma_a+\sigma_m$ (Fig. 2)

$$\varepsilon_m + \varepsilon_a = \varepsilon_{Apl} + \frac{\sigma_{\max}}{E} = \varepsilon_{Apl} + \frac{\sigma_m}{E} + \frac{\sigma_a}{E} \tag{2}$$

where stress amplitude σ_a is unknown.
From hysteresis loop and Ramberg-Osgood relationship, we can use the amplitudes of elastic ε_{ael} and plastic ε_{apl} strains:

$$\varepsilon_a = \varepsilon_{ael} + \varepsilon_{apl} = \frac{\sigma_a}{E} + \varepsilon_{apl} \tag{3}$$

Substituting elastic part in Eq.(2) using Eq.(3), after transformation, the mean stress σ_m can be calculated from the following formula:

$$\frac{\sigma_m}{E} = \varepsilon_m + \varepsilon_{apl} - \varepsilon_{Apl} \tag{4}$$

This form of equation (Young modulus) suggests that mean stress is responsible for elastic part of deformation.
However, the parameter ε_{apl} in Eq.(4) is still undefined. Also to solve this problem, the Ramberg-Osgood equation can be used. Bearing in mind, that the shape of the stable hysteresis loop does not change for the same strain amplitude and different mean strains we can calculate stress amplitude σ_a using relation

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \qquad (5)$$

It is very important to use coefficients K' = K'(ε_m=0) and n' = n'(ε_m=0) obtained for standard, symmetric loading (ε_m=0 and σ_m=0) in the case of Eq.(4).
All the equations presented above are adequate for cyclic load with the mean load, where load conditions are constant during the test. However, it was mentioned before, for block loading location of the hysteresis loop can be different for each segment of block. Some researches of this problem [11] allows observing, that changing the men load during test a new, stable location of the hysteresis loop is registered. Strong flow of the mean strains along strain axis usually arises at the end of life of the specimen, so it can be assumed, that each, new position of the hysteresis loop stabilises at new levels of mean strain and stress (Fig.3).

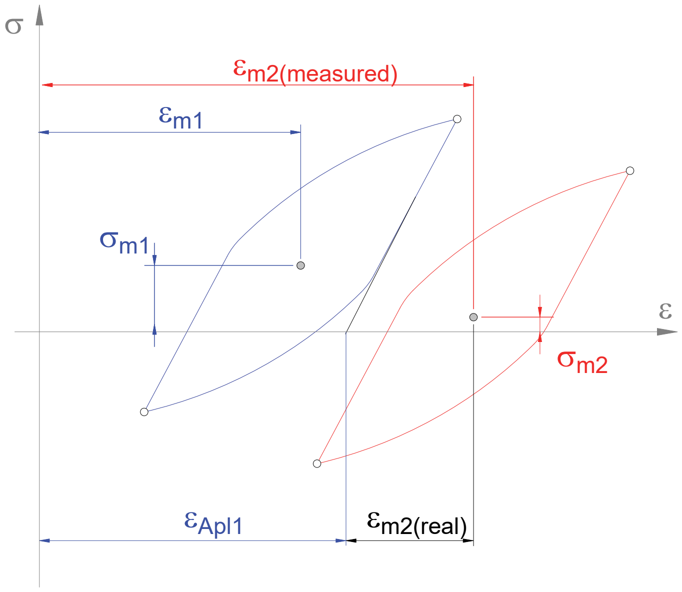


Figure 3: Location of the hysteresis loops for the next sequence in the block load.

After first block, where strain ε_{m1} and stress σ_{m1} exists a new position of the hysteresis loop is observed and described by parameters $\varepsilon_{m2(measured)}$ and σ_{m2}. Notation "measured" means mean strain of the measured strain history. It should be noted, that after first sequence some value of permanent deformation ε_{Apl1} exists in material after unloading (Fig.3). This part of strains participates as the initial state of the material for next stage of loads. In the case, for which the second block will have zero mean load value it leads to situation, that presented algorithm will resulting with non-zero mean stress, what is not corresponds to the real stress conditions. The strain ε_{Apl1} as the "starting" point for each sequence must be taken into account in calculations.

THE ALGORITHM FOR STRESS HISTORY CALCULATION

Having regard to the considerations presented above the following algorithm for stress history calculation can be defined, where all the steps must be repeated for each sequence in the block load for whole registered time history of the strain:

1.	Input data: ε_{max} ε_{min} ε_a ε_m
2.	Calculation of σ_{max} where K'(ε_m) and n'(ε_m) are defined for actual mean strain value: $$\varepsilon_a = \frac{\sigma_{\max}}{E} + \left(\frac{\sigma_{\max}}{K'}\right)^{\frac{1}{n'}}$$
3.	Calculation of ε_{Apl}: $$\varepsilon_{Apl} = \varepsilon_{\max} - \frac{\sigma_{\max}}{E}$$
4.	Calculation of σ_a where K'(ε_m=0) and n'(ε_m=0): $$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}}$$
5.	Calculation of ε_{apl}: $$\varepsilon_a = \varepsilon_{apl} - \frac{\sigma_a}{E}$$
6.	Calculation of the mean stress σ_m: $$\sigma_m = E(\varepsilon_m + \varepsilon_{ap} - \varepsilon_{Apl})$$
7.	Calculation of the damage accumulation degree for given stresses (σ_a, σ_m) and the fatigue life can be predicted.

Additionally, in order to define the stress history parameters, some kinematic models of cyclic deformation were used. Usually, those criteria base on the von Mises's plasticity surface as the yield criterion. For such calculation then the flow rule for a plastic strain increment calculation must be specified. Additionally, during computation with use of the constitutive equations it is important to define the way the plasticity surface is translated. Translation can be described by some hardening rules. During numerical tests it was found that the best results of calculations were obtained for Garud-Mroz [12] and Chu [13] models of the constitutive equations of the cyclic plasticity description. These cyclic plasticity models are used very often for energy based criteria for fatigue life estimation, eg. Lachowicz [14], to describe stress-strain state and to calculate energy dissipated in material.

FATIGUE TESTS

The fatigue tests conducted included subjecting the samples made of S355J0 steel to fatigue loads with including the mean load values. The Tab. 1 presents properties of the tested materials.

E *GPa*	σ_y *MPa*	σ_u *MPa*	ν	n'	K' *MPa*
210	357	535	0.30	0.2074	1323

C	Mn	Si	P	S	Cr	Ni	Cu	Fe
0.20	1.49	0.33	0.023	0.024	0.01	0.01	0.035	others

Table 1: Strength properties and chemical composition (%) of S355J0 steel.

The tests were performed under bending loads applied in blocks with different mean load values. Two paths of the change in the mean load value in blocks were applied (Fig.4): a) mean load was increased from zero to maximum value for the following sequences in blocks of loading, b) mean load was decreased from maximum to zero value in successive blocks of loading.

The mean value of the load was as follow: *1:* $\sigma_m = 0$, *2:* $\sigma_m = \frac{1}{3}\sigma_a$, *3:* $\sigma_m = \sigma_a$. The whole number of cycles N_b in block was divided to three equal parts $n_1=n_2=n_3=\frac{1}{3}N_b$. The block applied in the tests had a length N_b=15000 cycles.

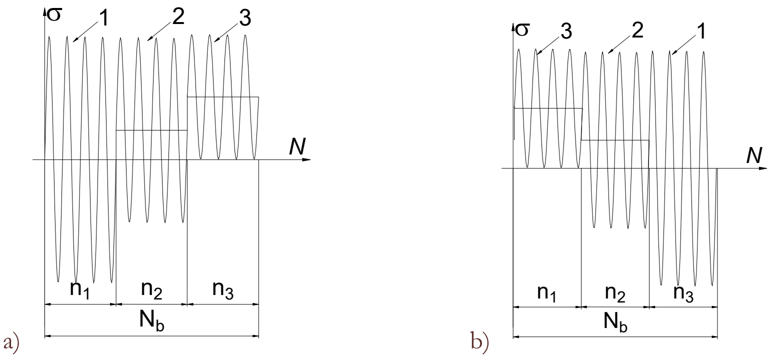
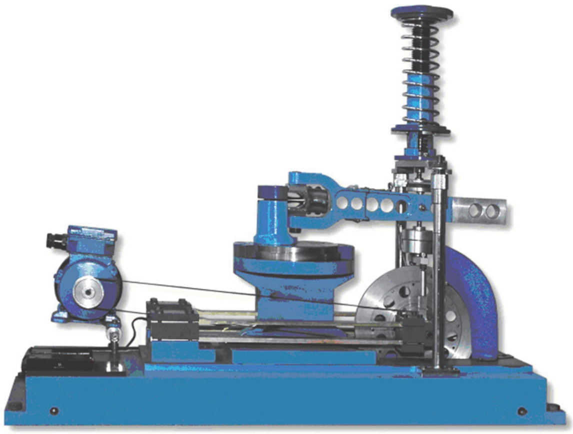
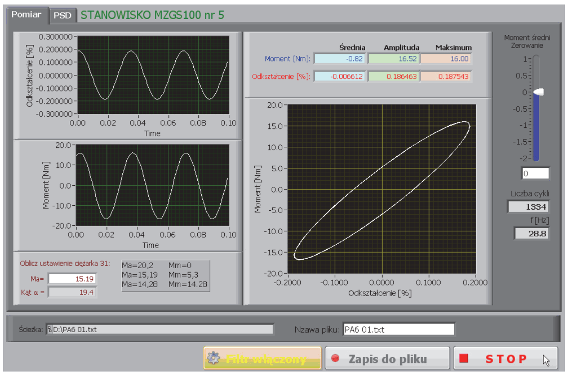


Figure 4: Block loading applied in fatigue tests: a) for increasing mean load value, b) for decreasing mean load value.

The view of the fatigue tests stand MZGS100 is presented in Fig. 5a. The stand allows realizing tests under cyclic bending with mean load value, which is applied by spring actuator. The applied loads and observed deformations (strains) of the specimens were measured during the tests. The strain bridge NI USB9237 and the author's software (Fig. 5b) were used. It was possible to observe on-line the time courses of loading (amplitude and mean value of the bending moment) and strains and additionally moment-strain curve was displayed.


a)


b)

STANOWISKO MZGS100 nr 5

	Średnia	Amplituda	Maksimum
Moment [Nm]:	-0.82	16.52	16.00
Odkształcenie [%]:	-0.006612	0.186463	0.187543

Oblicz ustawienie ciężarka 31:
Ma= 15.19
Kąt α = 19.4

Ma=20,2 Mm=0
Ma=15,19 Mm=5,3
Ma=14,28 Mm=14.28

0
Liczba cykli 1334
f [Hz] 28.8

Ścieżka: D:\PA6 01.txt
Nzawa pliku: PA6 01.txt

Figure 5: Fatigue tests: a) the view of the fatigue tests stand, b) software's user interface.

An example time histories of bending moment and corresponding strains are shown in Fig. 6.

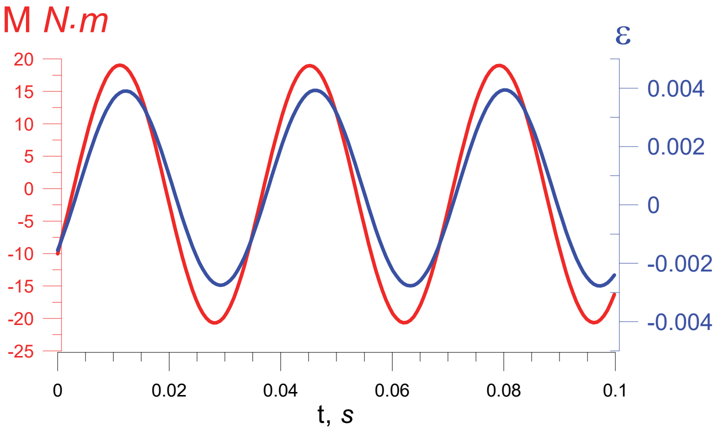


Figure 6: Registered moment and strains history.

Then, the registered signals were used to define the changes of the moment-strain relation for both of applied block load paths. The results of fatigue test are presented in Fig. 7 and Fig. 8 for the load paths shown in Fig. 4a and Fig. 4b.

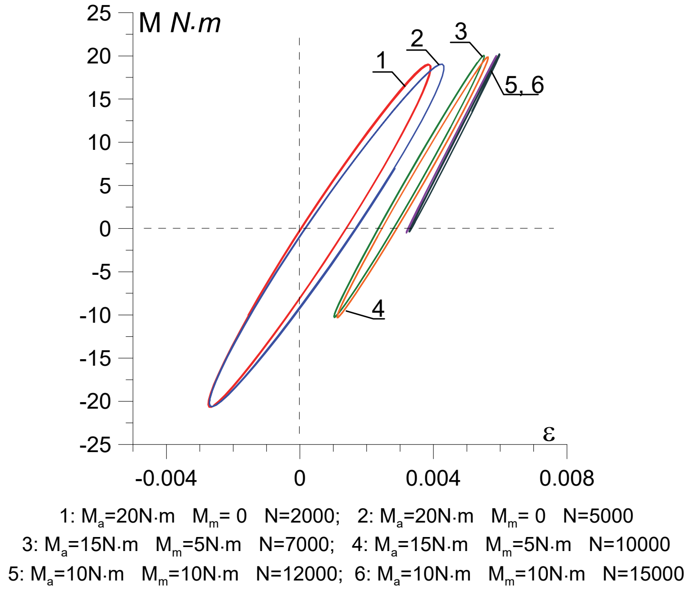


Figure 7: Hysteresis loops at the increasing mean load value.

In the case of Fig. 7 higher value of the moment amplitude in the first phase of fatigue testing resulted with strain amplitude ε_a=0.3% after 2000 cycles. The increase in the mean value of load in each sequence resulted in a shift of the loop towards the average value of ε_m=0.35%. When M_a=M_m=10N·m, the increase of the mean strain value to ε_m=0.45% was observed but the variable strains are in the elastic range (curves 5 and 6 in Fig. 7). The maximum strain of ε_{max}=0.6% and the mean strain $\varepsilon_{m(max)}$=0.47% were recorded.

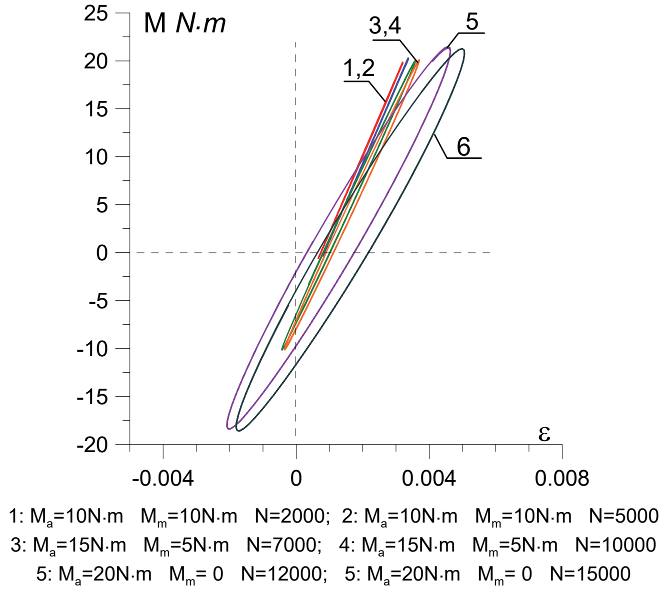


Figure 8: Hysteresis loops at the decreasing mean load value.

For the case shown in Fig. 8 in the initial phase of the test the highest value of the mean moment was applied. In the case where M_a=15N·m and M_m=5 N·m (curves 3 and 4 in Fig. 8), there is no increase plastic strain as compared to the corresponding case (curves 3 and 4 in Fig. 7) with the increase of the mean load value. This may indicate the strengthening of the material caused by the mean load at the beginning of the block. The reduction in the mean moment value to zero in the last block enlarged the area of the hysteresis loop and a little shift of the hysteresis loop after 3000 load cycles is observed. At the same time, the mean load ε_m=0.2% was recorded that remained after the strain (curves 5 and 6 in Fig. 5). The maximum strain of ε_{max}=0.5% and the mean strain $\varepsilon_{m(max)=}$0.15% were recorded.

RESULTS OF CALCULATIONS

For registered histories of the strains the proposed algorithm and two kinematic models (Garud-Mroz and Chu) of cyclic deformation were used to calculate the stress history parameters: stress amplitude and mean stress value in this case. Figs. 9 and 10 presents hysteresis loops as stress-strain relationship calculated by the use of Garud-Mroz model. Form of the graphs corresponds to the measurement results presented in Fig. 8 and Fig.9, respectively.

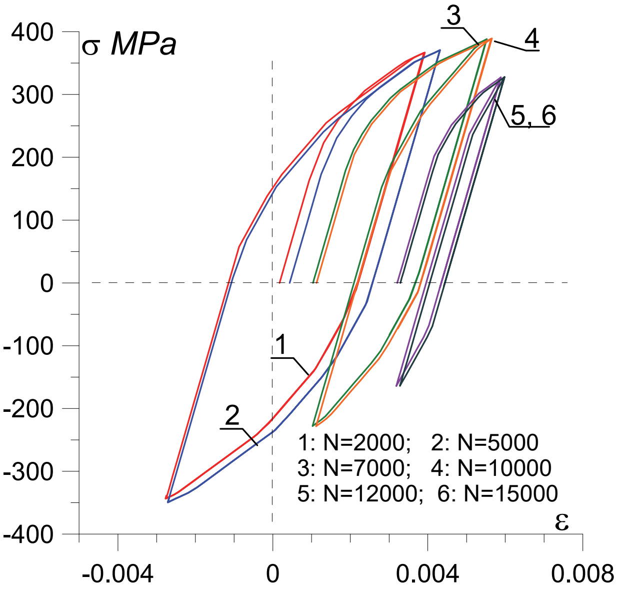


Figure 9: Stress-strain loops at the increasing mean load value calculated with the use of Garud-Mroz model.

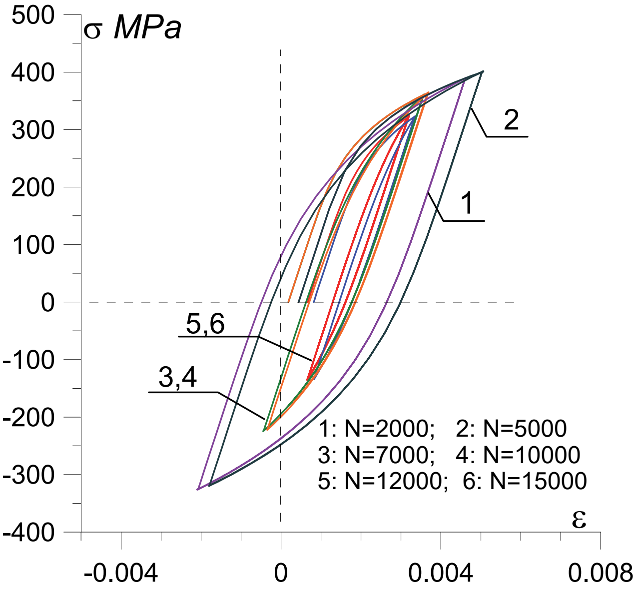


Figure 10: Stress-strain loops at the decreasing mean load value calculated with the use of Garud-Mroz model.

It can be seen, that for curves 5 and 6 of Fig. 9 some compression stresses reordered. The same effect is visible for curves 1 and 2 on the diagram for the case of decreased mean load (Fig. 10).
The aim of performed calculations is to establish a parameters of the stress history (stress amplitude σ_a and mean stress σ_m in this case) for each sequence of the applied block loads respecting both paths of changes of the mean load using proposed model, Garud-Mroz proposal and Chu also. Results of these investigations are presented in the Fig. 11 for increased mean load value and in the Fig. 12 for decreased mean load value.

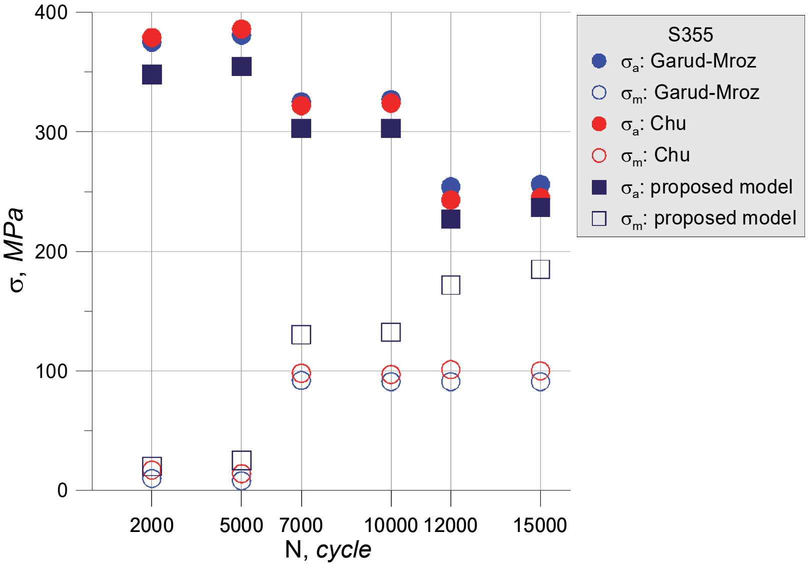


Figure 11: Comparison of the stress history parameters calculated by proposed model and models of Garud-Mroz and Chu for increased mean load value.

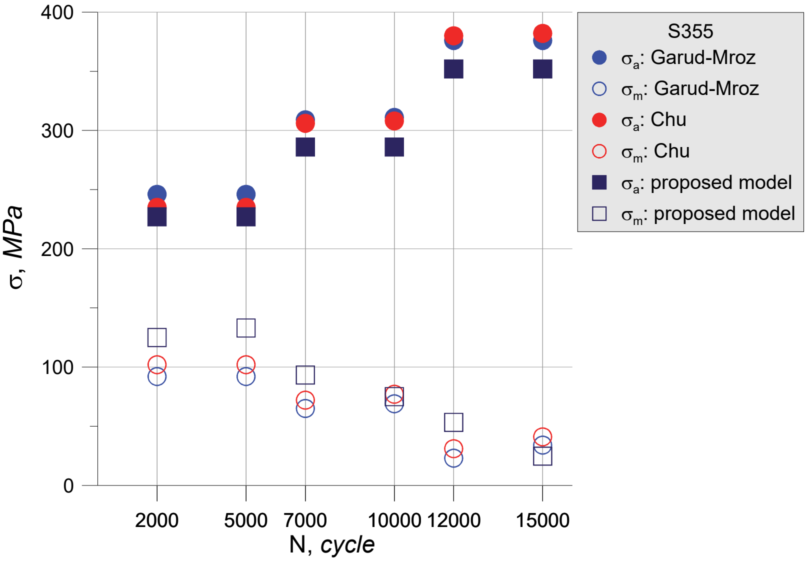


Figure 12: Comparison of the stress history parameters calculated by proposed model and models of Garud-Mroz and Chu for decreased mean load value

Comparing all analyzed models it can be seen, that stress amplitude are very close to each other for all cases, however for mean stress the proposed model gives results with higher values: about 40% for 7000 and 10000 cycles (second sequence in block load) and 80% for 12000 and 15000 cycles (third sequence in block load). It will generate higher level of damages – then lower, predicted fatigue life will be calculated for such load sequence. In general, such observations are indicated in the research.

SUMMARY AND CONCLUSIONS

The algorithm of the stress history parameters calculation is presented in this paper and its application to the block loads with influence of the mean load value is described. The sequences in block load differ with values of the mean load for each sequence of the block. Taking into account results of the test and calculations the following conclusions can be drawn:

- fatigue tests present significant changes of the strain develop in material for both analyzed load path. If the hysteresis loop is moving along strain axis for the load with increased mean load values (Fig. 4a) in the case of decreasing mean load value it is observed, that after first sequence with higher mean load value some hardening effect occurs,
- Garud-Mroz and Chu cyclic plasticity models gives very similar results of calculations of stress amplitude and mean stress value for both analyzed cases of the load path (Fig. 11 and Fig.12),
- proposed model is more sensitive for mean value in the block loads in the case of increased mean load value for following sequences in the block comparing to the cyclic plasticity models (Fig. 11), where for second case of loads similar results for all of three analyzed models were obtained (Fig. 12).

REFERENCES

[1] Kocańda, S., Szala, J., Basis for the calculation of fatigue, PWN, Warszawa (1989) (in Polish).
[2] Kocańda, S., Kocańda, A., Low cycle fatigue strength of metals, PWN, Warszawa (1989) (in Polish).
[3] Morrow, J., Cyclic plastic strain energy and fatigue of metals. International Friction, Damping and Cyclic Plasticity, ASTM STP, Philadelphia (1965).
[4] Łagoda, T., Macha, E., Będkowski, W., A critical plane approach based on energy concepts: Application to biaxial random tension-compression high-cycle fatigue regime, International Journal of Fatigue, 21 (1999) 431-443.
[5] Łagoda, T., Robak, G., Słowik, J., Fatigue life of steel notched elements including the complex stress state, Fatigue life of steel notched elements including the complex stress state, Materials and Design, 51 (2013) 935–942.
[6] Van Paepegem, W., Degreck, J., Effect of load sequence and block loading on the fatigue response of fibre-reinforced composites, Mechanics of Advanced Materials and Structures, 9(1) (2002) 19-35.
[7] Fatemi, A., Yang, L., Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials, International Journal of Fatigue, 20(1) (1998) 9-34.
[8] Chiou, Y.C., Yip, M.C, Effect of mean strain level on the cyclic stress-strain behavior of AISI 316 stainless steel, Materials Science and Engineering, A354 (2003) 270-278.
[9] Memon, I., Zhang, X., Cui, D., Fatigue life prediction of 3-D problems by damage mechanics with two-block loading, International Journal of Fa-tigue, 24 (2002) 9-37.
[10] Pawliczek, R., Lachowicz, C.T., The mean stress effect on fatigue behavior of constructional steels subjected to variable amplitude bending, 2nd Inter-national Conference on Material and Component Performance under Variable Amplitude Loading, Eds C.M.Sonsino and P.C McKeighan, DVM, Berlin (2009) 1095-1102.
[11] Pawliczek, R., Influence of the mean load value in fatigue block loading on strains, Key Engineering Materials, Trans Tech Publi-cations, Switzerland, 598 (2014) 195-200.
[12] Garud, Y. S., A new approach to the evaluation of fatigue under multiaxial loadings, Trans ASME J. of Pressure Vessel Technol., 103 (1981) 118-125.
[13] Chu, C. C., A Three Dimensional Models of Anisotropic Hardening in Metals And Its Application to The Analysis of Sheet Metal Formability, Journal of the Mechanics and Physics of Solids, 32 (1984) 197-212.
[14] Lachowicz, C. T., Energy based method for analysis of the fatigue life of materials, machines components and structures, Printing House of Opole University of Technology, Opole (2013) (in Polish).