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COMPARISON ANALYSIS OF LOW-CYCLE PROPERTIES OF 45 STEEL UNDER UNIAXIAL LOADING AND BENDING

The paper presents comparative analysis of the results of low- cycle fatigue experiments on specimens made of 45 steel under uniaxial loading and bending. The analysis involves, among other things, the cyclic properties and the fatigue life of the specimens in a wide range of loading conditions. The experimental techniques used during bending enabled us to estimate the influence of strain distribution on fatigue life. The materials data obtained under the loading conditions mentioned above were employed to estimate the fatigue life of the structural elements. The results of experiments and calculations are presented in the form of fatigue curves. They also show the influence of axial loading and bending on the accuracy of the calculations.

- b - elastic exponent,
- c - plastic exponent,
- E - modulus of elasticity,
- K' - coefficient of cyclic stress-strain curve,
- K_f - notch factor,
- K_t - stress concentration factor,
- M_g - bending moment amplitude,
- M_{gr} - maximal value bending moment in cycle,
- n' - exponent of cyclic stress-strain curve,
- $2N_f$ - reversals to failure,
- r - notch root radius,
- R_m - ultimate tensile strength,
- α - material constant,
- Δe - nominal strain range,

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ΔS - nominal stress range,
$\Delta\varepsilon_{ac}$ - total strain range,
$\Delta\varepsilon_{ae}$ - elastic strain range,
$\Delta\varepsilon_{ap}$ - plastic strain range,
$\Delta\sigma$ - local stress range,
$\Delta\varepsilon$ - local strain range,
σ_a - stress amplitude,
σ_{ar} - maximal value stress in cycle,
σ'_f - fatigue strength coefficient,
ε'_f - fatigue ductility coefficient.

1. Introduction

The present paper was motivated by the results of Tucker [1] and Morrow [2] who assumed that the fatigue life of the notched specimen can be predicted by uniaxial fatigue tests on smooth specimens, provided that the uniform strain distribution within these specimens is equal to the strains just at the notch root. T-M assumptions are usually adopted to predict the fatigue life of structural members. These assumptions simplify the testing procedures considerably. However, one should require that the computations performed according to this model provide results that are in agreement with the results of experiments. It turned out that it is not so [3], [4], [5]. In this paper the problem is reconsidered once more.

A simple explanation of the discrepancies between the T - M assumption, on the basis of the tests and computations performed, may be derived from Fig. 1, and can be summarised as follows:

- the distributions of stress and strain in front of the notch significantly differ from the distributions in the smooth specimen (in the notch area there is a strain gradient, while in the specimen under uniaxial loading one may observe a uniform distribution of strains),
- the replacement of a small area in front of the notch with the standard specimen does not involve the scale effect.

Another reason for the observed discrepancies between the model and real fatigue tests may stem from the procedure of adopting fatigue properties of the material taken from the period of fatigue stabilisation of these properties. However, in certain situations, e.g. during the irregular loading, the stabilisation period is not observed [6], [7], [8].

The main goal of the present work is to estimate the influence of strain and stress distribution on the fatigue life obtained under uniaxial loading and bending. Complementary aims are:

- appraisal of local stress and strain modelling in the notch zone by using a smooth specimen under uniaxial loading and bending conditions, investigation of the material fatigue properties in the stabilisation period during uniaxial and bending loading.

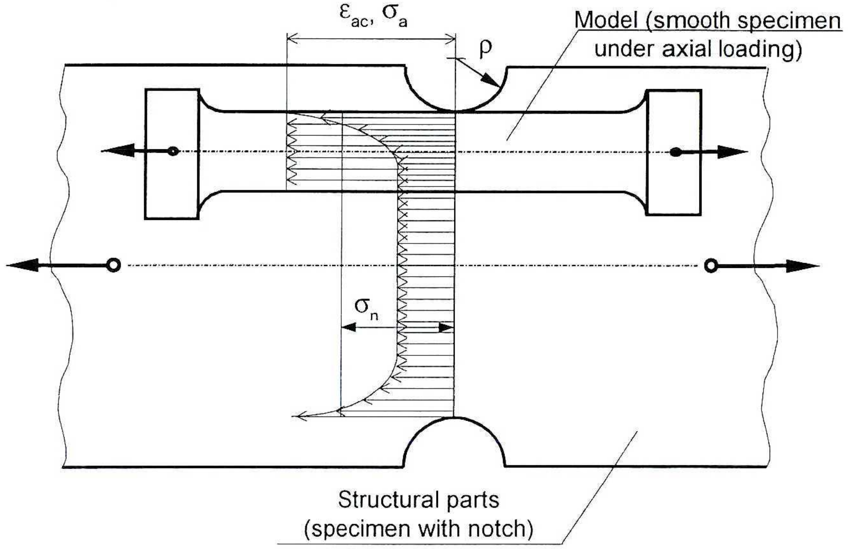


Fig. 1 The distribution of stress in the notch zone and modelling of deformation in the notch zone with the smooth sample under axial loading

2. Methodology and program of experimental tests

It is difficult to analyse the influence of strain gradient on fatigue life utilising the results of the investigations of the notched specimens only, due to uncertainties concerning the strain and stress distribution in the front of the notch. Thus, a special methodology has been adopted that makes it possible to control the strain and stress gradients with acceptable accuracy. The basic idea of this methodology is presented in the Fig. 2.

The quantitative influence of the strain distribution on fatigue life was tested during the bending fatigue tests varying the specimen height H and fixing the strain level ε_{ac} at the specimen surface. Linear strain distribution was assumed in the specimen from the zero value at the longitudinal specimen axis to ε_{ac} at the surface. The heights of the specimens were: $H = 8$, 12 and 16 mm. The strains ε_{ac} at the specimen surfaces were controlled at the levels shown in the Table 1. Thus, the strain gradient depends on the specimen height for a given ε_{ac}. The ratio of inertia moment of the specimen cross-section to the specimen height was kept constant. Table 1 contains main experimental parameters controlled during the test.

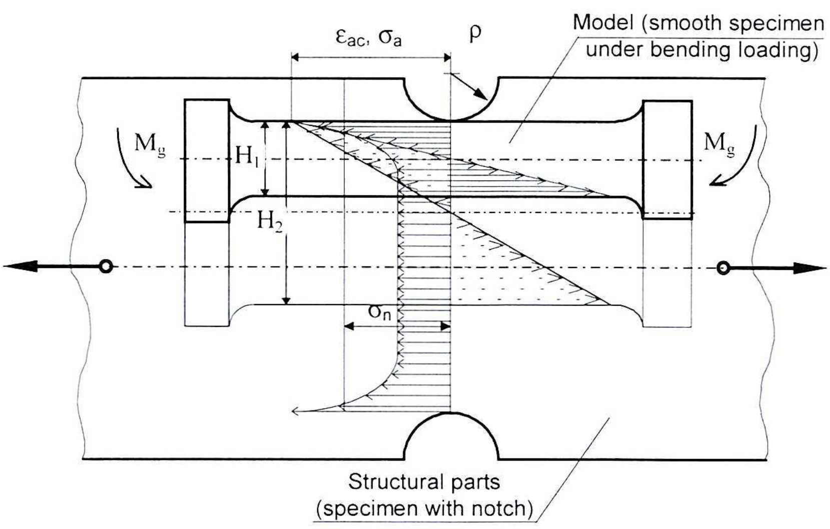
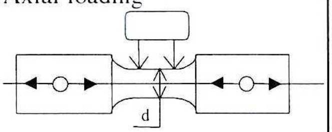
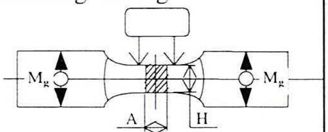
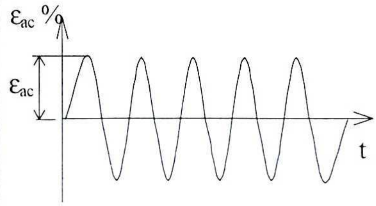
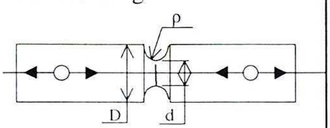
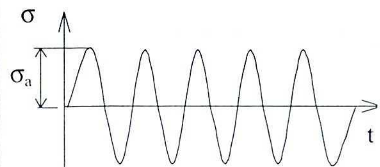


Fig. 2 Modelling of deformation in the notch zone using the smooth sample under bending loading

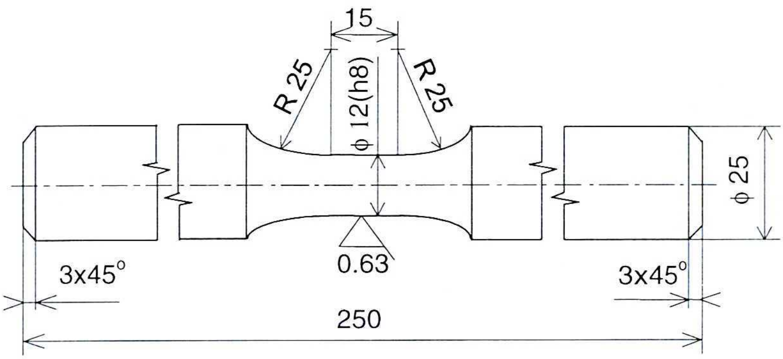
Table 1.

Investigation programs

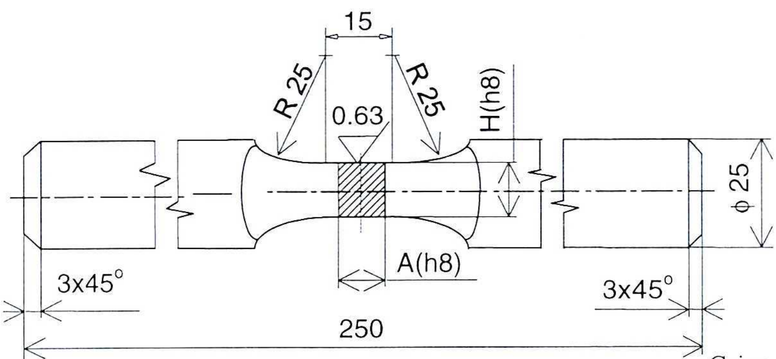
Kind of loading	Dimension	Schema of loading program
Axial loading  Bending loading 	d=10 mm A=5.63 mm A=10.0 mm A=22.5 mm H=8 mm H=12 mm H=16 mm	 ε_{ac}= 0.0035 ε_{ac}=0.005 ε_{ac}=0.008 ε_{ac}= 0.01 ε_{ac}=0.02 ε_{ac}=0.04
Axial loading 	d= 10 mm D=20 mm ρ=0.5 mm K_t=3.5	 σ_a=135 MPa σ_a=160 MPa σ_a=185 MPa σ_a=270 MPa σ_a=330 MPa σ_a=375 MPa

The specimens were made of normalised 45 steel. Tables 2 and 3 contain the most important mechanical properties and chemical composition of the material. In the Fig. 3 the geometry of the specimens is shown. Fatigue tests were performed on Instron and MTS machines.

a)



b)



Execution	Dimension specimen	
	A mm	H mm
1	5.63	16.0
2	10.00	12.0
3	22.50	8.0

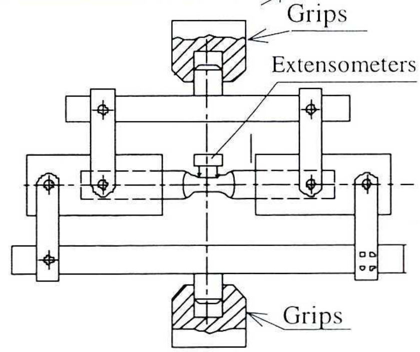


Fig. 3 Specimen used during fatigue test: a) specimen for testing under uniaxial loading; b) specimen and testing device for plane bending

Table 2.

Mechanical parameters of normalised 45 – steel

R_m [MPa]	R_e [MPa]	A_5 [%]	Z [%]	HB
730	435	25	44	190

Table 3.

Chemical constitution of normalised 45- steel

C [%]	Mn [%]	P [%]	S [%]	Si [%]	Mo [%]	Cr [%]	Ni [%]	Fe [%]
0.476	0.593	0.015	0.027	0.201	0.047	0.160	0.116	98.1

The length of fatigue crack was not measured in the test. Fatigue failure was defined by "modulus method" recommended in paper [9]. In this method, failure is defined by the value of Q_N parameter obtained from the ratio

$$Q_N = E_{NT} / E_{NC}, \quad (1)$$

where: E_{NT}- modulus for unloading following a peak tensile stress,
E_{NC}- modulus for loading following a peak compression stress.
It was accepted to consider the specimen as failure when following condition was occurred

$$Q_N = 0.5Q_1, \quad (2)$$

where: $Q_1 = E_{NT1} / E_{NC1}$ – value of parameter Q_N for the first loading cycle.

Decreasing the value of Q_N parameter to the level of $Q_N = 0.5Q_1$ is mostly associated with the occurance in fatigue crack of the specimen. It can be seen as the hysteresis loop deformation and the reduction of stress values σ_{ar} or bending moment M_{gr} in the tensile semicycle. The above methodology on the selected samples is shown in Fig. 4.

3. Experimental results and discussion

3.1. Cyclic properties

The basic assumption of T-M fatigue life calculation method is the existence of the stabilisation period of the cyclic properties. Various parameters can be accepted for the analysis of courses of the stabilisation process. In this paper the following parameters were taken for the analysis of this process: σ_{ar} (for axial loading) and M_{gr} (for bending). The courses of changes for these parameters at five strain levels are presented in Fig. 4. During bending process for these specimens types, one could observe a similar character of changes of bending moment in function of the number of cycles. For this reason, in Fig. 5 the course of evolution of M_{gr} is presented for one specimen only (H=12 mm).

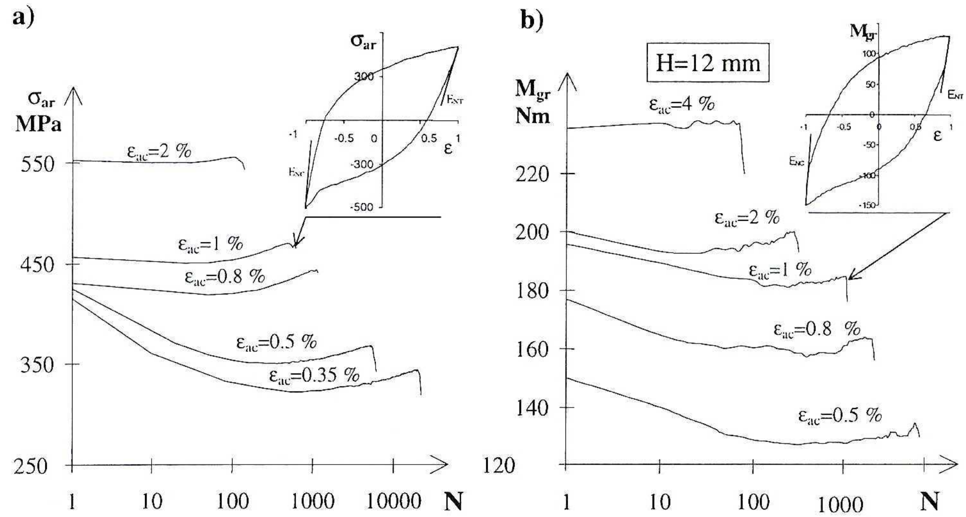


Fig. 4 Changes of σ_{ar} (a) and M_{gr} (b) in the function of the number of cycles and definitions of modulus method of failure determination

Changes of both parameters σ_{ar} and M_{gr} provide the proof of existence of the period of softening (until about 0.2 N_f) followed by the period of stabilisation and finally a period of weak hardening in the terminal phase of fatigue life. The changes of σ_{ar} and M_{gr} in function of number of cycles depend essentially on the strain amplitude ε_{ac}. The smallest changes refer to the high strain levels ($\varepsilon_{ac} = 2\%$ for axial loading and $\varepsilon_{ac} = 4\%$ for bending). The σ_{ar} and M_{gr} analysis enabled us to define the stabilisation period of cyclic properties (constant value of σ_{ar} and M_{gr}). On the basis of the analysis it can be stated that this period begins (for all ε_{ac} levels) from the number of cycles equal to $n = 0.3\,N_f$. The parameters of stabilised hysteresis loop were taken for this period. The examples of hysteresis loops for this period for axial loading and bending are presented in Fig. 5. Additionally, in Fig. 5 there are presented cyclic -stress-strain curves and static tensile stress- strain curves.

Let us begin the analysis of the cyclic properties of 45 steel under uniaxial loading and bending with the comparison of the cyclic and monotonic stress - strain curve. One may observe in Fig. 4 that the cyclic properties of 45 steel under uniaxial loading and bending conditions depend on the amplitude of total surface strain. For strains $\varepsilon_{ac} < 0.7$ per cent the material is softened, for strains $\varepsilon_{ac} > 1$ per cent the steel displays slight hardening. The transition from the softening region to the hardening region for both types of loading used takes place for the total surface strains close to 0.8 per cent. For strains from the range 0.7 per cent $< \varepsilon_{ac} < 1$ per cent apparent cyclic stabilisation for tested steel is observed.

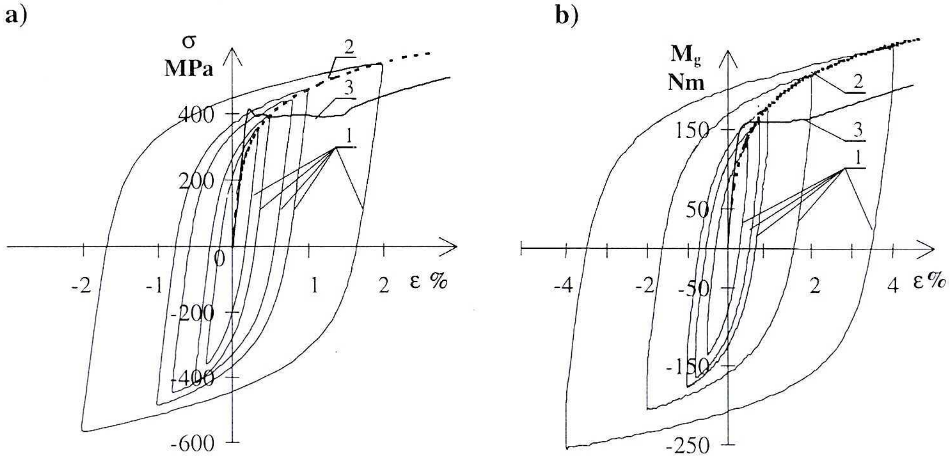


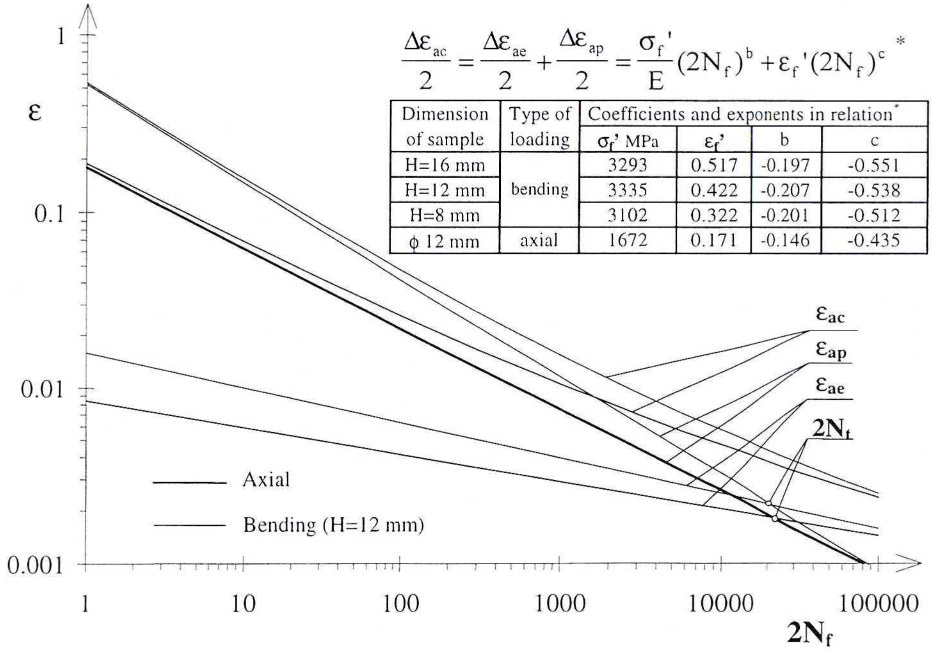
Fig. 5 Hysteresis loop (1), cyclic-stress-strain curves (2) and static tensile stress-strain curves (3): a) axial loading, b) plane bending

It is necessary to explain here that changes of bending moment M_{gr}, which were observed during bending test, enable us only indirectly to evaluate the course of stabilisation process. It results from the fact of averaging the variable strain and stress courses in bent specimens by total bending moment M_{gr}. A detailed analysis of strain distribution in bent specimens in relation to the distance from specimen surface could be performed using MES method. However, to carry out such simulation it is necessary to know cyclic properties of the material determined during axial loading. This problem will be considered in the further works of the author.

3.2. Fatigue life estimation

The analysis of the effect of strain gradient, modelled by varying the specimen height at constant ε_{ac}, on fatigue test results has been performed and the selected results are shown in Fig. 6. The results of the fatigue life of smooth uniaxially loaded specimens are also included in this figure. The Morrow relation describes the strain-life dependence. All coefficients and exponents are also shown in Fig. 6. The influence of coefficients and exponents of Morrow's equation on the accuracy of the fatigue - life calculation is shown in the section 3.3 of the present work.

Fatigue life under bending conditions depends essentially on the specimen height. The highest values of fatigue life at the same strain levels were obtained for specimen with the height of 16 mm, the lowest, in turn, for specimen with the height of 8 mm. These differences were caused by the influence of differentiated distribution of strain and stress obtained for various specimens heights.



$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ae}}{2} + \frac{\Delta\varepsilon_{ap}}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \quad *$$

Dimension of sample	Type of loading	Coefficients and exponents in relation*			
		σ_f' MPa	ε_f'	b	c
H=16 mm	bending	3293	0.517	-0.197	-0.551
H=12 mm		3335	0.422	-0.207	-0.538
H=8 mm		3102	0.322	-0.201	-0.512
ϕ 12 mm	axial	1672	0.171	-0.146	-0.435

Fig. 6 Fatigue curves for axial loading and bending

As it was expected, the fatigue life values obtained under bending conditions are higher than those obtained under axial loading. In order to carry out quantitative evaluation of life increase under bending, an additional parameter $a = N_{f(bending)} / N_{f(axial)}$ was introduced. Changes of this parameter in function of ε_{ac} are presented in Fig. 7.

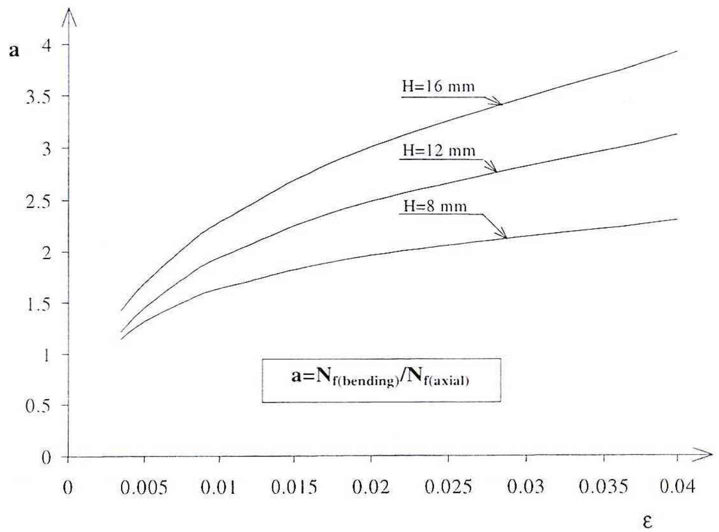


Fig. 7 Fatigue life under axial loading and bending

The diagram analysis shows that the life increase under bending depends on the strain ε_{ac} and on the specimen height H. The least increase of fatigue life refers to the specimen with the height of 8 mm and equals: from 20 % for the low ε_{ac} values to 120 % for high levels of ε_{ac}. The highest increase of fatigue life refers to the specimen with the height H=16 mm, and equals from 40 % for low ε_{ac} values to 350 % for high levels of ε_{ac}. One may conclude that these differences resulted from different distributions of strains. Thus, this conclusion questions the main assumption of the T-M model that notched bar tests can be replaced by smooth uniaxial tensile tests.

3.3. Fatigue life calculation

The appraisal of the local strains at the notch root modelling has been performed by fatigue life calculation and by the comparison of results obtained with experimental data. The fatigue life calculations have been made for notched specimens used during experimental program. The fatigue life of notched specimens was calculated utilising Morrow's equation [2] in the form

$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ac}}{2} + \frac{\Delta\varepsilon_{ap}}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \,. \tag{3}$$

However, the strains used in this equation were calculated at the notch root as the local strain. The solution of the system of equations describing the hysteresis loop and the Neuber's hyperbola [10] is one of the methods of calculating local stress and strain.

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \,. \tag{4}$$

The Neuber's rule links the nominal stress and strain, and the local stress and strain in the notch zone

$$K_f(\Delta S \Delta e)^{1/2} = (\Delta\sigma\Delta\varepsilon)^{1/2} \,. \tag{5}$$

The notch factor can be defined from Peterson's formula [11],

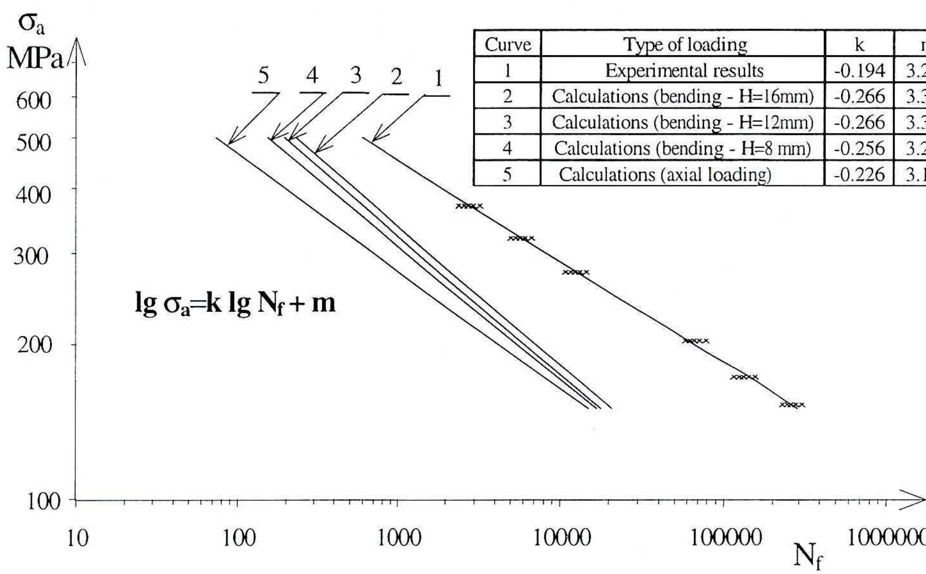
$$K_f = 1 + \frac{K_t - 1}{1 + \alpha/r} \,, \tag{6}$$

where K_t is the theoretical stress concentration factor, r denotes the notch radius and α is a material parameter which may be approximated for steels by the expression $2.32\times10^4 R_m^{-1.8}$ (mm), where R_m is the ultimate strength of material in [MPa].

Experimental data from both uniaxial and plane bending tests have been used. The results of fatigue investigation in a form of fatigue life graph are presented in Fig. 8. Regression lines described by equation

$$\lg \sigma_a = k \lg N_{f+m}, \tag{7}$$

were estimated for particular kinds of loads, which were realised on 6 levels of the stress amplitude varying from 135 to 375 MPa. The experimental results and computed curves are shown in Fig. 8.



Curve	Type of loading	k	m
1	Experimental results	-0.194	3.237
2	Calculations (bending - H=16mm)	-0.266	3.327
3	Calculations (bending - H=12mm)	-0.266	3.300
4	Calculations (bending - H=8 mm)	-0.256	3.258
5	Calculations (axial loading)	-0.226	3.120

Fig. 8. The results of tests and calculation of notched specimens fatigue life

The mutual position of fatigue life curves 1 (for tests results) and 2, 3, 4, 5 (calculations results) shows that calculation results are situated in the safe area of fatigue life. The curve most deviated from the experimental one is curve 5 obtained from calculations based on axial loading data. Significant agreement of calculation results (diagrams 2, 3, 4) and test results (curve 1) was obtained for bending data.

4. Summary

From the results obtained one may conclude:

1. The results of the low cycle fatigue of the normalised 45 steel by bending and uniaxial loading indicate the qualitative similarities of the fatigue processes for these two schemes of loading. This similarity allows for using analogous procedures to describe the phenomena of hardening and weakening of cyclic strain curves and fatigue curves.
2. Variation of hysteresis loop parameters: stress σ_a and bending moment M_g with number of cycles, indicates the phenomena of material hardening and softening. The course of stabilisation process of cyclic properties of the 45 steel in the function of number of cycles under axial loading and bending depends on the strain level.

3. Fatigue life of normalised 45 steel under uniaxial and bending loading differs considerably. Differences are about 20% for low levels of strains and 350 % for high levels of total strain ε_{ac}.
4. Fatigue life of the bent specimens depends on their height within the whole range of strain ε_{ac} used. It indicates the possibility of the quantitative description of the strain gradient influence on the fatigue life.
5. The calculation results based on axial loading data and test results are characterised by high differences. Results presented question the basic assumptions of the T-M model that do not take into account the strain and stress gradients in front of the notch as well as the scale effect. The confirmation of this fact is increasing agreement of the test and calculation results in the case of using in computations the data from bending loading.

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Analiza porównawcza własności niskocyklowych stali 45 podczas obciążenia osiowego i zginania

Streszczenie

W pracy przedstawiono analizę porównawczą wyników niskocyklowych badań zmęczeniowych stali 45 w warunkach obciążenia osiowego i zginania. Przeprowadzona analiza obejmuje między innymi własności cykliczne oraz trwałość zmęczeniową w rozpatrywanych warunkach obciążenia. Metodyka badań przyjęta podczas zginania umożliwiła ponadto ocenę wpływu rozkładu odkształcenia na trwałość. Wyznaczone w rozpatrywanych warunkach obciążenia dane materiałowe wykorzystano do obliczeń trwałości zmęczeniowej elementów konstrukcyjnych. Wyniki badań i obliczeń przedstawiono w formie wykresów zmęczeniowych.

Uzyskane rezultaty wskazują na wpływ źródła danych (obciążenie osiowe lub zginanie) na zgodność wyników obliczeń z wynikami badań.