FATIGUE LIFE OF S355JR STEEL UNDER UNIAXIAL CONSTANT AMPLITUDE AND RANDOM LOADING CONDITIONS

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The results of fatigue tests of samples made of the S355JR steel under random tension-compression with nonzero mean stress are presented. The procedure of experimental research is described. The obtained experimental results are presented with the use of Wöhler fatigue graphs. The algorithm for the determination of the fatigue life uses among other things a rain flow cycle counting procedure as well as the Palmgren–Miner linear damage accumulation hypothesis and six selected models that take into account the effect of the mean stress on the tested durability. The paper presents the charts for comparison of the experimental and computed lives. It is indicated which of the considered models describes the impact of the mean stress on the fatigue life of the tested material within the scatter error 3.

Keywords: *fatigue, mean stress, S355JR steel.*

Introduction. The initial force affecting a structural element and even its inherent weight has a significant influence on the fatigue phenomenon. These types of stresses are called the initial or mean stresses and are often overlooked by designers in the design process of connections or components due to fatigue. In many branches of industry the adequate consideration of the mean stress plays a significant role due to the prevalence of time-varying external forces, as well as internal forces in structures and machine components [9]. We can also mention a particularly important and difficult case which involves the correct consideration of mean stress, which is the case of multi-axial load with nonzero value of the mean stress [3, 4, 6, 7]. In this case no one has been able to propose an efficient and reliable computation model so far. Steels belong to the most common groups of structural materials used in the machines construction mainly due to their availability, price and good mechanical properties [10] or corrosion resistance [2]. The literature review points out that fatigue tests of the S355JR steel, analyzed in this study, are rare. Therefore, the main objective in this work is to verify the developed algorithm [12] determining the fatigue life based on original experimental results. The case of tension-compression of unnotched round specimens with different values of the mean stress is analyzed. The computational algorithm was constructed taking into account the state of knowledge in determining the fatigue life in a random uniaxial stress state. The Rainflow cycle counting procedure, used together with the linear cumulative damage hypothesis by Palmgren–Miner [16] and six selected models which took into account the effect of the mean stress on the fatigue, have been used in the algorithm. The mean stress effect on the fatigue life was taken into account by transforming the stress amplitude designated for each cycle with the Rainflow method. The coefficient K [4, 14] was derived for six models to perform this task.

Description of fatigue tests. The results of original research on the S355JR steel performed on the fatigue testing bench SHM250 for tension-compression are presented. The research was performed under constant as well as random loads. The experiments

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were carried out with two stress ratios $R = -1$ and $R = 0$ for constant amplitude and $R = 0$ for random load. The basic strength properties for the S355JR steel are summarized in Table 1. Its chemical composition is as follows: 0.18 C; 1.3 Mn; 0.45 Si; 0.04 P; 0.03 S; 0.3 Cr; 0.2 Cu; 0.2 Ni; Fe – rest. Test samples used in the research are shown in Fig. 1.

Table 1. Strength properties of the S355JR steel

R_e	R_m	A_{10}	Z	E,	N
MPa		%		GPa	
394	611	20	51	213	0,31

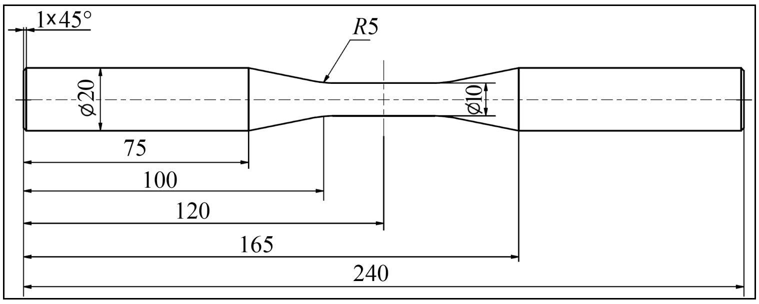


Fig. 1. Shape and dimensions of the fatigue test samples.

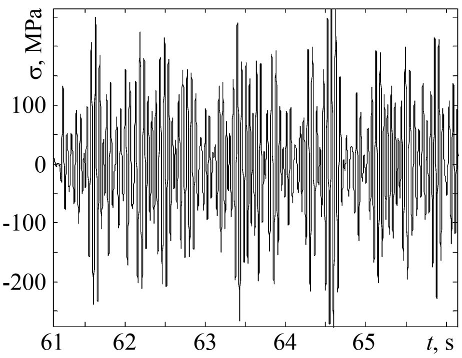


Fig. 2. Record of the sample random stresses used in the experiment before scaling to the appropriate R ratio.

The test samples were prepared according to the ASTM E466-07 [1] standard. The tests for random loading conditions were performed with the use of a special stochastic loading module that had been added to the existing driving software. A cross-section of the used signal is shown in Fig. 2. The used signal has a narrowband characteristic with the dominating frequency of 20Hz. The characteristic of the signals corresponds to the stress observed in the selected structural elements, although they are generated by noise band filtering with a normal distribution. The random tests are performed for random loading with the stress ratio $R = 0$, which means that they were preloaded with the stress equal to the maximum global stress amplitude of the course. The mentioned stress ratio can be calculated using the formula:

$$R = \frac{\sigma_{min}}{\sigma_{max}}, \qquad (1)$$

where σ_{min}, σ_{max} are the minimum and maximum stresses. The results for the constant as well as random amplitude tests are shown in Fig. 3 in the form of Wöhler fatigue life curves.

The crack shape obtained from the experiments was characteristic for the high-cycle fatigue, though it did not demonstrate the formation of a significant narrowing in the diameter of the sample thus indicating a significant strain influence.

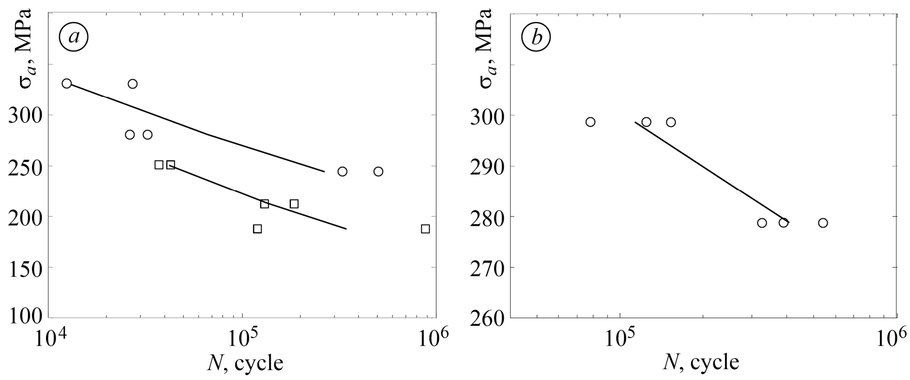


Fig. 3. Experimental results presented in the form of Wöhler curves for S355JR steel:
a – constant amplitude tension-compression for $R = -1$ (○) and $R = 0$ (□);
b – random amplitude tension for $R = 0$ (○).

Mean stress correction equations. In literature there is a large variety of equations taking into account the mean stress. They are the so called correction equations, which define the material with the use of certain strength parameters and subsequently are applied for the scaling of a non-zero mean stress signal (transform) to an equivalent zero mean signal.

In this work the following equations are used:

Gerber equation:

$$\frac{\sigma_a}{\sigma_{aT}} = 1 - \left(\frac{\sigma_m}{R_m}\right)^2, \tag{2}$$

Kwofie:

$$\frac{\sigma_a}{\sigma_{aT}} = \exp\left(-\alpha_K \cdot \frac{\sigma_m}{R_m}\right), \tag{3}$$

Morrow:

$$\frac{\sigma_a}{\sigma_{aT}} = 1 - \frac{\sigma_m}{\sigma'_f}, \tag{4}$$

Goodman:

$$\frac{\sigma_a}{\sigma_{aT}} = 1 - \frac{\sigma_m}{R_m}, \tag{5}$$

Oding:

$$\sigma_{aT} = \sigma_a^2 + \sigma_m \cdot \sigma_a = \sigma_a \cdot \sigma_{\max}, \tag{6}$$

Niesłony–Böhm:

$$\sigma_{aT} = \sigma_a + (\sigma_{a,R=-1} - \sigma_{a,R=0}) \cdot \frac{\sigma_m}{\sigma_{a,R=0}}, \tag{7}$$

where σ_a is stress amplitude; σ_{aT} is transformed stress amplitude; σ_m is mean stress value; R_m is ultimate strength of material; σ'_f is fatigue strength coefficient; α is material mean stress sensitivity coefficient [5]; σ_{af} is fatigue limit for tension-compression; $\sigma_{a,R} = -1$ and $\sigma_{a,R} = 0$ are amplitudes designated from the Wöhler tension curves for ratios $R = -1$ and $R = 0$.

A diagram explaining the above models is presented in Fig. 4. In this paper an attempt is undertaken to verify these classical empirical formulae with the one presented by the authors [12] on the example of experimental results of the S355JR steel. An explanation of the generation of the test signal was presented in the previous section [8]. Nevertheless, the algorithm of the fatigue life calculation can be divided into several main parts e.g.: cycle and half cycle counting from the random course according to the Rainflow method [11]. At present this is the most reliable cycle counting method recommended among other things by the ASTM society.

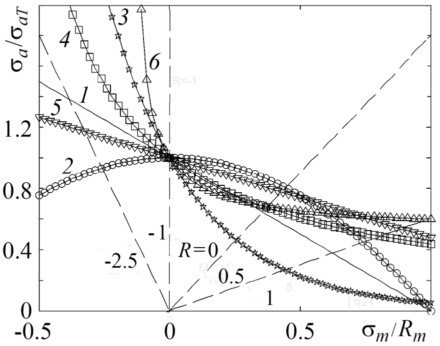


Fig. 4. Diagram explaining the characteristics of some mean stress compensation models according to Kluger and Łagoda [3]: *1* – Goodman; *2* – Gerber; *3* – Kwofe ($\alpha = 0.2$); *4* – NB; *5* – Morrow; *6* – Oding.

As mentioned above, this research deals with verification of the compensation models of equivalent transformed amplitudes due to the mean stress. Five literature proposals and one model developed by the authors have been chosen for the verification. It was assumed that the stress course subjected to transformation was stationary with a constant mean stress value σ_m. In paper [7] it was proven that for this types of stress courses the mean stress can be calculated in a global way. These assumptions allow us to use the following transformation formula:

$$\sigma_{aiT} = \sigma_{ai} \cdot K \ , \tag{8}$$

where σ_{aiT} is the transformed stress amplitude; σ_{ai} is the stress amplitude designated from the equivalent course with the use of the cycle counting algorithm; K is coefficient dependent on the transformation method being the function of the strength parameters and the mean stress value σ_m.

For the K coefficients the appropriate functions are used in the calculation procedure obtained from the models by Oding, Goodman, Morrow, Gerber and Kwofie [4, 11, 13] and presented in Table 2.

Table 2. The *K* coefficient formulas used in the calculation process

Oding (6)	Goodman (5)	Morrow (4)	Gerber (2)	Kwofie (3)
$K = \sqrt{1 + \frac{\sigma_m}{\sigma_a}}$	$K_{Go} = \frac{1}{1 - \frac{\sigma_m}{R_m}}$	$K_M = \frac{1}{1 - \frac{\sigma_m}{\sigma'_f}}$	$K_{Ge} = \frac{1}{1 - \left(\frac{\sigma_m}{R_m}\right)^2}$	$K_K = \frac{1}{\exp\left(-\alpha \cdot \frac{\sigma_m}{R_m}\right)}$

A model developed by the authors is also used [12]. It employs fatigue material parameters obtained from two limit states: tension-compression with the ratio $R = -1$ and one way tension $R = 0$. These parameters have been read out of the appropriate Wöhler curves. It is assumed that the intermediate state between the states of material effort can be described with a linear function. The results for the random $R = -1$ have been taken out from previous experiments for this material. The K_{NB} coefficient is as follows:

$$K_{NB} = 1 + (\sigma_{a,R=-1} - \sigma_{a,R=0}) \cdot \frac{\sigma_m}{(\sigma_{a,R=0})^2} \ . \tag{9}$$

In the cumulative damage process the Palmgren–Miner [16] hypothesis is used:

$$D(N) = \begin{cases} \sum_{i=1}^{j} \frac{n_i}{N_0 (\sigma_{af} / \sigma_{aiT})^m} & \text{for} \quad \sigma_{aiT} \geq a_{PM} \cdot \sigma_{af} \ , \\ 0 & \text{for} \quad \sigma_{aiT} < a_{PM} \cdot \sigma_{af} \ , \end{cases} \tag{10}$$

where $D(N)$ is degree of damage for a number of cycles N; a_{PM} is coefficient allowing to take into account amplitudes beneath σ_{af}; m is Wöhler curve slope for tension-compression; n_i is a number of stress cycles with the amplitude σ_{aiT}; N_0 is number of cycles corresponding to the fatigue limit σ_{af}.

The algorithm last step is the calculation of fatigue life. It is possible after assessing the degree of damage $D(N)$ for a number of cycles existing in a loading unit. The durability in a number of cycles is calculated from the following formula:

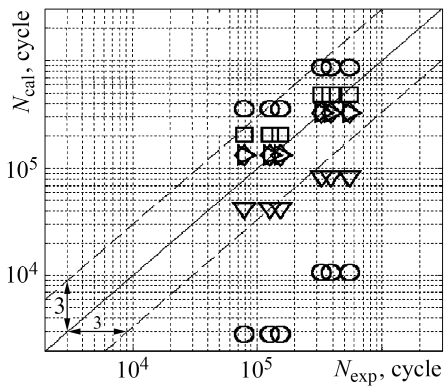
$$N_{\mathrm{cal}} = \frac{N}{D(N)}, \tag{11}$$

where N_{cal} is calculated fatigue life; N is a number of cycles in a unit; $D(N)$ is the whole degree of damage for the observation time.

CONCLUSIONS

Mean stress compensation models have been verified in the random loading conditions. For this purpose a computation algorithm has been used which consists of the rain flow cycle counting procedure as well as the linear Palmgren–Miner cumulative damage hypothesis. The computation results are compared with the experimental ones for six mean stress compensation models as presented in Fig. 5. It can be noticed that the computation results using the Goodman model differ to the greatest degree from the experimental results. Two models – the one proposed by Morrow and the one established by the authors of the paper propose satisfactory results in most cases.

Fig. 5. Comparison of the experimental and calculated fatigue life of the S355JR steel for random R = 0 developed by Niesłony with:
○ – Gerber;
□ – Kwofe;
◇ – Morrow;
O – Goodman;
▽ – Oding;
▷ – Niesłony–Böhm.



Some detailed observations are also formulated: subjecting the S355JR steel to a random loading with a nonzero mean stress results in the lower fatigue life in comparison with the zero mean value case; results from the uniaxial stress state under tension-compression are obtained from transformation models by Gerber, Kwofie, Morrow and the one presented by the authors of this paper which are within the value of scatter of 3. Most of the comparison results using the Oding model are situated in the not accepted scattering area. However it is important to notice that this model is very conservative and doesn't overestimate the fatigue life after amplitude correction. Results obtained by the Goodman model are not found in the accepted scatter area. Due to this fact the model is not suitable for fatigue life prediction for this steel type.

РЕЗЮМЕ. Подані результати випробувань на втому зразків, виготовлених зі сталі S355JR за випадкового стиску–розтягу з ненульовим середнім напруженням. Експериментальні результати подані кривими Велера, а алгоритм передбачає визначення границі втоми шляхом апроксимації встановленої лінійної залежності, гіпотезу накопичення лінійних пошкоджень Palmgren–Miner та вибір з шести моделей, які враховують вплив середнього навантаження на досліджувану довговічність. Подано діаграми, на яких порівняно експериментальну та обчислену довговічності. Вказано, які з розглянутих моделей описують вплив середнього навантаження на втомну довговічність досліджуваного матеріалу в межах похибки 3.

Ключові слова: *втома, середній стрес, S355JR сталь.*

РЕЗЮМЕ. Представлены результаты испытаний на усталость образцов, изготовленных из стали S355JR при случайном сжатии–растяжении с ненулевым средним напряжением. Экспериментальные результаты представлены кривыми Велера, а алгоритм предусматривает определение границы усталости путем аппроксимации установленной линейной зависимости, гипотезу накопления линейных повреждений Palmgren–Miner и выбор из шести моделей, учитывающих влияние средней нагрузки на исследуемую долговечность. Представлены диаграммы сравнения экспериментальной и рассчитанной долговечности. Указано, какие из рассматриваемых моделей описывают влияние средней нагрузки на усталостную долговечность исследуемого материала в пределах погрешности 3.

Ключевые слова: *усталость, среднее напряжение, S355JR сталь.*

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