Acta Sci. Pol.
Architectura 16 (1) 2017, 3–10
acta_architectura.sggw.pl ISSN 1644-0633 DOI: 10.22630/ASPA.2017.16.1.01

ORIGINAL PAPER

Received: 12.01.2017
Accepted: 01.03.2017

FATIGUE STRENGTH OF RIBBED REINFORCING BARS MADE OF THE B500SP STEEL

Olga Szlachetka✉[1], Marek Dohojda[1], Ryszard Mazurczuk[1], Małgorzata Lusawa[2]

[1] Faculty of Civil and Environmental Engineering, Warsaw University of Life Sciences – SGGW, Warsaw, Poland
[2] Warbud S.A., Warsaw, Poland

ABSTRACT

In the paper, the fatigue strength of ribbed reinforcing bars, not embedded in concrete, with the diameter of 32 mm, made of the B500SP steel grade for pulsating tensile stress, has been determined. The fatigue tests were performed on the Instron 8806 machine under axial tensile loading. Each of the fatigue tests was run until damage or up to $2 \cdot 10^6$ cycles of loading. The fatigue tests were performed on 12 specimens. The specimens were cut from one bar of the length 12 m. The fatigue strength of the steel being tested was determined by the classical method consisting in making of a Wöhler curve (S – log N curve). The determined fatigue strength Z_{rj} = 135 MPa for $2 \cdot 10^6$ cycles constitutes ca. 22% of the tensile strength and also is much lower than the yield point (it is ca. 26% of its value). The paper identifies the factors that may affect the value of the fatigue strength.

Key words: fatigue tests, strength of materials, reinforcing bar, B500SP steel

INTRODUCTION

Ribbed reinforcing bars have numerous applications in building engineering. They can be found in beams, slabs, foundations etc. Presently, reinforcing bars are made of numerous steel grades characterised by high strength values. Reinforced concrete structures such as bridges, crane beams or various coastal structures are exposed to changing loads (Krasnowski, 2015), that is why the fatigue strength of ribbed reinforcing bars is very important.

Material fatigue is a gradual damage resulting from occurring and development of cracks as an effect of repeating, periodically variable stresses (Łubiński, Filipowicz & Żółtowski, 2005). Cyclic stresses which cause a fatigue fracture are not only lower than ultimate strength (R_m) but can also be significantly smaller than proportional limit stress (R_e or $R_{p0.2}$) – Banasiak (2000). An additional danger of fatigue fracture consists in the fact that they occur abruptly and unexpectedly (Buch, 1964).

Fatigue tests are usually carried out with ferroconcrete elements (Furtak, 1985), often additionally reinforced by carbon fibers CFRP bands (Kaiser, 1989; Deuring, 1993; Derkowski, 2006). The tests with reinforcing bars not embedded in concrete are carried out relatively rarely (Tilly, 1979).

In the axial force fatigue testing the specimen is loaded so that the stress changes cyclically according to a sinusoidal wave-form (PN-EN ISO 15630-1:2011). Steel for the reinforcement and prestressing in concrete) (Fig. 1).

✉olga_szlachetka@sggw.pl

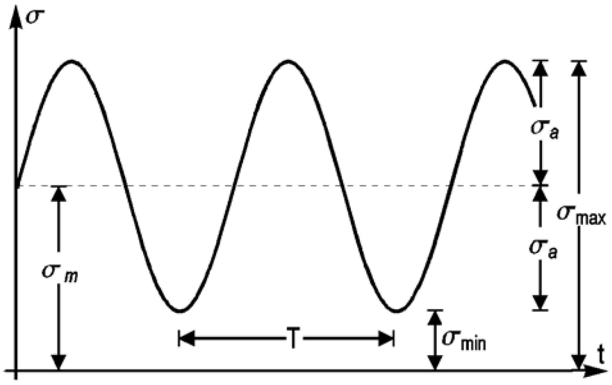


Fig. 1. Stress cycle diagram

Stress changes between a maximum $\sigma_{\max}$ and minimum $\sigma_{\min}$ tensile stress. The mean stress (σ_{m}) is the algebraic average of the maximum stress and the minimum stress in one cycle T:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{1}$$

The stress amplitude σ_a is equal to:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{2}$$

The range of stress $\Delta\sigma$ is the algebraic difference between the maximum stress and the minimum stress in one cycle:

$$\Delta\sigma = 2\sigma_a = \sigma_{\max} - \sigma_{\min} \tag{3}$$

The cycle type is specified by two factors R and κ. Factor R is the ratio of the minimum stress to the maximum stress, and factor κ is the ratio of the stress amplitude to the mean stress:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}, \qquad \kappa = \frac{\sigma_m}{\sigma_a} \tag{4}$$

When $\sigma_a = \sigma_m$ and $\sigma_{\min} = 0$ then this is a pulsating or repeated tensile stress ($R = 0$, $\kappa = 1$). When both the maximum and minimum stresses are tensile stresses and the stress rations are $1 < \kappa < +\infty$, $0 < R < 1$ then this is a fluctuating tensile stress. For more cycle types where R can take range from +1 to –1 see Boardman (1990).

Requirements for fatigue strength tests depend on the grades of reinforcing bars (IBDiM, 2007; ITB, 2011). For example the results of investigations on BSt500S steel bars (ductility class B) with the diameter of 16 mm and mechanical properties shown in Table 1 were presented by Łyszczarz, Olber & Korczak (2011).

Table 1. Mechanical properties of bars made of the BSt500S steel (Łyszczarz et al., 2011)

Diameter [mm]	Yield point R_e [MPa]	Tensile strength R_m [MPa]	Percentage total elongation at maximum force A_{gt} [%]
16	573	641	9.9

The fatigue tests described by Łyszczarz et al. (2011), were carried out for samples exposed to fluctuating tensile stress. The maximum load of the first specimen was set in such way that the maximum stress was equal $0.7R_e$ i.e. $F_{up} = 81$ kN. The number of cycles was programmed as $2 \cdot 10^6$, according to the standard PN-EN ISO 15630-1:2011. The practical endurance limit of the bar with the cross section area equal $S_n = 201.29$ mm^2 amounted 108.58 MPa (Table 2).

Table 2. Parameters obtained in the tests – damage of the bar made of the BSt500S steel (Łyszczarz et al., 2011)

Number of cycles N	Force range F_r [N]	Maximum force F_{up} [N]	Practical endurance limit [MPa]	Stress ratio R [–]
1,302,798	13,825.87	21,857.68	108.58	0.632

AIM OF THE PAPER

The aim of this paper is to determine the fatigue strength Z_{rj} of ribbed reinforcing bars, not embedded in concrete, with the diameter of 32 mm, made of the B500SP steel (PN-H-93220:2006). Stal B500SP o podwyższonej ciągliwości do zbrojenia betonu), for pulsating tensile stress ($R = 0$, $\kappa = 1$). The fatigue tests were performed according to the standard PN-EN-15630-1:2011 under axial tensile loading. Each of the fatigue tests was run until damage or up to $2 \cdot 10^6$ cycles of loading, whichever comes first.

MATERIAL AND METHODS

The tests were performed in the Laboratory – Water Centre of the Faculty of Civil and Environmental Engineering at the Warsaw University of Life Sciences (SGGW), in the Strength of Materials and Building Constructions Laboratory. Part of the results was used in a MSc. thesis by Lusawa (2014).

The fatigue tester applied in the tests is an INSTRON 8806 machine (Fig. 2). It is a hydraulic machine for testing various types of structural materials subjected by tensile as well as compressive loadings within the range up to 2,500 kN, both for static and fatigue loadings.

The tests were performed on 15 specimens of ribbed reinforcing bars in total made of the B500SP steel, manufactured in the CELSA steel mill in Ostrowiec Świętokrzyski. The bars had the diameter $d = 32$ mm, cross section area $S_n = 804$ mm^2 and length $L = 800$ mm. The specimens were cut from one bar of the length 12 m to obtain as homogeneous testing material as possible.

It must be emphasized that, in the case of the fatigue testing, the rectilinearity of specimens is of great importance. They can be straightened manually (if it is possible) or with application of a straightener. In the case of the specimens being tested there was no need to straighten them.

The fatigue strength of the steel being tested was determined by the classical method consisting in making of a Wöhler curve

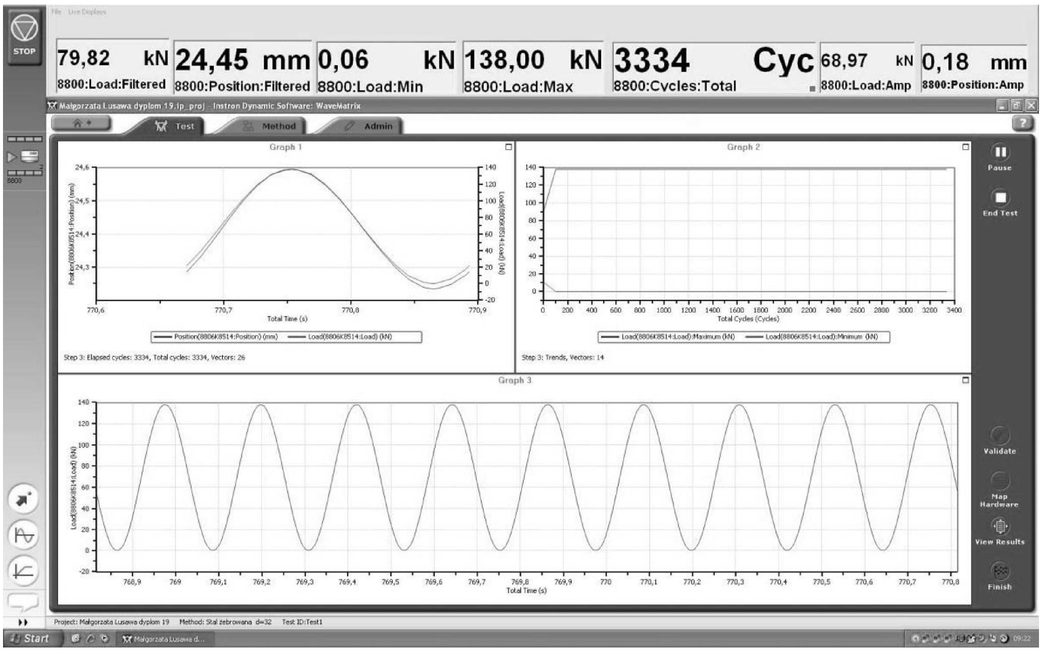
Fig. 2. Specimen № 5 during the test

(*S*-*N* curve). The investigations started from static tests to determine the ultimate strength R_m and proportional limit stress R_e for the steel. The test was performed according to the standard PN-EN 6892-1:2010. Metallic materials. Tensile testing.

Then, getting down to the fatigue tests, the first specimen was loaded until the tension stress $\sigma_{\max}$ achieved ca. 0.67 R_m ($\sigma_{\min} = 0$, $\sigma_m = \sigma_a = 0.5\ \sigma_{\max}$) – Kocańda (1985). After the first specimen had been damaged, the next ones were further loaded so as to achieve each time increasingly lower maximum stresses $\sigma_{\max}$. In total, twelve specimens were loaded in such a way.

Up to the sixth specimen inclusive, in the consecutively following tests, the differences ca. 40 MPa were assumed and applied between the values of the stress $\sigma_{\max}$. The values $\sigma_{\max}$ of the consecutive tests were chosen basing on the initial points on the Wöhler curve. Such a reduction of the stresses enabled to obtain greater and greater number of cycles *N* causing the specimen's damage. Only one from the tested specimens survived, withstanding over $2 \cdot 10^6$ loading cycles. The frequency of the loading cycles felt into the range 3.5–4.5 Hz.

To handle the data from the fatigue tests, the Instron WaveMatrix computer program was applied. Figure 3 presents a window of the Instron WaveMatrix program with displays and graphs depicting the run of the tests.



79,82 kN 8800:Load:Filtered
24,45 mm 8800:Position:Filtered
0,06 kN 8800:Load:Min
138,00 kN 8800:Load:Max
3334 Cyc 8800:Cycles:Total
68,97 kN 8800:Load:Amp
0,18 mm 8800:Position:Amp

Małgorzata Lusawa dyplom 19.ip_proj - Instron Dynamic Software: WaveMatrix

Step 3: Elapsed cycles: 3334, Total cycles: 3334, Vectors: 26

Step 3: Trends, Vectors: 14

Project: Małgorzata Lusawa dyplom 19 Method: Stal zebrowana d=32 Test ID:Test1

Fig. 3. Instron WaveMatrix program window during a test

RESULTS OF INVESTIGATIONS

Static tests

The average values of the tensile strength and the yield point, obtained in the performed static tests, are presented in Table 3. The value of the yield point was calculated according to the algorithm of the Bluehill program according to the standard PN-EN ISO 6892-1:2010.

Basing on the tests results, it can be stated that the steel under consideration is a high ductility steel. It is well seen in the elongated form of the fracture (Fig. 4).

Table 3. Results of static tests

Specification	Tensile strength R_m [MPa]	Yield point R_e [MPa]
Average values	615.32	516.92
Standard deviation [MPa]	0.44	0.64

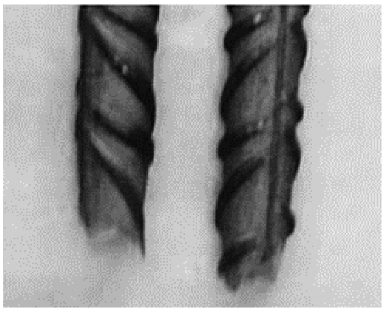


Fig. 4. Fracture of the specimen № 1 in static tensile test

Fatigue tests

The specimens had cross section area $S_n = 804$ mm^2 and free length between the grips 450 mm. The first specimen was loaded according to the methodology described above. The stress $\sigma_{\max}$ was equal 0.67 $R_m = 0.67 \cdot 615.32$ MPa ≈ 412 MPa ($\sigma_{\min} = 0$, $\sigma_m = \sigma_a = 206$ MPa). The next specimens were subjected to the loads giving smaller maximum values. The test parameters are presented in Table 4. Table 5 presents the results of the fatigue tests. In the column 2, the number of cycles is written after which the given specimen has broken (except for the specimen № 12 which withstood $2 \cdot 10^6$ loading cycles and did not break).

Table 4. Parameters of the performed fatigue tests

Specimen №	Frequency f [Hz]	Maximum stress $\sigma_{\max}$ [MPa]	Minimum stress $\sigma_{\min}$ [MPa]	Stress amplitude, average stress $\sigma_a = \sigma_m$ [MPa]	Maximum force F_{up} [kN]	Force range $F_r = 2\,\sigma_a \cdot S_n$ [kN]
1	3.5	412.94	0	206.47	332	332
2	3.5	373.13	0	186.57	300	300
3	3.5	330.85	0	165.42	266	266
4	3.5	288.56	0	144.28	232	232
5	3.8	251.24	0	125.62	202	202
6	4.0	211.44	0	105.72	170	170
7	4.5	191.54	0	95.77	154	154
8	4.5	191.54	0	95.77	154	154
9	4.5	171.64	0	85.82	138	138
10	4.5	151.74	0	75.87	122	122
11	4.5	144.28	0	72.14	116	116
12	4.5	131.84	0	65.92	106	106

As it follows from the above reasoning, it's possible to identify a safe limit of stress level, below which the sample will not brake, regardless of the number of load cycles.

Four specimens were rejected because the test conditions were not fulfilled (the specimens broke in the jaw or in its vicinity). This is a typical problem that occurs during fatigue test of reinforcing bars (Krasnowski, 2015). During testing the specimen № 9, the testing machine stopped after 850,544 cycles because of the power failure, which lasted around 35 minutes. According to Kocańda (1985) short interruptions in loading do not affect negatively a test result, that is why the test was restarted after this 35 minutes and specimen was accepted. The results for the accepted specimens served to draw the Wöhler curve presented in Figure 5.

Table 5. Results of fatigue tests for the individual specimens

Specimen №	Number of cycles N	Stress σ_{max} [MPa]	Maximum force F_{up} [kN]	Remarks
1	30,186	412.94	332	
2	26,532	373.13	300	broken in the jaws (specimen rejected)
3	159,057	330.85	266	
4	220,011	288.56	232	
5	364,425	251.24	202	
6	491,699	211.44	170	
7	222,902	191.54	154	broken in the jaws (specimen rejected)
8	350,608	191.54	154	broken in the jaws (specimen rejected)
9	1,244,090	171.64	138	the machine stopped after 850,544 cycles, after 35 min. the test was restarted
10	1,543,530	151.74	122	
11	940,011	144.28	116	broken in the jaws (specimen rejected)
12	2,000,000	131.84	106	not broken

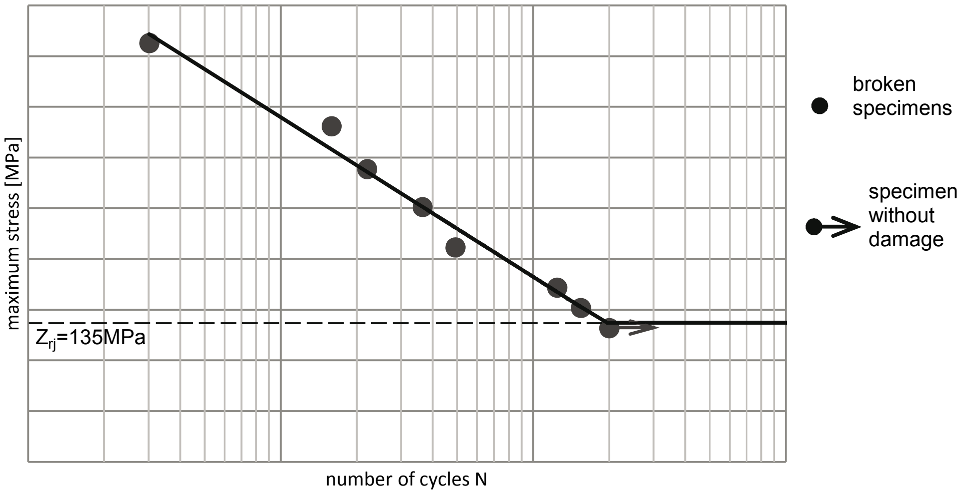


Fig. 5. Wöhler curve σ_{max} – log N for $\sigma_{min} = 0$

The regression curve for the obtained results is described by the equation:

$$\sigma_{max} = -68.41 \log N + 1{,}127.5 \tag{5}$$

and the correlation coefficient is equal $R^2 = 0.9805$. The regression curve equation was determined in MS Excel. To determine the correlation coefficient R^2 was used the least squares method.

The approximated value of practical endurance limit amounts ca. 152 MPa (number of cycle 1,543,530). To obtain more exact value of the practical endurance limit, more points in the lower part of the Wöhler curve is needed.

Using the Wöhler curve (Fig. 5), for $2 \cdot 10^6$ cycles, the endurance limit has been determined from Eq. (5), as equal $Z_{rj} = 135$ MPa.

The fatigue fractures of the tested specimens are of the character of brittle fractures. When analysing the fatigue fracture of the specimens, a fatigue damage zone as well as the immediate damage zone can be easily distinguished (Fig. 6).

The fatigue damage zone has a characteristic smooth and snail-shell-like surface. The immediate damage zone is coarse-grained. The higher the stress level, the less smooth the fatigue damage zone. Along with the reduction of the stress values the share of the fatigue damage zone increases in comparison to the immediate damage zone.

The fatigue fractures in the specimens very often (in four cases) arose in the clamp or in the distance smaller than twice the diameter of the bar.

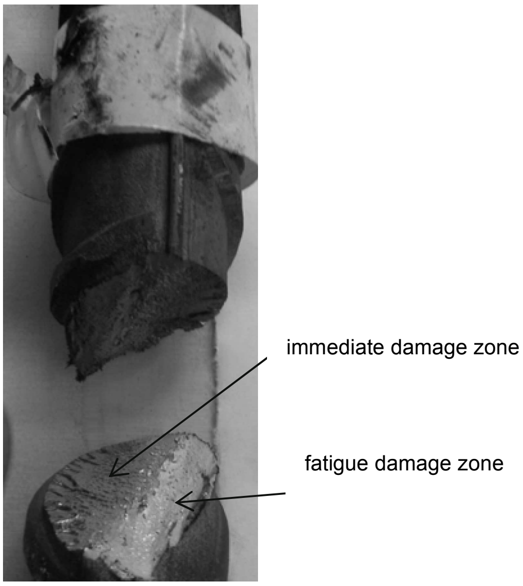


Fig. 6. Fatigue fracture of the specimen № 4

It must be emphasized here that the determined Wöhler curve (Fig. 5) presents the number of cycles N after which the fracture arose, but the process of fatigue had started considerably earlier. It is proven by fatigue cracks occurring on the specimens.

CONCLUSIONS

The fatigue of the reinforcing steel is not fully recognized, described and worked out as a phenomenon. The loads changing cyclically evoke very complicated processes in materials. Among researchers still exist a lot of theories and hypotheses concerning causes triggering off the fatigue cracks.

The determined fatigue strength $Z_{rj} = 135$ MPa for $2 \cdot 10^6$ cycles constitutes ca. 22% of the tensile strength and is also much lower than the yield point (it is ca. 26% of its value). The determined value of the fatigue strength could be affected mainly by two factors. As it was highlighted by Zakrzewski and Zawadzki (1983), materials are more prone to the fatigue under the frequency of 10 Hz. However it must be emphasized here that according to the standards PN-EN ISO 15630-1:2011 and PN-H-93220:2006 the acceptable frequency of load changes falls into the range between 1 and 200 Hz. Moreover, the reduction of the fatigue resistance of the specimens could be undoubtedly affected by their ribbing and structure heterogeneity, arising during shaping. The disadvantageous influence of the ribs results mainly from the phenomenon of the notch. These doubts should be dispelled in further investigations, e.g. metallurgic tests concerning the structure of the bars.

REFERENCES

Banasiak, M. (2000). *Ćwiczenia laboratoryjne z wytrzymałości materiałów*. Warszawa: Wydawnictwo Naukowe PWN.

Boardman, B. (1990). Fatigue Resistance of Steels. *Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1. *ASM Hadbook.* (pages 673–688). ASM International.

Buch, A. (1964). *Zagadnienia wytrzymałości zmęczeniowej*. Warszawa: Wydawnictwo Naukowe PWN.

Derkowski, W. (2006). Badania wpływu wzmocnienia taśmami z polimeru i włókien węglowych na trwałość zmęczeniową zginanych belek żelbetowych. *Zeszyty Naukowe. Budownictwo / Politechnika Łódzka*, *(55)*, 10–16.

Deuring, M. (1993). *Verstärken von Stahlbeton mit gespannten Faserverbundwerkstoffen*. Unpublished doctoral thesis, Bericht, 224, Dübendorf: EMPA.

Furtak, K. (1985). Nośność przekrojów normalnych w zginanych elementach żelbetowych poddanych obciążeniom zmiennym ze szczególnym uwzględnieniem obiektów mostowych. *Budownictwo Lądowe, 64.* Kraków: Wydawca Politechnika Krakowska.

Instytut Badawczy Dróg i Mostów [IBDiM], (2007). *Aprobata techniczna IBDiM nr AT/2007-03-223. Pręty żebrowane do zbrojenia betonu BSt 500 S.* Warszawa.

Instytut Techniki Budowlanej [ITB], (2011). *Aprobata techniczna ITB nr AT-15-6740/2011. Stalowe pręty i walcówka żebrowana B500SP do zbrojenia betonu.* Warszawa.

Kaiser, H. P. (1989). *Strengthening of reinforced concrete with epoxy-bonded carbon fibre plastics*. Unpublished doctoral thesis, Dissertations ETH, 8918, Zurich, Ch-8092, Switzerland.

Kocańda, S. (1985). *Zmęczeniowe pękanie metali*. Warszawa: Wydawnictwo Naukowo-Techniczne.

Krasnowski, K. (2015). Concrete-reinforcing steel bars-applications and fatigue tests. *Biuletyn Instytutu Spawalnictwa*, *(1)*, 13–20**.**

Lusawa, M. (2014). *Badania zmęczeniowe prętów żebrowanych o średnicy 32 milimetry ze stali B500SP*. Praca magisterska. Szkoła Główna Gospodarstwa Wiejskiego w Warszawie, Warszawa.

Łubiński, M., Filipowicz, A. & Żółtowski, W. (2005). *Konstrukcje metalowe. Cz. 1.* Warszawa: Wydawnictwo Arkady.

Łyszczarz, P., Olber, B. & Korczak, A. (2011). Badania zmęczeniowe prętów żebrowanych ze stali BSt500S. In H. Dyja (ed.), *XII Międzynarodowa Konferencja Naukowa „Nowe technologie w metalurgii i inżynierii materiałowej”* (pages 474–477). Częstochowa: Wydawnictwo Politechniki Częstochowskiej.

PN-EN ISO 6892-1:2010. Metallic materials. Tensile testing. Part 1: Method of test at room temperature.

PN-EN ISO 15630-1:2011. Steel for the reinforcement and prestressing in concrete. Test methods. Part 1: Reinforcing bars, wire rod and wire.

PN-H-93220:2006. Stal B500SP o podwyższonej ciągliwości do zbrojenia betonu. Pręty i walcówka żebrowana.

Tilly, G. P. (1979). Fatigue of steel reinforcement bars in concrete: a review. *Fatigue & Fracture of Engineering Materials & Structures*, *2(3)*, 251–268. doi: 10.1111/j.1460-2695.1979.tb01084.x.

Zakrzewski, M. & Zawadzki, J. (1983). *Wytrzymałość materiałów*. Warszawa: Wydawnictwo Naukowe PWN.

WYTRZYMAŁOŚĆ ZMĘCZENIOWA PRĘTÓW ŻEBROWANYCH ZE STALI B500SP

STRESZCZENIE

W pracy określono wytrzymałość zmęczeniową żebrowanych prętów zbrojeniowych, w stanie niezabetonowanym, o średnicy 32 mm, wykonanych ze stali B500SP, przy naprężeniach jednostronnie rozciągających w cyklu odzerowo tętniącym. Badania zmęczeniowe wykonano przy obciążeniu osiowym na maszynie Instron 8806. Każdą próbę zmęczeniową prowadzono do pęknięcia lub do osiągnięcia $2 \cdot 10^6$ cykli obciążeń. Badaniom zmęczeniowym poddano 12 próbek. Próbki były cięte z jednego pręta długości 12 m. Wytrzymałość zmęczeniową badanej stali wyznaczono metodą klasyczną, polegającą na sporządzeniu wykresu Wöhlera (S – log N). Wyznaczona wytrzymałość zmęczeniowa Z_{rj} = 135 MPa dla $2 \cdot 10^6$ cykli stanowi około 22% wartości wytrzymałości na rozciąganie i jest również dużo mniejsza niż granica plastyczności (stanowi około 26% jej wartości). W pracy określono czynniki mogące mieć wpływ na wyznaczoną wartość wytrzymałości zmęczeniowej.

Słowa kluczowe: badania zmęczeniowe, wytrzymałość materiałów, pręt zbrojeniowy, stal B500SP