INVESTIGATION OF THE VARIABILITY OF EPSTAL STEEL STRENGTH PARAMETERS

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The paper deals with the variability of mechanical properties of EPSTAL steel rods produced in Polish steelworks, i.e. yield stress Re, tensile strength Rm, and elongation Agt. Our study is based on fundamental engineering static room-temperature tensile tests for large series specimens which have been made by manufacturers as the part of a factory quality control. Statistical analysis of these results shows that the stress-strain relationship of steel tensile tests should be described by a one-dimensional stochastic process, and three the most important mechanical parameters, i.e. the yield stress, tensile strength, and elongation by random variables. Based on the statistical elaboration of experimental data, it was found that the yield stress and tensile strength of steel rods produced in the years 2016 - 2017 had the coefficients of variation of less than 3%, and there is a reasonable basis for the manufacturer to increase the characteristic value of EPSTAL steel rods yield stress by a few percentages.

Keywords: EPSTAL steel bars, yield stress, tensile strength, elongation, random variables, histograms, main descriptors of a random variable.

1. INTRODUCTION

EPSTAL steel is reinforcing steel for reinforced concrete structures. It meets the requirements for the grade of B500SP according to the standards of PN-H-93220 [1] and PN-EN 10080 [2]. It also meets the requirements of class C according to the Eurocode 2 [3] and the class of A-IIIN according to the old Polish standards of PN-B-03264 [4] and PN-S 10042 [5]. The grade B500SP means that the steel is intended for use in construction (B), with the characteristic yield stress of 500 MPa, weldable steel (S), and with increased ductility (P).

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EPSTAL steel is characterized by the following mechanical properties:

- strength and strain parameters characterized by high stability,

- resistance to dynamic loads: fatigue and cyclic,

- bending resistance with deflecting,

- very good bond to concrete,

- weldability in the full range of bar diameters, i.e. from 8 to 40 mm.

The static tensile test is the basic method for determining the strength and strain properties of steel. Full information on the principle of performing the tensile test of steel, the shape and dimensions of the samples with the determination of the test parameters, i.e. the values of strength, elongation, and narrowing of the samples along with what the test report should contain, is given in the standard PN-EN ISO 6892-1 [6]

The purpose of this article is to examine the variability of strength and elongation parameters of EPSTAL steel produced in Polish steelworks, i.e. the yield stress R_e, tensile strength R_m, and elongation A_{gt} under the highest load. Our study is based on fundamental engineering static room-temperature tensile tests for large series specimens which have been made by manufacturers as the part of a factory quality control. Statistical analysis of these results showed that the stress-strain relationship of steel tensile tests should be described, in the terms of probability theory, as a one-dimensional stochastic process and three the most important mechanical parameters, i.e. the yield stress, tensile strength, and elongation under the highest load, as random variables. Based on the statistical elaboration of experimental data, it was found, that the yield stress and tensile strength of steel bars produced in the years 2016 - 2017 had the coefficients of variation less than 3%, and there is a reasonable basis for the manufacturer to increase the characteristic value of the steel bars yield stress by a few percentage.

2. TENSILE TEST OF EPSTAL STEEL AS A RANDOM PHENOMENON DESCRIBED BY A ONE-DIMENSIONAL STOCHASTIC PROCESS

Let us consider an experiment, in which some number (n) of EPSTAL steel specimens of the same diameter is tested to determine their mechanical properties (a static tensile test). For example, for a reinforcing rod with a diameter of 16 mm, after testing ten samples, the following results for the yield stress, tensile strength, and elongation under the highest load are presented in Table 1.

A question arises: which values should be considered as the yield stress, tensile strength, and elongation under the highest load? For such the question, there is no answer in a set of deterministic quantities, i.e. in a set of quantities that are exactly known. Such the question can be answered only in a set of probabilistic concepts, i.e. using the concepts of the probability theory, which describes random phenomena. Observing such phenomena, we state that in a given test the actual outcomes are (to some degree) unpredictable. Such phenomena are characterized by experimental observations, that are invariably different from one test to another (even if performed under identical conditions). In the case of EPSTAL steel, the main sources of variation in the values of the mechanical parameters R_e, R_m, and A_{gt} are:

− the variability of the material properties for the production of ingots, i.e. scrap and ferroalloys (especially the variability of the chemical composition of scrap metal is of decisive importance here and is reflected in the property variation),
− in the rolling process: the temperature distribution of the ingot on its length and variability of water parameters in controlled cooling after the last rolling stand (pressure and flow).

Table 1. The yield stress, tensile strength, and maximum elongation for 10 static tensile tests of 16 mm diameter rods

R_e [MPa]	R_m [MPa]	A_{gt} [%]
535	621	14,5
539	631	15
539	636	14
535	638	13,1
555	652	14,3
566	652	13,1
538	636	13
535	635	13,4
548	638	15,6
553	646	15,1

It is possible to control these variations only within certain limits, e.g. by adjusting the water flow to obtain the most uniform strength properties and additionally by setting the appropriate ingot heating strategy to reduce the temperature spread over the band-length. After one tensile test of the steel sample, we obtain a stress-strain diagram which is recorded with the function $\sigma(\varepsilon)$. Let us consider the experiment, in which we made 15 tensile tests of steel specimens, and received 15

stress-strain diagrams. Let us assume that we compiled these charts in one common drawing shown in Fig. 1. From this figure, we conclude that the graphs do not overlap with uncertain, accidental discrepancies between them. Therefore, at the present stage of knowledge, tensile tests of steel samples and stress-strain diagrams derived from them should be described with a one-dimensional stochastic process, which mathematically describes the relationship $\sigma(\varepsilon, e)$, where e is an elementary event consisting in a tensile test of a steel specimen.

From an engineering point of view, the following interpretation of the stochastic process $\sigma(\varepsilon, e)$ is preferable (Ang and Tang [7], Chmielewski [8]):

a) let us suppose that the elementary event e_1 occurred, i.e. we made the tensile test on one specimen and received the function $\sigma(\varepsilon, e_1) = \sigma(\varepsilon)$ (because e_1 is fixed) which we call the implementation of the stochastic process. After doing n tensile tests we get n implementations of the process. Example 15 of implementations are shown in Fig. 1,

b) let ε be determine, e.g. $\varepsilon = 1\%$, and e is variable. Then we get a cross-section of the process which is a random variable. Two sections are important for construction engineers, the first for the yield stress Re, the second for the tensile strength Rm,

c) let ε be determine and e determine, then we only get a number, that we call the state of the process.
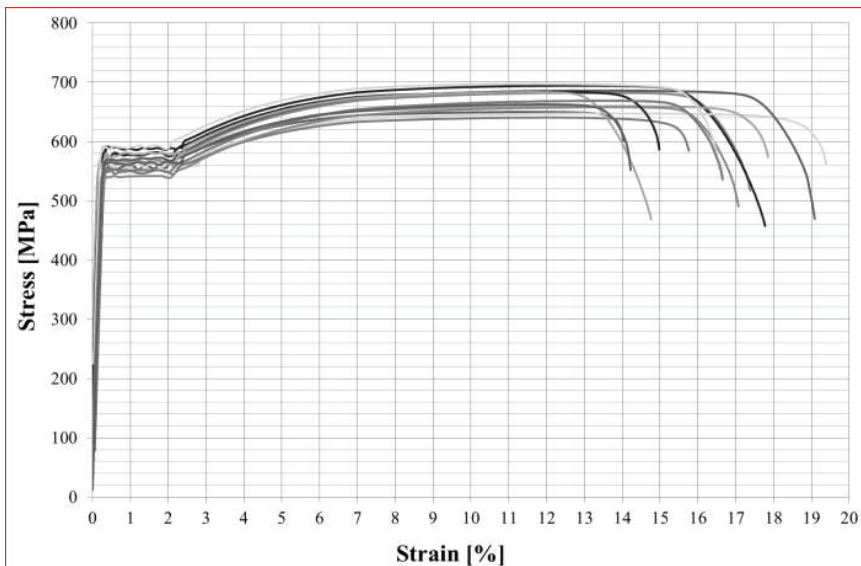

Fig. 1 The collection of stress-strain diagrams for 15 steel samples subjected to the tensile test, which constitutes 15 implementations of the stochastic process $\sigma(\varepsilon, e)$

3. EXPERIMENTAL STUDIES OF RANDOM VARIABLES R_E, R_M AND A_{GT}, THEIR HISTOGRAMS AND NUMERICAL PARAMETERS

The full probabilistic descriptions of the continuous random variables R_e, R_m, and A_{gt} are their probability distributions, i.e. cumulative distribution functions or probability density functions. If they are known, on their basis we can calculate the probabilities of possible events, as well as main descriptors of random variables, e.g. mean values, variances, standard deviations, etc.

In order to learn the aforementioned values and properties, it is necessary to collect experimental data which in our case is performed by producers as part of factory quality control. For the authors, the above data is the basis for statistical inference for the needs of civil engineers.

Statistical inference includes the following steps:

- collecting n experimental data for each random variable which we call a trial,
- preparing histograms and calculating selected main descriptors for them,
- adopting the theoretical probability distribution and conducting its verification on the basis of statistical tests.

In order to investigate the variability of the strength and elongation parameters of EPSTAL steel reinforcing bars, the following assumption regarding the number of samples was adopted. The number of static tensile tests of bar samples with the same diameters made in a specific year was taken for the number of samples and the histograms were constructed for them, on the basis of which the selected estimators of main descriptors were calculated. For example, Figs. 3, 5, and 7 show histograms of yield stress, tensile strength and elongation under the highest load of reinforcing bar of diameter = 16 mm produced in 2016, where n is the sample size, $\overline{R_e}$, $\overline{R_m}$, and $\overline{A_{gt}}$ are the average values of the trial, s is the standard deviation of the trial, v is the coefficient of variation of the trial, $R_{e,5\%}$ is the experimental characteristic value, R_{emin} is the smallest value of the trial, R_{emax} is the largest value of the trial. Figs. 4, 6, and 8 show histograms with the same main descriptors for reinforcing bar of diameter = 16 mm, but produced in 2017. Figs. 9 and 10 show histograms with their main descriptors for reinforcing bars for all their diameters, i.e. 10, 12, 16, 20, 25, 28, 32 mm.

4. CHARACTERISTIC VALUES OF THREE RANDOM VARIABLES R_E, R_M, AND A_{GT} OF EPSTAL STEEL

The standard PN-EN 1990 (2004) which is the basic standard of construction engineers, in Section 4.2 *"Properties of materials and products"* gives the following definitions of material properties:
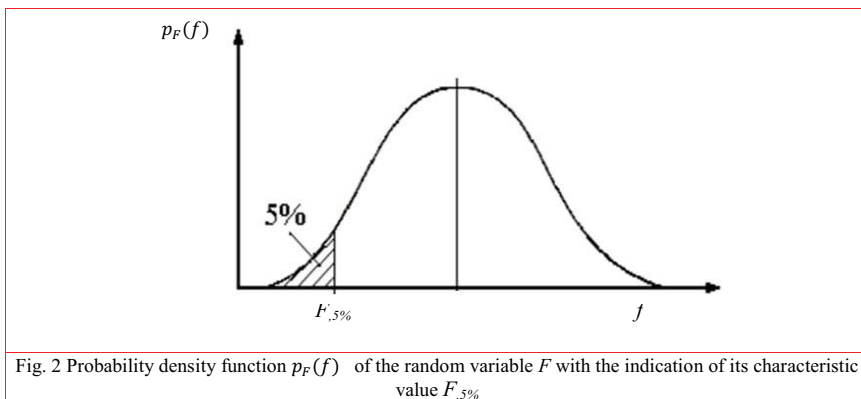
(1) It is recommended that the material properties (including soil and rock) or products are determined by their characteristic properties.

(2) Unless otherwise stated in EN 1991 to EN 1999: when the lower material value is unfavorable, the characteristic value is to be set as 5% quantile.

On the basis of the above mentioned standard, the characteristic strength of random variables of yield stress and tensile strength which we refer to as $R_{e,5\%}$ and $R_{m,5\%}$, is defined as follows: "these are strength values below which 5% of the population of all possible strength determinations can be found", i.e. the values of both strengths achieved by a minimum of 95% of the samples tested for a given series of trials . In a similar way, we define the characteristic value of the variable of the elongation Agt. From the probability calculus, the characteristic value of the continuous random variable F is defined precisely as the quantile of 0.05 (5%). For the probability density function $p_F(f)$ the characteristic value is defined as

$$\int_{-\infty}^{F,5\%} p_F(f)\, df = 0.05 \,. \tag{1}$$
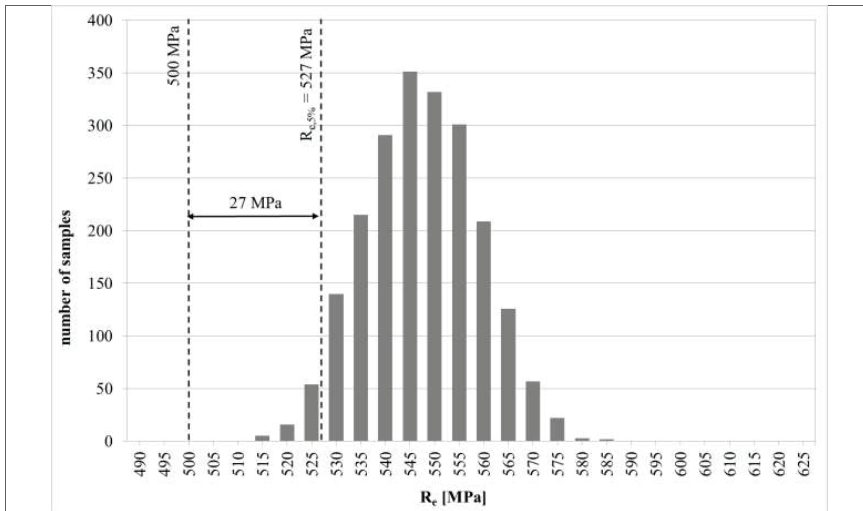
Graphical interpretation of Eq. (1) is shown in Fig. 2.

Fig. 2 Probability density function $p_F(f)$ of the random variable F with the indication of its characteristic value $F_{,5\%}$

Fig. 3 Histogram of yield stress of 16 mm diameter bars, 2016 results: n = 2124, $\overline{R_e}$ = 545 MPa, s = 11.397 MPa, ν = 2.09 %, Re,5% = 527 MPa, Re,min = 513 MPa, Re,max = 581 MPa
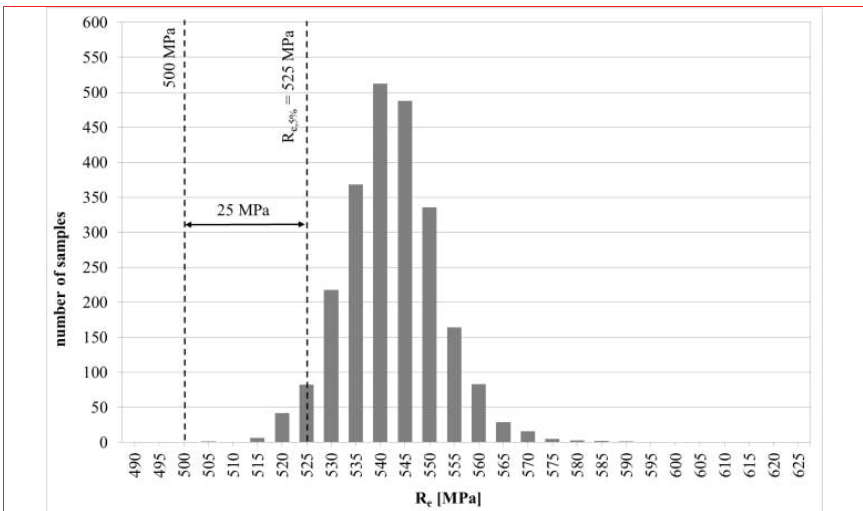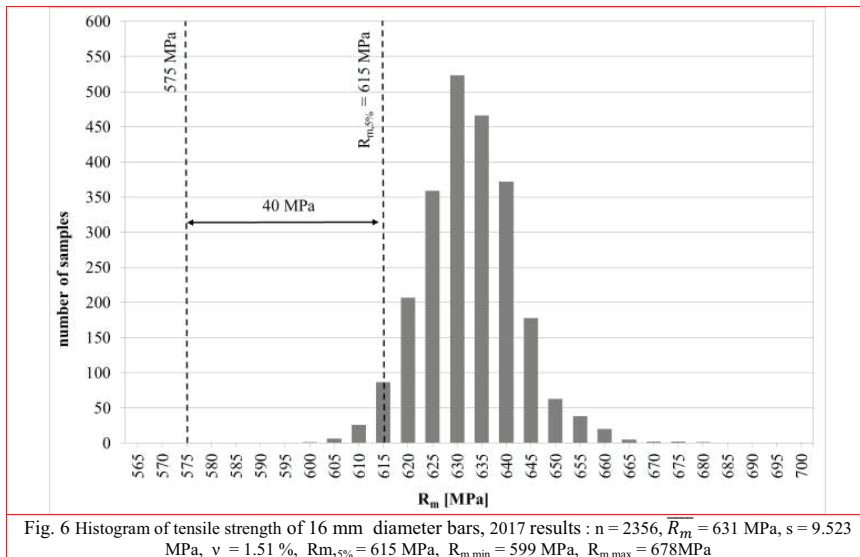

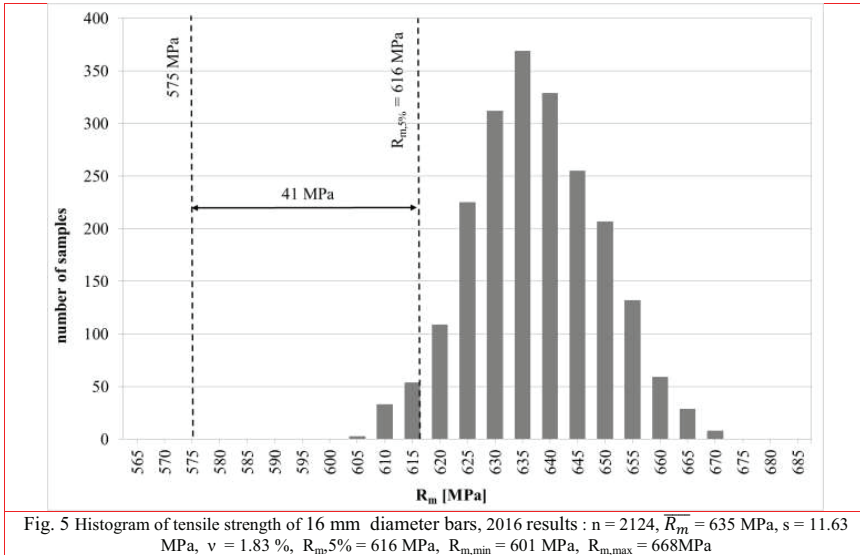Fig. 4 Histogram of yield stress of 16 mm diameter bars , 2017 results: n = 2356, $\overline{R_e}$ = 540 MPa, s = 9.677 MPa, ν = 1.79 %, Re,5% = 525 MPa, Re,min = 502 MPa, Re,max = 590 MPa

Fig. 5 Histogram of tensile strength of 16 mm diameter bars, 2016 results : n = 2124, $\overline{R_m}$ = 635 MPa, s = 11.63 MPa, v = 1.83 %, R_m,5% = 616 MPa, $R_{m,min}$ = 601 MPa, $R_{m,max}$ = 668MPa

Fig. 6 Histogram of tensile strength of 16 mm diameter bars, 2017 results : n = 2356, $\overline{R_m}$ = 631 MPa, s = 9.523 MPa, v = 1.51 %, $R_{m,5\%}$ = 615 MPa, $R_{m,min}$ = 599 MPa, $R_{m,max}$ = 678MPa
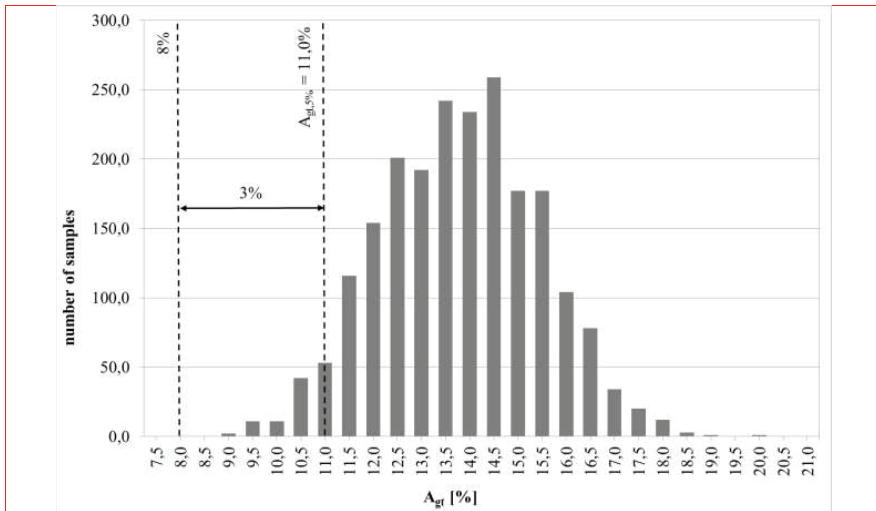
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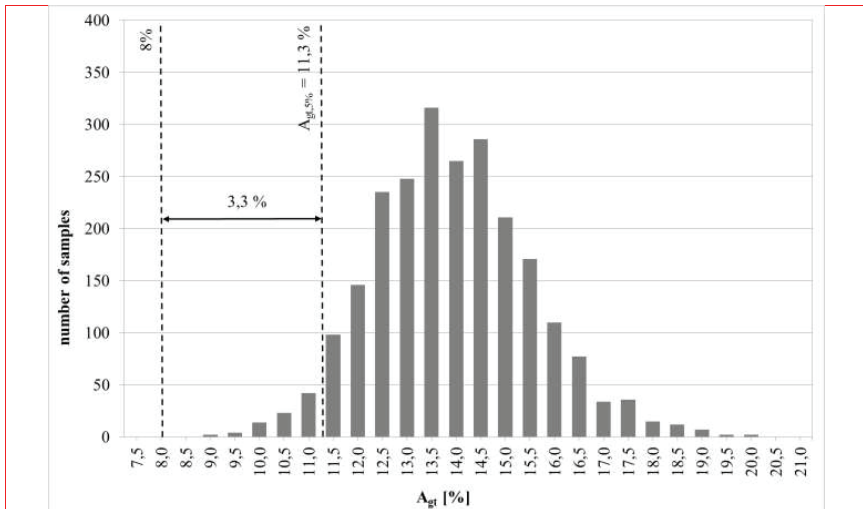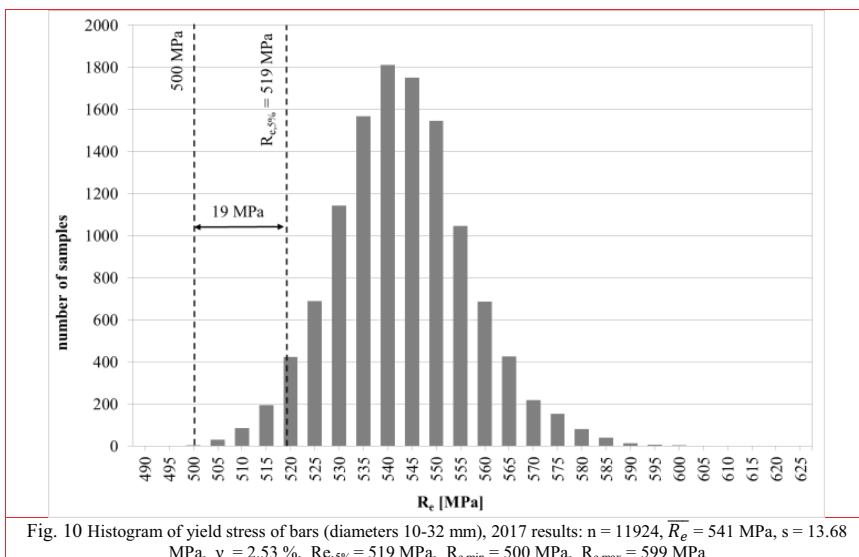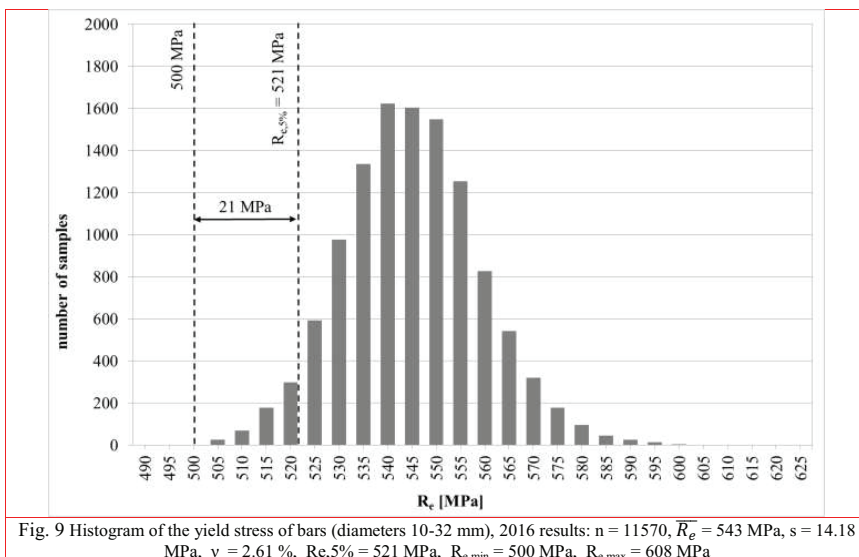

Fig. 8 Histogram of elongation of 16 mm diameter bars under the highest load, 2017 results: n = 2356, $\overline{A_{gt}}$ = 14.0 %, s = 1.615 %, v = 11.752 %, Agt,5% = 11.3 %, $A_{gt,min}$ = 8.6 %, $A_{gt,max}$ = 19.6 %

Fig. 9 Histogram of the yield stress of bars (diameters 10-32 mm), 2016 results: n = 11570, $\overline{R_e}$ = 543 MPa, s = 14.18 MPa, ν = 2.61 %, Re,5% = 521 MPa, $R_{e,min}$ = 500 MPa, $R_{e,max}$ = 608 MPa

Fig. 10 Histogram of yield stress of bars (diameters 10-32 mm), 2017 results: n = 11924, $\overline{R_e}$ = 541 MPa, s = 13.68 MPa, ν = 2.53 %, Re,5% = 519 MPa, $R_{e,min}$ = 500 MPa, $R_{e,max}$ = 599 MPa

Histograms of the yield stress, tensile strength and elongation under the highest load for reinforcing steel bars of other diameters, i.e. 10, 12, 20, 25, 28, and 32 mm, were also constructed, and their main descriptors were calculated. Yield stress experimental descriptors are presented in Table 2.

Table 2. The experimental values of the yield stress for bars with different diameters and collected for all diameters

Diameter	n	$\overline{R_e}$	s	v	$R_{e,5\%}$	$R_{e,min}$	$R_{e,max}$
2016 year							
10 mm	1836	543	14.18	2.61	521	500	608
12 mm	3537	540	13.33	2.47	520	500	608
16 mm	2124	545	11.40	2.09	527	513	581
20 mm	1777	539	11.86	2.20	519	503	574
25 mm	1405	552	13.57	2.46	531	510	598
28 mm	338	547	13.75	2.51	524	504	593
32 mm	446	557	11.82	2.12	536	525	586
10-32 mm	11570	543	14.18	2.61	521	500	608
2017 year							
10 mm	1776	539	15.48	2.87	514	500	598
12 mm	3870	537	13.68	2.54	517	502	596
16 mm	2356	540	9.68	1.79	525	502	590
20 mm	1712	540	12.13	2.25	521	505	597
25 mm	1184	550	9.69	1.76	534	518	589
28 mm	260	557	9.32	1.67	542	536	599
32 mm	603	553	15.08	2.73	528	505	591
10-32 mm	11924	541	13.68	2.53	519	500	599

5. CONCLUSIONS

EPSTAL steel producers perform static tensile tests of steel samples thousands of times per year (several hundred times for some diameters) as part of the factory quality control. These are multiple tests, repeated under the same room-temperature conditions, giving different results. There is, therefore, a full basis for a probabilistic description of the mechanical parameters of EPSTAL steel bars which are presented in this paper. On the basis of statistical elaboration of data concerning these parameters from the last two years, i.e. 2016 and 2017, the following conclusions were formulated:

1. The tensile testing phenomenon of EPSTAL steel samples should be described by a one-dimensional non-stationary stochastic process $\sigma(\varepsilon,e)$.

2. Mechanical properties of steel rods, i.e. the yield stress, tensile strength, and elongation should be described with continuous random variables. The histograms of these parameters, for individual diameters and static tensile tests recorded in the years 2016 – 2017 were constructed. For the purpose of illustration, several histograms are shown in Figs. 3 through 10. The estimators of the main descriptors of these three random variables were also calculated. Yield stress experimental descriptors, for rods with different diameters and collectively for all diameters, are presented in Table 2.

3. The coefficients of variation of the yield stress of bars with diameters from 10 to 32 mm, produced in the years 2016 – 2017, assumed values in the range: 2.09 - 2.61% for 2016 and 1.79 - 2.87% for 2017. These are small values, i.e. the variability of the yield stress results is small. The steel produced is of very good quality.

4. The coefficients of variation of the tensile strength of bars with diameters from10 to 32 mm, produced in the years 2016 – 2017, assumed values in the range: 1.60 - 2.24% for 2016 and 1.43 - 2.28% for 2017. These are small values, i.e. the variability of the tensile strength results is small.

5. The experimental characteristic values of the yield stress, i.e. $R_{e,5\%}$, are in the range from 519 to 536 MPa in 2016 and from 514 to 542 MPa in 2017. The current characteristic value adopted by the manufacturer at the level of 500 MPa is undervalued, for bars with a diameter of 10 mm by around 3%, and for bars with a diameter of 16 mm or more - by 5% to even 6%.

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Tab. 1. The yield stress, tensile strength, and maximum elongation for 10 static tensile tests of 16 mm diameter bars

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BADANIE ZMIENNOŚCI PARAMETRÓW WYTRZYMAŁOŚCIOWYCH STALI EPSTAL

Słowa kluczowe: Stal EPSTAL, proces stochastyczny, parametry wytrzymałościowe, zmienne losowe, histogramy.

SUMMARY:

1. Wstęp

Przedmiotem niniejszego artykułu jest zbadanie zmienności parametrów wytrzymałościowych stali EPSTAL produkowanej w polskich hutach, tj. granicy plastyczności R_e wytrzymałości na rozciąganie R_m i wydłużenia pod największym obciążeniem A_{gt}, na podstawie wyników statycznej próby rozciągania próbek stali wykonanej przez producentów w ramach zakładowej kontroli produkcji. Analiza statystyczna tych wyników wykazała, że zależność naprężenie-odkształcenie prób rozciągania stali należy opisać w języku rachunku prawdopodobieństwa jako jednowymiarowy proces stochastyczny, zaś trzy najważniejsze parametry wytrzymałościowe: granicę plastyczności, wytrzymałość na rozciąganie i wydłużenie pod największym obciążeniem, jako zmienne losowe. Na podstawie opracowania danych eksperymentalnych stwierdzono, że granica plastyczności i wytrzymałość na rozciąganie prętów produkowanych w latach 2016 – 2017 mają współczynniki zmienności na poziomie mniejszym niż 3%, ponadto istnieje uzasadniona podstawa, aby producent podwyższył wartość charakterystyczną granicy plastyczności prętów stalowych o kilka procent.

2. Materiały i metody

W celu zbadania zmienności parametrów wytrzymałościowych prętów zbrojeniowych stali EPSTAL przyjęto następujące założenie dotyczące liczebności prób. Za liczebność próby przyjęto liczbę statycznych prób rozciągania próbek prętów o jednakowych średnicach (10,12,14,16, 20, 25, 28 i 32 mm) wykonanych w ciągu jednego roku. Dla tak przyjętej liczby prób sporządzono histogramy dla trzech zmiennych losowych, tj. granicy plastyczności, wytrzymałości na rozciąganie i wydłużenia dla wszystkich produkowanych średnic i produkcji prętów w latach 2016 i 2017.

3. Wyniki

Na podstawie sporządzonych histogramów obliczono następuj estymatory liczbowe: wartości średnie próby $\overline{R_e}$, $\overline{R_m}$ i $\overline{A_{gt}}$, odchylenia standardowym próby (s) i współczynniki zmienności próby (v). Na histogramach podano także liczebność każdej próby (n), najmniejszą wartością próby i największą wartością próby.

4. Wnioski

Na podstawie przeprowadzonych badań i ich statystycznego opracowania sformułowano następujące wnioski.

1. Zjawisko rozciągania próbek stali EPSTAL należy opisać jednowymiarowym niestacjonarnym procesem stochastycznym $\sigma(\varepsilon,e)$.

2. Wielkości mechaniczne prętów stalowych, tj.: granica plastyczności, wytrzymałość na rozciąganie i wydłużenie pod największym obciążeniem są jednowymiarowymi zmiennymi losowymi, dla których zbudowano histogramy tych wielkości dla poszczególnych produkowanych średnic i produkcji prętów w latach 2016 i 2017. Obliczono także estymatory parametrów liczbowych tych wielkości.

3. Współczynniki zmienności granicy plastyczności prętów o średnicy od 10 do 32 mm produkowanych w latach 2016 i 2017 przyjęły wartości w następujących przedziałach: 2,09 – 2,61% w 2016 roku i 1,79 – 2,87% w

2017 roku. Są to wartości małe, tzn. rozrzut granicy plastyczności jest mały. Produkowana stal jest bardzo dobrej jakości.

4. Współczynniki zmienności wytrzymałości na rozciąganie prętów o średnicy od 10 do 32 mm produkowanych w latach 2016 i 2017 przyjęły wartości w następujących przedziałach: 1,60 – 2,24% w 2016 roku i 1,43 – 2,28% w 2017 roku.

5. Doświadczalne wartości charakterystyczne granicy plastyczności, tj. wartości $R_{e,5\%}$ są zawarte w przedziałach 520 – 536 MPa w 2016 roku i 514 – 534 MPa w 2017 roku. Dotychczasowa wartość charakterystyczna przyjęta przez producenta na poziomie 500 MPa jest zaniżona, dla prętów o średnicy 10 mm około 3%, zaś dla prętów od średnicy 16 mm od 5 do nawet 6%.