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Reflection of statistical nature of steel strength in steel structures standards

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The article contains a publications systematic review on the problem of construction steels strength statistical description. Mechanical characteristics of modern steels have a statistical variance, which is well described by normal law. The main attention is paid to the steels' statistical strength characteristics selection of different periods, such as mathematical expectation, standard deviation (standard), coefficient of variation, etc. The analysis confirmed the high security of normative and design resistances of low-carbon and low-alloy steels rolling profiles. The data presented in the article are intended for use in numerical structural reliability calculations. The design standards evolution for steel structures is analyzed in the justification sense of normative and design resistances and the experimental statistics involvement

Keywords: strength of steel, yield strength, normative resistance, design resistance, coefficient of homogeneity

Відображення статистичного характеру міцності сталі у нормах проєктування сталевих конструкцій

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Стаття містить систематизований огляд публікацій у ведучих науково-технічних журналах із проблеми статистичного опису міцності будівельних сталей. Міцність сталі – це вирішальний параметр несучої здатності будівельних металевих конструкцій. Тому об'єктивне оцінювання міцності сталі має велике значення для забезпечення і розрахунку надійності конструкцій та належного обґрунтування норм проєктування. За наявності численних факторів, що впливають на міцність сталі, цілком природно, що показники міцності мають певну змінність, наочне уявлення про яку дають статистичні криві розподілу різних характеристик сталі. Межа текучості й інші механічні характеристики сучасних сталей мають статистичний розкид, котрий добре описується нормальним законом, що було неодноразово підтверджено даними випробування зразків сталі. Заводські випробування міцності сталі виконуються багато років у великих масштабах, створюючи значний масив статистичної інформації, проте загальна інформаційна база цих даних відсутня. Головну увагу приділено вибірці статистичних характеристик міцності сталей різного періоду, таких як математичне сподівання, середньоквадратичне відхилення (стандарт), коефіцієнт варіації та ін. Аналіз підтвердив високу забезпеченість нормативних опорів і кутової сталі, швелерів та балок з маловуглецевої сталі марок Ст3пс і Ст3сп. У більшості випадків виконується вимога про забезпеченість значень нормативних опорів будівельних матеріалів з імовірністю 0,95 для сталі марки Ст3. Показано, що забезпеченість розрахункових опорів профільного прокату зі сталей Ст3сп і Ст3пс завжди вища від імовірності 0,999. Наведено дані статистичної обробки результатів механічних випробувань низьколегованих будівельних сталей 14Г2, 10Г2С1, 15ХСНД, 10ХСНД та високоміцних сталей. Подані у статті дані призначені для використання у чисельних розрахунках надійності конструкцій. Проаналізовано еволюцію норм проєктування сталевих конструкцій у сенсі призначення нормативних і розрахункових опорів та залучення до цього дослідних статистичних даних

Ключові слова: міцність сталі, межа текучості, нормативний опір, розрахунковий опір, коефіцієнт однорідності

Introduction

The steel strength is a crucial parameter of the metal structures load-bearing capacity. Therefore, an objective steel strength assessment is of great importance for ensuring and calculating the structures reliability and the proper design standards justification. It is known that the steel smelting process is quite complex and not perfectly controlled (high temperature, melting process time, the content of alloying impurities, etc.). Subsequently, during rolling, the metal is compressed, the grains are crushed and their orientation along and across the rolled metal is changed, which affects the metal mechanical properties. The steel properties are also affected by the rolling temperature and subsequent cooling. In addition, with increasing rolling thickness, the metal mechanical properties decrease. In the presence of such numerous factors that affect the steel strength, it is natural that the strength indicators have a certain variability, a clear idea of which is given by statistical distribution curves of different steel characteristics. The yield strength and other modern steels mechanical characteristics have a statistical variance, which is well described by normal law, which has been repeatedly confirmed by steel samples test data. Therefore, the undoubted relevance of regular steel strength statistical studies is associated with the constant design standards revision.

Review of research sources and publications

The initial data on the steel mechanical characteristics are obtained as a result of molten steels samples standard acceptance tests in the metallurgical plants laboratories. The main purpose of these data is to assess the quality and rejection of substandard metallurgical products. In addition, steels statistical test results are used in the design standards preparation and revision. This process was especially intensified with the limit states calculation method introduction [1, 2]. Numerous publications of domestic researchers since the 1940s [3-16] are devoted to the steel mechanical characteristics statistical description, in particular its strength. This problem is actively discussed by foreign experts [17-20]. Reliable steel strength statistical parameters are especially needed to assess the metal structures reliability. This is emphasized, in particular, in the publications prepared by the scientific school "Reliability of building structures" of the National University "Yuri Kondratyuk Poltava Polytechnic" [21-24].

Definition of unsolved aspects of the problem

Steel strength factory tests are performed for many years on a large scale, creating a significant array of statistical information. However, there is no common information database for these data. Some of them have been published in various scientific and technical journals, articles collections, conference proceedings. Access to these publications is difficult, especially since some institutions have begun to destroy paper magazines in recent years, citing the transition to electronic publications. However, in reality, the translation into electronic form has so far occurred only for publications published after 2000.

Problem statement

The article contains a systematic publications review in leading scientific and technical journals on the construction steels strength statistical description problem. The main attention is paid to the statistical strength characteristics selection of different period steels, such as mathematical expectation, standard deviation (standard), variation coefficient, etc. These data are intended for use in numerical designs reliability calculations. In addition, the evolution of the steel structures design norms is analyzed in terms of changes in the purpose of normative and design resistances and the experimental statistics involvement.

Basic material and results

The article content is an organized publications review of such scientific and technical journals as "Industrial and civil construction" (formerly "Construction industry" and "Industrial construction"), "Industrial construction and engineering structures", "Construction mechanics and calculation of structures", "News University. Construction and architecture", "Building materials", "Automatic welding", etc. The review is compiled for the period from the 40s of the twentieth century to the present. The paper version was mainly used for journals published before 2000, which were in the scientific and technical library of the National University "Poltava Polytechnic Yuri Kondratyuk", one of the most complete book storages in Ukraine. Information on later editions digitized from electronic libraries and electronic versions of journals.

Low-carbon steel St3. Statistical low-carbon steel strength studies were initiated before World War II V. Kuraev under the leadership of prof. N. Streletsky [1]. Based on them, the minimum value of yield strength and allowable stress was determined for steel grade St3 equal to $[\sigma]$ =1600 kg/cm^2.

With the transition in 1955 of the steel structures calculation to the limit states method NiTU 121-55 "Standards and technical conditions for the design of steel structures" were introduced. For steel grade St3 in these standards was introduced normative resistance R^n = 2400 kg/cm^2, which was equal to the defective minimum in the steel samples acceptance tests according to the relevant GOST. The strength deviation possibility from the normative resistance in the smaller direction due to the selectivity of rolled product size control and variability was taken into account by the homogeneity coefficient k = 0.9. The design tensile, compression and bending resistance was defined as $R = kR^n = 0.9 \cdot 2400 = 2100$ kg/cm^2. The design resistance was equal to the minimum probable value of the yield steel strength, which was defined as

$$R = \bar{\sigma}_y - 3\hat{\sigma}_y, \qquad (1)$$

where $\bar{\sigma}_y$ and $\hat{\sigma}_y$ – the yield strength mathematical expectation and standard deviation (standard).

The design resistance was determined on the basis of statistical processing of steel grade St3 6 thousand factory tests results of different plants [2].

In the 60s of the last century in the metallurgical industry there were significant changes in low-carbon steel production: developed oxygen-converter smelting, mastered new deoxidation schemes (semi-quenched steel), increased open-hearth furnaces capacity, increased ingot weight. This is reflected in the next edition of SNiP II-B.3-62 "Steel structures. Design standards". They introduced two calculated supports – the yield strength of $R = 2100$ kg/cm^2 (as before) and the temporary resistance of $R_p = 2600$ kg/cm^2. It were separated open-hearth and converter steels, as well as steel deoxidation degrees: calm (sp), boiling (kp) and semi-calm (ps).

The mentioned metallurgical technology development and design norms revision had a certain influence on the steels mechanical properties. Therefore, CNDIBK carried out statistical processing of the open-hearth thick steel St3 acceptance tests results according to GOST 380-60 with a thickness of 2 – 60 mm at three metallurgical plants: Magnitogorsk Metallurgical Plant (MMK), Kommunarsky Metallurgical Plant and Ilyich Metallurgical Plant (Mariupol) [4]). The obtained results are given in table 1. These studies have shown that the rolled low-carbon steel St3 mechanical properties in these years have decreased significantly (especially in terms of yield strength and toughness). Therefore, it was concluded that the steel acceptance testing method at that time (especially the yield strength determination) needed significant improvement.

With the data given in table 1 the statistical processing results of various metallurgical enterprises steel VSt3 mechanical tests results published a little earlier are connected [3]:

– yield strength:

$\overline{\sigma}_y = 281{,}0$ MPa; $\hat{\sigma}_y = 23{,}4$ MPa; $\sigma_{y\max} = 350{,}0$ MPa;

– temporary resistance:

$\overline{\sigma}_u = 456{,}4$ MPa; $\hat{\sigma}_u = 216$ MPa; $\sigma_{u\max} = 520{,}0$ MPa.

It is known that in cases where the control tests results meet the GOST and TU standards, the consumer can get a metal with the strength characteristics values below the standard resistances. In the article [5] the deviations probabilistic analysis are considered in norms by homogeneity coefficient (coefficient of reliability on material) is executed.

In preparation for the next steel structures revision, in the late 70's CNIDBK conducted a large-scale data processing of steel St3 26 thousand acceptance tests [7], the results of which are partially given in table 1. They generally correspond to the previous tests results and confirm a smaller data statistical scatter on the temporary resistance compared to the yield strength. The statistical information resulting array was linked to the main steel structures calculation provisions at the limit states. In particular, the steel St3 normative and design resistances probabilistic provision estimation was carried out (Table 2).

Data analysis of table 2 allowed substantiating the following conclusions:

– the standard sheet metal resistances provision up to 10 mm St3ps and St3kp steels thick is low, which is explained by a significant less strong rolled steel share;

– high security of normative resistances R_{yn} and R_{un} of angle steel, channels and beams from the St3ps and St3sp brands steel;

– the requirement to ensure the building materials normative resistance values with a 0.95 probability for steel St3 in most cases is met;

– the calculated resistances values security after strength limit is higher, for which the security in all cases is close to $P \approx 1.00$, and the safety characteristic $\gamma = 5 – 9$;

– the rolled steel design resistances probabilistic provision from St3sp and St3ps steels is always higher than the 0.999 probability, with safety characteristics $\gamma = 4 – 6$. Therefore, CNDIBK proposed to increase the design resistance BSt3sp to 230 MPa and BSt3kp to 220 MPa, which was implemented during the revision of design standards.

In the new edition of SNiP II-23-81 «Steel structures» it were introduced for steel St3 two strength groups (at the suggestion of the Institute of Electric Welding named after EA Paton), grades were replaced by classes (steel St3 was assigned to classes C235, C245 and C255 depending on the degree of deoxidation and strength groups), differentiation was introduced depending on the rolling type (sheet or shaped) and the profiles thickness. To move from the normative to the design resistance instead of the homogeneity coefficient now the reliability coefficient for the material is used:

$$R_y = R_{yn}/\gamma_m\,; \quad R_u = R_{un}/\gamma_m\,, \qquad (2)$$

where R_{yn} and R_{un} – normative resistances, respectively, after the yield strength and temporary resistances;

R_y and R_u – similar design resistances.

Substantiated statistically new reliability coefficients on the material differ insignificantly from the unit: $\gamma_m = 1.025 – 1.100$.

The CNDIBK staff article [8] summed up the results of the first SNiP II-23-81 implementation years, which led to significant savings in steel in construction. Subsequent editions of the Ukraine DBN B.2.6-198:2014 «Steel structures. Design standards» norms and Russia's SP 16.13330.2017 «SNiP II-23-81*» do not differ in principle from SNiP II-23-81 in terms of steels strength rating of [16].

Recently, the light thin-walled steel structures use has expanded. It was found that the cold steel profile formation leads to their strengthening. To detect it, the statistical processing of two steels samples test results was performed [9]. The obtained strengthening factor is well described by normal law and has the following parameters:

– 14G2 – $\overline{m} = 1.17$, $\hat{m} = 0.082$, $V = 6{,}4$ %;

– VSt3sp – $\overline{m} = 1{,}31$, $\hat{m} = 0{,}066$, $V = 5{,}0$ %.

Table 1 – Statistical data on the mechanical characteristics of sheet steel St3

Steel	Date, source	$\bar{\sigma}_y$, MPa	$\hat{\sigma}_y$, MPa	V_y, %
Yield strength				
St3kp	1968 [4]	284,1 – 310,7	21,9 –25,7	7,55
	1980 [7]	266,0	29,0	10,9
St3ps	1968 [4]	293,6 – 312,2	21,5 – 26,8	7,30
	1980 [7]	265,0 – 289,0	25,0 – 30,0	9,9
St3sp	1968 [4]	232,6 – 294,0	15,9 – 25,9	5,8 – 9,1
	1980 [7]	268,0 – 294,0	22,0 – 27,0	8,7
Temporary resistance				
Steel	Date, source	$\bar{\sigma}_u$, MPa	$\hat{\sigma}_u$, MPa	V_u, %
St3kp	1968 [4]	422,4 – 433,0	23,4 – 29,1	5,83
	1980 [7]	410,0	30,0	7,32
St3ps	1968 [4]	441,8 – 436,0	20,6 – 27,1	4,75
	1980 [7]	420,0 – 437,0	25,0 – 27, 0	6,07
St3sp	1968 [4]	417,0 – 459,0	19,2 – 23,4	5,54
	1980 [7]	433,0 – 440,0	20,0 – 25,0	5,15
Designations: $\bar{\sigma}_y$, $\hat{\sigma}_y$, V_y – accordingly average value, standard, coefficient of yield strength variation; $\bar{\sigma}_u$, $\hat{\sigma}_u$, V_u – the same as the strength limit (temporary resistance).				

Table 2 – Probabilistic provision of normative and design resistances of steel St3

Profile	Steel	Normative resistance		Design resistance			
				after yield strength		after limit of strength	
		P(R$_{yn}$)	*P(R$_{un}$)*	γ_y	*P(R$_y$)*	γ_u	*P(R$_u$)*
Sheets	St3kp	0,893	0,841	1,94	0,974	5,00	≈ 1
	St3ps	0,894-0,991	0,929-0,989	1,97-3,12	0,976-0,9986	5,92-7,07	≈ 1
	St3sp	0,921-0,998	0,984-0,996	2,15-3,82	0,984-0,9999	6,96-8,65	≈ 1
Steel angular	St3kp	0,989	0,913	3,09	0,999	5,65	≈ 1
	St3ps	0,999	0,985	4,05	0,99997	7,72	≈ 1
	St3sp	0,999	0,993	3,92	0,9998	7,07	≈ 1
Chan-nels, beams	St3kp	0,999	0,985	4,04	0,99997	7,95	≈ 1
	St3ps	0,9999	0,9996	5,24	≈ 1	8,95	≈ 1
	St3sp	0,9999	0,999	5,67	≈ 1	6,46	≈ 1
Designations: γ_y , γ_u – normalized deviations of calculated resistances from average values (safety characteristics)							

Low-alloy steels. It is no coincidence that statistical studies of the ordinary strength low-carbon steel properties were the most extensive. According to the data from the end of the 1980s, 80% of this rolled steel with yield up to 245 MPa strength was used for the building steel structures production. High strength low-alloy steels with 325 –345 MPa yield strength of were 15%, rolled high-strength steels with at least 390 MPa yield strength – only 5% [8]. Therefore, it was important to deploy research on strength steels.

Back in the 1955 – 1957 postwar period, the Chelyabinsk Plant of Metal Structures performed large-scale statistical mechanical tests of natural alloy steel NL2 (15HSND) (30 thousand tons), supplied by MMK, Kuznetsk Metallurgical Plant (KMK), Nizhny Tagil Metallurgical Plant and Plant named after Dzerzhinsky [10]. The NL2 steel yield strength distribution was well described by the normal law with the characteristics of $\bar{\sigma}_y$= 382.0 MPa, $\hat{\sigma}_y$= 27.3 MPa. The author of the publication, a well-known specialist B. Belyaev calculated the coefficient of homogeneity K_{cp} = 0.757 according to the author's method, taking into account the minus tolerances on the cross rolled sections dimensions, which gave the following steel NL2 (15HSND) design resistance value:

$$R = K_{cp}\,\bar{\sigma}_y = 0.767\times382 \approx 290 \text{ MPa}.$$

Therefore, a reasonable conclusion was made that the 290 MP design resistance adopted in the norms of

NiTU 121-55 is in full compliance with the actual mechanical properties of NL2 steel. However, B. Belyaev criticized the rejecting steel system, because the 340 MPa rejection minimum was at a standard 1.43 distance from the average value, which led to the probable steel 7.6% rejection. Therefore, the author of the article proposed to accept the rejection minimum at the level of 3 standards, ie 382 – 3×27.3 = 300 MPa.

In the mid-1960s, statistical processing of the mechanical tests results of low-alloy construction steels 14G2, 15 HSND, 10 HSND in the amount of 225, 575 and 507 factory tests, respectively, at MMK, NTMZ, KMK, OHMK (Orsko-Khalilovsky) and other metallurgical enterprises was performed [3]. The obtained results are summarized in a table. 3, the data for steel 15HSND differ from the previous ones [10] by a higher standard – 34.5 MPa compared to 27.3 MPa at the same average values.

A detailed low-alloy steel 10G2S1 statistical study was conducted in the late 60's B. Uvarov at the Ilyich Metallurgical Plant (Mariupol) [11]. Sheets with a 26 – 119 mm thickness were studied, the samples number was 1200. The mechanical characteristics distribution curves the were close to normal with a slight asymmetry. A decrease in the steel mechanical characteristics with increasing sheet thickness was found. This general trend was described by the following regression equations:

– average value:

$\bar{\sigma}_y = 41.3 - 0.085\delta$;

$\bar{\sigma}_u = 56.5 - 0.039\delta$;

$\bar{\sigma}_5 = 27.7 - 0.019\delta$.

– standard:

$\hat{\sigma}_y = 2.67 - 0.006\delta$;

$\hat{\sigma}_u = 2.70 - 0.014\delta$;

$\hat{\sigma}_5 = 2.29 - 0.007\delta$.

Here the strength σ is in kg/mm^2; thickness δ in mm; relative elongation σ_5 in %.

The yield strength standards and temporary resistance decrease with increasing thickness due to the mechanical properties alignment with slow thicker sheets cooling.

The homogeneity coefficient was determined in the usual way

$$k = \frac{1-\gamma\sqrt{V_y^2 + V_f^2}}{1-\gamma^2 V_f^2},$$

where γ – safety factor (accepted in the norms equal to 3);

V_y – yield strength variation coefficient;

V_f= 0.043 – variation coefficient by area.

After substituting the numerical values into the formula, the homogeneity coefficient was obtained k = 0.79. The formula for the design resistance was obtained by the regression line equation

$$R = 32.6 - 0{,}068\delta$$

It turned out that with increasing sheet thickness for every 15 mm, the design resistance decreases by 10 MPa. This was taken into account in table 4.

The recommended rolled products division into groups narrower than the norms could have some economic effect, but was not fully implemented.

In the early 80's, experts from the Moscow Institute of Civil Engineering (MIBI) conducted high-strength steels statistical studies [12]. Data on strength class C70/60 steel 12GN2MFAYU were obtained by the acceptance tests results at OHMK, the sample size – 4 thousand tests. Sheet metal with a 12 – 40 mm thickness was tested.

The obtained results: the average yield strength value $\bar{\sigma}_y$ = 710,4 MPa; temporary resistance $\bar{\sigma}_u$ = 806,4 MPa; average elongation $\bar{\sigma}_5$ = 16,11%. Steel within the batch is heterogeneous (327 tested batches): the properties distribution standard within the batch in the general distribution standard shares is: 0,53 after the yield strength and 0,48 after the temporary resistance.

The investigated rolled metal meets the requirements for steel of class C 70/60: $ʃ_y$ ε 60 MPa; $ʃ_u$ ε 70 MPa; ™$_5$ ε 12 %. According to the test results, high-strength steel grade 12GN2MFAYU can be considered promising for responsible welded metal structures operating under dynamic loads and operated at negative temperatures below -40 ° C.

Table 3 – Statistical data on the mechanical characteristics of low-alloy steels

Steel	Yield strength σ_y, MPa			Temporary resistance σ_{uy}, MPa		
	$\bar{\sigma}_y$	$\hat{\sigma}_y$	$\sigma_{y\,max}$	$\bar{\sigma}_u$	$\hat{\sigma}_u$	$\sigma_{u\,max}$
14G2	398,8	36,0	510,0	552,0	38,6	670,0
15XSNДD	389,2	34,5	500,0	562,4	30,0	660,0
10XSNДD	458,7	37,6	580,0	597,5	34,6	710,0

Table 4 – Recommended sheet steel design resistances

Thickness, mm	До 38	39 –52	53 – 68	69 – 82	83 – 98	99 – 110
R, MPa	300	290	280	270	260	250

The new high-strength steel properties statistical analysis with nitride hardening grade 16G2AF was performed at OHMK on the basis of a 6.5 thousand tests sample [13]. Sheet metal with a thickness of 10 – 40 mm was tested. Steel in the normalized state had an yield strength average value $\bar{\sigma}_u$ = 470 MPa; temporary resistance $\bar{\sigma}_u$ = 650 MPa. Heat-treated steel had slightly higher characteristics – the yield strength average value $\bar{\sigma}_y$= 550 MPa; temporary resistance $\bar{\sigma}_u$ = 680 MPa. Steel within the batch is heterogeneous (816 batches were tested): the normalized steel properties distribution standard within the batch in the general distribution standard shares is: 0,518 after the yield strength and 0,607 after the temporary resistance. It was concluded that the developed steel in terms of both strength and plastic characteristics meets the requirements for high-strength steels.

Recent publications describe new high-strength steels of large thickness [14, 15]. Rolled steels C345, C375, C390 and C440 have high engineering properties and good weldability. Thermomechanical high purity hardened steels can be referred to the third construction steels generation and be used in the most responsible and unique building metal structures.

Conclusions

A systematic works review on the problem of construction steels strength statistical description is realized. The main attention is paid to a sample of different periods steel strength statistical characteristics, such as mathematical expectation, standard deviation (standard), variation coefficient, etc. These data are intended for use in structures reliability numerical calculations. The steel structure design norms evolution is analyzed in terms of changes in the purpose and provision of normative and design resistances and the experimental statistics involvement.

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