Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 03, March, 2024

Strength and Deformability of Structural Steel for Use in Construction

Begman Kulbayev [1], Vladimir Lapin [1*], Alexandr Shakhnovich [1], Yeraly Shokbarov [1], Tursymbai Tuleyev [1], Serik Aldakhov [1], Yerken Aldakhov [1], Alimzhan Ali [1]

[1] *Kazakh Research and Design Institute of Construction and Architecture JSC, 21 Solodovnikova, Almaty, Kazakhstan.*

Received 16 November 2023; Revised 12 February 2024; Accepted 19 February 2024; Published 01 March 2024

Abstract

The purpose of the study is an experimental determination of the stress-related characteristics of the structural steel produced in the Republic of Kazakhstan for use in conventional and earthquake-resistive construction. Since 2015, the construction industry has been using European regulatory documents—Eurocodes—as a statutory framework. In particular, the Eurocode 1993 for steel structures and the Eurocode 1998 for the design of earthquake-resistant structures However, the study of stress-related properties of structural steel using experimental methods of ISO standards has not been performed. Therefore, in the construction industry of the Republic of Kazakhstan, steel-work structures have been used in fairly limited volume since 2015. The experimental studies were conducted on 7 types of structural steel with thicknesses of 8, 10, and 20 mm manufactured by Arcelor Mittal. The yield strength, ultimate tensile strength (breaking stress), and tensile strength at break were studied. The experimental studies were carried out on the basis of ISO standards. In each test run, 5 samples were used. In two series, 20 samples each were tested, which made it possible to estimate the yield strength and strength distribution functions. The correlation relationships between Brinell hardness and yield and strength limits have been studied. As a result of experimental studies, it was found that the strength and deformability parameters fully comply with the requirements of Eurocode 1993. Based on the application of the Student's test, it is revealed that the distribution functions of yield strength and resistance correspond to the normal law (Gaussian function). The calculation of a three-story, two-span residential building with box section columns for construction in an area with a seismicity of 8 points is performed by the finite element method. The work results will significantly increase the scope of Kazakhstani structural steel use in seismic and conventional areas of the Republic of Kazakhstan.

Keywords: Yield Strength; Tensile Strength; Steel Hardness; Construction Steel; Eurocode; Relative Rupture Strain.

1. Introduction

The steelwork structures meet the main requirements of construction – industriality, reduction of the volume and duration of construction works, low construction costs. Steelwork structures are widely used in construction practice, including high-rise construction. The experience in the application of steel structures in the construction industry is detailed in Vedyakov et al. [1]. The issues of the selection of steel structure materials with respect to the present-day regulatory and operational requirements and capabilities of global and domestic metallurgical production are considered in detail. Among rather actual studies, it stands to mention the theory of application of constructions from rolled steel of large thickness, the methodology of quality assessment of plates, and its work features in constructions [2]. The dependences of properties of heavy-thickness sheets and alloying, heat treatment, and peculiarities of production are analyzed. The steel performance in the fabrication and operation of structures is described. The properties of new-generation steels for large-thickness rolled products are discussed. Examples of the application of these materials in the latest unique structures are provided.

* Corresponding author: lapin_1956@list.ru; vlapin@kazniisa.kz

http://dx.doi.org/10.28991/CEJ-2024-010-03-09

One of the latest achievements is the study of modular steel-framed high-rise buildings [3]. A module connection to the main wall to assemble modules into a main wall system plays a key role in load transfer in modular high-rise buildings. In the Republic of Kazakhstan, the application of such systems seems to be very promising. However, its mechanical mechanisms have not been systematically studied. This study proposes an innovative module connection to the main wall that can be installed and detached with good feasibility and efficiency during the construction and dismantling process.

The structural steel has the ability to resist alternating loads. The steel-framed buildings are therefore highly earthquake-resistant. In the study of Gioncu & Mazzolani [4], this is demonstrated by the example of different types of steel-frame buildings. The steel-frame buildings suffer noticeable earthquake damage, usually when there are obvious design errors. They behave well under repeated earthquake effects (aftershocks), as shown in the study [5]. Even with the most unfavorable long-period ground vibration, it is possible to develop structural solutions to ensure the seismic resistance of the building [6]. They have a plastic reserve, which allows them to successfully resist seismic impact [7]. The effect of enclosing structures on the structural steel frame response has been studied [8].

In order to use constructional steel for the design and manufacture of building structures, it is always necessary to perform a cycle of experimental studies to determine the stress-related properties of steel. Mechanical performance of structural steel, i.e., values characterizing its strength, plasticity, elasticity, and elastic constants, necessary for material selection and calculations of designed structural components, is determined by mechanical testing of standard specimens under load made of the steel types under study [9–12]. At that point, experimental studies should use the appropriate standards governing test methodologies.

Mechanical tensile testing is one of the most important types of engineering tests used for all metallic materials, which determines the material's performance. In the study of Vaz-Romero et al. [9], experiments were performed on PC52 steel samples (0.22% C) using the INSTRON 8801 universal testing machine to determine yield strength, tensile strength, strain at break, and Young's modulus. The strain rates used during the tests were within the range typical of static tensile tests as recommended in ASTM Standard E8/E8M-16a and ISO 6892-1:2016, as is typical for steel testing.

In the study of Wang & Kodur [10], the tensile tests were conducted using specimens with six different design lengths ranging from 20 mm to 140 mm, which were tested over a wide range of loading velocities from 1 m/s to 7.5 m/s. The experimental studies were also described by a mathematical model based on the finite element method. It was found that there is a strong correlation between the applied velocity and the gauge length of a specimen.

The mechanical properties of steel are important not only for evaluating the behavior of individual steel elements but also for predicting the performance of the entire structure [11]. When exposed to fire, the mechanical properties of steel deteriorate with increasing temperature. The mechanical degradation depends on the exposure temperature. In practice, degradation represents the mechanical property reduction factor recommended by specific effective design standards. The tensile properties of multilayer samples are reviewed in the study of Yang & Lin [12]. The challenging task of studying the mechanical properties of high-tensile steel samples exposed to high temperatures during welding is discussed in the study of Gardnerand & Nethrcott [13].

Therefore, mechanical tensile testing is a fairly universally applicable approach to studying the strength and deformability characteristics of structural steel. In this paper, we set the task of determining the characteristics of strength and deformability of structural steel produced by Kazakhstani plants, in particular the Arcelor-Mittal plant in Temirtau, Kazakhstan. It is necessary to determine the yield strength, tensile strength (tensile strength), and relative rupture strain. In this respect, test and sample preparation methods shall comply with the requirements of Eurocode 1993 in accordance with the relevant ISO standards: ISO 6892-1:2016 "Metallic Materials. Tensile Testing. Part 1. Method of Test at Room Temperature" and ASTM E8/E8M-16a "Standard Test Methods for Tensile Testing of Metallic Materials". These two standards specify that tensile testing for the above material characteristics shall be conducted at strain rates in the range of 10-5 s-1 to 10-3 s-1, depending on the material performance and the test method used.

It should be noted that in this statement, this task is extremely relevant. The solution to this problem will allow the steel structures to be widely used again within the Republic of Kazakhstan, the regulatory framework for construction of which, since 2015, is based on the application of Eurocodes.

Over 45% of the territory of the Republic of Kazakhstan falls within the seismically active areas, in this respect, the significant area is occupied by extremely seismically hazardous zones of 8–9 and over points on the MSK-64 scale. Therefore, solving this problem will renew the use of steel construction in seismic areas. Consequently, the cycle of studies regarding the use of Kazakhstan steel under the pressing issue of verifying the requirement of compliance with the characteristics of Kazakhstan steel Eurocode 1993 [14], started in Kazakhstan by the work of Kulbayev et al. [15, 16], will be continued. Previously, such a task was not solved in the Republic of Kazakhstan. It should be noted that the Russian Federation has also started harmonizing its regulations with foreign standards [17].

The minimum plasticity of steel shall be expressed by the ceiling limits of the following values:

- f_u/f_y – ratio of the minimum tensile strength $\mathrm{f_u}$ to the minimum yield strength f_y;
- Relative elongation after rupture of the sample length 5.65 $\sqrt{\mathrm{A_0}}$ (where $\mathrm{A_0}$ – original cross-sectional area);
- Critical strainε_u, corresponding to the ultimate strength $\mathrm{f_u}$.

The following values are recommended:

$$f_u/f_y, \geq 1.10 \tag{1}$$

Relative elongation after rupture not less than 15%: (2)

$$\varepsilon_\mathrm{u} > 15\ \varepsilon_\mathrm{y}, \text{ where } \varepsilon_\mathrm{u} \text{ – elastic strain } (\varepsilon_\mathrm{y} = f_y/\mathrm{E}, \text{Young's module}) \tag{3}$$

The above relations should be verified by experiment.

For the case of National Annexes, condition (1) is stiffened:

$$f_u/f_y, \geq 1.30 \tag{4}$$

Therefore, it is necessary to address the following objectives:

- The most used steel grades in the Republic of Kazakhstan need to be experimentally investigated to determine compliance with Eurocode 1993 (1)-(3) and National Annexes (4) requirements;
- To clarify requirements (4) based on the experimental studies performed;
- To establish correlations between the Brinell hardness BH and the above strength and deformability characteristics.
- To evaluate the feasibility of using Kazakhstani structural steel in earthquake-resistant construction.

Such tasks have not been investigated before.

2. Methods and Objects

The types of steel most commonly used in the Republic of Kazakhstan have been selected for experimental studies of construction steel. A batch of 8, 10, and 20 mm-thick structural steel with certificates of conformity from ARCELOR-MITTAL (Kazakhstan, Temirtau), AMET, and several metallurgical plants was obtained under the sponsorship of IMSTALCON JSC (constructional ironworks in Taraz). Table 1 shows the steel manufacturer, thickness in mm, and grade. The manufacturing and testing of samples were carried out according to GOST 6696-66, ISO 4136-89, ISO 5173-81, and ISO 5177-81. The mechanical tensile testing of structural steel specimens was carried out using a UMM-5 tensile machine with a calibration certificate dated February 24, 2023. The tensile machine is accredited for testing according to the test requirements of ST-RK ISO. In each test run, 5 specimens of 8–20 mm thickness were used (St3Sp5, 09G2S). These are the most common steel grades in the Republic of Kazakhstan. The processing of experimental data was carried out using the MATLAB mathematical package.

Table 1 shows the main stress-related properties of steel with indications of manufacturer, grade, and plate thickness taken according to the certificate information.

Table 1. Mechanical performance of structural steel

No.	Manufacture	Grade	Section, mm	Ultimate strength	Yield stress	Impact strength, J/cm²		Impact strength after aging	Elongation, %
						KCU	KCV		
1	Arcellor-Mitall	St3Sp5	8	459	316	–20°C 78	+20°C 147	KCU, +20 65	–
2	Arcellor-Mitall	St3Sp5	10	475	320	–20°C 50– 81– 69	+20°C 176– –183 –184	KCU 69– 73– 61	32
3	Arcellor-Mitall	09G2S	8	530	420	–40°C 125 120	–	+20 115 95	29
4	Arcellor-Mitall	09G2S	10	540	440	–40°C 92 92	–	+20 61 64	30
5	Amet, Ashinskiy Metallurgical Works	St3Sp5,SV	20	440–445	285–290	–20°C 49–67	+20°C 65– 85	56–76	31 31
6	Amet, Ashinskiy Metallurgical Works	09G2S	20	520–525	360–365	40 100–95	–	65–80	28 29
7	Severstal, Cherepovets	St3Sp50	10	400	245	152.7	216	187.3	32

For structural steel samples from Table 1, the value of impact strength at -20 °C is not less than 49 J/cm², which exceeds the Eurocode requirement of 34 J/cm². This is understandable; the climatic conditions in Kazakhstan and the Russian Federation are quite severe. In the production of structural steel, the factor of cold resistance (cold brittleness) of metal structures has always been taken into account.

Table 2 analyzes the ratio of tensile strength to yield strength (4). It is found that it is performed in all cases except for 09G2S-grade steel. It is known that the certificate records the minimum value of the parameter determined for the entire batch. Therefore, these 2 sheets of steel must certainly be tested.

Table 2. Strength characteristics of steel according to certificates

No.	Ultimate strength, MPa	Yield strength, MPa	Ratio (4)
1	459	316	1.45
2	475	320	1.48
3	530	420	1.26
4	540	440	1.23
5	440–445	285–290	1.54-1.53
6	520–525	360–365	1.44
7	400	245	1.63

The elongation after rupture is approximately 2 times the requirements of Eurocode 93. It should be noted that the sample of structural steel No. 7 from Table 1 is characterized by very qualitative characteristics: the highest tensile strength to yield strength ratio and the high impact strength of the new material after aging. Therefore, to verify conditions (1) and (4), experimental studies on mechanical tensile testing of Kazakhstan-made structural steel samples shall be conducted in accordance with ISO standards.

3. Results

3.1. Experimental Studies

Tensile tests of structural steel samples were carried out using the experimentation facility of SAPA INTERSYSTEM LLP. The sample size complies with the requirements of the ISO 6892-1-2010 standard. The tensile strength, yield strength, and relative elongation after rupture have been determined. The UMM-5 tensile testing machine with a calibration certificate dated February 24, 2023, was used in the tensile strength test. The organization is accredited for testing according to the test requirements under the ST-RK ISO. Figures 1 and 2 show the specimens prepared for testing and after testing.

Figure 1. Samples before testing

Figure 2. Samples after testing

Tables 3 to 5 summarize the probability characteristics of 7 series of tests with 5 samples in each of them. Table 6 summarizes the results of the calculations for testing criterion (4) in view of experimental data and using the certificate data from Table 1.

Table 3. Probabilistic characteristics of yield strength, MPa

No.	Sample average	Median value	Standard	Coefficient of variation
1	326.4	326.6	1.08	0.003
2	293.2	293.2	4.64	0.016
3	454.6	455.0	4.26	0.009
4	446.1	455.0	21.85	0.050
5	317.4	317.3	17.34	0.054
6	451.3	460.3	22.11	0.049
7	270.2	278.3	14.56	0.054

Table 4. Probabilistic values of tensile strength, MPa

No.	Sample average	Median value	Standard	Coefficient of variation
1	467.4	467.4	2.14	0.005
2	457.6	457.3	4.32	0.009
3	577.8	577.1	1.50	0.003
4	545.6	544.5	3.89	0.007
5	475.2	484.7	24.92	0.052
6	563.1	574.5	28.93	0.051
7	461.9	466.5	24.87	0.054

Table 5. Probabilistic values of relative elongation at break, %

No.	Sample average	Median value	Standard	Coefficient of variation
1	32	32	0.71	0.022
2	34	34	1.0	0.029
3	30.2	30	1.1	0.036
4	36.0	36	0.71	0.020
5	30.4	30	2.07	0.068
6	29	29	1.22	0.042
7	37	37	1.58	0.043

The analysis of Table 6 shows that for the 09G2S steel, the Eurocode requirement in terms of National Annexes is not fulfilled. This also comes out of the results of the calculation using certificate data, where for 09G2S steel, in two cases out of three, the ratio 4 is also not fulfilled. It should be noted that the estimates from experimental data and certification results are very close, except for 1 case.

Table 6. Characteristics from correlations (3) according to experimental and certificate data

No.	According to experimental data	Data from the certificates
1	1.43	1.45
2	1.36	1.48
3	1.27	1.26
4	1.22	1.23
5	1.50	1.54-1.53
6	1.25	1.44
7	1.71	1.63

In terms of relative elongation after rupture, the Eurocode 93 conditions are fulfilled for all steel grades, including 09G2S steel.

Therefore, it can be said that experimental information indicates compliance of strength and deformation characteristics of Kazakhstan steel with Eurocode requirements (1). The above results are obtained from 5 tests for each type of steel. Additional tests should be carried out (Section 3.2). Note also that condition (3) is always fulfilled due to high deformability of the Kazakhstani steel.

3.2. Testing of Two Series of Samples

Additional studies of two types of structural steel st3sp5 and 09G2S with a thickness of 10 mm were carried out under the experimentation facility of scientific centre of SAPA INTERSYSTEM LLP. In each test, 20 samples prepared according to ST RK EN standards were used. The tests were performed using ST RK ISO 0892-1-2017. This number of samples is the minimum necessary for statistical measurements.

The purpose of the study was to clarify correlation (3) and to estimate the probability distribution function of strength and deformability parameters of domestic construction steel (Section 4). This is performed as required by the Eurocode 1990, where it is proposed to determine the correspondence to one of the two distributions - normal or lognormal. Using the distribution function, it is possible to obtain the estimated values of strength and deformability characteristics with the necessary reliability.

Tables 7 and 8 set out the test results - values of relative elongation, yield strength and ultimate tensile strength.

Table 7. Values of strength and deformability parameters of St3Sp5 steel

Sample number	Elongation at break, %	Yield strength, MPa	Ultimate tensile strength (breaking stress), MPa	Ratio (3)
1	29	276.0	443.1	1.61
2	29	277.5	446.4	1.61
3	28	268.8	450.8	1.68
4	28	274.0	455.9	1.66
5	27	291.7	463.0	1.59
6	28	285.1	452.9	1.58
7	28	280.2	448.4	1.60
8	29	266.3	438.7	1.65
9	27	273.1	461.6	1.69
10	29	273.9	439.4	1.60
11	29	269.3	440.1	1.63
12	29	273.0	443.1	1.62
13	28	279.8	449.8	1.61
14	27	291.4	462.6	1.59
15	29	275.1	445.4	1.62
16	27	271.2	457.6	1.69
17	27	274.5	459.3	1.67
18	27	275.7	464.7	1,69
19	28	275.3	447.6	1.63
20	28	283.3	449.7	1,59
Average	28.05	276.8	451.0	1.63
Median value	28	275.2	449.8	1.63
Standard	0.83	6.82	8.34	
Coefficient of variation	0.03	0.03	0.02	

Pay attention to the significant adjustments to the values of the strength-to-ductility ratio. If for the 09G2S high-strength steel on a sample of 5 elements this value is 1.23, then considering the results from Table 8 this value is already 1.29. A similar change for St3Sp5 steel (Table 7) from 1.54 to 1.63. This indicates the insufficiency of 5 tests for correct determination of stress-related properties of structural steel.

The ratio (4) is practically fulfilled or will be fulfilled with further increase in the number of tests. Consequently, the requirement of the National Annexes for 09G2S steel will obviously be met if requirement (4) is slightly reduced $f_u/f_y, \geq 1.29$.

Table 8. Values of strength and deformability parameters of 09G2S steel

Sample number	Elongation at break, %	Yield strength, MPa	Ultimate strength, MPa	Ratio
1	26	449.5	581.6	1.29
2	26	461.7	585.4	1.27
3	26	454.3	588.0	1.29
4	26	465.9	585.0	1.26
5	26	457.2	585.2	1.28
6	27	440.7	576.9	1.31
7	26	460.2	585.0	1.27
8	26	450.9	582.2	1.30
9	27	458.8	579.2	1.26
10	26	453.2	587.0	1.30
11	27	442.0	579.0	1.31
12	27	460.9	577.9	1.25
13	28	441.6	574.3	1.30
14	30	440.2	564.3	1,28
15	30	428.9	561.6	1.31
16	30	429.5	563.9	1.31
17	27	458.8	578.8	1.26
18	28	439.9	573.8	1.30
19	30	430.8	564.2	1.29
20	27	445.7	576.8	1.29
Average	27	448.54	577.51	1.29
Median value	27.2	450.2	578.90	1.29
Standard	1.53	11.42	8.25	-
Coefficient of variation	0.06	0.025	0.014	-

3.3. Calculations of Building Fragment

The calculable building represents a framed metal structure with rigid disks of slabs and coverings in the form of reinforced concrete monolithic slab. The building sizes in the longitudinal direction are 24 m. The dimensions of the building transversely are 12 m. The dimensions of building between the axes are 6 m each. The building has 3 floors 3 m high. The frame stiffness in cross direction is ensured by rigid pinching of the main columns of the frame in the foundation. The spatial stability of the frame elements is ensured by a system of longitudinal and transverse metal beams and monolithic reinforced concrete slabs 200 mm thick made of B25 grade concrete.

The columns are designed from 250×8 composite boxes on the outer contour and 250×10 and 250×8 composite boxes on the inner contour. The beams are I-beams 25B1, 20B1, 18B1. Steel grade S255 STO ASCHM 20-93.

3.4. Comparative Analysis

- The calculations of a 3-storey building with metal frame work according to SNiP RK 2.03-30-2006 and NTP RK 08-01.5-2013 have been performed. The calculation was carried out on the basis of numerical method of FEA in displacements using the "LIRA-SADP 2022 R2.1" software package. The calculation was performed under the requirements of I and II limit states and accidental limit state for seismic impacts.
- The periods of the first and second forms of eigen oscillations, determined by the standards of SNiP RK 2.03-30-2006 T1=0,58s and T2=0,56s differ from those obtained according to the norms of NTP RK 08-01.5-2013, which are T1=1.01s and T2=0.94s, accordingly.
- Distortions of the 1st, 2nd and 3rd floors from seismic impact along the X $\Delta_к$ axis varies from 0.0042m to 0.00697 m, that meets the condition (5.12) SNiP RK 2.03-30-2006, which is $\Delta_к$ = 0.15m.
- Distortions of the 1st, 2nd and 3rd floors from seismic impact along the U $\Delta_к$ axis varies from 0.0061m to 0.0083 m, that meets the condition NTP RK 08-01.5-2013, which is $\Delta_к$ = 0.15m.

Therefore, transition to calculations of load-bearing metal structures of the building under SP RK EN 1998-1:2004/2012 “Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings" and NTP RK 08-01.5-2013 results in moderate increase in consumption of materials, increases the reliability of the building as a whole.

4. Discussion

The correlation analysis of the results of experimental studies of mechanical tests was performed using the Scilab and MATLAB mathematical packages.

Linear correlation test is performed;

$$BH = A \times x + b \quad (5)$$

where x is one of the parameters - yield strength, tensile strength, relative strain at rupture. Table 9 offers three variations of the coefficients of the Equation 5. The first line of each parameter corresponds to steel St3Sp5, and the second - 09G2S. The values of correlation coefficients are also given here. Figures 3 to 5 show the correlation dependencies from Table 9.

Table 9. Parameters of linear correlation functions

Variant	Name	A	b	Correlation Coefficient	Note
1	Yield strength	0.1635	94.5384	0.61	7 points (STAT software module)
		0.1741	90.3511	0.63	
	Tensile strength	0.2720	15.9195	0.73	
		0.2945	5.5695	0.75	
	Relative rupture strain	-1.9401	213.29	-0.28	
		-0.4507	167.95	-0.07	
2	Yield strength	0.1514	101.54	0.57	5 points without special steel (STAT1 software module)
		0.1682	94.49	0.59	
	Tensile strength	0.2359	36.546	0.67	
		0.2523	29.164	0.64	
	Relative rupture strain	-3.8024	272.25	-0.32	
		-3.6448	271.97	-0.42	
3	Yield strength	0.2068	88.100	0.86	5 points without a thickness of 20 mm (STAT2 software module)
		0.2202	82.744	0,88	
	Tensile strength	0.3078	5.649	0.92	
		0.3699	-23.937	0.96	
	Relative rupture strain	-2.5725	241.116	-0.46	
		-2.2841	238,894	-0.29	

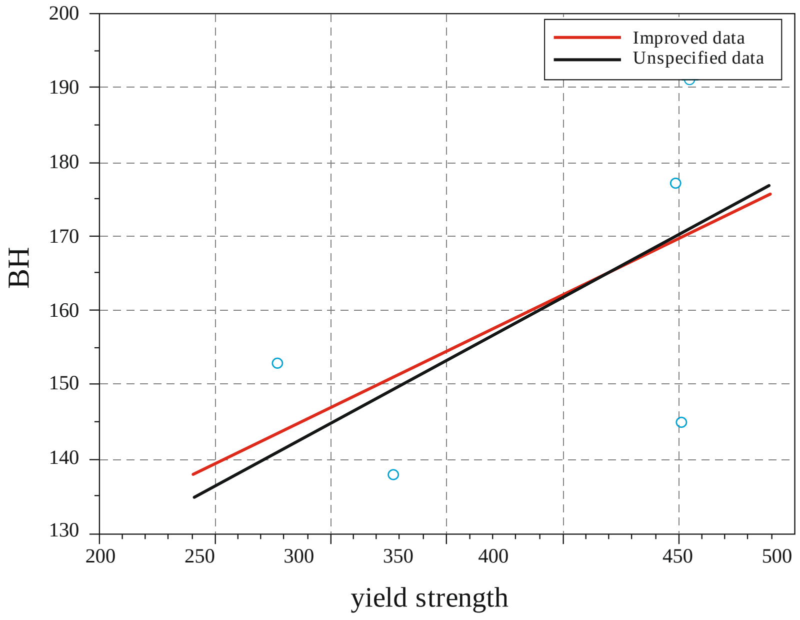

Figure 3. Correlation dependencies between yield strength and Brinell hardness (variant 3)

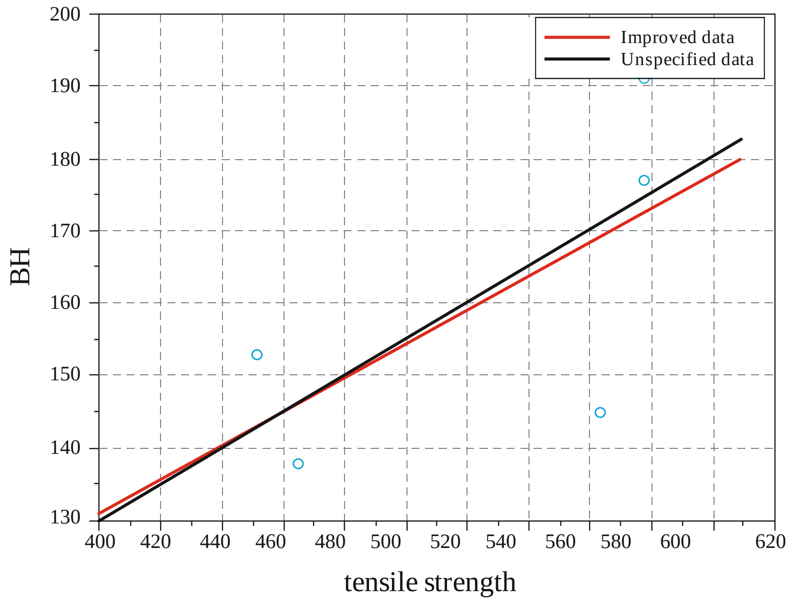

Figure 4. Correlation dependencies between tensile strength and Brinell hardness (variant 3)

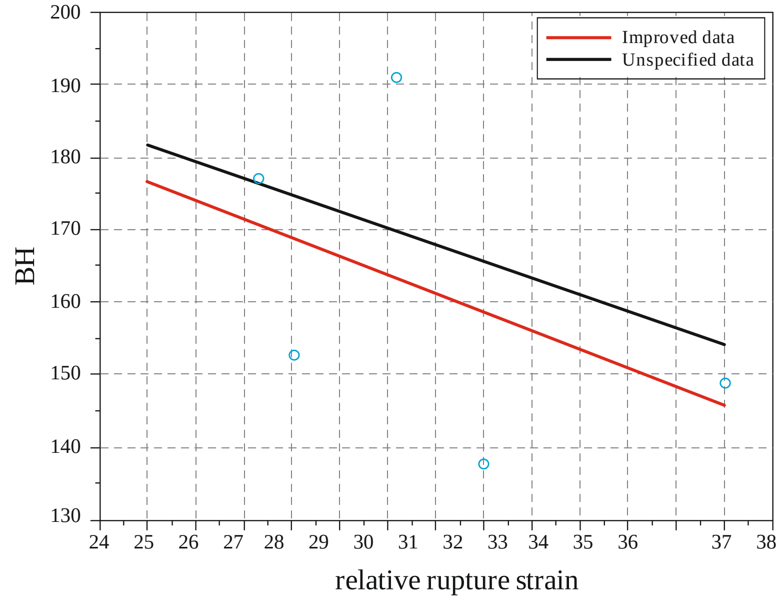

Figure 5. Correlation dependencies between relative rupture strain and Brinell hardness (variant 3)

Note that the characteristics of strength and deformability of structural steel are most accurately determined in the 3rd variant of the parameters of the linear correlation function. This is determined by the fact that the sample is the most homogeneous - 20 mm thick steel sheets are excluded. Therefore, for 8-10 mm thick steel sheets, stress-related properties should be determined according to the 3rd variant of parameters.

For example, for yield strength of steel St3Sp5

$$BH = 0.2068 * x + 88.100 \quad (6)$$

For the tensile strength of steel St3Sp5

$$BH = 0.3078 * x + 36.546 \quad (7)$$

For tensile strength at break of the steel St3Sp5

$$BH = 2.5725 * x + 241.116 \quad (8)$$

By solving the above equations with respect to BH, it is possible to determine values of yield strength, tensile strength, relative strain at break by values of BH. It is possible to determine these characteristics from Figures 3 to 5 by setting the value of BH hardness.

The strongest correlation between the Brinell hardness values and tensile strength and yield strengths values (variant 3, Table 9). The correlation between the tensile strength at break and Brinell hardness values is weaker, but is available. These results are quite substantial. For simple hardness tests according to Equation 1 and coefficients from Table 9, it is possible to approximate the values of yield strength and tensile strength, as well as the values of tensile strength at break.

To estimate the distribution function of strength and deformation parameters, we will use Student's test.

For the yield strength case, the probability value p=0.845, which is close to the theoretical p =0.8156 (Figure 6). Therefore, it can be considered, a hypothesis for normality cannot be rejected. The distribution function of tensile strength corresponds to the normal distribution to a lesser extent, relative rupture strain - does not correspond to the normal distribution at all.

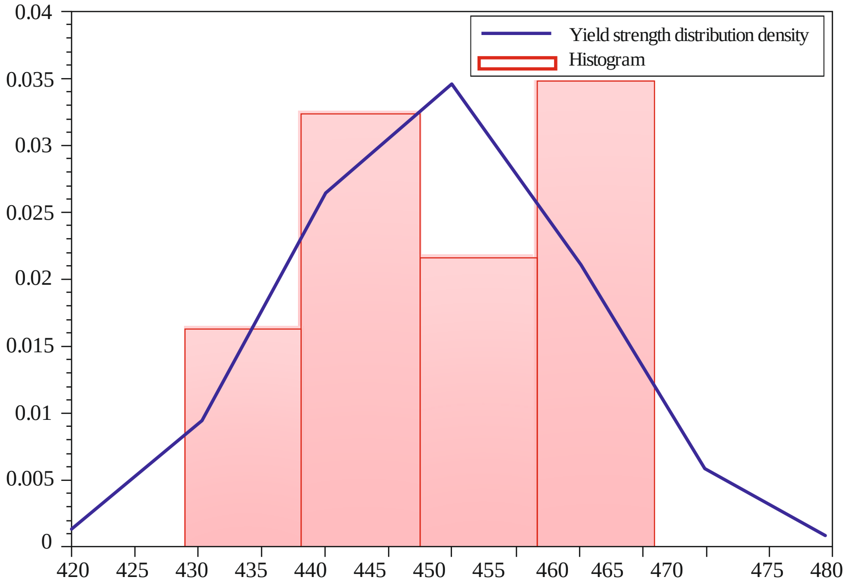

Figure 6. Yield strength distribution density

If we know the distribution function, e.g. yield strength, it is possible to determine estimated values at a given reliability.

The results of this work will contribute to the return to extensive use of steel structures in earthquake-resistant construction in the Republic of Kazakhstan. Following the introduction of a new statutory framework based on the Eurocode in 2015, the use of steel structures in seismic areas has practically stopped. It was not known whether the strength and deformation characteristics of Kazakhstani structural steel meet the requirements of the Eurocode. Whether such steel could be used in earthquake-resistive construction. At that, earthquakes with intensity up to 10 points are possible within the territory of Almaty city area [18-20], at least 40% of areas in the territory of the Republic of Kazakhstan are earthquake prone [21].

Although before 2015, steel structures have been widely used in the practice of earthquake-resistant construction even in 9-point regions. The earthquake focuses take place even within the territory of Almaty city [19]. For example, the 11-storey steel-framed building in Almaty, located at a distance of 1 km from the tectonic fault in the city, was designed in 1970 [22]. The station of engineering and seismometric service was installed on the building.

Different types of steel structures are used in seismic areas [23-26]. The use of steelwork structures is particularly attractive in high-rise construction [24]. In Gioncu & Mazzolani [4] performance f buildings with metal framing in various earthquakes is analyzed. It is noted that with the right design solution, the building successfully resists seismic impact. In this respect, attention should be paid to the rational design of butt joints [27]. It has been established that when designing steel-framed buildings, it is useful to use various damping devices [28], including the hydraulic dampers [29], as well as the brand new double dampers [30].

Therefore, the results of this work will allow designing steel structures for construction in earthquake-prone areas of the Republic of Kazakhstan, particularly, based on latest achievements in the area of optimal methods of calculation of such structures [31].

5. Conclusion

The main output of work is that structural steel produced by Arcelor-Mittal fully complies with the requirements of Eurocode 1993 and National Annexes in terms of yield strength, breaking stress (tensile strength), and relative strain at break. For National Annexes, it is proposed to correct the ratio of strength and yield strength to be equal to not less than 1.23. The tensile strength at break significantly exceeds the requirements of the Eurocode. Such results were obtained for the first time. With that, the local steel has high impact toughness characteristics, which allows structural steel to be used for construction in the northern regions of the Republic of Kazakhstan with temperatures down to -40 degrees. The calculation under Eurocode 1998 of the fragment of a frame building with closed columns at 8-point seismic impact. In this respect, the column misalignment limits are not exceeded, suggesting the design capability for steel frames of earthquake-resistant buildings in seismically active regions. The use of local structural steel will reduce the cost of earthquake engineering costs by reducing the cost of transportation costs (logistics). The wide use of steel structures in earthquake-resistant construction in areas with a seismicity of 9 points is expected in Almaty, Kazakhstan, where earthquakes with magnitudes over 8 have occurred (the Keminskoye earthquake of 1911).

The correlation dependences between the Brinell hardness of metal and values of yield strength, strength, and tensile strength at break were obtained for Kazakhstan steel for the first time. Hardness is a fundamental property of the near-surface layer of a material, which is determined experimentally quite simply. Through the hardness value, it is possible to pass to the values of impact strength. The specified empirical dependencies can be used for the operational determination of stress-related properties of structural steel, for example, when performing survey work. The estimation of the distribution function by the Student's test, which can be taken as normal, is performed for the yield strength and tensile strength.

6. Declarations

6.1. Author Contributions

Conceptualization, B.K., V.L., A.S., Y.S., T.T., S.A., Y.A., and A.A.; methodology, B.K., V.L., A.S., Y.S., T.T., S.A., Y.A., and A.A.; investigation, B.K. and V.L.; writing—original draft preparation, B.K., V.L., A.S., Y.S., T.T., S.A., Y.A., and A.A.; writing—review and editing, B.K., V.L., A.S., Y.S., T.T., S.A., Y.A., and A.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are contained within the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

We express our gratitude to the "Imstalcon" Joint Stock Company for sponsor support in the form of structural steel supply for the fulfillment of these research activities,

6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Vedyakov, I., Odessky, P.D., Konin, D.V., Egorova, A.A. (2015). Steel for rolling I-beams with parallel faces of shelves in Industrial and civil construction (PGS), No. 6, 30-35.

[2] Odessky, P. D., & Kulik, D. V. (2005). New Generation Steel in Unique Structures. Internet Engineering, 1-176. (In Russian).

[3] Shan, S., & Mou, B. (2024). Development of an innovative module-to-core wall connection for steel-framed modular high-rise buildings. Journal of Constructional Steel Research, 214, 108494. doi:10.1016/j.jcsr.2024.108494.

[4] Gioncu, V., & Mazzolani, F. (2013). Seismic design of steel structures. CRC Press, London, United Kingdom. doi:10.1201/b16053.

[5] Jin, J., Nagae, T., & Chung, Y. L. (2023). Seismic and collapse behavior of existing high-rise steel buildings under long-period earthquakes. Journal of Constructional Steel Research, 211. doi:10.1016/j.jcsr.2023.108151.

[6] Grigorian, M., Sedighi, S., & Mohammadi, H. (2023). Plastic design of sustainable steel earthquake resistant structures. In Engineering Structures (Vol. 289). doi:10.1016/j.engstruct.2023.116178.

[7] Gryniewicz, M., Roberts, M. J., & Davies, J. M. (2021). Testing and analysis of a full-scale steel-framed building including the consideration of structure-cladding interaction. Journal of Constructional Steel Research, 181. doi:10.1016/j.jcsr.2021.106611.

[8] Baciu, F., Rusu-Casandra, A., & Pastramă, S. D. (2019). Low strain rate testing of tensile properties of steel. Materials Today: Proceedings, 32, 128–132. doi:10.1016/j.matpr.2020.03.469.

[9] Vaz-Romero, A., Rodríguez-Martínez, J. A., & Arias, A. (2015). The deterministic nature of the fracture location in the dynamic tensile testing of steel sheets. International Journal of Impact Engineering, 86, 318–335. doi:10.1016/j.ijimpeng.2015.08.005.

[10] Wang, W., & Kodur, V. (2020). Tensile test on steels at elevated temperatures. Material Properties of Steel in Fire Conditions, 3, 43–120. doi:10.1016/b978-0-12-813302-6.00003-5.

[11] Rout, M., & Murugabalaji, V. (2023). Tensile properties variation along the thickness direction of hot rolled austenitic stainless steel. Materials Science and Engineering: A, 865. doi:10.1016/j.msea.2023.144643.

[12] Yang, X. J., & Lin, F. (2023). Experimental and analytical studies on tensile behavior of kinked steel plates. Journal of Constructional Steel Research, 204. doi:10.1016/j.jcsr.2023.107874.

[13] Gardnerand, L., & Nethrcott D. (2005). Designers' Guide to Eurocode 3: Design of Steel Structures. General rules and rules for buildings. Institution of Civil Engineers (ICE), London, United Kingdom.

[14] EN 1993-1-12. (2007). Eurocode 3: Design of steel structures –Part 1-12: Additional rules for the extension of EN 1993 up to steel grades s700. European Committee for Standardization, Brussels, Belgium.

[15] Kulbayev, B., Lapin, V., Tuleyev, T., Aldakhov, S., Aldakhov, Y., & Ali, A. (2023). Hardness specification of structural steel used in the Republic of Kazakhstan. E3S Web of Conferences, 389. doi:10.1051/e3sconf/202338901002.

[16] Kulbayev, B., Lapin, V., Shakhnovich, A., Tuleyev, T., Aldakhov, S., Aldakhov, Y., & Ali, A. (2023). Experimental Research of Impact Toughness of the Kazakhstani Construction Steel— Assessment of Compliance with the Provisions of 1993 Eurocode. Open Journal of Civil Engineering, 13(04), 664–676. doi:10.4236/ojce.2023.134044.

[17] Kulbayev, B., Lapin, V., Shakhnovich, A., Tuleyev, T., Aldakhov, S., Aldakhov, Y., & Ali, A. (2023). Weld Joint Efficiency of the Kazakhstani Constructional Steel. Open Journal of Civil Engineering, 13(04), 802–813. doi:10.4236/ojce.2023.134052.

[18] Vedyakov, I. I., Odesskiy, P. D., & Gurov, S. V. (2018). About regulation of materials in the new of rules SP 16.13330. Steel structures. Actualized edition of SNIP II-23-81. Industrial and civil construction, 8, 61-69.

[19] Galperin, R. M., Nersesov, I. L., & Galperin, E. I. (1985). Seismic regime of Almaty for 1972–1982 years. Science, Moscow, Russia. (In Russian).

[20] Sadykova, A. B., Silacheva, N. V., & Stepanenko, N. P. (2021). Seismic micro zoning of the territory of Almaty on a new methodological basis. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 1(445), 127–134. doi:10.32014/2021.2518-170X.18.

[21] Kurskeev, A. K., Timush, A. V., Shatsilov, V. I., Sydykov, A., Gorbunov, P. N., & Sadykova, A. B. (2000). Seismic zoning of the Republic of Kazakhstan. Evero, Almaty, 219.

[22] Lapin, V., Makish, N., Kassenov, K., Omarov, Z., & Kassenov, D. (2021). Instrumental records received in 11 storey steel frame building during a remote earthquake. E3S Web of Conferences, 258, 9078. doi:10.1051/e3sconf/202125809078.

[23] Vedyakov, I. I., Suslov, L. S., Marisiuk, A. A., Kashin, O. V, & Novozhilov, M. V. (2023). Bearing capacity of a steel frame of a multi-storey modular building with consideration of the rigidity of quick-assembled connections. Earthquake Engineering. Constructions Safety, 6, 8–44. doi:10.37153/2618-9283-2023-6-8-44.

[24] Nemchinov, Yu. I. (2015). Seismic Resistance of High-Rise Buildings. NIISK, Kyiv, Ukraine.

[25] Fang, C., Wang, W., Qiu, C., Hu, S., MacRae, G. A., & Eatherton, M. R. (2022). Seismic resilient steel structures: A review of research, practice, challenges and opportunities. Journal of Constructional Steel Research, 191, 107172. doi:10.1016/j.jcsr.2022.107172.

[26] Wasse, A. D., Dai, K., Wang, J., & Sharbati, R. (2024). State-of-the-Art Review: Seismic Design and Performance Assessment of Special Concentrically Braced Frames Developed for Complex Industrial Building Structures. International Journal of Steel Structures, 1-16. doi:10.1007/s13296-024-00815-w.

[27] Pawar, G. D., & Dawari, V. B. (2023). Seismic design of bolted beam to column connections in tubular steel structures – A review. Materials Today: Proceedings, 1-6. doi:10.1016/j.matpr.2023.03.150.

[28] Pu, W., & He, C. (2022). Seismic design framework for steel structures with hysteretic and viscous dampers. Journal of Constructional Steel Research, 194, 107330. doi:10.1016/j.jcsr.2022.107330.

[29] Ras, A., & Boumechra, N. (2016). Seismic energy dissipation study of linear fluid viscous dampers in steel structure design. Alexandria Engineering Journal, 55(3), 2821–2832. doi:10.1016/j.aej.2016.07.012.

[30] Mahjoubi, S., & Maleki, S. (2016). Seismic performance evaluation and design of steel structures equipped with dual-pipe dampers. Journal of Constructional Steel Research, 122, 25–39. doi:10.1016/j.jcsr.2016.01.023.

[31] Gholizadeh, S., & Salajegheh, E. (2010). Optimal seismic design of steel structures by an efficient soft computing based algorithm. Journal of Constructional Steel Research, 66(1), 85–95. doi:10.1016/j.jcsr.2009.07.006.