Scientific Research Publishing

Open Journal of Civil Engineering, 2023, 13, 802-813
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Weld Joint Efficiency of the Kazakhstani Constructional Steel

Begman Kulbayev, Vladimir Lapin, Alexander Shakhnovich, Tursymbai Tuleyev, Serik Aldakhov, Yerken Aldakhov, Alimzhan Ali

Kazakh Research and Design Institute of Construction and Architecture, Almaty, Kazakhstan
Email: lapin_1956@list.ru

How to cite this paper: Kulbayev, B., Lapin, V., Shakhnovich, A., Tuleyev, T., Aldakhov, S., Aldakhov, Y. and Ali, A. (2023) Weld Joint Efficiency of the Kazakhstani Constructional Steel. *Open Journal of Civil Engineering*, **13**, 802-813.
https://doi.org/10.4236/ojce.2023.134052

Received: November 16, 2023
Accepted: December 25, 2023
Published: December 28, 2023

Abstract

In the Republic of Kazakhstan, the regulatory framework in construction based on Eurocodes has been in force since 2015. However, Kazakhstani produced steel has not been studied for compliance with the requirements of Eurocode 1993. This has resulted in limited use of Kazakhstani structural steel in construction. The feasibility of using structural steel in welded joints has been experimentally investigated. To verify the application of such joints in construction, including earthquake engineering, experimental studies of welded joints made of structural steel produced by Arcelor-Mittal in Temirtau have been carried out. In total, 7 types of structural steel of various thicknesses were selected. Five specimens have been used in each series of tests. The Brinell hardness values of the weld joint, yield strength of steel and tensile strength, relative rupture strain were determined. It was found that for all types of structural steel, the quality of weld joints complied with the requirements of Eurocode 1993—a sample rupture appeared along the plates (main body of the metal), not along the weld joints. It has been established that structural steel produced in the Republic of Kazakhstan fully complies with the requirements of Eurocode 1993. The studies on the dependence of Brinell hardness values of weld joint steel on the yield strength, tensile strength and relative rupture strain have been carried out. The correlation dependences between the values of yield strength of steel and tensile strength, relative rupture strain and BH Brinell hardness were studied. The results of work will allow for significantly increasing the use of Kazakhstani structural steel in seismic and conventional areas of the Republic of Kazakhstan.

Keywords

Yield Strength, Tensile Strength, Steel Hardness, Construction Steel, Eurocode, Weld Joints

1. Introduction

Over 45% of the territory of the Republic of Kazakhstan refers to seismically active areas, and the significant area is occupied by extremely seismically hazardous areas of 8 - 9 and over points on the MSK-64 scale. A certain portion of these territories are particularly attractive for development as it has rich reserves of natural resources, the other part of the territory is an active recreation area for the population. Despite the inaccessibility, seismic hazard, complex ground and climatic conditions, the construction of buildings and structures in seismically active areas develops actively. The development of these territories poses new challenges for the construction industry concerning assurance of earthquake resistance of buildings and structures.

The experience in the use of steel structures suggests that they can be successfully used in the design and construction of earthquake-resistant buildings and structures, including the high-rise buildings. Note that steel works are typically factory fabricated, very light and strong. The steel is an isotropic material that performs almost equally in tension and compression. This determines the widespread use of steel works in construction, including earthquake-resistant construction.

However, following the transition to a new regulatory framework in 2015, the use of steel structures in construction, including earthquake-resistant construction, was significantly reduced. This has occurred due to the peculiarities of the new regulatory framework based on the Eurocode. The construction steel had to meet the requirements of Eurocode 1993 [1] [2].

In [3] the design principles of earthquake-resistant steel frames of industrial buildings are discussed. Special attention is given to the causes of damage to steel frames under seismic load, as well as to the requirements to be observed when designing steel frames in seismically active areas. The most appropriate materials that can be used in order to strengthen the structural steel frame by making it work properly with respect to the occurred seismic loads have been studied. The analysis of materials of past accidents in Russia and other countries of the world has allowed to identify the following leading causes of these damages: 1) irregularities in the manufacturing procedure of assembly operations—34%; 2) errors in the performance of construction joints—26%; 3) infringement of operating procedures—16%; 4) availability of seismic instability above the predicted level due to insufficient argumentation of the seismicity of the construction site—13%; 5) low quality and insufficiency of intended operations on seismic protection to in accordance with current requirements—7%; 6) lack of clear recommendations on earthquake protection of frames in high seismic conditions to date—7% [4].

The various aspects of the design of frames made of steel cold-formed profiles are discussed in [5].

The types of steelwork damage are discussed in [6].

The damage to butt joints in violent earthquakes is discussed in more detail in the [7] [8] [9]. The high-hardness steel with yield strengths of more than 460 MPa is widely used in many construction projects. The use of high-strength steel with yield strengths greater than 690 MPa has become an important topic of applied research because of its distinctive mechanical properties. The researchers seek to explore the utilization capacity of high-strength steel in engineering construction projects. On the other hand, brittle damage of beam-to-column welded joints has been observed in strong earthquakes such as the Northridge earthquake [8] and the Kobe earthquake [9]. The damage of this type occurred mainly at the butt weld joints connecting the bottom flange of the beam end to the column flange.

The experimental results of steel frames under cyclic loading are available [10]. In all cases, the strength of welded joints under static and cyclic loads was considered.

Therefore, for the use of Kazakhstani structural steel in earthquake-resistant construction it is necessary to verify experimentally the welded joint strength for compliance with the requirements of Eurocode 1993.

Consequently, the cycle of researches on the actual problem of verification of the requirement of compliance of Kazakhstan steel characteristics with Eurocode 1993 [2], started in Kazakhstan by the work [1] continues. Previously such a task was not solved in the Republic of Kazakhstan.

2. Materials and Methods

At the first stage, samples of welded joints were made from 7 types of construction steel most used in the Republic of Kazakhstan. The second column of **Tables 1-4** indicates the steel manufacturer, thickness in mm and grade. The manufacturing and testing of samples was performed according to GOST 6696-66, ISO 4136-89, ISO 5173-81, ISO 5177-81. The welding of plates made of structural steel was performed as "butt welded". UONI electrodes have been used for welding.

Table 1. Statistical characteristics of Brinell hardness of the weld joint based on the test results.

N°	Manufacturer, Thickness, mm	Brinell hardness, average value	Standard deviation	Coefficient of variation
1	Arcelor-Mittal, 8	141.0	3.46	0.02
2	Arcelor-Mittal, 10	149.9	1.52	0.01
3	Arcelor-Mittal, 8	151.0	8.51	0.06
4	Arcelor-Mittal, 10	149.8	11.45	0.08
5	Amet, 20	173.0	4.64	0.03
6	Amet, 20	167.2	4.82	0.03
7	Severstal, 10	147.4	8.20	0.06

Table 2. Statistical characteristics of tensile strength based on the test results.

N°	Manufacturer, Thickness, mm type	Average value	Standard deviation	Coefficient of variation
1	Arcelor-Mittal, 8, St3SP5	451.08	1.43	0.003
2	Arcelor-Mittal, 10, St3SP5	441.6	1.52	0.004
3	Arcelor-Mittal, 8, 09G2S	580.60	1.61	0.005
4	Arcelor-Mittal, 10, 09G2S	538.20	1.3	0.002
5	Amet, 20, St3SP5, SV	468.80	1.79	0.004
6	Amet, 20, 09G2S	524.8	1.79	0.003
7	Severstal, 10, St3SP5, SV	438.40	1.14	0.003

Table 3. Statistical characteristics of yield strength based on the test results.

N°	Manufacturer, Thickness, mm	Average value	Standard deviation	Coefficient of variation
1	Arcelor-Mittal, 8, St3SP5	323.72	5.90	0.018
2	Arcelor-Mittal, 10, St3SP5	292.60	1.52	0.005
3	Arcelor-Mittal, 8, 09G2S	450.00	5.48	0.012
4	Arcelor-Mittal, 10, 09G2S	429.60	3.65	0.008
5	Amet, 20, St3SP5, SV	327.80	4.55	0.014
6	Amet, 20, 09G2S	418.60	1.79	0.0042
7	Severstal, 10, St3SP5, SV	253.80	2.39	0.0094

Table 4. Statistical characteristics of elongation at break based on the test results.

N°	Manufacturer, Thickness, mm	Average value	Standard deviation	Coefficient of variation
1	Arcelor-Mittal, 8, St3SP5	31.0	1.0	0.032
2	Arcelor-Mittal, 10, St3SP5	33.20	0.84	0.025
3	Arcelor-Mittal, 8, 09G2S	28.60	1.14	0.040
4	Arcelor-Mittal, 10, 09G2S	35.20	1.30	0.037
5	Amet, 20, St3SP5, SV	30.20	0.84	0.028
6	Amet, 20, 09G2S	29.80	0.84	0.028
7	Severstal, 10, St3SP5, SV	37.00	1.00	0.0027

The welds were then tested for the BH Brinell hardness using the certified TKM-359M hardness tester.

The mechanical tensile testing of welded joint samples was performed using a UMM-5 tensile testing machine with a calibration certificate dated February 24, 2023. The breaking machine allows you to create forces up to 100 tons. The organization is accredited for testing according to the test requirements of ST RK ISO.

In each tests series, 5 specimens with thickness of 8 - 20 mm were used. (Kazakhstan made St3SP5, 09G2S). Section 3.2 presents the results of mechanical stress tests.

The processing of experimental data was performed using the MATLAB mathematical package.

3. Results

The studies of BH Brinell hardness of welded joints of structural steel samples were carried out at the experimental base of Kazakh Scientific Research and Design Institute of Civil Engineering and Architecture JSC. The findings demonstrate that the hardness characteristic of the butt joint is a very stable characteristic, with a variation coefficient in the range of 0.01 - 0.06. The correlation dependencies between the Brinell hardness of the welded joint and the physical and mechanical characteristics of the steel are further analyzed. Table 1 summarizes the BH hardness characteristics of the weld joints.

Results of Tensile Strength Test

According to paragraph "4.2 Welding consumables" SP RK EN 1993-1-8:2005/2011 EN 1993-1-8:2005, the value of yield strength, tensile strength, elongation at break and minimum impact strength of the weld metal on Charpy specimens shall be equivalent to or higher than the values established for the base metal.

Tables 2-4 present statistical data on the processing of experimental results for the values of temporary resistance (tensile strength), yield strength and relative rupture strain. The Matlab program package was used for calculations. The deformation and strength characteristics with the required security can be determined by the values of mean values and standard deviations.

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

f_u/f_y —ratio of the minimum value of tensile strength f_u to the minimum value of yield strength f_y; relative elongation after fracture of the specimen with the length of $5.65\sqrt{A_0}$ (where A_0 —original cross-sectional area); critical strain ε_u, corresponding to the ultimate strength f_u.

According to NP RK 1993-1-1:2005/2011 Design of structural steel. Part 1 - 8. General regulations and rules for buildings.

The ceiling values of the ratio of ultimate strength to yield strength, elongation at break and elastic strain of steel shall meet the following requirements:

$$f_u/f_y \geq 1.3; \quad (1)$$

elongation at break – at least 15%; (2)

$$\varepsilon_u > 15\varepsilon_y, \text{ where elastic strain } \varepsilon_y = f_y/E, \quad (3)$$

where E—Young's modulus.

Figure 1 shows samples of welded joints before testing, and Figure 2 after testing. This means that in all 35 tests, the fracture of welded joints has not occurred along the weld, but along the base metal. Consequently, the weld joint strength is not less than that of structural steel. Therefore, the basic requirement of Eurocode 1993 has been fulfilled.

Analysis of Table 5 demonstrates that condition (1) from National Annexes is not fulfilled for 3 cases—steel 09G2S, thickness 8, 10 and 20 mm. For the case of the general requirements of Eurocode 1993 (SP RK EN 1993-1-1:2005/2011 Design of structural steel. Part 1-1. General rules and regulations), the requirement is weaker f_u/f_y, ≥ 1.10. Consequently, for 09G2S steel the general requirements are fulfilled, but for the National Annexes they are not fulfilled. However, requirements (1) have been formulated without proper experimental verification. Therefore, the condition (1) can be diminished, for example, f_u/f_y, ≥ 1.24.

Figure 1. Construction steel specimens prepared for impact toughness testing.

Figure 2. Samples of weld joints after testing.

Table 5. Ratio from the Formula (1.3).

N˚	Manufacturer, Thickness, mm	Ratio from the Formula (1.3)
1	Arcelor-Mittal, 8, St3SP5	1.39
2	Arcelor-Mittal, 10, St3SP5	1.51
3	Arcelor-Mittal, 8, 09G2S	1.29
4	Arcelor-Mittal, 1009G2S	1.25
5	Amet, 20, St3SP5, SV	1.43
6	Amet, 20, 09G2S	1.25
7	Severstal, 10, St3SP5, SV	1.73

The most important result of the experimental studies of weld joints is that the rupture of welded joints was not along the welds, but along the base metal body. Consequently, the weld joint strength is not less than the strength and deformability of structural steel.

Figures 3-5 show the relationship between the Brinell hardness of the weld and the values of the tensile strength, yield strength and relative rupture strain. Figures 6-8 show the relationship between the Brinell hardness of the base metal and the specified characteristics of structural steel.

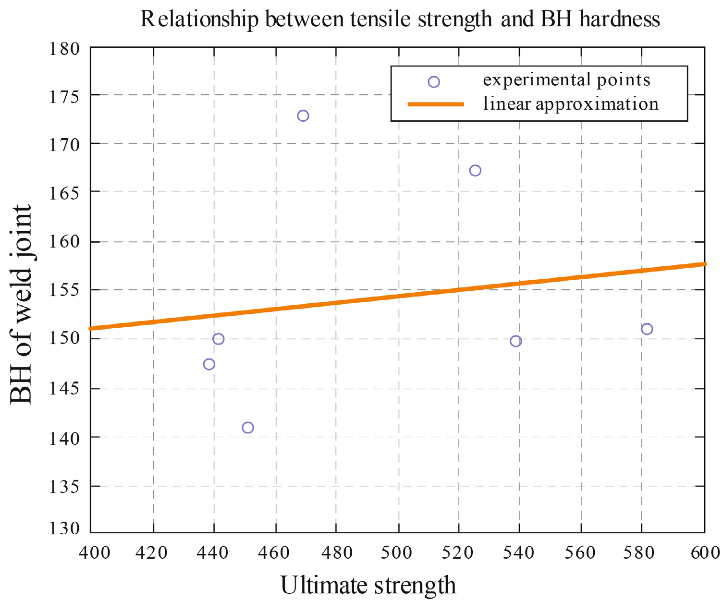

Figure 3. Relationship between ultimate strength and Brinell hardness of weld joint.

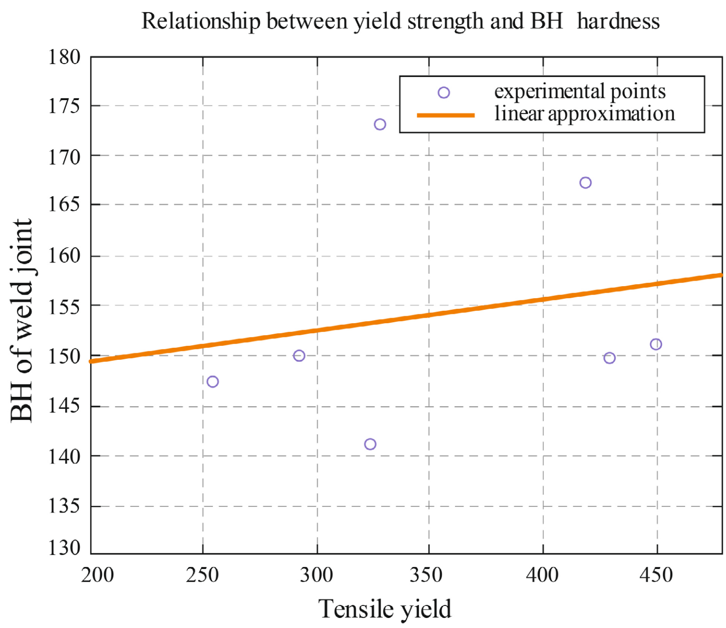

Figure 4. Relationship between the yield strength and Brinell hardness of weld joint.

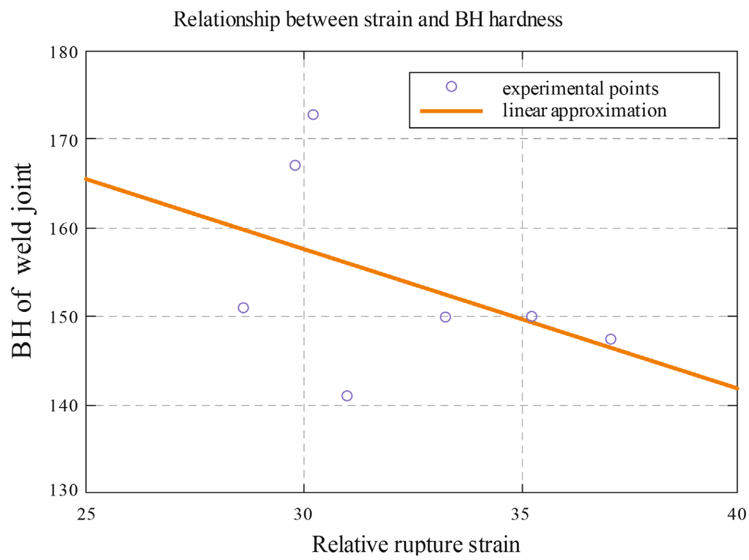

Figure 5. Relationship between relative rupture strain and Brinell hardness of weld joint.

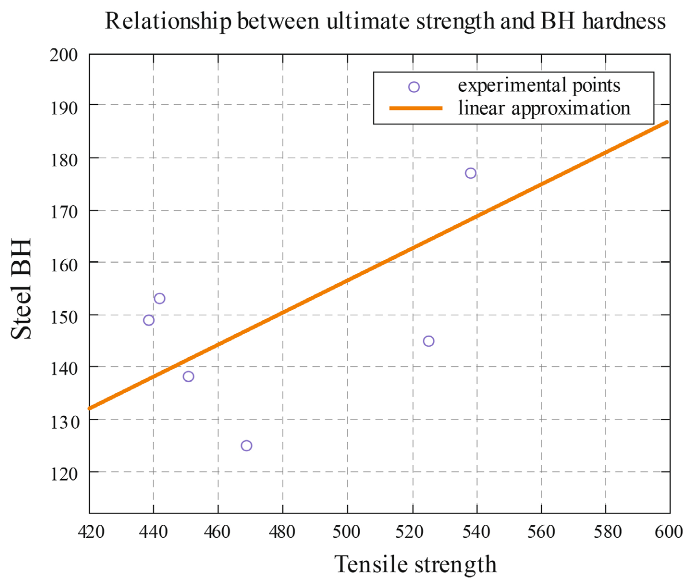

Figure 6. Relationship between the ultimate strength and Brinell hardness of steel.

Table 6 summarizes the values of the correlation coefficient for each regressional relationship shown. The line number is the same as the graph number.

The analysis of Table 6 shows that the value of weld joint hardness is loosely correlated with the values of strength and yield strength of the base metal. For the case of relative rupture strain there is a correlation. For the case of hardness values of structural steel directly, there is a reliable correlation between the values of tensile strength and yield strength of structural steel. There is no such correlation for the case of relative deformations. It shows that the availability of weld joint affects the strength and deformability characteristics of the base metal (structural steel) to some extent. Quite an interesting result has been obtained.

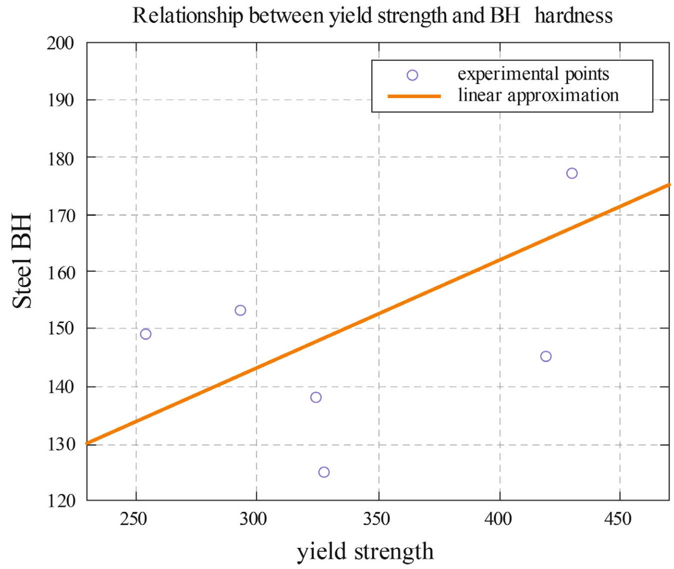

Figure 7. Relationship between the yield strength and Brinell hardness of steel.

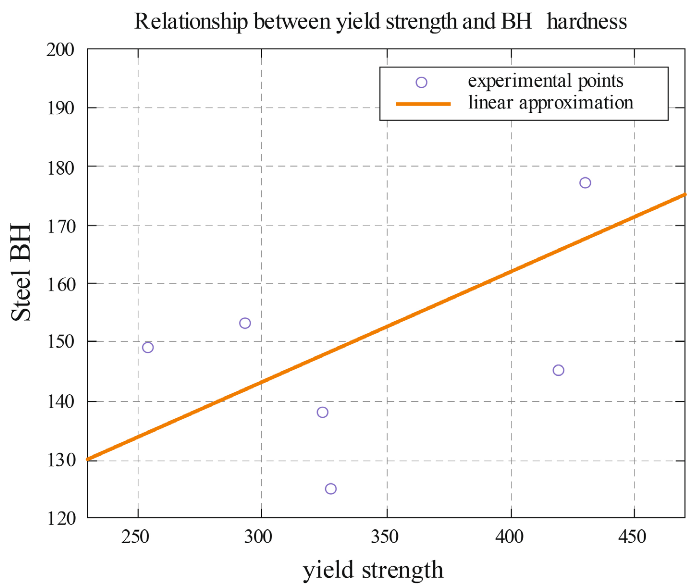

Figure 8. Relationship between the relative rupture strain and Brinell hardness of steel.

Table 6. Correlation coefficients for graphical dependencies in Figures 3-8.

N°	Correlation coefficient	
1	0.16	Weak correlation
2	0.20	Weak correlation
3	−0.43	Correlation is available
4	0.75	Reliable correlation
5	0.63	Reliable correlation
6	0.02	No correlation

4. Discussion

Prior to the introduction in Kazakhstan of a new regulatory framework in construction based on Eurocode in 2015, the steel produced in the Republic of Kazakhstan was intensively used in earthquake resistant construction. In Almaty city located in the area of seismicity of 9 points, steel-frame buildings up to 30 floors high were intensively constructed. After 2015, the local structural steel has virtually ceased to be used.

Therefore, the result obtained for the Kazakhstani structural steel that the strength of the weld joint should be not less than the strength of the base metal [2]. The results of these experimental studies suggest that the Kazakhstani structural steel meets these requirements. This would enable the local structural steel to return for wide application in the construction industry of the Republic of Kazakhstan.

This is particularly topical for earthquake-resistant construction in the Republic of Kazakhstan. The use of local structural steel will reduce the cost of construction in earthquake-prone areas.

According to the experimental data, it is found that the condition of Eurocode 1993 f_u / f_y, ≥ 1.1 for the Kazakhstani steel is fulfilled every time (**Table 5**). According to the values of relative rupture strain, condition (2) is also fulfilled at any time (**Table 4**). (3) condition is also satisfied all the time for the types since the Young's modulus values are 3 orders of magnitude higher than the yield strength values, and the relative strain values from the table are quite large.

The results of **Table 6** show that there is a very weak correlation between weld stiffness and the parameters from **Tables 2-4**, which is a bit of an unexpected result. Usually this correlation is quite significant. The reason seems to be the following. The welded joint is made with such high quality that it affects the overall strength of the test sample. However, this also violates the stable correlations between the hardness of the BH weld and the strength characteristics of structural steel.

For the Brinell hardness of the base metal from [1], the correlation relationship is more significant (**Table 5**).

The positive results of the welded joints study will promote a return to the use of Kazakhstani steel in the construction of steel-framed buildings.

And it should be noted that local structural steel can be used in the construction of high-rise buildings in earthquake-prone areas of Kazakhstan [11] [12].

5. Conclusions

1) The experimental studies to determine the values of hardness, yield strength, temporary resistance (tensile strength), relative rupture strain of welded joints samples 8 - 20 mm thick 7 most common samples of local structural steel are conducted in the Republic of Kazakhstan for the first time. These are the first studies of locally produced structural steel that can be used to adjust the National Applications of the Eurocode 1993. The application of the Eurocode 1993 in

the Republic of Kazakhstan becomes scientifically justified.

2) In all tests, the yield strength, tensile strength, relative elongation at break were equivalent to or higher than the values specified for the base metal, which complies with the requirements of Eurocode 1993. This result testifies to the high quality of structural steel produced in Kazakhstan and will contribute to its wide application in construction practice.

3) In all tests of welded joint specimens, ruptures have occurred along the parent metal, which is the fulfillment of the requirements of Eurocode 1993. This is evidence of the sufficient quality of the electrodes used for welding in the construction industry of Kazakhstan.

4) The regressional dependences between hardness of structural steel and yield and strength limits **Figure 6**, **Figure 7** can be used to predict the values of these characteristics at different hardness of steel. These dependencies are useful for the rapid determination of the yield strength of steel during survey work.

5) The main findings of this work allow using the Kazakhstani structural steel for design and construction of steel structures according to the requirements of Eurocode 1993 in earthquake-prone and ordinary areas of the Republic of Kazakhstan. Steel structures are actively used in nine-point seismic zones in the city of Almaty in the construction of buildings up to 30 floors high.

Acknowledgements

We express our gratitude to the Imstalcon Joint Stock Company for sponsoring in the form of supplies of structural steel for the performance of these scientific studies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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