ТРАНСПОРТНЕ БУДІВНИЦТВО

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Experimental evaluation of Strength and Deformability of Steel Nails for Wooden Structures

Purpose. The main purpose of the paper is to discuss the experimental studies to determine in laboratory conditions the characteristics of nail steel of one of the most common companies on the modern construction market of Ukraine – ExpertFix (Denmark). **Methodology.** To achieve this goal the tests were carried out for tensile testing of nails of a classic round cross-section of 5 diameters in the range from 4 to 7 mm, manufactured according to the German standard. **Findings.** According to the results of the study, diagrams of the work of steel nails under load were constructed, which turned out to be very close to the classical diagram of the work of high-strength steel. The destruction of the samples occurred according to a visco-plastic scheme with the formation of a characteristic «neck» at the rupture site. The recorded strength level is from 450 to 700 MPa at a relative deformation of up to 13%. **Originality.** The obtained characteristics of nails correspond to high-strength steels of classes C390–C500 according to the standard of Ukraine, but do not correspond to steels of grades St1–St3, for which current theoretical approaches to the design of nodal connections have been developed. Therefore, the use of such nail products in practice requires adjustment and clarification of existing approaches and methods of their use in wooden structures, which in turn requires the intensification of scientific research in this direction. **Practical value.** The practical usage of the strength characteristics of steel nails obtained during experimental studies allows for the correct and reasonable design of nodal connections of wooden structures based on the current Ukrainian standard. It also provides a basis for developing more advanced calculation approaches for assessing their performance.

Keywords: wooden structures; nodal connections; nail; steel; mechanical characteristics of steel

Introduction

Wood structures are becoming increasingly popular in the world today. They are gradually «conquering» more and more new industries, especially in the field related to everyday human activity. Wood is used for both residential and public construction. At the same time, the properties of wood allow it to be used for both low-rise and high-rise construction, including for rather complex engineering cases of earthquake-resistant construction. The latter trend is especially popular in modern Mediterranean countries, where the lower part of the load-bearing frame of buildings is often assumed to be more rigid and designed from reinforced concrete, and the rest of the structure is a spatial system of wooden elements [11].

This popularity of timber is due to a number of its positive qualities. These include, first and foremost, very high environmental friendliness of the material, which is ensured by growing construction timber in specialised areas closed from external influences, such as mountain plantations. In addition, such controlled growth conditions will improve the physical and mechanical qualities of such wood, as it has significantly fewer defects compared to wood growing in conventional forests. The second important positive feature of wood is its high architectural and expressive properties, which contribute to the creation of very im-

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pressive construction projects. The exterior of such objects is very memorable, leaving only pleasant impressions. The interior made of wood is so attractive to most residents that, according to them, they cannot refuse wood and switch to finishing with other building materials. An additional unique property of wood that attracts an increasing number of people around the world is its good thermal insulation qualities. In practice, residents of wooden buildings describe this phenomenon as if wood «radiates warmth» and note it as a very positive thing.

Wood is also a fairly versatile material in terms of climatic conditions for its use. Modern wood structures are traditionally built in areas with a rather harsh and cold climate, especially in Scandinavia [19]. Likewise wood is quite popular for construction in areas with humid and hot climates, especially in Asia. Such diverse natural and climatic conditions are fully manifested in the territory of modern China, so the use of wood is particularly interesting and relevant for this country [20].

We should also mention the wide range of modern wood products. Not only do they have all the advantages of conventional wood, but they also have improved mechanical characteristics and construction performance. These products primarily include glued wood beams [13]. It is used to build structures that can cover significant spans of about 30 m and above. In order to increase fire resistance, load-bearing elements made of glued laminated timber can be covered with special finishing boards made of wood wool, which, according to the studies, eliminates the risk of fire [7]. In general, such a composite combination of materials will contribute to a significant increase in the competitiveness of modern wood in the construction market.

Currently, a number of the latest structural solutions for timber frames have been developed in the world [17]. The main problematic issue in the design and subsequent operation of such wooden structures is the arrangement of nodal joints [16]. The reliable operation of the entire structure largely depends on their high-quality and reliable behaviour. Therefore, in design practice, increased attention is paid to nodal connections.

This does not bypass the sphere of scientific research. The performance of nodal joints in wooden structures is analysed from both theoretical and practical perspectives. Moreover, experimental studies are dominant in this regard, as they provide invaluable material that can be further processed, summarised and presented in the form of theoretical approaches and practical methods in the regulatory framework [18]. On the other hand, methods of strengthening existing nodal connections continue to be improved and developed [15].

In Ukraine, the main regulatory document that also regulates the design of nodal connections of wooden structures is the standard [1]. According to it, the main types of joints are contact connections and connections with working ties. The latter include nailed connections.

Nailed connections are now very common in the world. In building structures, such connections often play a key role in determining the load-bearing capacity of the entire structure. Although various metal alloys and polymer mixtures are used as nail materials, steel remains the main and classic type of material that is mass-produced around the world. Therefore, an essential component of the load-bearing capacity assessment in the design practice of nailed joints is to take into account the mechanical characteristics of the steel used for nail production.

In Ukraine, there is currently no official national standard that would regulate the geometric dimensions and shape of steel nails, as well as the steel grades used to make them. The closest analogue, which is not currently an official standard of Ukraine, is the standard [3]. In design practice, the most common type of nail in accordance with this standard is the «round nail», which has a cross-section of the shank in the form of a circle (Fig. 1). The main geometric dimensions in accordance with the standard [3] are presented in Table 1.

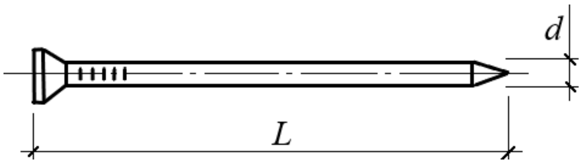

Fig. 1. Round nail – general shape and dimensions: *d* – nail diameter; *L* – nail length

In the European practice, which is now actively used in the construction industry of Ukraine, the main regulatory document is the standard [12]. According to it, the nail also has the shape of a «round nail» (Fig. 1), and its main geometric di-

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mensions are given in Table 1. As can be seen, compared to the Ukrainian standard, the number of standard sizes is much larger, and there are also certain differences in the geometry of nails.

Table 1

Geometrical dimensions of round nails (mm)

DSTU 4028:2008		DIN 1151	
d	*L*	*d*	*L*
–	–	0.9	13
–	–	1.0	15
–	–	1.2	20
–	–	1.4	25
–	–	1.6	30
1.8	32, 40, 50, 60	1.8	35
2.0	40, 50	2.0	40
–	–	2.2	45, 50
2.5	50, 60	2.5	55, 60
–	–	2.8	65
3.0	70, 80	–	–
–	–	3.1	65, 70, 80
–	–	3.4	80, 90
3.5	90	–	–
–	–	3.8	100
4.0	100, 120	–	–
–	–	4.2	100, 110, 120
–	–	4.6	130
5.0	120, 150	5.0	140
–	–	5.5	140,160
6.0	150, 200	6.0	180
–	–	7.0	210
–	–	7.6	230, 260
8.0	250	–	–
–	–	8.8	260

Nails with a diameter of 4–7 mm are used for load-bearing elements of modern building structures made of wood and wood-based materials. Smaller diameters do not provide the required load-bearing capacity, so they are used only for minor structural elements or for fixing finishing structural elements. Nails of large diameters of 8 and 8.8 mm have serious difficulties with their placement in elements, as it is necessary to ensure the minimum distance between the nail axes, which, according to the current standard of Ukraine [1], can reach 10 nail diameters. This requires large cross-sections of load-bearing structural elements, which is not always justified. On the other hand, the process of installing large diameter nails requires mandatory pre-drilling of holes, which makes it more complicated and expensive.

A separate aspect is the steel grade of the nail. According to standards [3, 12], this information is not available. Yet, it is key in terms of assessing the nature of the nail performance in wood. It is known that a nail must be sufficiently flexible to prevent wood splitting. However, on the other hand, too high deformation properties can lead to technological difficulties with the installation of nails in structural elements, as the process itself involves mostly impacts that can bend the nail shank before it is completely immersed in the wood. It is also worth noting the possible danger of increased deformability of the nailed joint itself if the nail steel is highly ductile. Therefore, the issue of choosing the right steel grade for nails remains quite important.

It is also worth noting that the correct choice of steel for building structures leads to a significant improvement in its structural characteristics, primarily static ones [14]. Depending on the steel grade, it is also possible to influence the dynamic characteristics of the structure, which allows for their control [8]. This is especially evident in case of seismic impacts on structural elements [10]. Often, steel in general becomes the «weak point» of a structure, which leads to emergencies and complete cessation of operation [9].

In domestic practice, specialised professional literature recommends using carbon steels of ordinary quality of grades St1–St3 for nails. According to the current Ukrainian standard [4], such steels have a rather narrow range of changes in the main mechanical characteristics – strength and stiffness. A selection of these characteristics for rolled steel thicknesses up to 10 mm is shown in Table 2.

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According to the current standard in Ukraine [1], one of the main design characteristics of a nail is the «characteristic value of the bending moment of plastic deformation». For smooth round nails, it is calculated by expression (1):

$$M_{y,Rk} = 0.3 \cdot f_u \cdot d^{2.6}, \qquad (1)$$

where f_u – tensile strength of steel.

Thus, the main practical problem faced by specialists in the design of nailed joints of wooden structures is the assessment of the mechanical characteristics of nail steel. It is impossible to solve this problem theoretically, as each batch of nails is manufactured at a specific enterprise and in a specific country. Currently, the Ukrainian construction market is home to a wide variety of suppliers of metal hardware products, which are often not accompanied by special certificates or contain false information about the steel characteristics. Therefore, the only way to obtain reliable mechanical characteristics of nail steel is to conduct laboratory testing.

Table 2

Mechanical characteristics of carbon steel

Steel	Yield strength (MPa)	Tensile strength (MPa)	Percent elongation, %
St1	195 – 205	305 – 410	34 – 35
St2	215 – 225	325 – 430	32 – 33
St3	235 – 255	360 – 480	26 – 27

Purpose

The main purpose of the research is to conduct laboratory tests to determine the main mechanical characteristics of nail steel. This makes it possible to correctly determine the theoretical bearing capacity of nailed joints of wooden structures in the future.

To achieve this purpose, the following tasks were formulated and solved during the research:

1. To select the most popular nail sizes in the modern construction market of Ukraine.
2. To measure the geometric dimensions of nails before testing.
3. To conduct a tensile test on the nails of the selected sizes.
4. To evaluate the obtained mechanical characteristics of nail steel after testing.
5. To analyse the compliance of the mechanical characteristics of steel with known brands.

Methodology

Let us consider the solution of all the above tasks in sequence.

Since there is currently no specialised standard in Ukraine for testing nails in general and steel nails in particular, the organisation and conduct of these experimental studies were based on the current standard [5]. According to this standard, the determination of the mechanical characteristics of nails can be performed on samples without preliminary machining, i.e. directly on the nails.

Nail standard sizes. Based on the data in Table 1, nails of the most famous manufacturer ExpertFix (Denmark) were selected for experimental studies. This company has been present in the construction market of Ukraine for a long period of time and therefore enjoys well-deserved consumer confidence due to its price-quality ratio.

Based on the data of experts in the design and manufacture of wood structures, 5 nail sizes with the diameters declared by the manufacturer were selected for testing: 4.2 mm; 5.0 mm; 5.5 mm; 6.0 mm; 7.0 mm.

Initial geometrical dimensions of the nails. Test samples were selected from existing batches and their geometrical dimensions were carefully measured. For each size, three samples were measured. Measurements were made in two cross-sections according to the recommendations of the standard [5]. The number of samples was taken on the basis of a series of previous studies that established a high correlation and stability of both geometric dimensions and mechanical characteristics for steel round nails. The data obtained are presented in Table 3.

During the general inspection and measurements of the nail samples, the following geometric shape defects were identified:

– for samples with a diameter of 4.2 mm, a reduction in diameter compared to the nominal one. For the tests, the actual diameter was input into the measuring unit;

– for samples with a diameter of 5.0 mm, the axis was not straight. Samples with a straight axis were selected for testing;

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– for samples with a diameter of 6.0 mm, the flattening of the point. Samples with the correct shape of the point were selected for testing;

– for samples with a diameter of 7.0 mm – a reduction in diameter compared to the nominal one. For the tests, the actual diameter was input in the measuring unit.

To ensure that the proportionality criterion was met, the test base was determined for the samples in accordance with the standard [5]:

$$L = 11.3 \cdot \sqrt{A}, \quad (2)$$

where A – cross-sectional area of the sample.

The finally adopted measurement base is shown in Table 3.

Fig. 2 shows the appearance and overall dimensions of nails of different sizes selected for testing.

Tensile tests. For the laboratory tests, we used a universal tensile testing machine UG20/2 with a specialised computer system for recording and preliminary processing of test results. A general view of the measuring unit is shown in Fig. 3. The installation was pre-calibrated and has a certificate of compliance with Class 1 requirements according to the standard [6]. The unit also met the recommendations of Annex A of the standard [5].

The measuring unit can operate in two ranges – up to 2 tonnes and up to 20 tonnes. The first range was used for nails with a diameter of 4–6 mm, and the second range was used for nails with a diameter of 7 mm. In order to ensure rigid nailing during the tests, special attachments with small notches were used (Fig. 4), which also allowed for the necessary clearances in the fastening grips. The attachments were aligned in the grips to ensure purely tensile deformations and avoid bending deformations in accordance with the recommendations of the standard [5].

Table 3

Geometrical dimensions of round nails

Sample	Diameter, mm		Cross-sectional area, mm^2	Length, mm		Measurement base, mm
	nominal	real		nominal	real	
42 – 1					121.0	
42 – 2	4.2	4.0	12.57	120.0	120.8	40.0
42 – 3					120.4	
50 – 1					146.0	
50 – 2	5.0	5.0	19.64	150.0	146.5	50.0
50 – 3					148.6	
55 – 1					150.6	
55 – 2	5.5	5.5	23.75	150.0	150.3	55.0
55 – 3					150.4	
60 – 1					197.3	
60 – 2	6.0	6.0	28.27	200.0	198.2	60.0
60 – 3					198.4	
70 – 1					248.3	
70 – 2	7.0	6.9	37.39	250.0	248.0	70.0
70 – 3					248.8	

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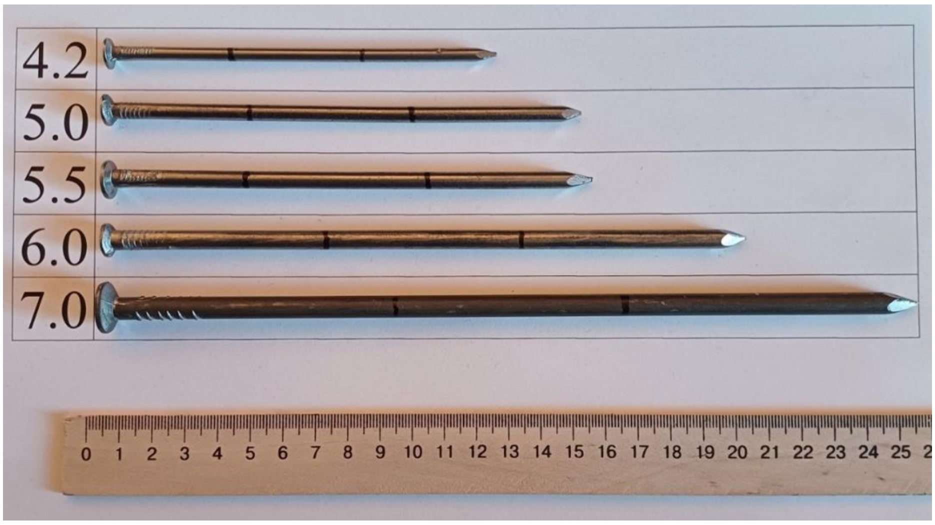

Fig. 2. General view of the test nails

Fig. 3. Measuring unit for testing steel nails

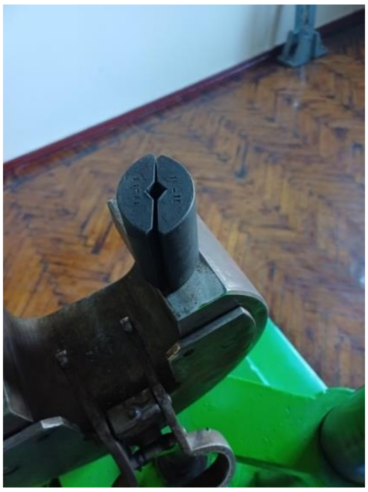

Fig. 4. Nail attachments

The test process consisted of a gradual tensile load on the samples fixed in the grips. The loading rate during the tests remained constant at 150 N/s, which, according to some estimates, can be classified as a mild loading mode. This made it possible to obtain a more correct diagram of the nail material under load, as well as to minimise micro-displacement of the nails during the tests. This speed corresponds to method A1 of testing samples according to the recommendations of the standard [5].

Findings

Diagrams of steel performance. The obtained diagrams for different sizes of nails have a form that is not typical for the classical carbon steel diagram. In general, typical diagrams are shown in Figs. 5 and 6 in the «force-strain» and «force-time» axes, respectively.

Structurally, the diagrams consist of 5 separate sections separated by characteristic points:

S_1 – beginning of elastic behaviour;

S_u – end of elastic behaviour (conventional yield strength);

S_v – tensile strength;

S_e – damage boundary;

S_0 – end of work.

Section *1* corresponds to the process of «self-accommodation», when the existing gaps are selected and the sample takes its rigid position during testing.

Section *2* corresponds to the process of elastic deformation of steel in its classical sense.

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Section *3* corresponds to the process of steel hardening in its classical sense.

Section *4* corresponds to the fracture process, when a neck is formed on the sample and it breaks at the point S_e.

Section *5* has no meaningful value and is generated automatically by the measuring unit.

Fig. 7 shows the resulting pattern of fracture of the sample during testing. For all the tested nail diameters, the fracture pattern was recorded to be the same, close to a visco-plastic fracture with the formation of a characteristic «neck» at the fracture site.

Mechanical characteristics of steels. Table 4 presents quantitative summarised test results obtained by processing the experimental diagrams.

Table 5 shows the calculated values of the coefficient of variation. As can be seen, for samples of all diameters, the coefficient of variation does not exceed 7% for strength and 19% for deformability, which is a fairly good indicator. This indicates the high quality and homogeneity of the steels used to make the nails.

Table 5

Coefficient of variation of the test results

Nominal diameter of the nail, mm	Coefficient of variation, %		
	yield strength conventional	tensile strength	elongation
4.2	1.39	1.16	16.83
5.0	6.63	2.96	18.05
5.5	0.28	0.74	5.09
6.0	3.34	2.13	11.69
7.0	1.18	1.69	3.17

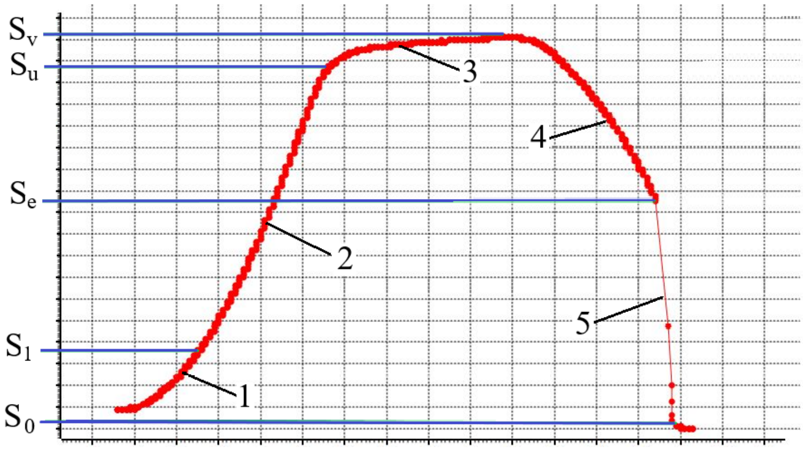

Fig. 5. Typical diagram of nail steel behaviour in the force-strain axis

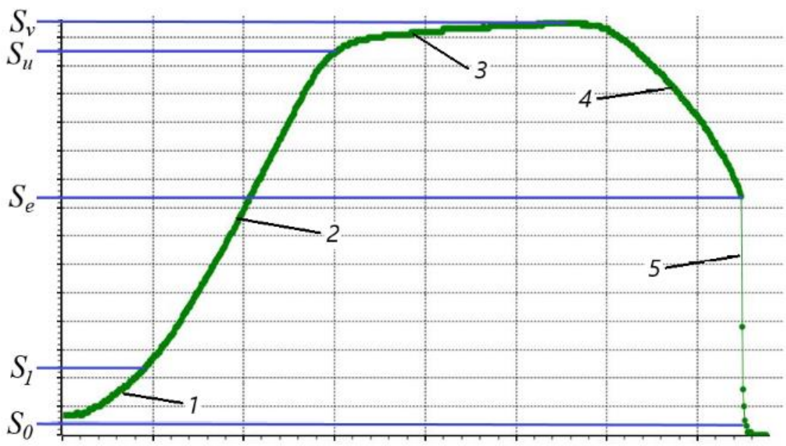

Fig. 6. Typical diagram of nail steel behaviour in the force-time axis

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a *b*

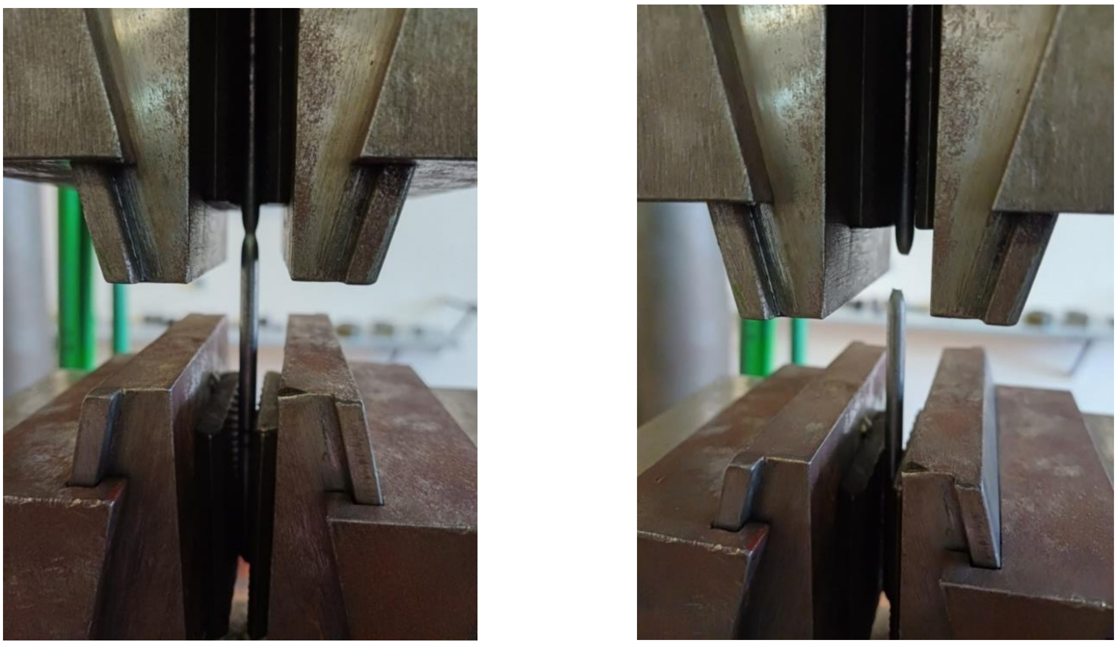

Fig. 7. Destruction of a steel nail:
a – formation of the «neck»; *b* – destruction of the «neck»

Table 4

Mechanical characteristics of steel nails

Nail (nominal diameter – sample No.)	Conventional yield strength Su, MPa	Conventional yield strength (average), MPa	Tensile strength Sv, MPa	Tensile strength (average), MPa	Elongation, mm (%)	Elongation (average), mm (%)
4.2 – 1	636	629	700	692	2.9 (7.3)	3.0 (7.5)
4.2 – 1	631		692		3.5 (8.8)	
4.2 – 1	619		684		2.5 (6.3)	
5.0 – 1	463	457	524	524	3.3 (6.6)	4.2 (8.4)
5.0 – 1	424		509		4.7 (9.4)	
5.0 – 1	483		540		4.5 (9.0)	
5.5 – 1	564	564	610	615	3.3 (6.0)	3.4 (6.2)
5.5 – 1	563		619		3.6 (6.5)	
5.5 – 1	566		615		3.3 (6.0)	
6.0 – 1	430	447	488	499	6.6 (11.0)	7.6 (12.7)
6.0 – 1	458		506		8.3 (13.8)	
6.0 – 1	453		502		7.9 (13.2)	
7.0 – 1	601	594	660	648	6.3 (9.0)	6.3 (9.0)
7.0 – 1	587		644		6.5 (9.3)	
7.0 – 1	595		639		6.1 (8.7)	

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Based on the obtained mechanical strength characteristics of steel, the «characteristic values of the bending moment of plastic deformation» can be calculated for the design of nodal joints using expression (1). They are given in Table 6 for the yield strength and tensile strength separately.

Table 6

Characteristic values of the bending moment of plastic deformation

Nominal nail diameter, mm	Characteristic values of bending moment, N·mm	
	by yield strength	by tensile strength
4.2	7 874	8 663
5.0	9 002	10 322
5.5	14 235	15 522
6.0	14 146	15 791
7.0	28 065	30 616

In accordance with the current standard in Ukraine [1], «characteristic values of the bending moment of plastic deformation» should be used in the future to determine the characteristic bearing capacity of nailed joint fasteners.

Originality and practical value

Based on the laboratory experimental studies of nail steels for nodal joints of wooden structure elements, we obtained the diagrams of steel performance (Figs. 5 and 6). Samples of nails of five diameters in the range of 4–7 mm were tested. For all cases, the diagram has the same type of appearance typical of high-strength steels and is close to the classical form of diagrams for such steels. The diagrams themselves were generated automatically using the applied load control system built into the laboratory setup.

The resulting diagram clearly shows the presence of 5 sections (Figs. 5 and 6). Section 1 is associated with the peculiarities of the gripper operation in the test setup, when gaps are selected and samples are «accommodated» for wire samples. In this section, we observed quite significant deformations, which were not only partially related to the deformation of the steel itself. Therefore, such deformations were not taken into account in the further processing of the experimental results.

Section 2 of the diagrams is characterised by purely elastic steel behaviour. At the same time, this section smoothly transits into section 3, which is characterised by the phenomenon of steel hardening after plastic deformation. The highest point on the diagram corresponds to the tensile strength of the steel and was specifically recorded by the measuring system during the tests. In section 4 of the diagram, the formation of a «neck» was observed during the tests, in which the samples subsequently fractured (Fig. 7). Section 5 does not have a separate physical content and was «completed» by the measuring unit in automatic mode.

The quantitative mechanical characteristics of nail steels obtained during the experimental studies (Table 4) include two strength indicators – yield strength and tensile strength, as well as one deformability indicator – longitudinal percent elongation. It was found that the test results for different nail samples from the same batch are quite stable. The quantitative results differ by up to 7%, which corresponds to a low value of the coefficient of variation (Table 5). No gross errors were detected during the experimental studies, which indicates the high quality of the material from which the steel nails are made.

The steel strength values allow us to characterise the steels as high-strength steels, which coincides with the nature of the obtained performance diagrams. At the same time, the ratio of the yield strength to the tensile strength for the samples presented in Table 7 and for all samples exceeds 0.8, which is also typical for high-strength steels. To more accurately determine the grade of steel in practice, it is necessary to additionally perform a chemical analysis of the steel, however, for the design of nodal nail connections of wooden structures, such information is not required and therefore was not established in the course of these studies.

In accordance with the Ukrainian standard [2], based on the obtained results, it is possible to tentatively determine the strength class of steel (Table 8). As can be seen, in all cases, the steel characteristics do not correspond to St1–St3 steels (Table 2), which are used to manufacture nails in domestic practice. Therefore, this further supports the need for special laboratory tests to determine the characteristics of nail steels.

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Table 7

Ratio of strength characteristics of steels

Nominal nail diameter, mm	Ratio	Approximate strength class of steel
4.2	0.91	C500
5.0	0.87	C390
5.5	0.92	C500
6.0	0.90	C390
7.0	0.92	C500

Conclusions

1. In recent years, nailed connections have been increasingly used to create building structures made of wood. In this case, nails made of high-quality steels are applied, which provide improved reliability and durability of such connections. To determine the load-bearing capacity of the connections, it is necessary to take into account the mechanical characteristics of the steel. Given the lack of uniform standards in the world practice for nail steels, it is necessary to conduct special laboratory tests to determine the type of steel and its main characteristics. In this study, we focused on the analysis of nails manufactured by ExpertFix (Denmark). This company enjoys the well-deserved trust of consumers around the world due to its price-quality ratio.

2. Experimental laboratory tests on tensile strength of nail samples with a diameter of 4–7 mm allowed us to obtain a diagram of steel performance under load. It is qualitatively close to the classical diagram of high-strength steel. Fracture of the samples was recorded according to the visco-plastic scheme with the formation of a characteristic «neck» at the fracture point.

3. The main mechanical properties for all nail diameters under consideration are in the following ranges:

– conventional yield strength – 450–630 MPa;
– tensile strength – 500–700 MPa;
– absolute elongation – 3–8 mm;
– percent elongation – 6–13%.

The average coefficient of variation of the experimental results obtained is 5%, which indicates the high quality of the manufacturer's steels.

4. The obtained steel characteristics correspond to high-strength steels of classes C390–C500 in accordance with Ukrainian standards. Since the current Ukrainian methodology for the design of nailed joints is focused on steels of ordinary strength, it requires certain adjustments and clarifications to reproduce the correct behaviour of nails made of high-strength steels.

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Експериментальна оцінка міцності та деформативності сталевих цвяхів для дерев’яних конструкцій

Мета. Метою даної публікації є обговоренні проведених експериментальних досліджень з визначення в лабораторних умовах характеристик сталі цвяхів однієї з найбільш поширених на сучасному будівельному ринку України компаній – ExpertFix (Данія). **Методика.** Для досягнення мети були проведені випробування на розтяг для цвяхів класичного круглого поперечного перерізу 5 діаметрів в діапазоні від 4 до 7 мм, виготовлених за стандартом Німеччини. **Результати.** За результатами дослідження були побудовані діаграми роботи сталі цвяхів під навантаженням, які виявились дуже наближеними до класичної діаграми роботи високоміцної сталі. Руйнування зразків відбувалось за в’язко-пластичною схемою з утворенням характерної «шийки» в місці розриву. Зафіксований рівень міцності становить від 450 до 700 МПа при відносній деформації до 13 %. **Наукова новизна.** Отримані показники відповідають високоміцним сталям класів С390–С500 за стандартом України, проте не відповідають сталям марок Ст1–Ст3, для яких розроблено чинні теоретичні підходи щодо проєктування вузлових з’єднань. Тому застосування в практиці подібних цвяхових виробів потребує коригування та уточнення існуючих підходів та методик їх використання в дерев’яних конструкціях, що в свою чергу потребує активізації наукових досліджень в цьому напрямку. **Практична значимість.** Практичне використання характеристик міцності сталевих цвяхів, отриманих під час експериментальних досліджень, дозволяє коректно та обґрунтовано проектувати вузлові з'єд-

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нання дерев'яних конструкцій на основі чинного українського стандарту. Це також створює основу для розробки більш досконалих розрахункових підходів для оцінки їхньої працездатності.

Ключові слова: дерев'яні конструкції; вузлові з'єднання; цвях; сталь; механічні характеристики сталі

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