

EXPERIMENTAL STUDY OF THE PHYSICAL AND MECHANICAL PROPERTIES OF STEEL SELF-TAPPING SCREWS FOR TIMBER STRUCTURES

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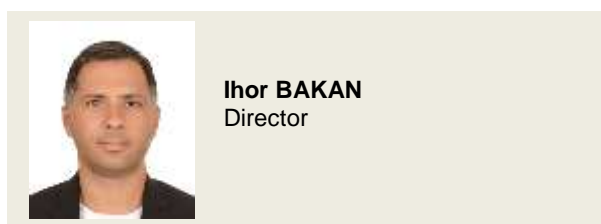
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Abstract. One of the main issues currently considered important for the design of timber structures is the assessment of the load-bearing capacity of various types of joint connections. For connections on steel self-tapping screws, this problem is associated with an empirically recorded undesirable effect – “snapping off” of the screw head under conditions of a sharp drop in temperature. To ensure the correct functioning of such elements, it is necessary to know their basic mechanical characteristics, which, according to current methodologies, must be taken into account during design. This also opens up prospects for the correct assessment of the behaviour of the entire joint under load.

The aim of the experimental laboratory studies conducted is to determine and evaluate the main mechanical characteristics of steels for self-tapping screws. Products from the Danish company ExpertFix were used as the test specimens. Tests were carried out on self-tapping screws of three sizes with nominal diameters of 4.2, 5.5 and 6.0 mm. The tests were conducted on a universal tensile testing machine UG20/2, equipped with a certified computerised system for recording measurement results.

The research yielded performance diagrams for the steel used in self-tapping screws, plotted against deformation levels and time. In qualitative terms, the diagrams closely resembled the classic performance diagrams for alloy steels. The specimens failed in a brittle manner without the formation of a plastic “neck”. The recorded strength ranges from 800 to 1000 MPa, which is characteristic of high-strength steels. At the same time, the absolute elongation does not exceed 11%,



and the relative elongation – 45%. In accordance with current Ukrainian standards, such steels may be provisionally classified as C620 grade steels, albeit with certain reservations. The calculated values of the plastic deformation bending moment for the considered screw diameters are 1015 kN·cm, 2370 kN·cm, and 3231 kN·cm, respectively.

As for the prospects for further research, it is necessary to highlight the need to expand the range of self-tapping screw sizes under investigation and their manufacturers, including domestic suppliers. It is also envisaged to develop proposals for revising the methods for experimental determining of the mechanical properties of steel fasteners for timber structures.

Keywords: timber structures; joint connections; self-tapping screw; steel; mechanical properties of steel.

PROBLEM STATEMENT

At present, humanity is actively continuing its search for new building materials, primarily of the composite type. According to many experts, these materials have the potential to replace traditional building materials.

At the same time, thanks to their unusual and often simply unique properties, such materials are increasingly being used in spheres associated with building structures.

Meanwhile, traditional building materials, which have been used in the construction industry since time immemorial, are in no hurry to give up their positions. One such material is timber, which, according to a number of experts, has recently even been experiencing a kind of renaissance [1]. In this context, both traditional structural systems are being used and new systems are being developed, including hybrid types [2, 3]. This trend is particularly pronounced in regions rich in forest resources, such as the countries of the Asian region [4]. However, even for other countries that are not traditionally rich in forest resources, such as Ukraine, the design and building of timber structures is an integral part of modern construction. Therefore, research aimed at studying the behaviour of timber structures has been and remains highly relevant worldwide [5, 6].

ANALYSIS OF PREVIOUS RESEARCH

One of the key areas of research into timber structures is the analysis and determination of the load-bearing capacity of structural joints [7, 8]. The high-quality, reliable and long-lasting performance of joints largely ensures the functionality of the entire structural system; therefore, in engineering practice, it is the design of joints that requires the greatest attention and must be based on highly accurate methods of their development [9].

Currently, the behaviour of structural joints is the subject of comprehensive scientific research, with assessments being made from both theoretical and practical perspectives [10]. As an analysis of the available international specialist literature shows, considerable attention is being paid to experimental research in this field, since it is precisely experiments with real or model specimens of joint connections that provide the invaluable data on which engineering methods for assessing the load-bearing capacity of joints can subsequently be based [11]. Methods for

assessing the performance of existing joint connections are also continuing to be refined, including connections using steel nails [12] and self-tapping screws [13].

This type of joint has already become quite well-known and popular in engineering practice; however, during experimental studies, the main focus is on the behaviour of the structural element itself, whilst the behaviour of the self-tapping screw is overlooked [14]. This is because, on the one hand, the self-tapping screw is assumed by default to have a high load-bearing capacity, which ensures that the resulting joint has a load-bearing capacity higher than that of the structural element itself. On the other hand, research often evaluates the performance of the “self-tapping screw”+“element” system, which is analysed in terms of certain specific types of stress-strain state [15, 16].

One of the main contemporary approaches to improving the performance of self-tapping screw joints is the use of new materials with improved physical and mechanical properties instead of steel. Such materials include aluminium alloys. However, their use requires the application of special oxide coatings to prevent electrochemical corrosion and extend the service life of the self-tapping screws [17]. Nevertheless, the “weak point” of such elements is the level of surface adhesion to the timber. There is also a need to install special aluminium washers, which complicates the design of the entire assembly [18]. Therefore, the use of modern high-strength steels should be considered more promising.

The current Ukrainian standard for the design of timber structures, DBN V.2.6-161:2017 [19], includes recommendations for determining the load-bearing capacity of structural joints. According to the classification presented, such joints are divided into contact joints and joints with working ties. The latter category includes connections using cylindrical dowels, a variant of which is self-tapping screws (self-taps).

Self-tapping screws have been quite widely used in construction practice in Ukraine over the last 20 years. However, their widespread use has recently begun to be phased out. The

main reason for this is an undesirable effect that has begun to be observed during the operation of wooden roof elements – it consists in the fact that, upon a sharp drop in temperature, the head of the self-tapping screw snaps off, i.e. it breaks off. There is no data on this phenomenon in the specialist literature, so this issue should currently be considered unexplored.

The main assumption put forward by most experts is that self-tapping screws are of poor quality. It is therefore necessary to assess the load-bearing capacity of such products available on the Ukrainian market. In doing so, the primary focus should be on a quantitative assessment of the mechanical properties of the steel from which the self-tapping screws are manufactured. As analysed above, all existing studies focus on examining the behaviour of the joint itself; therefore, the assessment of the self-tapping screw performance under load is treated as a separate, specific task.

The relevance of such a study is heightened by the fact that the current standard DBN V.2.6-161:2017 [19] was introduced into Ukrainian design practice relatively recently and has introduced fundamentally new approaches to the design of timber structural joints [20] – expression (12.31) defines the “characteristic value of the bending moment of plastic deformation”, which is one of the main design characteristics of cylindrical dowels:

$$M_{y,Rk} = 0.3 \cdot f_{u,k} \cdot d^{2.6}, \quad (1)$$

where $f_{u,k}$ – tensile strength of the treenail steel.

Thus, in design practice, there is a need for a correct assessment of the mechanical characteristics of self-tapping steel screws under tensile loading. The research conducted is dedicated to solving this problem.

It is also worth noting that, at present, the only standard in force in Ukraine governing the geometric dimensions and shape of steel self-tapping screws is DSTU EN ISO 1479:2022 [21]; however, this standard applies only to self-tapping screws with a hexagonal head. As the current Ukrainian market is dominated by self-tapping screws with round heads, their main geometric dimensions should be

determined in accordance with standard DBN V.2.6-161:2017 [19] and are shown in Fig. 1.

Thus, the scientific task of assessing the level of design characteristics of steel self-tapping screws arises for the possibility of further substantiation of the bearing capacity of such connections.

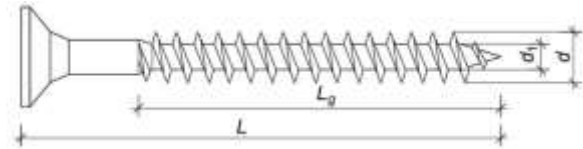


Fig. 1 Self-tapping screw – general shape and dimensions: d – external diameter; d_1 – internal diameter; L – total length; L_g – thread length

Рис. 1 Самонарізний гвинт – загальна форма та розміри: d – діаметр зовнішній; d_1 – діаметр внутрішній; L – довжина повна; L_g – довжина різьби

MAIN RESEARCH

The aim of this work is to organise and conduct laboratory tests on steel self-tapping screws to determine the tensile mechanical properties of the steel. This provides the basis for subsequently determining the load-bearing capacity of self-tapping screws and the joint connections of timber structures as a whole. The research was based on the standard DSTU ISO 6892-1:2019 [22] currently in force in Ukraine. In accordance with the recommendations of this standard, the mechanical properties of steel self-tapping screws can be determined using specimens without prior mechanical processing. Therefore, the tests were carried out directly on the self-tapping screws.

For the experimental studies, self-tapping screws from the manufacturer ExpertFix (Denmark) – a brand widely available in Ukraine – were selected, with the following stated diameters of three types: 4.2 mm; 5.5 mm; 6.0 mm. For each size, three specimens were selected from the total batch and subjected to thorough measurement in accordance with the recommendations of standard DSTU ISO 6892-1:2019 [22]. The number of specimens was determined based on a series of preliminary experimental tests, which demonstrated a high degree of consistency in the results obtained

[23]. To ensure compliance with the proportionality criterion for the specimens, the test basis was determined in accordance with the standard [22] using the expression:

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

where A – cross-sectional area of the specimen.

The adopted measurement basis is given in Table 1. This table also provides information on the actual diameters of the self-tapping screws, as the nominal diameter takes the thread into account. The cross-sectional area was calculated based on the actual diameter.

Table 1. Geometric dimensions of self-tapping screws
Табл. 1. Геометричні розміри саморізів

Specimen	Diameter, mm		Cross-sectional area, mm ²	Measurement base, mm
	nominal	actual		
42-1	4.2	4.1	11.34	40.0
42-2				
42-3				
55-1	5.5	5.4	11.34	55.0
55-2				
55-3				
60-1	6.0	6.0	11.34	60.0
60-2				
60-3				

Laboratory tests were carried out on a UG20/2 universal tensile testing machine, which is equipped with a computerised recording and data processing system (Fig. 2,a). The apparatus complies with Class 1 requirements in accordance with DSTU EN ISO 7500-1:2017 [24] and the recommendations of Annex A to DSTU ISO 6892-1:2019 [22].

To ensure the self-tapping screws were securely clamped during testing, special grips with fine serrations (Fig. 2,b) were used, which self-centred in the machine's grips to ensure the application of an axial tensile load.



a



b

Fig. 2 Test rig for steel self-tapping screws: *a* – general view; *b* – Aligning clamps. Photo by Ihor Bakan
Рис. 2 Установка для випробування сталевих саморізів: *a* – загальний вигляд; *б* – вирівнювальні захвати. Автор фото Ігор Бакан

During the tests, the tensile load was applied gradually at a constant rate of 150 N/s, which corresponds to the Type A1 test method as recommended by the DSTU ISO 6892-1:2019 standard [19].

The load-performance diagrams for the steel self-tapping screws obtained during the tests are shown in Fig. 3 (on the “force-deformation” axes) and in Fig. 4 (on the “force-time” axes).

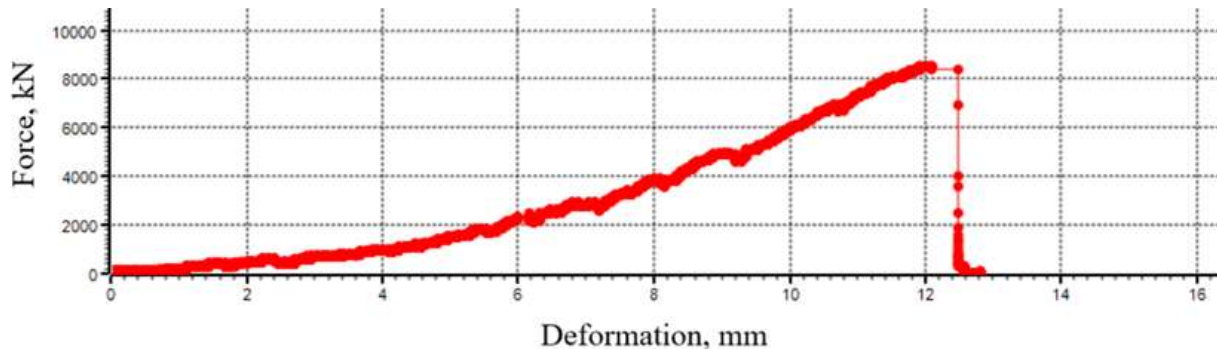


Fig. 3. Typical diagram of the operation of self-tap steel on the “force-deformation” axes.

Рис. 3. Типова діаграма роботи сталі саморіза в осях «зусилля-деформації»

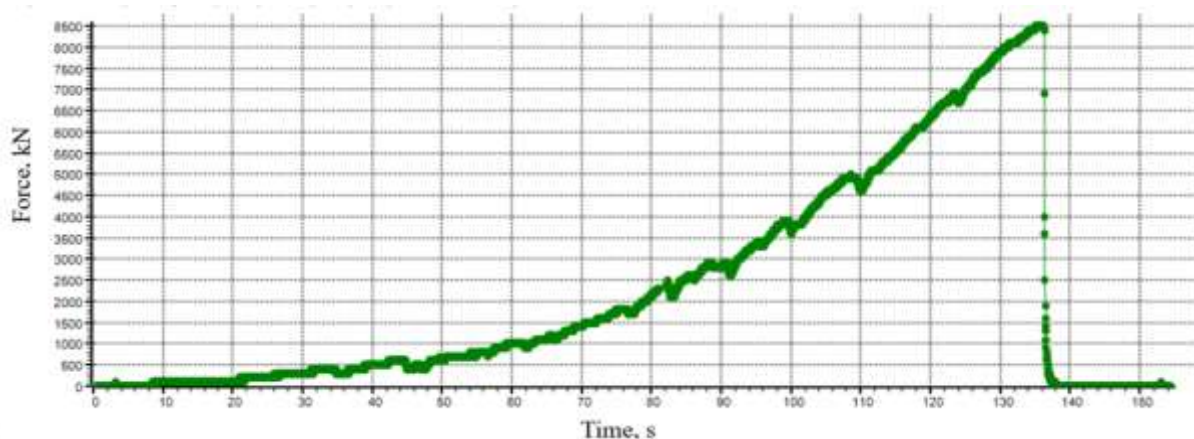


Fig. 4. Typical diagram of the operation of self-tap steel on the “force-time” axes.

Рис. 4. Типова діаграма роботи сталі саморіза в осях «зусилля-час»

Structurally, the diagrams consist of two sections – the first inclined section from the start of loading to the highest point of the diagram, and the second vertical section from the highest point of the diagram to the horizontal axis. The first section corresponds to the behaviour of the steel under load and is, in fact, the main part of the diagram. The second section characterises the decrease in strength after the specimen breaks and is, in fact, non-working, due to the specific features of the clamping device of the tensile testing machine.

Fig. 5,a shows the fracture pattern of the specimen during testing. For all tested self-tapping screw specimens, the fracture

behaviour remained fairly typical and was of a brittle nature. No neck formation was observed at the fracture point, which also indicates the low ductility of the steels.

Fig. 5,b shows the fracture pattern of the specimen during testing. For all tested self-tapping screw specimens, the fracture behaviour remained fairly typical and was of a brittle nature. No neck formation was observed at the fracture point, which also indicates the low ductility of the steels.

Table 2 presents the summarised quantitative results of the tests on steel self-tapping screws, which were obtained by analysing the experimental diagrams.



Fig. 5 Failure of a steel self-tapping screw: *a* – appearance before failure; *b* – appearance after failure.
Photo by Ihor Bakan

Рис. 5 Руйнування сталевих саморізів: *a* – вигляд до руйнування; *б* – вигляд після руйнування.
Автор фото Ігор Бакан

Table 2 Mechanical properties of steel self-tapping screws

Табл. 2 Механічні характеристики сталевих саморізів

Screw (nominal diameter – specimen number)	Tensile strength, MPa	Tensile strength (average), MPa	Elongation, mm (%)	Elongation (average), mm (%)
4.2-1	794	811	6.5 (31)	7.6 (29)
4.2-2	820		8.6 (21)	
4.2-3	820		7.8 (35)	
5.5-1	940	939	7.3 (37)	7.8 (40)
5.5-2	936		7.7 (38)	
5.5-3	942		8.5 (44)	
6.0-1	1015	1021	11.2 (49)	10.3 (45)
6.0-2	1015		9.4 (40)	
6.0-3	1032		10.2 (45)	

Table 3 shows the coefficients of variation calculated from the experimental data obtained. As can be seen, overall, the coefficient of variation does not exceed 5% for the tensile

Table 3. Coefficient of variation of test results

Табл. 3. Коефіцієнт варіації результатів досліджень

strength values and 24 % for elongation, which is a satisfactory result.

Nominal diameter of self-tapping screw, mm	Coefficient of variation, %	
	tensile strength	elongation
4.2	2.43	19.76
5.5	4.33	23.11
6.0	1.78	20.45

These values indicate a sufficient level of quality and homogeneity of the steels from which the self-tapping screws are made.

The significant level of elongation of the experimental samples obtained during the tests can be explained by the occurrence of a triaxial stress state in the zone of destructive crack formation, which suppresses plastic deformations. In this case, a brittle fracture pattern is observed, which is quite typical for high-strength steels in general.

Table 4. Characteristic values of the bending moment of plastic deformation

Табл. 4. Характеристичні значення згинального моменту пластичної деформації

Nominal screw diameter, mm	Characteristic values of the bending moment, kN·mm
4.2	10152.90
5.5	23698.99
6.0	32310.24

The strength levels achieved by self-tapping steels for structural timber joints allow these steels to be classified as high-strength. In accordance with the current standard DBN V.2.6-198:2014 [25], such steels may be classified as type C620, albeit with certain reservations. Overall, such steels do not comply with the current Ukrainian standards in terms of mechanical properties, and this further highlights the need for specialised experimental studies, of the type presented in this paper, to accurately assess the load-bearing capacity of timber structural joints.

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

Based on the theoretical analysis of Ukraine's current regulatory framework, the current state of the fastener market in Ukraine, and the results of the experimental studies on the tensile strength of steel self-tapping screws, the following conclusions can be drawn:

1. At present, timber structures are quite often joined using self-tapping screws. Moreover, such fasteners are used not only for small-scale structures but also for the manufacture of industrial-scale structures. As the self-tapping screws

Based on the obtained values of the tensile strength of steel, the “characteristic values of the bending moment of plastic deformation” calculated using equation (1) are given in Table 4. In accordance with the current standard DBN V.2.6-161:2017 [19], these values may be used subsequently to calculate the characteristic load-bearing capacity of fasteners on self-tapping screws.

available on the Ukrainian market are, in most cases, accompanied by rather dubious certification documentation, there is a need for a proper assessment of the key mechanical characteristics of such products.

2. The resulting tensile performance diagram for the steel of the self-tapping screws closely approximates that of alloy steels. The key characteristic point on the diagram was the breaking point. The specimens failed in a brittle manner without the formation of “neck” type plastic deformations at the point of fracture.
3. The main mechanical properties obtained for the analysed diameters of steel self-tapping screws fall within the following ranges:
 - tensile strength – 800–1000 MPa;
 - absolute elongation – 7–11 mm;
 - relative elongation – 30–45%.

At the same time, the coefficient of variation of the obtained experimental results does not exceed 5% for the tensile strength and 25% for elongation, which indicates a satisfactory level of quality of the manufacturer's steels.

Based on the overall results obtained, the self-tapping screws under investigation can be provisionally classified as C620 grade steel.

- The values of the bending moments of plastic deformation $M_{p,y,Rk}$ determined on the basis of mechanical characteristics are 1015 kN·cm (for diameter 4.2 mm), 2370 kN·cm (for diameter 5.5 mm) and 3231 kN·cm (for diameter 6.0 mm). These values should be used in the future to assess the level of load-bearing capacity of connections on steel self-tapping screws in design practice.

The following areas should be noted as prospects for further research:

- conducting experimental studies on self-tapping screws with large nominal diameters (from 6 mm);
- conducting experimental studies on self-tapping screws from other manufacturers currently available on the Ukrainian market, including domestic ones;
- developing and submitting proposals for the amendment of current Ukrainian standards regarding the conduct of experimental studies on steel fasteners for timber structures.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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**ЕКСПЕРИМЕНТАЛЬНЕ
ДОСЛІДЖЕННЯ
ФІЗИКО-МЕХАНІЧНИХ
ХАРАКТЕРИСТИК СТАЛЕВИХ
САМОРІЗІВ ДЛЯ ДЕРЕВ'ЯНИХ
КОНСТРУКЦІЙ**

Igor БАКАН

Анотація. Однією з головних проблем, які в теперішній час виявляються важливими для проектування конструкцій з деревини, є оцінка несучої здатності різних типів вузлових з'єднань. Для з'єднань на сталевих самонарізних гвинтах ця проблема пов'язується із зафіксованим емпірично небажаним ефектом – «відстрілювання» шляпки саморізу за умов різкого зниження температури. Для передбачення коректної роботи таких елементів необхідно знати їх основні механічні характеристики, які згідно чинних методик мають враховуватись при проектуванні. Також це в подальшому відкриває перспективи для коректної оцінки рооти всього вузлового з'єднання під навантаженням.

Метою проведених експериментальних лабораторних досліджень є визначення та оцінка основних механічних характеристик сталей для саморізів. В якості бази випробувань прийнято виробу датської компанії ExpertFix. Проводились випробування саморізів 3 типорозмірів із номінальними діаметрами 4.2,

5.5 та 6.0 мм. Випробування проводились на універсальній розривній машині УГ20/2, обладнаною сертифікованою системою комп'ютерної фіксації результатів вимірювань.

За результатами досліджень були отримані діаграми роботи сталі самонарізних гвинтів в залежності від рівня деформацій та часу. Руйнування зразків відбувалось за крихкою схемою без утворення пластичної «шийки». Зафіксований рівень міцності коливається в межах від 800 до 1000 МПа, що характерно для високоміцних сталей. При цьому абсолютне видовження не перевищує 11 %, а відносне видовження – 45 %. Відповідно до чинних стандартів України такі сталі можуть бути умовно віднесені до сталей класу С620, проте з певними обмовками. Розраховані значення згинального моменту пластичної деформації для розглянутих діаметрів саморізів становлять 1015 кН·см, 2370 кН·см та 3231 кН·см, відповідно, що має використовуватись для оцінки несучої здатності.

В якості перспектив подальших досліджень слід вказати на необхідність розширення спектру досліджуваних типорозмірів саморізів та їх виробників, в тому числі й вітчизняних постачальників. Також передбачається розробка пропозицій щодо коригування методик експериментального визначення механічних характеристик сталевих кріпильних елементів для конструкцій з деревини.

Ключові слова: конструкції з деревини; вузлові з'єднання; саморіз; сталь; механічні характеристики сталі.

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