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Bearing capacity of rafter systems made of steel thin-walled structures in attic roofs

Несущая способность стропильной системы из стальных тонкостенных конструкций в чердачных крышах

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Key words: stress strain state; force method; statically indeterminate systems; attic roofs; steel thin-walled structures; timber rafter structures

Ключевые слова: напряженно-деформированное состояние; метод сил; статически неопределимые системы; чердачные крыши; легкие стальные тонкостенные конструкции; деревянные стропильные системы

Abstract. In the article as an alternative of strengthening of existing rafters or replacing them by new timber elements there is an offer to consider the replacing timber rafters by elements of steel thin-walled structures (STWS). The authors have proposed the methodology for calculation the statically indeterminate frame structures with the use of force method. Selected sections of rafters made of STWS and timber for various constructive schemes of pitched roofs were analyzed. The results shown that using of STWS reduces the major repair cost by 13.5 % due to less material consumption compared with a timber structure.

Аннотация. В статье в качестве альтернативы деревянным стропильным конструкциям крыш предлагается рассмотреть вариант устройства стропильной системы из легких стальных тонкостенных конструкций. Предложена методика расчета статически неопределимых стропильных рамных конструкций с использованием метода сил. В результате анализа напряженно-деформированного состояния элементов подобраны сечения стропильных ног из ЛСТК и из дерева для различных конструктивных схем скатных кровель. Показано, что применение ЛСТК позволяет снизить стоимость капитального ремонта скатных крыш на 13,5 % за счет меньшего расхода материалов по сравнению с деревянными стропильными конструкциями.

Introduction

The roof is a construction that transfers the dead load, climatic and other kinds of acting load to the bearing sub-structure. Besides its technical functions, the roof structure creates the most important architectural element of the building.

According to accessible data from the Housing Committee of St. Petersburg, the total roofs area of St. Petersburg is more than 24 million square meters. More than 50 percent of these roofs are in dissatisfactory condition. In the historic center, the roofs area is more than 8 million square meters. The actual unfavourable state of these roofs raise a question of their needed partial and/or overall repairing [1].

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Nowadays, many researches in the pitched roof repair field are focused on the technologies of roofing. In addition, special attention is paid to repair the roofs for the roofing the operated space (so-called attic). This category is dealt in the work of V.P. Semenikhina, which investigated the causes and factors that reduce the operating parameters of the sloping surfaces of the combined type and formed an effective organizational and technological solutions to reduce the cost and complexity of work on the roofing and repair of combined inclined roofs [2].

Problems of pitched roofs is also dealt in the works of famous scientists: V.B. Belevich [3], N.D. Boyko, Y.G. Krupnik, N.S. Kocharian, and others. Most scientists involved in individual issues related to the defects, damages, roofing, repair and reconstruction of sloping roofs, without considering their complex.

Thus, nowadays, versions of constructive solutions sloping attic pitched roofs with using STWS and how to replace the traditional timber elements by steel thin-walled elements are insufficiently understood.

The construction of buildings, based on steel thin-walled structures (STWS) is a type of innovation fast frame construction. As a direct alternative to timber frame construction, as well as other traditional types of constructions, this technology has a number of advantages, foremost among which are the speed of construction, environmental friendliness and low cost of construction in most cases. is an technology of building erection it is really cheaper. The absence of welding and wet processes makes STWS really quickly erectable technology [4, 8, 23].

The aim of the article is to create an universal calculation procedure, that allows the assessing of stress-strain state of the structures during major repairs and/or replacing of timber structures, that are in an emergency condition.

Recent years, Russia is actively engaged in the development and research of new designs of STWS. Works of E.L. Airumyan, [4], I.I. Vedyakov, [5] and others are focused on the investigation of the designs of bearing frame structures, solid-walls or lattice (truss) crossbars of thin-walled profiles up to 3 mm thick. Numerical and experimental researches of bolted joints, as well as connections to the self-tapping screws are presented by B.I. Belyaev, [6] V.S. Kornienko, and others. N.P. Abovsky and L.V. Endzhievsky proposed a method of sheet elements connection by means of special washers, forming the keyed-bolt connection. B.M. Veynblat and G.I. Buneev found, that the difference of thickness of connected elements has an impact on the carrying capacity of bolted connections. [7]

The theory of steel thin-walled structures with open cross-section was described by the authors of a large number of scientific papers devoted to this subject. The large majority researcments are based on works by V. Z. Vlasov[8].

During the development of this theory many kinds of proposals were presented for its amendment, related to "attempts rejection of the hypothesis lack of progress and take into account the most impact deformation shift work thin-walled bar" in the works of Dzhanelidze and Panovko, [9] Goldenveiser, Vorobyov [10] , Meshcheryakov [11,12].

In Peter the Great St. Petersburg Polytechnic University active research of STWS is conducted. Experiments, computer modeling and simulation of STWS, in particular their local buckling and connections, as well as the implementation of the results into practice are realized within the mentioned research [13–23].

Methods of research

A vast number of constructive schemes could be considered and applied for rafter roofs repair. The exact number depends on rafter distance, span and slope angle variety. Consequently, it is quite difficult to use any software to get solution in general.

That’s why main method, used for achieving the research goals, was t-force method.

Goal of the investigation: expedience rationale of STWS using during major repair of pitched roofs.

The investigation procedure:

1. Solving the static problem in an analytical form for typical construction schemes roof systems developed in album series 1.169.5 " Constructive solutions of timber rafters under metal roof" of "LenzhilNIIproekt" (see Figures 1–5).

2. Choosing the suitable section of STWS rafter.

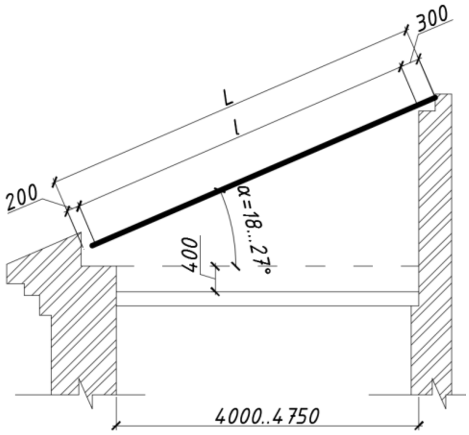

Figure 1. Non-combined rafters without braces

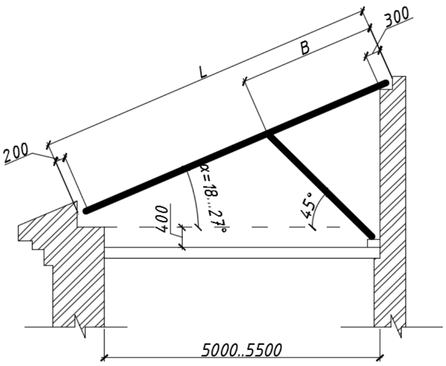

Figure 2. Non-combined rafters with braces

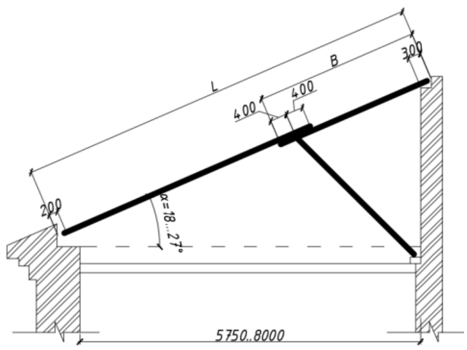

Figure 3. Combined rafters with braces

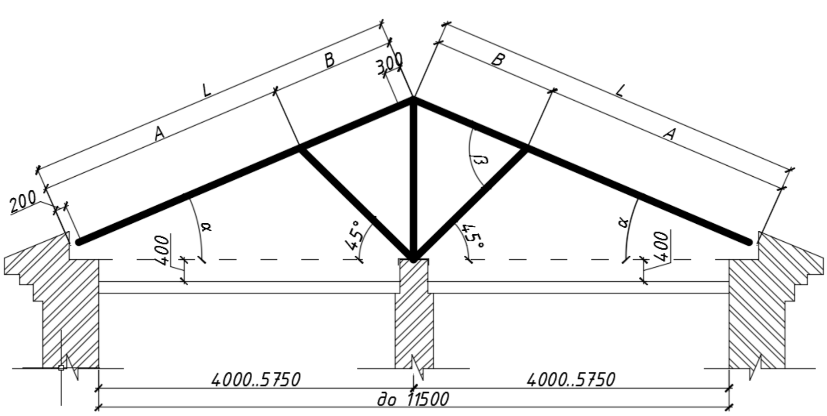

Figure 4. Non-combined rafter systems for saddle roofs

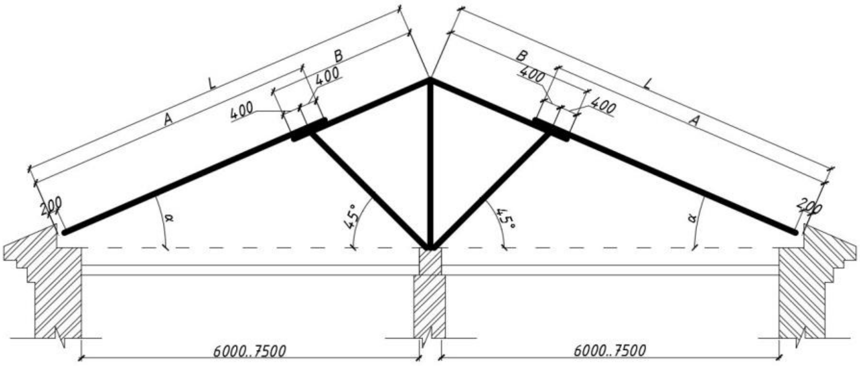

Figure 5. Combined rafter systems for saddle roofs

Rafter section of STWS for combined rafter system of saddle roofs with braces is considered for the applied analyses and calculation. The calculation procedure is the same for non-composite rafter system with bracers having one different connection and larger span values.

Static scheme of the structure is presented on Figure 6.

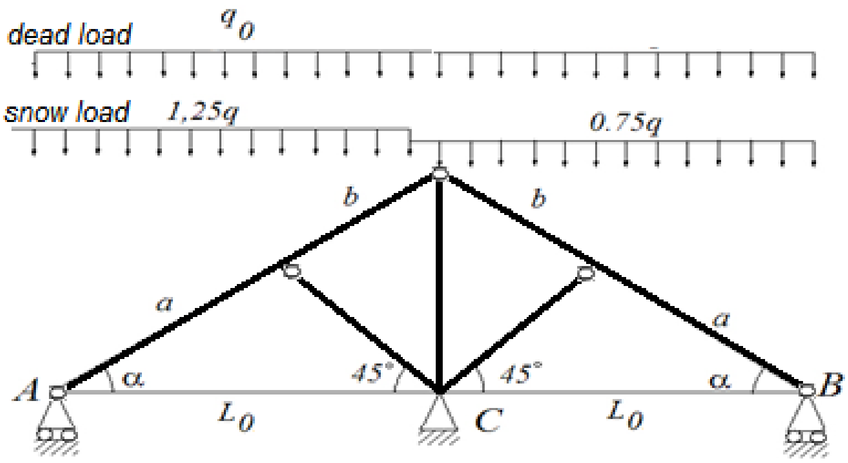

Figure 6. Static scheme of the structure

It is possible to simplify the problem by considering one half of a combined roof system for pitched roofs with braces.

The simplified model of the structure:

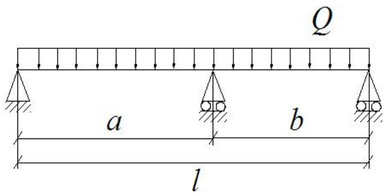

Figure 7. Simplified static scheme of the structure

The reckoning length of rafte:

$$l = LO/\cos\propto \quad (1)$$

Rafter step changes is considered 1,000; 1,100; 1,200; 1,300; 1,400 and 1,500mm. Load combination was considered according to table 1, where snow load to the rafter was calculated as:

$$q_1 = q_{snow} * n \quad (2)$$

n – rafter distance.

Table 1. Load cases

i	Type of load		Q_i , kg/m	n, m	Q_i , kg/m
1	Dead load (Self-bearing construction load consisting of rafter weight, lathing and roofing)	$q_{s.b.}$	-		10.1
2	Snow distributed loads, according to SP 20.13330.2011.	q_{snow}	180 kg/m^2	1.0…1.5	180…270

Maximum bending moment may be found by force method using.

Add an additional hinge on the support C and add an additional bending moment (Figure 8).

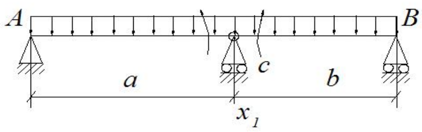

Figure 8. The equivalent system

The main loading is shown in Figure 9.

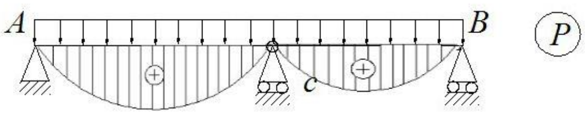

Figure 9. The main loading

The unit loading is shown in Figure 10.

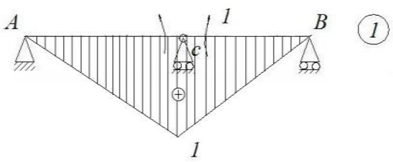

Figure 10. The unit loading

Multiplying of the diagram M_1 on itself:

$$\delta_{11} = \frac{a}{6EI}(0.0 + 4 \times 0.5 \times 0.5 + 1.1) + \frac{b}{6EI}(0.0 + 4 * 0.5 * 0.5 + 0.0) = \frac{2(a+b)}{6EI} \qquad (3)$$

Multiplying of diagrams M_1 and M_p:

$$\Delta_{1p} = \frac{a}{6EI}\left(0.0 + 4 * 0.5\frac{Qb^2}{8} + 0.1\right) + \frac{b}{6EI}\left(0.1 + 4 * 0.5\frac{Qb^2}{8} + 0.0\right) = \frac{Q(a^3 + b^3)}{24EI} \qquad (4)$$

The result of multiplying is coefficients of the equation (5)

$$\delta_{11}x + \Delta_{1p} = 0 \qquad (5)$$

By calculating the coefficients of the equation (5) it is able to find the maximum bending moment

$$X = \frac{-Q(a^2 - ab + b^2)}{8} \qquad (6)$$

$$M_{max} = \frac{-Q(a^2 - ab + b^2)}{8} \qquad (7)$$

The final bending moment diagram M_{max}:

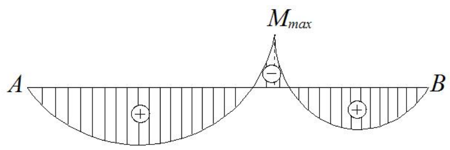

Figure 11. The final bending moment diagram M_{fin}

There is the finding of the reaction of central support (of brace).

Solving static indeterminacy is by force method. The reckoning scheme is the same in Figure 7. Affixing of unit force is in point C.

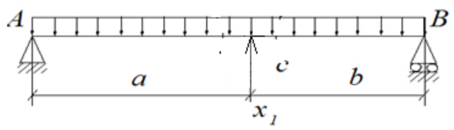

Figure 12. The equivalent system

The main loading is shown in Figure 13.

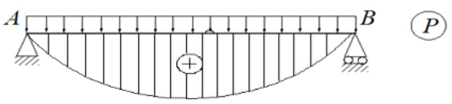

Figure 13. The main loading

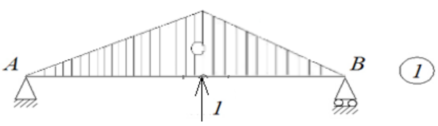

Figure 14. The unit loading

Similarly multiplying of diagrams by formulas (3) and (4) is for support C reaction determination for brace stability checking (compressed diagonal elements).

$$R_C = \frac{-q((a+b)^2 + ab(a+b))}{8ab} \qquad (8)$$

Choose the section of the rafter as rectangular with variable width and by accepting of height is h = 175 mm by formula

$$\sigma_{max} = \frac{M_{max}}{I_y} + \frac{N}{A} \le R \qquad (9)$$

R is determined as bending strength of timber from one side and yield stress of steel from other side. Because of identical method there is an ability to compare allowable stress and factual stress.

$$b = \frac{1}{13000000} * \left(\frac{6M_{max}}{175 * 175/_{1000}} + \frac{N}{175 * 175/_{1000}}\right) \qquad (10)$$

The cross-section of steel thin-walled structures is paired structural channels shape, chosen from Technical requirements. Therefore, there is no considering of bi-moment because of symmetrical shape of cross-section, rafter's constant step, so eccentricity will not appear.

The static calculation is the same in timber structures.

Finding the maximum bending moment is by loads 1,25Q and 0,75Q

$$M_{1max} = \frac{-1.25Q(a^2 - ab + b^2)}{8} \qquad (11)$$

$$M_{2max} = \frac{-0.75Q(a^2 - ab + b^2)}{8} \qquad (12)$$

Choose the section of the rafter by maximum bending moment according Russian Set of Rules SP 16.13330.2011 and technical requirements of company "BaltProfil".

Results and Discussion

The Comparative Analysis of the Selection Results of Rafters with Timber structures and STWS

Apply formulas (11) and (12) for the selection of the rafters of STWS.

Compare the obtained results with results for timber structures, received using the formula (10) and the ones from album series 1.169.5 "Constructive solutions of timber rafters under metal roof" of "LenZhilNIIProekt" (1990).

Initial data and the results are represented in Table 2.

Table 2. The results of calculations

<table>
<tr><th rowspan="2">L_0</th><th rowspan="2">α</th><th rowspan="2">b (design)</th><th rowspan="2">step</th><th rowspan="2">Chosen STWS section</th><th rowspan="2">Chosen timber section</th><th colspan="2">Album of technical solutions 1.169.5 (LenZhilNii-Proekt, 1990)</th></tr>
<tr><th>Top rafter</th><th>Bottom rafter</th></tr>
<tr><td>6000</td><td rowspan="7">18</td><td>82</td><td>1500</td><td rowspan="3">2×TN-175-2</td><td rowspan="7">2x50x200</td><td rowspan="7">2x40x125</td><td>2x60x200</td></tr>
<tr><td>6250</td><td>89</td><td>1500</td><td rowspan="4">2x60x225</td></tr>
<tr><td>6500</td><td>96</td><td>1500</td></tr>
<tr><td>6750</td><td>87</td><td>1200</td><td rowspan="2">2×TN-200-1,5</td></tr>
<tr><td>7000</td><td>94</td><td>1200</td></tr>
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<tr><td>6250</td><td>84</td><td>1500</td></tr>
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<tr><td>6750</td><td>98</td><td>1500</td><td rowspan="2">2×TN-200-1,5</td></tr>
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<tr><td>7500</td><td>96</td><td>1200</td></tr>
<tr><td>6000</td><td rowspan="7">22</td><td>92</td><td>1500</td><td rowspan="3">2×TN-175-2</td><td rowspan="7">2x50x200</td><td rowspan="7">2x40x125</td><td rowspan="3">2x60x200</td></tr>
<tr><td>6250</td><td>81</td><td>1500</td></tr>
<tr><td>6500</td><td>87</td><td>1500</td></tr>
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<tr><td>7500</td><td>92</td><td>1000</td></tr>
</table>

Analyzing the results, it is possible to draw the following conclusions:

The section of the upper rafter spar, adopted in the album of technical solutions, is less than the cross-section of the timber structures calculated in this work. This is a consequence of the fact that the album of technical solutions of timber rafters for metal roofing 1.169.5 for calculation there was applied a design scheme, different from the design scheme adopted in this paper.

However, the cross section of the lower rafter spar, adopted in the album of technical solutions, is larger than the cross-section of the timber structures calculated in this work. This is due to the fact that the album of technical solutions adopted different sections for the lower and upper rafter spars. This is also since different loads were applied to the design schemes.

Structures made of STWS or timber were calculated according to Russian Set of Rules SP 20.13330.2011, structures from album series 1.169.5 were calculated according to SNIP 2.01.07-85.

In Russian Construction Norms and Rules SNIP 2.01.07-85 (changes have been made N 1 and N 2, approved by resolutions of the State Construction Committee of Russia dated July 5, 1993 N 18-27 and of 29 May 2003 N 45, respectively) in particular, paragraph 5.2 has been changed, concerning the snow load values. Also, changes have been made to Attachment 3 concerning the schemes of application of snow loads and snow bags.

Based on this, it can be concluded that the use of the calculation scheme adopted in this paper, in calculations based on current standards and changed loads, makes it possible to save material compared to the version from the album of technical solutions.

The of Economic Efficiency Analysis of Application of Steel Thin-walled Structures in Major Repair of Attic Roofs

The economic expediency was made with the major repair of the building of the roof of 8-th mental hospital building in Druzhnoselo. Via software Smeta Wizard 4.0 there were worked out 2 estimates for the major repair. A rafter section from timber structures is 2x50x175; from STWS is the profile 2xTH-175-2.

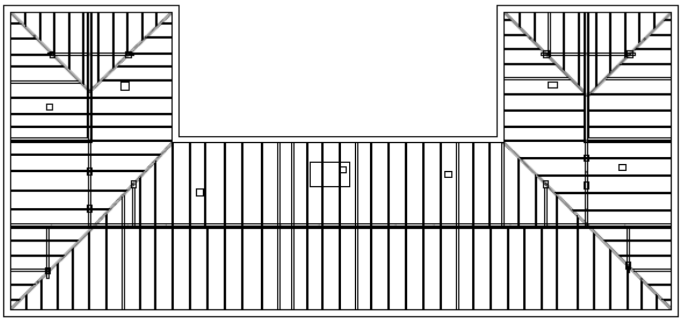

Figure 15. The rafter construction scheme

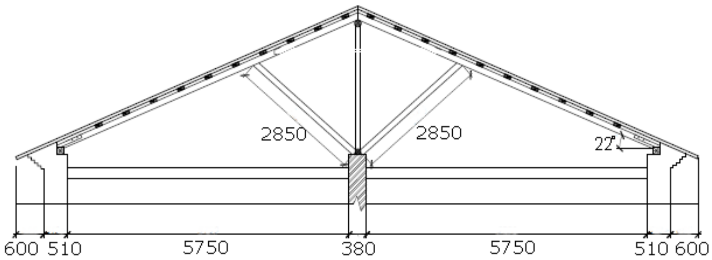

Figure 16. The cross-section construction scheme

The cost of repair is shown in Table 3. The prices are as of April 2015. The estimate is for the territorial unit prices.

Table 3. The hospital repair cost

	Estimate cost, RUR	Salary, RUR	Materials cost, RUR	Cost price, RUR
Timber structures	2 185 637.00	410 966.21	1 106 718.44	1 972 747
STWS	1 879 647.82	353 430.94	951 777.86	1 657 107

The cost comparison is shown in Figure 17.

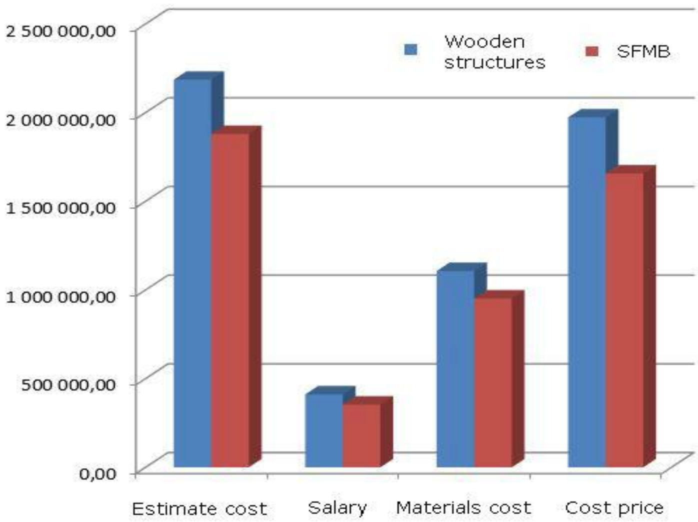

Figure 17. The cost comparison

The major repair by STWS using is cheaper because of less material consumption. The economy is 13 %.

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Conclusion

The result of the following conclusions:

1. The authors have proposed the methodology for calculation the statically indeterminate frame structures with the use of force method. The main idea of the proposed methodology is to simplify the design diagram (structural design) to beam and hereafter use the B.P.E. Clapeyron principle system.

2. Universal solutions are obtained for the selection of rafters made of timber or STWS using the proposed method.

3. The expediency of using the same sections of rafters (50 x 200 mm) and (50 x 175mm) for the same reckoning scheme due to their variable pitch.

4. The section select of STWS rafters for various constructive schemes of pitched roofs:

- For non-combined rafter system of one-pitched roof without braces there is 2xTH-200-1,5 for every overlapped span for unification. The rafter step is reducing with span increasing.

- For non-combined rafter system of one-pitched roof with brace there is 2xTH-175-1,5 for every overlapped span because of small difference of the span.

- For combined rafter system of one-pitched roof with brace there are three sections: 2xTH-175-1,5, 2xTH-175-1,5, 2xTH-200-2 for every overlapped span. The section is increasing with span increasing.

- For non-combined rafter system of saddle roof with brace there is 2xTH-175-1,5, 2xTH-175-2 for every overlapped span. The rafter step is reducing with span increasing.

- For combined rafter system of saddle roof with brace there is 2xTH-175-2, 2xTH-200-1,5, 2xTH-200-2 for every overlapped span. The rafter step is reducing with span increasing.

5. The STWS using allows reducing the major repair cost to 13.5 % because of less material consumption.

6. The research results were implemented in the activity of design institute OJSC "LenzhilNIIproyekt". In using for development of album of technical solutions for the attic roof rafter system.

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