Technical- and- economic efficiency of reinforced wooden structures

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Abstract. The article is devoted to the investigation of the technical and economic efficiency of the reinforced wooden structures by the example of the load beams with a span of 18 m. The efficiency has been estimated by the constructive, technical and economic indexes such as the relative height, relative installation weight and relative unit cost. All indexes have been considered in comparison to the equally efficient and equally rigid reinforced and unreinforced wooden structures. Technical and economic indexes of the beams have been given: the bulk, consumption of basic materials, labor intensity, factory price, total value, capital investments and reduced costs. The efficiency of using group reinforcement over a part of the beam length compression area has been substantiated.

Introduction
Wooden structures with group reinforcement over the part of the beam length belong to the promising building structures [3] and the their technical and economic efficiency considerations are currently important. Technical and economic efficiency of the new types of building structures has been estimated in comparison with the similar wooden structures used in construction that allows to study out their properties more completely and to determine the applicable scope.

The main indexes of the load-bearing building structures effectiveness are the design indexes: the cross-sectional dimensions and installation weight as well as technical and economic indexes: the consumption of the basic materials, factory cost, full value and reduced costs.

Evaluation of the efficiency of reinforced wooden structures by the design indexes
Evaluation of the reinforced wooden structures efficiency by the design indexes has been carried out by the following methodology.

At the first stage design indexes characterizing the effectiveness of similar structures with the same bearing capacity have been determined. Since the bearing capacity of structures is mainly characterized by the strength and deformability, the wooden beams reinforcement efficiency can be estimated in compliance with the conditions of the first and the second groups of the limit states, provided that the wooden beams cross-section decreases proportionally due to the reinforcement, i.e. the following equality must be satisfied (see Equation 1):

\[
\frac{h_0}{h_i} = \frac{b_0}{b_i} = \text{const.}
\]
where $h_0$ – is the design height of the reinforced structure cross section;

$h_0$ – is the effective width of the reinforced structure cross section;

$h$ – is the design height of the unreinforced structure cross section;

$b$ – is the calculated width of the unreinforced structure cross section.

The relative height of the reinforced and unreinforced beams has been determined by the formula (see Equation 2):

$$h_{rel} = \frac{h_0}{h}.$$  

(2)

Regarding equal strength [4] of the reinforced and unreinforced beams by the standard cross-section [2], relative height has been determined by the formula (see Equation 3), from the condition of the wood strength splintering along the grains by the formula (see Equation 4), from the condition of the identical deformability of the reinforced and unreinforced beams by the formula (see Equation 5):

$$h_{rel}^M = \frac{1}{\sqrt[3]{\beta}}.$$  

(3)

$$h_{rel}^O = \frac{\sqrt{\beta}}{\beta}.$$  

(4)

$$h_{rel}^f = \frac{1}{\sqrt[4]{\beta}}.$$  

(5)

where $\beta$, $\beta_1$ – are the reduction coefficients of the whole-wood cross section to the transformed section, defined for symmetric reinforcement by the formulas (see Equations 6, 7):

$$\beta = 1 + 3n\mu.$$  

(6)

$$\beta_1 = 1 + 2n\mu.$$  

(7)

where $n$ – is the reduction coefficient (ratio of the reinforcement and wood elastic module);

$\mu$ – is the reinforcement ratio.

The dependence “relative height of the cross section – the reinforcement coefficient” has been constructed (refer with Figure 1).

![Figure 1. Reduction of the wooden beams height due to the reinforcement](image)

The height of the unreinforced beam has been taken as a unit. The dependence has been built at the ratio of the reinforcement and wood elastic module, equal to 20 on change of the reinforcement ratio from 0 to 5%.
Analysis of this dependence has shown that the cross-sectional dimensions of the structures decrease most intensively in the range from 1.5 to 4 %. At the same time the cross-sectional area decreases by 15-26 % regarding equal rigidness of the structure and by 19-35 % regarding the equal strength of the beams across the normal cross section and with equal structural strength in the support cross sections by 8-13 %.

The relative mass of the reinforced and unreinforced beams has been determined by the formula (see Equation 8):

\[ G_{rel} = \frac{G_r}{G} \]  \hspace{1cm} (8)

where \( G_r \) – is the mass of the reinforced structure;
\( G \) – is the mass of the unreinforced structure.

Evaluation of the reinforced structures effectiveness by a single mass (one meter mass), depending on the equal bearing capacity of the reinforced and unreinforced structures, has been determined in compliance with beams equal strength by the normal section by the formula (see Equation 9), regarding equal strength of the support sections by the formula (see Equation 10), regarding the beams equal rigidity by the formula (see Equation 11):

\[ G_{rel}^\mu = \frac{1+15\mu}{\sqrt[3]{\beta^2}} \]  \hspace{1cm} (9)

\[ G_{rel}^Q = \frac{(1+15\mu)\bar{\beta}}{\beta} \]  \hspace{1cm} (10)

\[ G_{rel}^f = \frac{1+15\mu}{\sqrt[3]{\beta^2}} \]  \hspace{1cm} (11)

By the formulas (9-11), the dependence of the relative mass of the reinforced wooden section on the reinforcement ratio has been constructed (refer with Figure 2).

![Figure 2. Dependence of the installation weight of wooden structures on the reinforcement ratio](image)

Analysis of the graph has shown that under the equal rigidity of the structures the mass of the reinforced structure has been reduced by 11-13 % with the reinforcement ratio from 1.5 to 4 %, and at the equal strength across the normal cross section by 20-29 %. Under the equal strength of structures in the support sections, the mass of the reinforced structures has increased by 13-22 %.
Hence it appears that in order to design optimal in mass reinforced wooden structures it has been necessary to take into account the dependence on the type of the design limit states, to avoid the cross sections over-reinforcing (to maintain the reinforcement ratio in the range from 2 to 3 %.)

**Evaluation of the effectiveness of the reinforced wooden structures by the technical and economic indicators**

The relative unit cost (cost per meter) of the structures has been determined according to the method that allows to build the dependence of the reinforced structures relative cost on the coefficient of the reinforcement magnitude and the type of the limit-state design (refer with Figure 3).

The relative cost of the reinforced and unreinforced beams has been determined by the formula (see Equation 12):

\[ C_{rel} = \frac{C_a}{C}. \]

where \( C_a \) – is the cost of the reinforced structure;

\( C \) – is the cost of the unreinforced structure.

Evaluation of the reinforced structures effectiveness [5] by the unit cost depending on the equal bearing capacity of the reinforced and unreinforced structures has been determined from the condition of the beams equal strength across the normal cross section by the formula (see Equation 13), of the conditions of the support sections equal strength by the formula (see Equation 14), regarding the condition of the beams equal rigidity by the formula (see Equation 15):

\[ C_{rel}^M = \frac{1 + 9 \mu}{\sqrt[3]{\beta^2}}. \]

\[ C_{rel}^Q = \frac{(1 + 9 \mu) \beta}{\beta}. \]

\[ C_{rel}^f = \frac{1 + 9 \mu}{\sqrt[3]{\beta}}. \]

![Figure 3. Changes in the cost of wooden structures due to reinforcement](image)

Analysis of the cost of the reinforced wooden structures, depending on the coefficient of the reinforcement magnitude and the type of the design limit states, has shown that the reinforced structures whose bearing capacity mainly depends on the strength of the normal cross section, have the
lowest cost. In this case when the value of the reinforcement ratio is from 1 to 3 %, the cost of the
construction has been reduced by 20-36 % and the installation weight has been reduced by 16-26 %.

The cost of the reinforced structures whose bearing capacity is characterized by deformability has
increased slightly as compared with the above mentioned. Thus, with the coefficient of reinforcement
of 2 to 3 %, the weight of structures, that have the same stiffness as the unreinforced ones, has
decreased by 9-13 % and the cost has decreased by 14-24 %.

The cost of structures with bearing capacity depending on the strength of the support cross sections
with the coefficient of reinforcement from 0 to 1 %, has decreased by 4 % as compared with the non-
reinforced ones. With more than 1 % increase of the coefficient, the cost of the reinforced structures
has increased. When the reinforcement coefficient has been more than 3 %, the cost of the reinforced
structures has been higher than the unreinforced ones. Such a change in the cost of the high reinforced
structures \( \left( \frac{h}{l} = \frac{1}{17} \right) \) has been caused by the decrease of the cross-sectional area and the increase in
weight due to the reinforcement.

One of the ways to reduce material consumption [6] of such structures is the reinforcement over the
part of the length in the cross section compressed area. This method of arrangement of steel in the
span has reduced its consumption by 15-20 %, the installation weight of structures by 4-5 % and the
cost by 1.5-2 %.

Investigation of technical and economic efficiency of reinforced structures by the example of
beams with a span of 18 m

Through the example of a typical glued laminated beam of 1-462-2 spec. series 3 and the reinforced
wooden beam with a span of 18 m, technical and economic comparison according to the generally
accepted nomenclature of indexes can be made (refer with Table 1).

Reinforcement of the beam in the compressed area has been carried out with a pull-off, i.e. the
reinforcement is not brought up to the supports by one meter which allows to reduce the consumption
of reinforcing steel by 20 %. The total cost of the structures has been determined on the basis of the
factory cost, the cost of transportation and the cost of installing the beams on the construction site. The
cost of the installation has been assumed to be the same since their weights differ slightly.

It has been established that the total cost of the reinforced beams has been 12.5 %, and by the total
costs has been 15 % less at a certain (5-8 %) increase in labor intensity. It should be noted that
during the development of mass production of the reinforced structures, their technical and economic
indicators increase.

| Table 1. Technical and economic indexes of beams |
|------------------------------------------------|
| **Indexes** | **Glued beam with the span of 18 [m]** | **Reinforced** | **Standard** |
| --- | --- | --- | --- |
| Weight, t | 1.47 | 2.2 |
| Consumption of basic materials: | | | |
| - Timber [1], [m³] | 2.07 | 4.44 |
| - reinforcement, [kg] | 350.8 | |
| - glue, [kg] | 84 | 67 |
| Labor intensity of manufacturing, [person-hour] | 39.247 | 36.34 |
| Factory price, [rub.] | 2158.6 | 1998.7 |
| Total cost, [rub.] | 65422.5 | 98472 |
| Capital investment, [rub.] | 42265.3 | 52621.25 |
| Reduced costs, [rub.] | 98897.7 | 147339.5 |

Analysis of the technical and economic indexes of the reinforced wooden structures efficiency has
shown that the structures whose cross section dimensions and coefficient of reinforcement have been
determined by the strength conditions of the standard cross section, are the most effective. What is more, their effectiveness has been significantly increased by arranging the reinforcement across the part of the span in the cross section compressed area.

Summary
The following conclusions can be made on the basis of the experience of using load-bearing reinforced wooden structures in construction:
1. Reinforcement of the glued wooden structures over the parts of the length by a group way allows to increase their technical and economic efficiency by reducing the cross-sectional dimensions of the structures by 15–33 %, the construction height by 12–40 %, the installation weight by 15–33 % and the total cost by 6-38 %.
2. It has been established that the beams reinforced over the part of the length, that are actually beams of the uniform strength, with beams reinforced along the entire length, are considered to be the most promising in terms of the arrangement of the span reinforcement
3. Technical and economic analysis of the floor beam with a span of 18 m has shown that reinforcement over the part of the length allows to reduce the cost and reduced costs by 15 %.

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