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Wooden beams with reinforcement along a curvilinear trajectory

Деревянные балки с армированием по криволинейной траектории

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Ключевые слова: строительные материалы; строительство зданий; армирование деревянных балок; прочность; эластичность; сейсмостойкость; ресурсосбережение

Abstract. The article is devoted to the investigation of a new type of reinforcement of wooden beams for floors and coatings with using steel cable reinforcement located in a solid wood along a curved S-shaped trajectory. The basic principles of a new type of reinforcement are set up. The schemes of various reinforcement paths are given. Mathematical models of studied structures are formed. The stress-strain state of several beams with different variants of reinforcing paths in the working environment of the software complex SCAD, which calculates the beams studied by the finite element method, has been studied. The results of the work are presented in the form of indicators of deflections of beams and isopoles of stresses. A comparative analysis of the studied structures with non-reinforced beams and the traditional reinforcement method is carried out. Conclusions are made about the increase in the strength characteristics of the beams, in which the steel cable armature is used. The optimal trajectory path for the reinforcement groove is selected. The competitive advantages and prospects of using a new type of reinforcement are determined.

Аннотация. Статья посвящена исследованию нового вида армирования деревянных балок для перекрытий и покрытий с использованием стальной канатной арматуры, расположенной в массиве древесины по криволинейной S-образной траектории. Сформированы основные принципы нового вида армирования. Приведены схемы различных траекторий армирования. Сформированы математические модели изучаемых конструкций. Изучено напряженно-деформированное состояние нескольких балок с различными вариантами траекторий армирования в рабочей среде программного комплекса SCAD, выполняющего расчет исследуемых балок методом конечных элементов. Результаты работы представлены в виде показателей прогибов балок и изополей напряжений. Проведен сравнительный анализ изучаемых конструкций с неармированными балками и традиционным способом армирования. Сделаны выводы о повышении прочностных характеристик балок, в которых использована стальная канатная арматура. Выбрана оптимальная траектория паза врезки для арматуры. Определены конкурентные преимущества и перспективы применения нового вида армирования.

1. Introduction

For historical reasons wood has been used in the form of such constant cross-section units as beams, rafters, curved structures in the construction for centuries. Until the beginning of the 20th century there were no written references about the use of wood reinforcement. However, the high rates of construction and the growth of the construction industry technological level have led to a step change in the requirements for buildings and structures. Need for large-span buildings in public and industrial construction arose [1–4]. Economic conditions and a limited amount of natural resources have produced the desire to save construction materials in the mass low-rise construction. Steel and reinforced concrete structures became the most popular, but aesthetic requirements also grew along with the strength and economic ones. New concepts in the construction of buildings consisted in the principles of ecological compatibility and the maximum ambience of the habitable human environment with natural materials. All these requirements have led to interest in increasing the initial natural strength and deformation characteristics of timber structures.

In some degree the solution to this problem was the widespread use of glued wooden structures in construction that surpassed metal and reinforced concrete units for a number of reasons - they had a small installation weight due to the low wood density, relatively high rigidity and strength with sufficient reliability and durability and low cost. However, some wood properties, such as defects, a small yield of high-quality lumber from round timber, sectional massiveness, creep under sustained loading have also formed a number of drawbacks limiting the use of glued wooden structures [5–8].

Qualitatively new leap in the development of wooden structures occurred with the invention of reinforcing wooden structures with steel or fiberglass reinforcement. Reinforcement allowed to reduce wood consumption significantly, improve the quality and reliability of wooden structures, mainly working in bending and bending compression. Such structures have increased strength and rigidity in combination with a small installation weight that sets them apart from metal and reinforced concrete products and allows to mount an enlarge assembly in the construction of buildings and structures. This makes them indispensable in the construction of scattered structures in places remote from main communication lines in hard-to-reach areas, for use in large-span systems of buildings experiencing significant loads in the junctions.

It should be noted that wood today is one of the most popular construction materials. The volume of this natural resource consumption is constantly growing alongside with the growing volumes of low-rise suburban construction in Russia. Wood is extensively used: it is used in the construction of enclosing structures, covering and blanking beam systems, rafter systems [9]. Despite the fact that wood is a renewable natural resource, the volume of its reproduction is very limited.

At the proper time, the problem of saving wood when erecting buildings and structures led to the invention of the technology of reinforcing wooden beams. The question of introducing rigid steel reinforcement bars into the wood solid was thoroughly studied, by gluing them into milled grooves at the stage of gluing the beams structural parts. The use of the investigation and the emergence of the reinforced wooden structures school in Russia can not be overestimated [10]. These technologies provide substantial material savings and increase in strength and deformation characteristics, but require a factory, labor-intensive process for the manufacture of structures consisting of multistage processes: wood preparation, glueing layers, reinforcement, milling, etc. As a result, beams are much more expensive than their unreinforced counterparts. Therefore, reinforced wooden structures carved out a niche of similar products, especially when constructing public facilities and large-span structures, but they can not displace the beams from ordinary timber in the segment of low-rise construction.

In addition, the issues of reinforced wooden structures fragile destruction, their fire resistance due to the fluidity of adhesive compositions under the influence of high temperatures, the problem of strengthening the bearing zones during reinforcement, continue to be relevant today.

Workings intended to solution of similar problems such as strengthening the beams bearing zones, as well as investigation of the beams work with various longitudinal and transverse reinforcement has been carried out at Vladimir State University, at the Department of Building Structures under the guidance of V.Yu. Shchuko and S.I. Roshchina taking into consideration the increased strength of the reinforced beams in the central zones subjected to tensile deformation with bending, destruction of such beam construction often occurs in the bearing zones because of shear fracture stresses directed along the fibers [10–13]. Therefore, to date, the problem of strengthening the bearing zone of reinforced wooden beams is particularly timely.

The use of wood reinforcement due to the difference in the modulus of elasticity or the difference in the relative strain of wood fibers and reinforcement in mechanical tensile and compression tests (1.15 and 0.84 % for wood and 6-16 for reinforcement (deformations corresponding to the yield strength of 0.15 to 0.35 %)) leads to the fact that in all cases of combined work provided by glue bond of reinforcement with wood, the bearing capacity of the reinforcement will be rationally used. Stresses in the reinforcement will reach the yield point earlier than the strength of the wood will be exhausted. However, the reinforcement will prevent fragile destruction of the beam structure, because even in the area of extreme loads, when the strength of the wood is exhausted, the reinforcement will partially retain its load-bearing capacity, even if it exceeds the yield strength, demonstrating the effect of a strut-framed beam or strengthened bent. The investigations show that the reinforced beam does not collapse even after the destruction of the wood of the stretched zone and the increase in the effective stresses by 60–70 % of the magnitude of the destructive load. This property is extremely useful for the construction of buildings and structures in areas with increased seismic activity and responsible public facilities.

The article considers a new type of wooden beams reinforcement – the wire rope reinforcement along the original curvilinear path. Having analyzed the existing shortcomings of the traditional type reinforcement, it has been suggested to change the approach to reinforcing wooden beams: to use plain lay flexible cable instead of rigid steel reinforcement. The introduction of cable reinforcement into the solid wood will allow to obtain higher strength characteristics in comparison with the traditional reinforcement methods – ordinary steel reinforcement, since when the area is equal with the reinforcement, the rope cross section has greater tensile strength and due to a more detailed structure – greater adhesion properties with the glued layer between the wood and the reinforcing material. A curvilinear wave form in the bearing zones where the waves bend radius would coincide with the radius that the flexural rigidity of the steel cable armature imposes should be used instead of a rectilinear milling path. Compared with the existing methods of reinforcement, the proposed form makes it possible to increase the anchoring length in the bearing zones by 1.6–1.8 times [14]. All this will reduce the beam structures cross-sectional area which will lead to savings in wood and steel in the construction of ceilings and covering. It has been planned to use that has proven effective and already traditional multicomponent glue composition based on epoxy resin with hardener PEPA and plasticizer as a binder [15–18].

Due to its simplicity, the new reinforcement technology can be used not only in stationary conditions, but also on the construction site. In addition to all of the above, an important competitive advantage is the ecological component of application these structures in construction in addition to saving wood, the technology provides for minimizing the use of glue compounds (in comparison with glued wooden reinforced structures), which will reduce the harmful impact on the environment and people operating buildings with such constructions [18–21].

2. Methods

The main method of studying wooden beams in this work was the analysis of the stress - deformed state arising in the type of reinforcement that is being studied by creating mathematical models of beams with different trajectories of slot grooving for armature and their virtual testing in the SCAD software package.

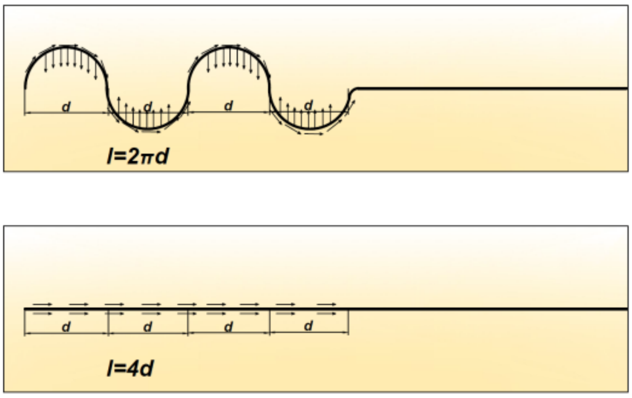

Figure 1. One of the variants of the proposed curvilinear form of anchoring

The proposed form of the reinforcement assumes consideration of the investigated structure volumetric stress, because of the uneven and asymmetric location of the reinforcement along the lower edge of the beam. There are changes in stresses not only in the plane of the longitudinal section of the beam, but also in its cross section. The stress-strain state becomes volumetric that does not allow the construction of diagrams for cross sections, since an infinite set of stress values correspond to each value of the section depth. Such problems are solved only with the help of the finite element method with the use of software systems due to the large (tens of thousands) number of system elements. This method makes it possible to create a realistic model of a reinforced beam with curvilinear reinforcement, to analyze the stresses and deformations arising in the process of loading to the fullest extent possible though the use of the Stress isofield color mapping. It is also possible to perform a comparative analysis of several variants of reinforcement under identical specified ideal conditions - exact geometry, the same loading, the same support fixation.

Figure 2. Demonstration samples of reinforcement along a curvilinear path

The survey objectives were implemented as follows: calculations were carried out for a non-reinforced beam, 3 reinforced beams with rope reinforcement d = 8 mm along a different trajectory (single and double). The beams visualizations are shown in Figures 4–7. The length of the beam is 4.8 m, the cross-section is 100 x 200 mm. The reinforcement is located on the low edge. The beam design model at issue has been constructed by adapting the initial data for the SCAD software running environment. Wood as the beam main material has been assigned as a three-dimensional body obtained by triangulation and extrusion of the beam projecting section. The same grip conditions have been given for all types of reinforcement (on the right - hingedly – a rigid point of support at a distance of 120 mm from the edge of the beam, on the left - hingedly – a simple support at a distance of 120 mm from the edge of the beam). The beam loading – the loading uniformly distributed across the area with the value of 2 tons/m2 is the design load for the ceiling rafters according to CR 64.13330.2011 Wooden structures. Revised edition of SNiP II-25-80. The load works on the upper plane of the beam.

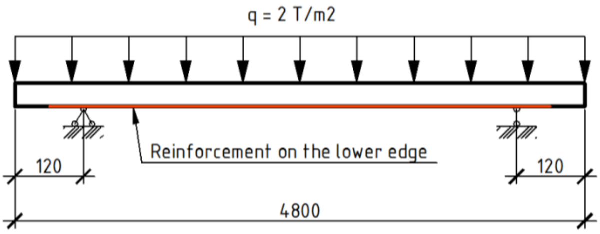

Figure 3. The tests design model

A full calculation by the multifrontal method using finite elements has been performed for the beams presented in the work. It should be noted that the SCAD PC allows to investigate the volumetric stress state of bodies only at the 1 stage of loading - under normal conditions of the structure operation. This is due to the fact that the orthotropic parameters assigned to the volume elements in this program are characterized only by elastic moduli and Poisson's coefficients in different directions.

It is possible to exude a number of indicators according to which the comparative analysis of the stress-strained state of the investigated types of reinforcement has been made from a set of the received results.

1. Isopoles of tensile and compressive stresses operating along the beam fibers. This type of graphical representation of stresses allows to understand how uniformly the stresses are redistributed in the reinforcement zones and throughout the volume of the beam. One can also sit in judgement on the intensity of the stresses at specific points of the beams and make appropriate conclusions about the degree of interaction between wood and reinforcing material according to the contrast grade of the isopoles colour.

2. The beams deflections in the middle of the span (formed by the displacement of the central lower girder connection of the beams along the vertical axis "Z"). It is possible to make a comparative analysis of the deformation parameters of the beams by the size of the deflection.

3. Results

As a result of the comparative analysis these characteristics allow to choose the most advantageous form of the curvilinear trajectory for milling the groove for the steel wire rope reinforcement and make conclusions about the effectiveness of the proposed reinforcement method in comparison with ordinary wooden unreinforced beams and beams with traditional reinforcement.

Consider the results of the study in more detail. Figures 4–19 show the images of longitudinal stresses isopoles in the investigated beams.

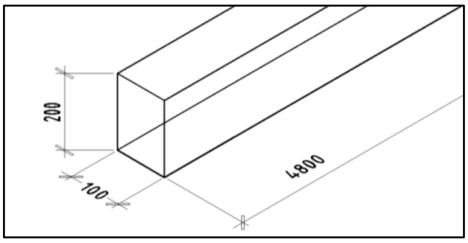

Figure 4. Visualization for an unreinforced beam

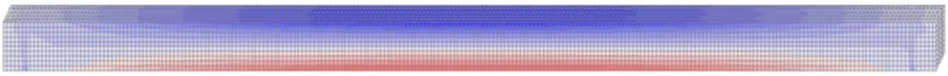

Figure 5. Visualization and the stresses isopoles for an unreinforced beam. General form

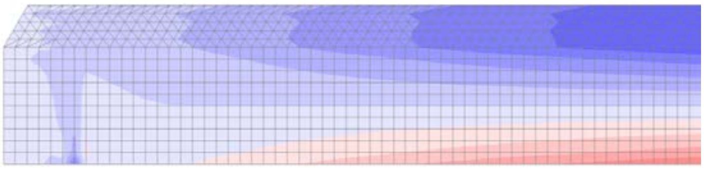

Figure 6. Visualization and the stresses isopoles for an unreinforced beam. View from above

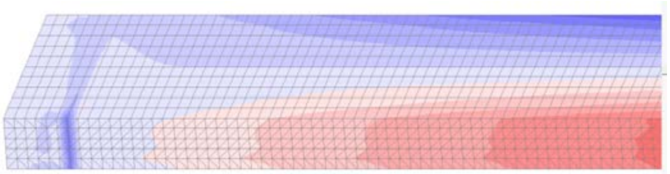

Figure 7. Visualization and the stresses isopoles for an unreinforced beam. Bottom view

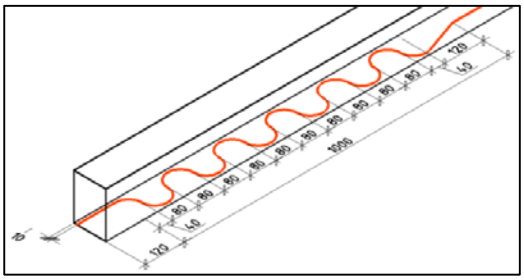

Figure 8. Visualization for a beam with a single reinforcement by wire rope cable

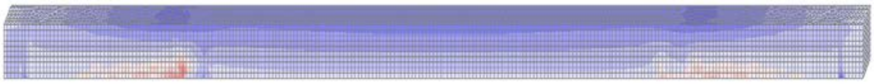

Figure 9. The stresses isopoles for a beam with a single reinforcement by wire rope cable. General form

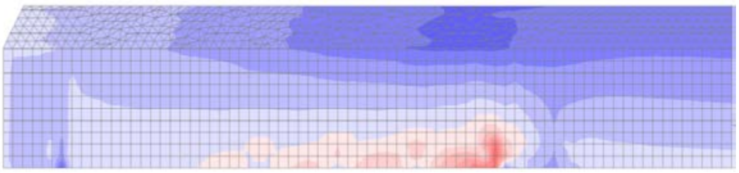

Figure 10. The stresses isopoles for a beam with a single reinforcement by wire rope cable. View from above

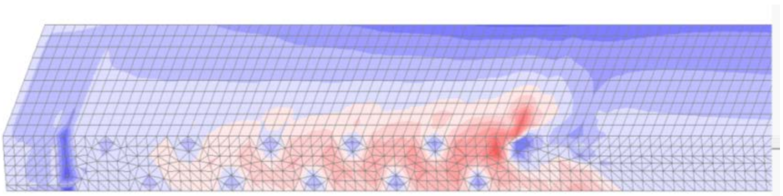

Figure 11. The stresses isopoles for a beam with a single reinforcement by wire rope cable. Bottom view

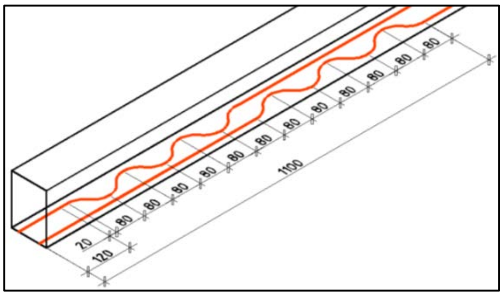

Figure 12. Visualization for a beam with the double unseat reinforcement

Figure 13. The stresses isopoles for a beam with the double unseat reinforcement. General form

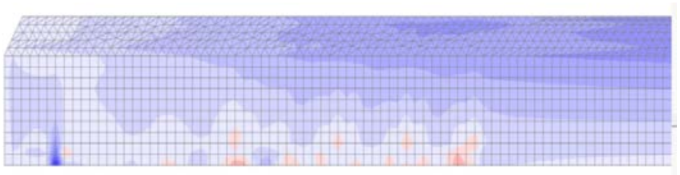

Figure 14. The stresses isopoles for a beam with the double unseat reinforcement. View from above

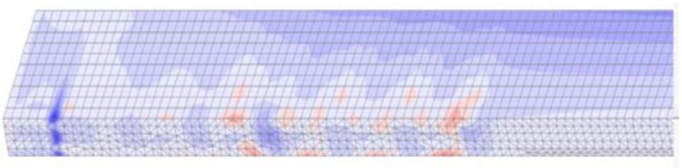

Figure 15. The stresses isopoles for a beam with the double unseat reinforcement. Bottom view

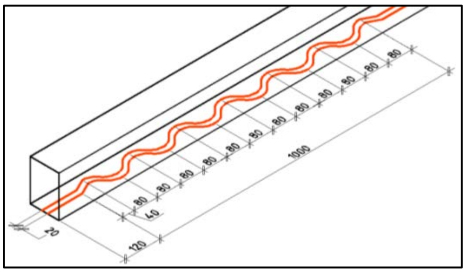

Figure 16. Visualization for a beam with double reinforcement by steel wire rope reinforcement without waves displacement

Figure 17. The stresses isopoles for a beam with double reinforcement by steel wire rope reinforcement without waves displacement. General form

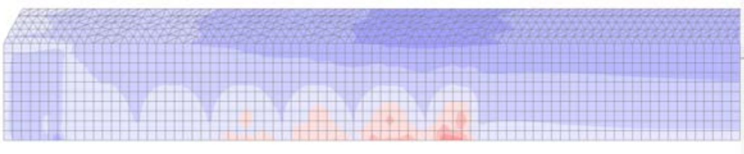

Figure 18. The stresses isopoles for a beam with double reinforcement by steel wire rope reinforcement without waves displacement. View from above

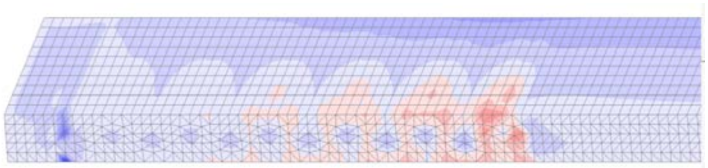

Figure 19. The stresses isopoles for a beam with double reinforcement by steel wire rope reinforcement without waves displacement. Bottom view

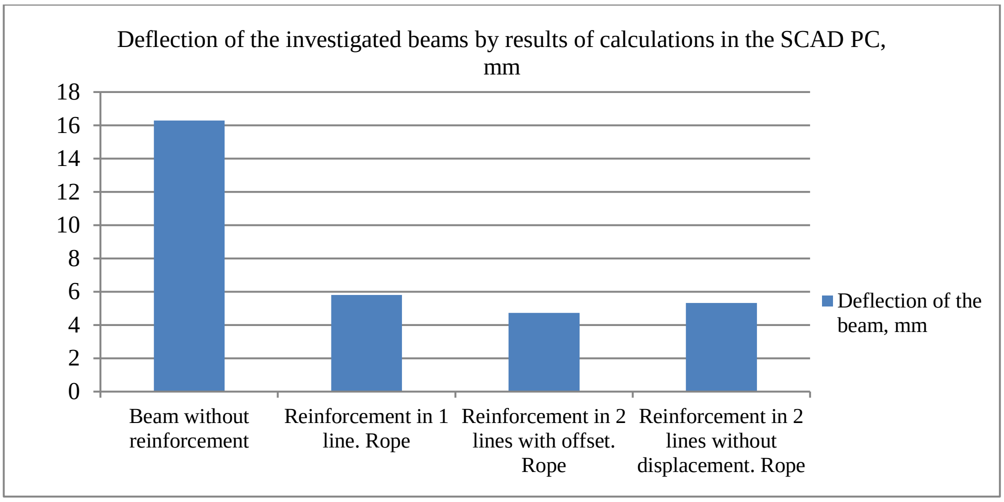

Figure 20. Comparison chart of the beams deflection

4. Discussion

At the Vladimir State University, developments have already been carried out aimed at a similar problem with the subject of this paper – strengthening the bearing zones of beams, as well as studying the work of beams with different types of longitudinal-transverse reinforcement [3, 4, 6–8]. In view of the increased strength of reinforced beams in central zones experiencing deformation of stretching with bending, the destruction of such girder structures occurs often in the prone zones due to shear stresses directed along the fibers. Therefore, to date, the problem of strengthening the piercing zones of reinforced wooden beams is especially urgent.

It has been proposed to perform longitudinal - transverse reinforcement of beams with the use of transverse plates - the use of this type of reinforcement made it possible to reduce the share of tangential stresses perceived by the wood by 20–25 %, which is especially important for high beams or for large transverse forces.

The conducted researches and development have formed a number of conclusive advantages of the wooden reinforced structures before analogues from not reinforced wood. The new technology offers a rational solution to the problem of reinforcing the suspension zones of the beams.

5. Conclusions

Based on the results of calculations, the reinforcement in 1 line with the s-shaped anchoring path turned out to be the most advantageous option from the point of view of strength and deformability (Fig. 5). Based on the obtained data, we can draw the following conclusions:

1. This type of reinforcement significantly changes the work of the timber in the beam;

2. Analysis of emerging strains and stresses shows a 3–4 times increase in strength for a design with a new type of reinforcement;

3. The proposed reinforcement technology provides a 64 % reduction in deformation by comparison with the non-reinforced structure, along with the largest indicator of reinforcement efficiency, harm to all the beams examined.

The prospect of the further investigation is connected with the reliability test of the mathematical model in practice, i.e. performing experimental tests.

In case of experimental verification of the calculation results, beams with a new type of reinforcement will provide a meaningful concurrence to unreinforced wooden structures. Beams of a new type can be used as cheaper and reliable alternative to ordinary wooden beam structures for purposes of strength characteristics with the advantage of reducing the projected floor structure height. The scope of their application is quite extensive – the production of coating and ceiling systems in low-rise, public and industrial construction. Due to the new beams increased elasticity, it is also possible to increase their ability to withstand the action of running value forces, which is important for areas with increased seismic activity.

Construction of energy-efficient buildings and structures is also one of the areas of application of the investigated structures in view of low heat conductivity, aesthetic surface appearance and orientation vector of this technology for resource economy.

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