Steel timber-concrete beams. Numerical and full-scale experiments

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Abstract. The first composite beams in the cross section of which concrete and wood were used, were patented at the end of the 19th century. In this article, technical solutions are analyzed based on works of the recent years. New beam designs have been developed. The Russian Federal Service for Intellectual Property (Rus. Rospatent) has issued patents to Kazan State University of Architecture and Engineering (KSUAE) for invention and utility model of new solutions of steel-concrete section beams. Analytical and experimental studies, the experience of using wood-concrete and wooden structures with reinforcement from different materials in the stretched area of the beam are studied. Based on their analysis, new solutions for steel-concrete beams were developed, in which bent steel profiles were used in the stretched zone of the beam, a research program was drawn up.

Numerical studies of steel-concrete beams and thickness variations of bent steel profiles, wall height, pitch, length and diameter of self-tapping screws were carried out.

Experimental studies were carried out using a beam model, the parameters of which are taken from the results of numerical studies. The methodology and test results of the beam are given. The test results are presented in the form of graphs of stresses, deformations, deflections. In conclusion, satisfactory convergence of the results of numerical and laboratory studies of the studied beams of composite section is noted.

Key words: timber-concrete beam, steel timber-concrete beam, numerical experiments, full-scale experiments, tensions, deflections.

1 Introduction

It is believed that the idea of using wood in concrete structures in a stretched area as a working armature arose in the late XIX century. A patent was obtained for a timber-concrete beam in 1896 in Switzerland. Then in different countries of Europe at the beginning of the 20th century, experimental studies of timber-concrete beams began-first in London, then in Italy.

The large-scale studies of timber-concrete structures were conducted in Soviet Russia under the supervision of prof. I. A. Kirienco. It is believed that the first anchors for bonding concrete to wood based on steel nails in these beams were proposed in France. However, according to this principle, the first series of plates were made in Fili and tests were carried out, the experimental plates were destroyed when the limit of wood tensile resistance was reached in the stretched zone of wooden beams.

In the same years, both experimental and analytical studies of such structures were conducted in European countries and the United States. In research at the University of Illinois (USA), not only nails, but also steel plates were used to bind timber to concrete. In the USA in the middle of the XX century more than a hundred bridges and port structures made of timber-concrete were built.

Since the second half of the XX century Europeans began to use timber-concrete in reconstructed buildings (Czech Republic, Germany, Italy, Austria, etc.).
In Russia, timber-concrete structures are mainly used in bridge structures. With the advent of glued structures, glued beams became the main load-bearing element of wood-concrete structures. In bridge construction, both pins (nails) and various staples and clamps are used to connect wood to concrete and in glued beams in the stretched zone, steel reinforcing rods are added to increase their load-bearing capacity.

In KSUAE at the beginning of the XXI century the candidate and doctoral dissertations of I.S. Abdarakhanov under the guidance of prof. I.T. Mirsayapov were compiled. They reflected the research of timber-concrete beams and ceilings in relation to the restored architectural heritage monument under different types of loads.

As noted above in the construction of bridge spans at high loads there is a need to strengthen the stretched zone of the steel reinforcement.

Rospatent issued several patents to KSUAE for a concrete beam [20, 21] where the steel bent profile is used in the stretched zone, and in the compressed zone as a formwork for monolithic concrete.

The practical value of the research of structural elements of composite sections is to study the stress-strain state of structural element and identify the structural features of each layer which are integral parts of such structures, the limits of the carrying capacity, which will allow to assess properly their maximum carrying capacity and will allow to design a reliable and economical design of composite sections.

An effective research program always requires an analysis of existing research. Let's consider the research described in the literature over the past 10 years.

Source [1] is devoted to the analysis of the stress-strain state of a reinforced concrete bending element of a "T"-shaped section. The stretched area of the timber beam and the compressed concrete shelf are reinforced with reinforcing steel rods. The article [2] is devoted to the methodology and results of testing of timber-concrete slabs with timber glued beams with toothed joints. The results of tests of reinforced plates with beams made of beech LVL for different types of connections are analyzed.

The article [3] considers finite element modeling of "T"-shaped beams made of timber and concrete, which are connected by screws. Numerical results are compared with experimental data.

Articles [4-7] are devoted to anchor connections between a concrete slab and a wooden beam. The first one is devoted to the research of strength, stiffness and failure modes of the joint. The second part of this group is devoted to modeling screw connections between two layers. The article [6] is devoted to experimental studies of connections from inclined screws included in wood. The article [7] also investigated toothed joints in massive wood-concrete panel floors and floors. Based on experimental studies, conclusions are made about the depth of the incision of the teeth, and structures with self-tapping screws are also studied.

The article [8] is devoted to numerical and analytical studies of the shear of perforated connectors between a beam and a plate. In the article [9] the connectors between a concrete slab and beams in the form of glued steel plates were experimentally investigated. The article [10] is devoted to research on the shear of the floor made of concrete composite and timber beams connected by a glued plywood board. The samples were tested for long-term loads of up to 13 months. The article [11] considers experimental studies of prefabricated panels consisting of corrugated sheets enclosed between two concrete layers.

Source [12] is devoted to the development of numerical models for analyzing the destruction of beams made of timber and concrete of reinforced concrete panels.

In [13], fragments of a floor element consisting of a composite concrete slab and wooden beams connected by steel mesh connectors and an adhesive veneer were experimentally studied at different distributions of transverse force and bending moment.

The article [14] analyzes the behavior of timber-concrete composite beams with toothed joints. In the article [15], timber-concrete composite floors of an old residential building reinforced with a carbon fiber strip in the stretched zone of beams are experimentally analyzed. Comparisons with numerical results are given; the article [16] is also devoted to experimental studies of timber-concrete beams reinforced with glass fibers.
The article [17] considers composite structures for multi-storey buildings, tests of their joints for bending and shear.

In [18], composite steel-timber-concrete floors consisting of multi-layer timber slabs and steel ribs from a bent profile are described.

In [19], floors made of concrete slabs and reinforced concrete prestressed and non-prestressed beams are considered. Based on the analysis of the stress-strain state, the possibility of using joint structures in wood-concrete floors is shown.

In Russia, the behavior of wood-concrete structures is described in the books by E.E. Gibshman, V.I. Kulish, Yu.O. Melnikov and others. In relation to floors, these questions are set out in the dissertation of I.S. Abdrahmanov.

Analysis of literature sources shows that research is mainly devoted to timber-concrete structures, if the load-bearing capacity of the beams is insufficient, they are reinforced with steel or plastic (fiberglass, carbon fiber) reinforcement. There are also studies where prestressed reinforcement is used in the beam stiffeners.

However, there are no studies on the stress-strain state of timber concrete beams, which do not have a bent steel profile in the stretched and compressed zones.

In KSUAE patents for steel and concrete beams were recieved in 2016 and 2019 [20, 21].

The purpose of this report is to analyze timber-concrete, timber-wood-concrete bending elements and numerical, experimental studies of steel-timber-concrete beams.

2 Materials and methods
Numerical study of the beam is performed using PC Ansys in three phases: during the first phase a finite element model is created; the second phase is the imposition on the physical model and boundary conditions and solving the system of equations of the FEM, the third phase is the analysis of the results of the calculation.

The Box 1 element is created from the entire steel-concrete beam with dimensions of 250×260×2000 for further research. The symmetrical operation of the beam is provided by the "Symmetry" function. This procedure simplifies the calculation, reduces the number of specified elements, which consequently reduces the amount of time spent on the calculation, and affects the speed and getting the correct result. In the future, when studying this beam, we will use the resulting model of steel and concrete beams to obtain its stress-strain state.

The next step in the simulation is to select materials for the created bodies and specify their properties.

![Figure 1](image1.png)

**Figure 1.** Size of steel-reinforced concrete beam.

![Figure 2](image2.png)

**Figure 2.** Modeling in "DesignModeler" of a beam forming part of a steel-timber-concrete beam with the length L=2m.
We used three materials from the General Materials library — to set the properties of three materials: concrete B20, steel C245 steel profiles, timber pine grade AB, for steel screws steel C245:
- Concrete (B20);
- Timber AB
- Structural Steel (C245 profiles);
- Structural Steel (C245 self-tapping screws).

In accordance with SP 16.13330.2017 "SNiP 2-23-81 Steel structures" table B. 5 "Normative and calculated resistance to tension, compression and bending of sheet, wide-band universal and shaped rolled products" for steel according to GOST 27772 C245 with a thickness of rolled products from 2 to 20 mm, the calculated bending resistance of steel at the yield point – $R_y=240$ MPa.

In accordance with SP 63.13330.2012 "Concrete and reinforced concrete structures. Fundamentals. Updated version of SNiP 52-01-2003 (with Changes № 1-3)" point 5. "Design requirements of concrete and reinforced concrete constructions" – the calculations on the durability of concrete and
concrete structures must be made when the conditions under which stress, strain and deformation in structures from various influences with regard to the initial stress condition (pre-stress, temperature and other effects) must not exceed the relevant values set by normative documents. The compressive resistance of concrete is represented by stresses that do not exceed the calculated compressive resistance of concrete $R_b$. Concrete of B20 class (concrete class for compressive strength) is used for steel of timber-concrete beams. According to Table 6.8 of this normative document, the calculated value of concrete resistance $R_b=14.5$ MPa.

Numerical studies were performed for different sheet thicknesses in the upper and lower zones, different steps and the length of self-tapping screws in the body of timber and concrete.

2.1 Research results
Based on the data of numerical experiments, a prototype of a steel-reinforced concrete beam was made.

The experimental study consisted of several stages, each of which had its own methodological features and in one way or another influenced the final result:
1. Production of a prototype.
2. Description of the test facility.
3. Preparing a test sample.
3.1. Bonding and isolation of tension sensors.
3.2. Installation of measuring devices and equipment. Placing the sample in the test position.
4. Research of physical and mechanical properties of steel, timber and concrete.
5. Sample testing.
6. Processing and analysis of test results.

For the production of samples, the most currently used steel grade (C245) was used, the concrete class laid according to the calculation was B20.

The geometric dimensions of the model were also caused by the capabilities of test bases and laboratories.
The anchor connection of the concrete, steel and timber parts of the steel-reinforced concrete beam sample was taken by calculation. The experimental steel-timber concrete beam had an I-beam section: the steel part was made of thin-walled cold-bent galvanized profiles with a thickness of 1 mm for the upper belt, 2 mm for the lower belt with the length of 2000 mm, paired between steel and wood with 4.8×51 mm self-tapping screws with a press shim; the concrete part had dimensions: length – 2000 mm, width – 250 mm, height – 90 mm.

The profiles used were steel profiles from the SRT assortment of the company «Steel faces».

Some of the dimensions of the manufactured profiles are taken from GOST 8282-83 "BENT STEEL PROFILES, C-SHAPED EQUAL-SECTION, ASSORTMENT", the rest are own developments.

The pitch of the self-tapping screws was assumed to be the same: 100, 125, 150, 175 and 200 mm, with an increase in the pitch to the middle of the beam. The screws were arranged in two rows in a staggered order. The joint work of concrete and steel fixed timbering of beams was provided by screwing screws into the walls of profiles released in the direction where the concrete should be. The work of steel and wood is also provided with self-tapping screws.

Concreting of the upper flange took place in one stage. Materials used: cement of the M500 grade, water, river sand, crushed stone of a fraction of 5÷20 mm. Concreting of the upper flange of the I-beam was performed in one stage. The mix was processed at the United Concrete Company plant.

Production of experimental steel-concrete structures was carried out in the following sequence. From both ends of the beams, pieces of plywood were tied together with wire, which served as a form. Care for freshly laid concrete was performed in accordance with the requirements of SP 70.13330.2012. To exclude the impact on the test results of the increase in the strength of concrete, as well as changes in the initial stress-strain state of the prototypes due to shrinkage, the test of steel-concrete structures was started after they were stored for at least 28 days in the laboratory at normal humidity and temperature, and the beams gained strength at the reinforced concrete plant in a special chamber. During this time the strength and deformative properties of concrete have almost stabilized.

The strength and deformative characteristics of the experimental composition of concrete were determined by testing auxiliary samples-cubes manufactured simultaneously with each of the main samples manufactured in the same temperature and humidity conditions.

Tests of auxiliary concrete samples were carried out in accordance with the methodology of GOST 244.52-80 and GOST 10180-78.

Testing of steel-reinforced timber concrete beams for bending was carried out in Kazan, KSUAЕ – Department of reinforced concrete and stone structures.

Steel-concrete beams were tested according to the scheme of a free-supported beam by two concentrated forces in the middle part of the span, applied at a distance of 200 mm from the vertical axis of the beam. The calculated span of the beams is 1,900 mm. the load was transmitted via the hydraulic system of the UMM-200 press to a bent steel-wood-concrete beam using a metal traverse at...
two points: in one through a movable steel roller with a diameter of 40 mm, and in the other through a fixed steel roller of the same diameter.

![Figure 11. Test bench with tested steel-timber-concrete beam.](image1)

![Figure 12. Tested steel-timber-concrete beam.](image2)

The uniform distribution of force across the cross-section width, which is especially important in composite structures, was provided by the installation of rigid metal gaskets installed on the structure of cement–sand solution under the supports of the traverse in the places where they rest on the beams (figure 11).

During the test, longitudinal deformation of concrete, timber and steel of tested steel-timber-concrete beam, deformation of timber, and of the absolute shear of the concrete slab relative to the timber pieces along the length of the contact zone "timber – concrete" and also deflections and crack widths were all measured. Deformations of concrete, timber and steel were recorded by resistance strain gauges with bases of 50 mm and 20 mm, respectively, through electronic equipment AID-4 with a magazine switch. Measurement of deflections in the net bending zone at any loading stage was performed using a caliper. Absolute shear deformations along the contact were measured on the basis of hour type indicators with a division price of 0.01 mm.

The general view and test scheme of steel concrete beams, the layout of tension sensors for concrete, timber and steel, and other measuring devices are shown in figures 11, 12.

After checking the performance of the load and force measuring systems, a trial load of the steel-timber-concrete beam was carried out with the load not exceeding 20-25 % of the permissible destructive load, and was carried out in several stages. The purpose of the trial loading was to study the behavior of the steel-reinforced concrete beam under load and firstly check whether the values of the measured parameters correspond to the expected values. After the necessary exposure under load, the beam was also unloaded to zero in order. Later, the test was carried out by loading steps of 0.1 of the expected destructive load. On the steps during exposure, deformations of concrete, timber and steel, absolute shear deformations, deflections, the nature of development and formation of cracks were recorded. The moment of formation of cracks is determined visually and is indicated by tension sensors. Breaking load was recorded in the readings of dial gages of test press and according to schedules specified load step on screen of the laptop connected to press. Complete physical destruction of samples, characterized by large plastic deformations, was taken as the limit state.

The prototype of a steel-timber-concrete beam was tested with a sequential short-term static load until complete destruction in order to establish the nature of the destruction work and the regularities of the development of deflections, deformations of concrete, timber and steel when they are deformed together as part of a single structure.

The tested steel-reinforced concrete beam was destroyed along the normal cross-section in the zone of pure bending, which resulted in increased plastic deformation in the middle part of the steel-reinforced concrete beam.
The first cracks of the wood material, which was located in the edge of the I-beam, appeared at the load of 4.8 t, usually along the fibers of the tree.

**Figure 13.** Development of normal cracks in concrete and destruction of steel-timber-concrete beam

**Figure 14.** General view, the nature of destruction of steel-timber-concrete beam.

### 3 Results and Discussion

Graphs of layer displacements, flange and wall stresses and deflection of steel-timber-concrete beams.
4 Conclusions

1. On the basis of numerical experiments, the features of the stress-strain state of steel-reinforced timber-concrete beams with different sheet thicknesses of the upper and lower zones with different pitch (step) and length of anchor screws on the effect of short-term static load when taking into account the elastic and elastic-plastic work of materials are studied:
   a) reducing the pitch of screw anchors reduces the deformability of the beam, for the considered cases from 50 to 200 mm by 9.8%;
   b) a smaller pitch (step) and an increase in the number of rows of anchors leads to an increase in the bearing capacity of the composite beam;
   c) when increasing the length of anchors, there was no noticeable increase in the strength and deformability of the beam;
   d) the maximum load-bearing capacity of beams is determined by a concrete compressed shelf; an increase in the thickness of steel sheets leads to a sharp increase in the load-bearing capacity, as well as an increase in the height of the wooden wall.

2. Laboratory testing of the model of steel-reinforced timber-concrete beam showed the corresponding to both the calculation and numerical experiments the carrying capacity of the beam, bearing capacity of joints in the "concrete-timber", "timber-steel" also corresponds to the calculated data. Discrepancies between laboratory data and numerical data:
   - for stresses in concrete 8-12%, in the steel lower flange up to 3-5%, in the wooden wall up to 10-13%;
   - for beam deflections -8%
   - by bearing capacity 10-16%
   - for the displacement of the upper belt relative to the wall 4-6%, and the lower - 5-8%.

3. Analysis of the results of numerical and laboratory studies of steel of steel-reinforced timber-concrete beams shows that it is necessary to study steel-concrete structures, both on models and on large-scale models.

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