Experimental study of SSS of a steel concrete beam taking into account the rigidity of the connecting seam

Alexey V Kozlov¹ and Vladimir A Kozlov²
¹Department of Roads and Bridges Designing, Voronezh State Technical University, 20 Let Oktyabrya st., 84, Voronezh, Russian Federation
²Department of Structural Mechanics, Voronezh State Technical University, 20 Let Oktyabrya st., 84, Voronezh, Russian Federation

E-mail: kozlov.a.v@inbox.ru, vakozlov@vgasu.vrn.ru

Abstract. The article presents the test results of a scale model of a single-span steel-reinforced concrete beam, which is as close as possible to the real structures of bridge spans with the combination of a reinforced concrete slab with steel beams using flexible pin stops. The distribution of the experimental values of shear deformations and normal stresses in the beam flanges is in good agreement with the calculated data, taking into account the shear stiffness of the joint, and differ in a number of values from those calculated by the classical approach.

1. Introduction
Works [1, 2] propose a specified algorithm for calculating single-span and continuous multi-span beams of bridge structures with the possibility of taking into account the flexibility of a shear joint between reinforced concrete and steel structural elements. This increases the accuracy of determining the stress-strain state (SSS) of a structure and refines the calculation of bridge structures.

This paper presents the results of field tests of a scale model of a single-span steel-reinforced concrete beam, close to the real structures of bridge spans made in accordance with the requirements of SP 35.13330.2011 [3] with the combination of a reinforced concrete slab with steel beams using flexible pin stops. The purpose of the experimental research is to study the effect of taking into account the linear shear stiffness of a joint with flexible pin stops on the stress-strain state of a steel-reinforced concrete beam. When carrying out non-destructive bending tests on a sample of a scale model of a beam, we determined its bearing capacity and shear deformation and analyzed the test results. We compared the obtained experimental values of shear strains and normal stresses in the flanges with the calculated values obtained using the proposed refined approach.

2. Description of the full-scale model, measuring and control equipment
To carry out the full-scale tests with the application of an external load, we used the INSTRON 600 KN hydraulic system as in previous experimental works [4, 5], to measure stresses and strains - a measuring module with linear displacement sensors, deflection meters and resistance strain gages. Visualization of the test scheme for a scale model of a steel-reinforced concrete beam is shown in figure 1, figure 2-4 show photographs of the beam at the stand, measuring and control equipment.
Figure 1. Schematic diagram of the location of the deflection meter and needle indicators.

Figure 2. Model of a single-span steel-reinforced concrete beam on a test bench
INSTRON 600 kN.
Figure 3. Indicator of displacement of the slab along the beam in the support section.

Figure 4. Strain gages in the middle of the span.
According to the accepted test methodology, a single-span hinged-supported beam with a concentrated force applied in the middle of the span is taken as a test scheme. Before the start of the tests, we checked the operability of the measuring systems and the press by means of a trial loading of the sample at the level of 20-25% of the theoretical bearing capacity of the beam. After the end of the test, the load was reduced to 0. At the next stage, the load was increased gradually, in steps of 0.1 of the theoretical bearing capacity of the beam. We recorded longitudinal shear deformations along the contact between the reinforced concrete slab and the steel section in the design sections continuously during loading or at each stage. At the same time, we measured the normal stresses in the upper and lower flanges of the beam and the deflection of the beam in the middle of the span.

In the scale model of the steel-reinforced concrete beam, the stops are installed in rows of 2 pieces with a step of 200 mm along the axis of the beam, therefore, there are 10 stops per 1 rm. In this case, the theoretical value of the linear shear stiffness of the joint of the scale model was 1673 MPa. The use of a joint structure with a high linear shear stiffness in this model is due to the fact that in short beams working in bending, shear stresses in the joint are closer to their bearing capacity than normal stresses in the rest of the composite beam. Therefore, to obtain the fixed results (with an approach to achieving the theoretical bearing capacity in a linear setting and deflections at the level of several tens of millimeters), it is necessary to arrange such a joint so that its bearing capacity is not exceeded and, accordingly, plastic work does not arise in it, which excludes the possibility of comparison the obtained results with analytical ones.

3. Finite element model with a compliant and rigid joint between the elements of a composite beam

Let us draw a diagram of a steel-reinforced concrete beam, made by the finite element method in the LIRA-SAPR software package, in which the slab is attached to the steel part with discrete (along the span) bonds. Figure 5: a) a model with compliant bonds (in black; very low rigidity, close to the conditional work of the parts separately); b) a model with rigid bonds (in red; in terms of rigidity characteristics, they correspond to the concrete of the slab).

![Figure 5. Conditional pair of FE-models of a composite bar with bonds that take tear and shear.](image-url)
For a clear demonstration of the influence of the bond compliance on the stress-strain state of a composite bar, we took two FE-models of a beam with a span of 10 m, loaded with a concentrated force of 343.4 kN in the middle of the span. The geometrical and mechanical (modulus of elasticity $E$, Poisson's ratio $\nu$) characteristics of the "slab" and "steel beam" in both models are the same, and the characteristics of the "stops" are fundamentally different: in diagram a) for flexible stops of black color, $E = 2.75 \text{ MPa}$, $\nu = 0.4$, in diagram b) for rigid red stops $E = 29400 \text{ MPa}$, $\nu = 0.2$.

Figure 6 shows the normal stresses in the end elements averaged over the height of the section of each element ("slab"; "steel beam" and "bond") at the bottom right:
- in the “slab”, the compressive stress is 0.444 $\text{MPa}$ in the beam with compliant bonds, while in the beam with rigid bonds – 1.59 $\text{MPa}$;
- in the “steel beam” the tensile stress in the beam with compliant bonds is 1.09 $\text{MPa}$, in the beam with rigid bonds – 4.36 $\text{MPa}$;
- in the "bonds" the shear force also changes very significantly: for the beam with compliant bonds, the longitudinal stress in the "bond" is 0.15 $\text{MPa}$, while for the beam with rigid bonds it is 1.25 $\text{MPa}$.

Thus, figure 5 and 6 clearly show the redistribution of the internal pair of forces with compliant and rigid bonds: with an increase in the shear stiffness of the joint, both the forces in it and the axial forces in the rods increase (since these axial forces are directly proportional to the difference in shear forces in the next bonds).

![Figure 6. SSS of schemes a) and b): a composite beam with flexible bonds (above) has a noticeably greater deflection; in this case, from the middle of the span to the ends, the slab shear along the beam increases.](image-url)
Figure 7 shows a diagram of the shear at the end of the beam (figure 6). Here $\delta_x = \delta_s + \delta_b$ is the absolute value of the mutual displacement of the reinforced concrete slab ($\delta_b$) along the steel beam ($\delta_s$);

$\Theta$ - the angle of rotation of both steel and reinforced concrete sections (the same, since the curvature of the axes of the slab and the beam is taken to be equal, that is, the calculation is carried out without the possibility of tearing the slab from the beam).

The presented scheme is based on the following provisions:

1) in the absence of any shear connection between the slab and the beam (including the friction of concrete against steel), the bending radii of the reinforced concrete slab and the steel beam have the same value but the bending centers are at a distance $Z_{b,s}$ from each other, in the same way, as well as the centers of gravity of the slab and beam sections;

2) in the support section, the centers of gravity of the slab and beam during bending from any load and in the absence of a shear connection remain in place since the bending lines of the central axes, in this case, are equidistant to each other (in the absence of shear connection the bending reinforced concrete slab and the steel beam are separate bending elements, in which, with pure bending in a linear setting, the centers of gravity remain in their places, and the rotation of the sections is carried out around them). The angles of rotation $\theta$ of the steel section and the reinforced concrete slab are thus equal due to the equidistance of the bending lines of the central axes;

3) in the zone of contact between the slab and the beam, the lower corner of the slab, due to the rotation of the section, is displaced forward (outward beyond the end of the beam) by the value $\delta_s$, and the upper angle of the steel beam - backward (inside the span) by the value $\delta_b$.

Figure 7. Shear diagram.

4. Experimental data, their comparison with numerical results

Table 1 shows the test results of a scale model of a single-span steel-reinforced concrete beam, table 2 shows the values obtained numerically using the finite-element model in the LIRA-SAPR software package, with similar loads. Table 1 and 2 show the stresses $\sigma_n$ - at the level of the lower part of the upper flange since the upper part is covered with a reinforced concrete slab and measurements are not possible there.

From a comparative analysis of the data in the tables, it follows that for the deflection $\Delta Z$ and normal stresses $\sigma_n, \sigma_u$ there is a satisfactory coincidence between the experimental and numerical values at all load steps, for shear $\delta_b$ this is observed in sections $x = 0$ and $x = 1$ m at a sufficiently large load value approaching the limit.

Figure 8 shows the graphical dependences of the magnitude of normal stresses $\sigma_n$ in the upper flange (ordinate axis, MPa) on the load (abscissa axis, kN) in the middle of the beam span. The upper curve line (light green) is the experimental data, the middle line (red) is the numerical calculation taking into account the slab slippage along the beam, the lower (blue) is the numerical calculation without the shear.

Similar dependencies are shown in figure 9 for normal stresses $\sigma_u$ in the lower flange of the beam.
Table 1. Test results of a full-scale model of a beam.

| Step | Load, kN | Slab shear along the beam $\delta_x$ (mm) in the section (m) | Deflection $\Delta Z$, mm | Normal stresses, MPa |
|------|---------|----------------------------------------------------------|--------------------------|---------------------|
|      |         | $x = 0$ | $x = 1$ | $x = 2$ |             | $\sigma_v$ | $\sigma_n$ |
| 1    | 35.3    | 0.001   | 0.010   | 0.024   | 2.206 | 11.54 | 29.58 |
| 2    | 67.2    | 0.0015  | 0.033   | 0.053   | 4.305 | 22.25 | 54.74 |
| 3    | 101.2   | 0.008   | 0.057   | 0.081   | 6.482 | 31.93 | 82.11 |
| 4    | 135.3   | 0.029   | 0.083   | 0.107   | 8.623 | 40.79 | 108.8 |
| 5    | 170.9   | 0.050   | 0.114   | 0.118   | 10.85 | 49.03 | 138.6 |
| 6    | 206.4   | 0.069   | 0.150   | 0.129   | 13.03 | 56.24 | 167.3 |
| 7    | 242.6   | 0.090   | 0.189   | 0.153   | 15.30 | 63.24 | 198.7 |
| 8    | 278.1   | 0.111   | 0.220   | 0.171   | 17.49 | 69.63 | 230.7 |
| 9    | 313.2   | 0.179   | 0.246   | 0.198   | 19.71 | 75.81 | 265.0 |
| 10   | 348.2   | 0.224   | 0.272   | 0.225   | 22.01 | 82.19 | 302.4 |

Table 2. Calculated values for the finite element model of the beam.

| Step | Load, kN | Slab shear along the beam $\delta_x$ (mm) in the section (m) | Deflection $\Delta Z$, mm | Normal stresses, MPa |
|------|---------|----------------------------------------------------------|--------------------------|---------------------|
|      |         | $x = 0$ | $x = 1$ | $x = 2$ |             | $\sigma_v$ | $\sigma_n$ |
| 1    | 35.3    | 0.033   | 0.034   | 0.027   | 2.568 | 9.571 | 29.68 |
| 2    | 67.2    | 0.055   | 0.059   | 0.047   | 4.422 | 18.21 | 56.51 |
| 3    | 101.2   | 0.078   | 0.085   | 0.069   | 6.398 | 27.43 | 85.09 |
| 4    | 135.3   | 0.102   | 0.112   | 0.092   | 8.380 | 36.67 | 113.8 |
| 5    | 170.9   | 0.125   | 0.139   | 0.115   | 10.45 | 46.32 | 143.7 |
| 6    | 206.4   | 0.152   | 0.167   | 0.138   | 12.51 | 55.94 | 173.5 |
| 7    | 242.6   | 0.177   | 0.195   | 0.162   | 14.61 | 65.75 | 204.0 |
| 8    | 278.1   | 0.201   | 0.223   | 0.185   | 16.68 | 75.37 | 233.8 |
| 9    | 313.2   | 0.226   | 0.250   | 0.208   | 18.72 | 84.88 | 263.4 |
| 10   | 348.2   | 0.250   | 0.277   | 0.230   | 20.75 | 94.37 | 292.8 |

Figure 8. Dependence of normal stresses $\sigma_v$ in the upper flange of the beam on the load.
Figure 9. Dependence of normal stresses $\sigma_n$ in the lower flange of the beam on the load.

From the analysis of the presented graphical dependencies, it follows that, taking into account the final stiffness of the joint between the steel-reinforced concrete slab and the beam, the compressive stresses in the upper flange of the beam increase in absolute value and very significantly, in the lower flange the tensile stress also increases but insignificantly.

5. A brief overview of experimental studies by foreign authors

It should be noted that experimental research is being carried out in this area by foreign authors. In particular, Korean authors [6–9], using sample tests, study the operation of the structure consisting of a concrete slab and a load-bearing steel beam in the form of perfobond strip (PBL) connectors, representing a perforated steel plate with steel reinforcement passing through the holes, and built-in in the concrete to transfer shear action between the concrete and steel components. While many studies on the behavior of PBL connectors can be found in the literature, the PBL load transfer mechanism still needs further refinement, as there are significant discrepancies among the existing equations for predicting connector shear. It is noted that samples of perforated ribbed shear connectors with transverse reinforcement in their holes show an increase in shear capacity under both static and cyclic loading. In [7, 8], the work of a composite structure made of profiled steel sheathing, perfobond ribs, reinforcement and concrete is considered. To simulate a prestressed reinforced concrete I-beam bridge, two types of formwork profiles with slab-beam connections were developed. The test results showed that perfobond ribs can be effectively used in shear joints between a reinforced concrete slab and a steel beam. Work [9] presents the results of tear tests of perforated ribbed connectors with rods embedded in a concrete slab under static loads. It was found that the efficiency of the perforated connectors is primarily influenced by transverse reinforcements and rods, and the load-bearing slab with the formwork perforated ribbed plate increases the rigidity and strength of the structure as a whole.

Works [10, 11] show the results of experimental shear tests of the combination of a partially filled steel lattice structure of the joint of a composite slab with reinforced concrete at the top and an inverted T-shaped steel beam at the bottom. According to the test results in the joint, the effect of shear resistance from friction between the steel beam and concrete was evaluated, with a different number of stops and diameters of reinforcing bars. An analytical dependence of the shear strength is obtained, the calculation results for which coincide with the experimental data within up to 10%.
In work [12], it is noted that in steel-concrete composite bridges under the action of shear forces, special attention should be paid to the design of the details of the connection of the concrete and steel. The work of a group shear bar connection for prefabricated span structures is considered. Based on the test results, design recommendations were obtained for a shear joint in the bridge span.

In [13], the influence of the orientation position of the perfobond rib shear of the connecting structure on the strength and shear during a series of tests with ultimate loads was investigated. Three types of the orientation of the perfobond rib in concrete were considered: normal, reverse and lateral. The test results showed that the shear capacity of the perfobond rib was highest in normal orientation, medium in reverse, and lowest in lateral orientation. The reason for the influence of perfobond rib orientation on shear strength was also analyzed.

In [14], on the basis of the analysis of the operation of the interface structure of a steel-reinforced concrete suspension bridge, the behavior of connecting rods under the action of a shear load and the effect of contact friction in the interface unit were investigated. The results obtained show that the presence of friction reduces the stresses in the connecting rods but does not affect the performance of the box beam and the rods under load.

The goal of work [15] by Polish scientists from the Technical University of Kosice is to improve the design of Wolfrhardt Andra perforated steel connectors, which, in comparison with other structures, have a low height and lower material consumption for steel. Five types of perforated steel strips developed in the laboratory of the Faculty of Civil Engineering were tested, their work was simulated on a numerical model performed in the ABAQUS finite element software package.

[16] presents an experimental study of PBL connectors, discusses in detail the behavior of the connectors, including fracture modes, ductility, and components of finite shear stiffness. In addition, an analytical model and a corresponding equation are proposed for predicting the ultimate resistance of PBL connectors during shear failure of an abutment, and the analytical results are checked for compliance with experimental data from the corresponding literature sources.

6. Conclusion
When carrying out full-scale tests of a scale model of the steel-reinforced concrete structure of the span bridge beam, the shear deformations of the slab along the beam near the place of application of the external load almost completely (up to ten microns) coincide with the theoretical value when calculated by the finite-element method, and slightly lower than the theoretical value by the analytical method. At the end section of the beam, the experimental shear values are 30-40% less than the theoretical ones, which is explained by the presence of friction between the slab and the beam, which accumulates from the center to the points of the supports, which is very difficult to reliably take into account by analytical calculation. It is especially important to confirm a significant increase in the normal stresses in the upper flange when the shear is taken into account: the experimental value is almost 2 times higher than that calculated by the standard SP35.13330.2011 method. Therefore, when designing steel-reinforced concrete bridge spans, it is necessary to take into account the shear stiffness between the steel beam and the reinforced concrete slab of the roadway.

References
[1] Yeremin V G, Kozlov A V 2019 Analytical Dependence of the Sift from the Shear Stiffness of the Seam Between the Concrete Slab and Steel Beam in Bridge Spans Russian Journal of Building Construction and Architecture (Voronezh: Publishing house of the Voronezh state technical University) 4 (44) pp 70–81
[2] Yeremin V G, Kozlov A V 2020 Analytical Expressions, Taking into Account the Shift Between the Concrete and Steel Structural Elements of Bridges in Continuous Multi-span Beams Russian Journal of Building Construction and Architecture (Voronezh: Publishing house of the Voronezh state technical University) 1 (45) pp 98–110
[3] SP 159.1325800.2014 Steel-reinforced Concrete Span Structures of Road Bridges Calculation
rules

[4] Kozlov A V, Kozlov V A, Khorokhordin A M, Churakov P P 2020 Experimental Studies of the Shear Stiffness of the Joint of a Steel-reinforced Concrete Structure with Flexible Pin Stops Scientific and technical journal "Structural Mechanics and Structures" (Voronezh: Publishing house of the Voronezh state technical University) 1 (24) pp 54–62

[5] Kozlov V A, Kozlov A V 2020 Mechanical Interaction of a Reinforced Concrete Slab and a Steel Beam in Bridge Spans Applied Mathematics, Computational Science and Mechanics: Current Problems IOP Conf. Series: Journal of Physics: Conf. Series 1479 012140 10 p

[6] Ahn J H, Kim S H, Jeong Y J 2008 Shear Behaviour of Perfobond Rib Shear Connector Under Static and Cyclic Loadings Magazine of Concrete Research 5 (60) pp 347–357

[7] Kim H Y, Jeong Y J, Kim J H, Park S K 2005 Steel-concrete Composite Deck for PSC Girder Bridges KSCE Journal of Civil Engineering 9 pp 385–390

[8] Kim H Y, Jeong Y J 2006 Experimental Investigation on Behaviour of Steel-concrete Composite Bridge Decks with Perfobond Ribs Journal of Constructional Steel Research 5 (62) pp 463–471

[9] Kim H Y, Jeong Y J 2010 Ultimate Strength of a Steel–concrete Composite Bridge Deck Slab with Profiled Sheeting Engineering Structures 2 (32) pp 534–546

[10] Choi J H, Kim S H, Park S R, Lee S Y 2007 Evaluation of Shear Strength of Partially Filled Composite Deck with Inverted T-Shaped Steel Journal of the Korean society of civil engineers 6A (27) pp 821–828

[11] Kim S H, Choi J H 2010 Experimental Study on Shear Connection in Unfilled Composite Steel Grid Bridge Deck Journal of Constructional Steel Research 11 (66) pp 1339–1344

[12] Shim C S, Lee P G, Kim D W 2011 Effects of Group Arrangement on the Ultimate Strength of Stud Shear Connection International Conference on Composite Construction in Steel and Concrete 2008 Ascelibrary.org.

[13] Su Q, Zhao C, Liu Y, Zeng M 2009 Effect of Orientation on the Shear Strength of Perfobond Shear Connectors IABSE Symposium Bangkok 2009 96 9 p

[14] You J T 2012 Analysis on Steel-concrete Interface of Hybrid Self-anchored Suspension Bridge Applied Mechanics and Materials 193-194 pp 1329–1333

[15] Kvočák V, Kožlejová V, Dubec ký D, Kanishchev R, Vaňová P 2019 Experimental and Software Analysis of Composite Action in Steel-Concrete Composite Bridges with Continuous Shear Connectors - ce/papers Wiley Online Library

[16] He S, Fang Z, Fang Y, Liu M, Liu L, Mosallam A S 2016 Experimental Study on Perfobond Strip Connector in Steel-concrete Joints of Hybrid Bridges Journal of structural steel research (118) pp 169–179