ADHESION OF COMPONENTS OF COMPOSITE STEEL AND CONCRETE CROSS SECTION IN ANALYSIS OF BEAMS WITH CONCRETE ENCASED SECTIONS

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Abstract: A brief overview of the issues of aggregate work of components of the composite steel and concrete section is made. It is presented various options for the layout of the cross-section of beams used in the practice of design. A review of the design of the regulatory documents regarding the issues of adhesion of cross-section elements is performed. The characteristic of experimental models is given. The features of destruction of models are shown. The reasons of the destruction are analyzed. The case of the loss of the bearing capacity of the element due to relaxation (loss) of adhesion at the steel – concrete interaction boundary is considered. Various shear surfaces of the concrete section are given. Calculations of the bearing capacity of the composite steel – concrete beams for each computational surface were performed, the obtained results were evaluated. Conclusions have been made on the question of ensuring aggregate work in case of composite steel – concrete beams with a fully encased steel core.

Keywords: concrete, steel, reinforced concrete, composite steel and concrete structure, shear, adhesion, stud

The late XX – early XXI centuries were marked by the extensive introduction of steel-concrete structures into building practice, the main types of which are columns and beams with stiff reinforcement. The significant development of high-rise construction required an increase in the bearing capacity of structural elements and at the same time a reduction in their dimensions. The columns made of the composite steel-concrete ensure these requirements [1]. The development of transport networks and an increase in the carrying capacity of transport lead to the
widespread use of composite steel – concrete structure in bridge construction. Majority of modern transport overpasses and bridge junctions are implemented using composite steel-concrete structure (beams), where a common design consideration is the combination of steel beams with a slab of concrete along top flange (Figure 1) [2]. Composite steel – concrete beams with a fully encased steel core also find appliance [3], as it is shown in Figure 2.

![Figure 1](image1.png)  
**Figure 1.** Example of composite steel-concrete beam – steel I-beam with reinforced concrete slab along top flange.  

![Figure 2](image2.png)  
**Figure 2.** Example of composite steel – concrete beam with a fully encased steel core.

The issues of adhesion with a fully encased steel section to concrete were also investigated by a number of authors [8]. Let us note that regulatory documents [4, 5] regulate placing of anchors for beams with rigid reinforcement (with a fully encased steel core), but the focus is on placing the stud only on the wall of a steel section (Figure 3).

![Figure 3](image3.png)  
**Figure 3.** Installation of anchor studs on the wall of the steel profile according to [4].

The special attention is not paid to placing the studs on the shells of the I-beam (in contrast to the case of a steel non-concrete beam with a reinforced concrete slab along the upper shelf). This can be explained by the layout of the composite steel - concrete section, when rigid reinforcement is distributed fairly evenly over the entire cross section and the distance from the top shell of the I-section (Figure 3) to the edge of the beam is small. At the same time, in Eurocode 4 [4], in section 6.7.4.2, there is a note on this issue - it is necessary to check the sufficiency of web reinforcement to resist shear force for zones of the concrete part of the cross section that do not have direct contact with the steel core by anchors (Figure 4 - considered a shear along the lines A-A).

![Figure 4](image4.png)  
**Figure 4.** Checking composite steel – concrete element under shear force along line A-A according to [4].
However, such a check is provided only for the composite steel-concrete columns in case when the load is attached either only to the steel or to the concrete part of the section. The need for such checks is not regulated for beams with rigid reinforcement and fully encased steel core, although in some cases it must be performed. Alternatively, the cross-sectional layout of beams with rigid reinforcement, when all or most of the steel core are located in the tension side, that implies a significant distance from the top shell of steel section to the edge of the cross-section (Figure 5).

In this case, in addition to strength analysis of the normal section of the element and the corresponding fracture features (chipping of compressed zone of the concrete or breakage of the tensile reinforcement), attention should be paid to the possibility of the component damage as a result of deterioration (loss) of adhesion at the steel-concrete interface and shear of the concrete part of the beam. A choice of line of shear is marked in red in Figure 6.

A series of experiments were performed to study the behavior of the composite steel-concrete beams using high-strength concrete. The described non-standard type of destruction is recorded in the process of testing, although a detailed study of damage of a similar type was not a purpose of these experiments. During the experimental studies, 9 models of composite steel-concrete beams of rectangular cross-section 200x150 mm and 1.5 m length were tested. The steel core is made in the form of an I-beam. The core material is C255 steel according to National Standard of Russian Federation GOST 27772-2015. The concrete of the models is high-strength of B75 ... B90 compressive strength class. Upper and transverse reinforcement have diameter 10 mm class A400 of steel 35GS. The percent of reinforcement is 7.8 ... 9.2%. The beams were tested for pure bending by attaching concentrated loads in 1/3 and 2/3 of the span of the models. The general view of the models is shown in Figure 7. A detailed description of the experiment is given in [9].
The destruction of the models was similar and characterized by the appearance of a large number of vertical and inclined cracks, as well as horizontal cracks on the upper and lower edges of the beam. This led to partial shear of the concrete of the protection cover and uncovering of the reinforcement cage and steel core in the extreme thirds of the beam span - between the point of support and the point of attaching of the load at the last stages of loading (Figure 8). At more detailed observing of the failure models, it is supposed, that a possible reason of the destruction is a violation of the adhesion between the upper shell of the steel I-beam and concrete.

In contrary to widespread destruction variant, the shear (Figure 9) occurred on the boundary of steel and concrete parts of section as it is shown in Figure 6. The destruction of a similar type is not considered in the literature before.

Theoretical calculations were performed to evaluate the obtained experimental results. The sequence of checking the shear strength of concrete along the indicated surfaces (Figure 6, 9) is given below. In the presented calculations, the characteristics of materials are assumed to be equal to it actual values.

1. The height of the compressed zone of the cross section was determined and compared with the experimental value. The sequence of calculations is described in detail in regulatory documents [5, 7]. The height of the compressed zone is \( x = 7.0 \) cm.

\[
S_1 = (\sigma_{b1} A_b + \sigma_{s1} A_s) - (\sigma_{b2} A_b + \sigma_{s2} A_s),
\]

Where \( \sigma_{b1}, \sigma_{b2} \) are compressive stresses in concrete in the right and left sections of the calculated part of the beam.

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Figure 8. Characteristic destruction of models of the composite steel – concrete beams (beam fragment – extreme third part of the span).

Figure 9. Possible location of the shear surface in the concrete during the destruction of the element caused by deterioration (loss) of adhesion at the steel-concrete interface.
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\[ \sigma_{s1}, \sigma_{s2} \] are stresses in the longitudinal reinforcement in the same sections, respectively. In the above formulas, the distance from the point of load attaching to the beam support and, respectively, the stresses \( \sigma_{b2} \) and \( \sigma_{s2} \) at the end of the beam is assumed to be equal to zero. Value of the shear force is:

\[
S = (R_b bx + R_{sc} A_{sc}') = 943.9 \cdot 15.0 \cdot 7.0 + 4440.0 \cdot 1.57 = 106 \, 080 \, \text{kg,}
\]  

where \( R_b = 943.9 \frac{\text{kg}}{\text{cm}^2} \), \( R_{sc} = 4440.0 \frac{\text{kg}}{\text{cm}^2} \)

are compressive strength of concrete and reinforcement rod respectively, 
\( b = 15 \, \text{cm} \) is cross section width, 
\( x = 7.0 \, \text{cm} \) is height of the compressed zone of the section, 
\( A_{sc} = 1.57 \, \text{cm}^2 \) is area of compressed reinforcement rod.

3. The shear strength \( R_t \) of an element for various computational surfaces is calculated:

\[
R_t = A_t R_{bt},
\]  

Where \( A_t \) is area of the calculated shear surface, \( R_{bt} \) is tension strength of concrete.

a) for the case shown in Figure 6:

\[
R_t = (l_1 \cdot l_2 \cdot 2) \cdot R_{bt} = (51.5 \cdot 2.9 \cdot 2) \cdot 68.3 = 20 \, 401 \, \text{kg},
\]  

where \( R_{bt} = 68.3 \frac{\text{kg}}{\text{cm}^2} \).

\( l_1 = 51.5 \, \text{cm} \) is the distance from the point of load attaching to the edge of the beam (length of the shear surface), 
\( l_2 = 2.9 \, \text{cm} \) is the distance from the edge of the flange of the I-beam to the edge of the cross section (width of the shear surface).

b) for the case shown in Figure 9.

Here we note that the contour of the calculated surface to determine the shear bearing capacity for concrete is accepted by the results of experimental studies. The specified computational contour accurately reflects the features of the destruction recorded during the experiments performed in this paper.

\[
R_t = (l_1 \cdot l_2 \cdot 2) \cdot R_{bt} = (51.5 \cdot 14.75 \cdot 2) \cdot 68.3 = 103 \, 765 \, \text{kg,}
\]  

where \( R_{bt} = 68.3 \frac{\text{kg}}{\text{cm}^2} \). 

\( l_1 = 51.5 \, \text{cm} \) is the distance from the point of application of the load to the edge of the beam (length of the shear surface). 
\( l_2 = 14.75 \, \text{cm} \) is the average width of the shear surface on the test results.

The obtained value of the shear strength of the element almost completely coincided with the fracture load. The difference is 2.2%.

4. A comparison of the theoretical and experimental bearing capacity of the beam, determined by the shear of concrete, is carried out. The values are quite close. We also note that the value of the carrying capacity for shear is quite close to the bearing capacity of the element obtained in the calculation for the normal section. At the same time, the limiting state in the cross section is reached at the moment of concrete shearing along the specified calculated surfaces. The concrete stresses in the compressed zone reach the limit values, and in the tensile rigid reinforcement, the stresses correspond to the yield strength.

**CONCLUSIONS**

A review on the subject of combining of elements of steel-concrete structures is carried out. The features of steel-concrete beam models’ destruction are analyzed for the bending tests. The destruction of the models is similar and characterized by the appearance of a large number of vertical and inclined cracks, as well as horizontal cracks. This leads to partial shear of the concrete of the protection cover and uncovering of the reinforcement cage and steel core in the extreme third of the beam span - between the point of support and the point of load attaching at the last stages of loading. The shear oc-
curs by the surface shown in red in Figure 9, in contrast to the most common type of destruction - by the interface of steel and concrete (Figure 6). The damage of a similar type in the literature has not been considered previously. This type of destruction can be considered as a new type of limit state concerning to the first group of limit states (by strength).

The possible variants of the computational destruction surfaces of the composite steel-concrete beams, caused by relaxation (loss) of adhesion at the steel-concrete interface, are considered.

The surface shown in Figure 6 and, respectively, the strength value determined by formula (4) are the most dangerous cases of destruction for elements with not enough transverse reinforcement or without it. In the case of powerful transverse reinforcement, the destruction surface takes a more complex shape, that is close to the shape shown in Figure 9. In this case, the fracture load should be determined by the relationship (5).

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