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Research paper

Adhesive-Bonded Joint Influence on Deflection of Composite Steel and Concrete Beams with Strengthening by External Steel Reinforcement

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Abstract

This paper presents experimental and theoretical research for calculating of composite steel and concrete beams deflection strengthened bonded steel plates. The use of epoxy-bonded plates to strengthen existing or damaged reinforced or composite steel beams concrete beams has been extensively researched. It has been proven to be a useful and reliable method of increasing the ultimate flexural capacity of both damaged and undamaged members. The actual deflection behavior in beams is probabilistic in nature and requires statistical methods for a rational analysis.

Keywords: *composite steel and concrete beam, adhesive-bonded joint, bearing capacity, deflection, external steel reinforcement.*

1. Introduction

Any renovation or reconstruction of building, as a rule, is accompanied by changing of loadings on building structures, and the amendment of their primary design schemes.

All these factors lead to the necessity of determination of their standard performance indicators, decision-making about their further destination like to strength, reconstruct or replace them.

The necessity of strengthening or renewal of building structures appears not only during the reconstruction or technical upgrading but also as a result of premature corrosion or mechanical deterioration.

Loss of serviceableness can appear in the result of the complications or unforeseeably by the project changes in the production technology, different damages, defects, etc. This question provokes the high interest to the problem of strengthening and reconstruction of the existing building structures.

Modern development of the industrial manufacturing, enhancement of civil facilities are tightly connected to the reconstruction, expansion, technical upgrading, and improvement of labor and living conditions at active enterprises in dwellings, administrative, and civil buildings.

Each building reconstruction, as a rule, is accompanied by changing of loadings on building structures, and the amendment of their primary design schemes.

The number of structures in the world (buildings and bridges) continues to increase, as does their average age. Already, there is a need for reinforcement and reconstruction. Complete replacement is too costly, but upgrading can fix the situation.

Industrial buildings may be adapted for new uses, increasing floor or slab loading. Externally bonded plates will increase capacity with negligible increase in construction depth. Structural alterations may require removal of columns or holes to be cut through slabs for purposes such as new lifts or services.

Loads on bridges are increasing, due to increases in the permitted vehicle weights as well as the volume of traffic. At the same time material deterioration is becoming more evident, particularly that due to reinforcement corrosion induced by contamination with deicing salts. This has already revealed the need for extensive strengthening.

The reasons for strengthening an existing structure are various and may be broadly divided into three categories:

- design or constructional shortcomings, or material deterioration, producing serviceability problems by excessive deflections, rotations or elements cracking.
- structure which has been performing in a satisfactory manner for a particular use, is required for a different purpose;
- structural damage caused by effects such as settlement, earthquakes, explosions, vehicle impacts, etc.

The development of adhesives based on synthetic epoxy resins has created new possibilities in the structural strengthening field [5]. An attractive new alternative of structural repair is one which consists of bonding external reinforcement to the critical members by means of the epoxy adhesive. This technique requires a minimum increase in the member size, allows a larger contact area between the joined materials and solves the problem of high local stresses encountered in the traditional methods using bolting, riveting or welding. The operation is quick and easy to execute, economical and keeps the disruption on site to a minimum

Predominantly during the reconstruction process, the strengthening of an element is performed via building-up of cross-section of a structural element. Qualitative adhesion of a structure under strengthening and strengthening material (adhesive) as well as providing of their efficient interaction is an important problem [8-9, 11].

The Quiton Bridges on the M5 motorway was the first (1975) in the UK which has been strengthened by bonded external reinforcement.

Bending tests were carried out on beams and the plate width-to-thickness (b/t) ratio was studied whilst maintaining the plate cross-

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sectional area constant. The external plate continued through and beyond the beam supports, with which they were not in contact, for a distance such that the bonded area was the same for each plate width. The external plate was not bonded to the concrete beam except in the anchorage areas beyond the supports.
The results showed that thin plating was more effective than thick narrow plating. The effective anchorage length l_a which allowed the plate to reach yield before shear failure adjacent to the bonded areas was found to be inversely proportional to the b/t ratio.
Therefore, as b/t increased (wide, thin plates), the anchorage length decreased.
Composite materials are widely used for various strengthening, upgrading or retrofitting applications of existing civil concrete or steel structures. A frequent flexural strengthening technique, consists of externally bonding a laminated composite plates to the tension face of a concrete or steel beam, by means of an adhesive layer. On the other hand, when shear strengthening is required, elements are bonded to the two sides of the beam. A number of advantages in the structural performance may results when plates are bonded to the external surface of structural members, despite the small changes in weight and dimension of the structural system.
The above mentioned information argues that the given problem is quite actual and of both practical and theoretical importance [1-4,6-7, 10, 12-14].

2. Methodology for Calculating of Composite Steel Beams Deflection and Experimental Set-Up

The deflection of composite steel beams, strengthened by external steel plates is calculated according to the general rules of structural mechanics depending on the bending and axial deformable characteristics of elements in cross-sections along the length (curvature, angle of deflection) and the bounded plastic deformations criteria.
The value of composite beam deflection, strengthened by external steel plate is determined by following equation:

- on the stage of designing
-

$$f = f_M k_f^{pl} - f_{CP} k_f^{pl} \tag{1}$$

on the stage of reinforcement

$$f = f_O k_f^{pl} + f_M k_f^{pl} - f_{CP} k_f^{pl} \tag{2}$$

where: f_M – deflection value of the beam from the action of external load, f_O – value of initial (existing) deflection of the beam, f_{CP} – of deflection of the beam from steel plate action of P_O, k_f^{pl} – coefficient which intends dependence of beam deflection under development of strains at the bottom fiber of the beam cross-section, which exceed the criteria of bounded plastic deformations $\varepsilon_{max} \geq 0{,}001$ (elastic and plastic state of beam cross-section) and in case when the development of strains at the bottom fiber of the beam cross-section do not exceed the criteria of bounded plastic deformations $\varepsilon_{max} < 0{,}001$ (plastic state of design cross-section of the beam).
For freely supported beams with constant cross-section along the whole length of the element, values of deflection f_M and f_O are determined, by the following equation, assuming that the curvature is changed proportionally to the value of bending moment:

$$f_M = S \cdot l^2 \left(\frac{1}{r} \right) \tag{3}$$

where: S – the coefficient, which is determined by the rules of structural mechanics, depending on the design scheme of element and type of external load, $1/r$ – curvature in cross-section with the largest bending moment, which is used for deflection determination, l – design span of the beam.
For determination of deflection of freely supported beam, value of coefficient S, under the action of two symmetrically concentrated forces on the distance a, is defined by following equation:

$$S = \frac{1}{8} - \frac{a^2}{6l^2} \tag{4}$$

The curvature $1/r$ of composite steel beams under the action of external load, except steel plate stress is determined by the following equation:

$$\frac{1}{r} = \frac{M}{0.85 \cdot I_{red} E_c} \tag{5}$$

where: M – design bending moment M or initial moment M_0, which acts at the design cross-section of the beam, 0.85 – coefficient, which is taken into account, the development of non-elastic deformations of concrete under the action of short-term load and 0.04 is assumed, under the action of constant and long-term loads, E_c – elastic modulus of concrete, I_{red} – moment of inertia of the beam design cross-section, which is adduced to concrete cross-section and where the tensile zone is excluded.
I_{red} is defined by following equation:

$$I_{red} = b_C Y_B^3 / 3 + \alpha_{a1} \left[I_a + A_a (Y_H - h_a / 2 - C_z)^2 \right] + \alpha_{a2} A_{sp} C_p^2 \tag{6}$$

where: b_c – design width of concrete cross-section; Y_B, Y_H – design cross-section heights of beam corresponding to upper and lower soffits of element to its horizontal neutral axis ($h = Y_B - Y_H$); I_a, A_a, h_a – moment of inertia of beam cross-section, area and height of adduced steel h-beam element; A_{sp} – summarized cross-section area of steel plates; C_z – protection layer of concrete on the lower soffit of beam cross-section; C_p – height from geometrical axis of steel plate cross-section to horizontal neutral axis of design beam cross-section; α_{a1}, α_{a2} – coefficients of adduced steel h-beam cross-section and steel plate to concrete, which are defined by following equation:

$$\alpha_{a1} = \frac{E_a}{E_c}, \alpha_{a2} = \frac{E_{sp}}{E_c} \tag{7}$$

where: E_c, E_a, E_{sp} – elastic modulus of concrete, adduced steel h-beam element and steel plate.
Moment of inertia of design cross-section of adduced composite steel beam, strengthened by steel plate (before appearance of cracks) is defined by the formula:

$$I_{red} = b_C h_B^3 / 12 + \alpha_{a1} \left[I_a + A_a (Y_H - h_a / 2 - C_z)^2 \right] + \alpha_{a2} A_{sp} C_p^2 \tag{8}$$

Using corresponding coefficients S and curvature $1/r$ we can obtain values of deflections f_M and f_O :

$$f_M = \frac{M}{0.85 \cdot I_{red} \cdot E_c} \cdot \left(\frac{3l^2 - 4a^2}{24} \right) \tag{9}$$

$$f_O = \frac{M_0}{0.4 \cdot I_{red} \cdot E_c} \cdot \left(\frac{3l^2 - 4a^2}{24} \right) \quad (10)$$

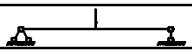
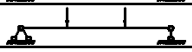
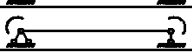
where: a – distance from unit load to beam support.
Curvature $1/r$ and deflection f_{CP} of composite steel beam from action of steel plate stress P_o is determined by following equations:

$$\left(\frac{1}{r} \right)_{cp} = \frac{P_0 C_p}{0.85 \cdot I_{red} E_c} \quad (11)$$

$$f_{cp} = \frac{0.125 \cdot P_0 \cdot C_p \cdot l^2}{0.85 \cdot I_{red} \cdot E_c} \quad (12)$$

Value of coefficient k_f^{pl}, which takes into account plastic-elastic state of design beam cross-section is given in Table 1.

Table 1: Value of coefficient k_f^{pl}

	Scheme of load application	ε_{max}		
		0.001	0.002	0.004
1		1.1	1.2	1.4
2		1.3…1.2	1.6…1.4	2.2…1.6
3		1.2…1.15	1.4…1.3	1.8…1.6
4		1.25…1.2	1.4…1.4	2.0…1.8
5	Movable load	1.6…1.4		

First values in the table 1 are corresponded to the constructive adduced steel h-beam element, which has symmetrical cross-section, second – asymmetrical one.

3. Experimental Set-Up

To determine the bearing capacity of the adhesive-bonded joint "steel-adhesive-steel" with-in the steel r/c structures, as well as its influence the strength and deformability, there were designed and manufactured the following specimens:

- Steel r/c elements (beams), using different concrete mixtures of different strength class;
- Standard concrete prisms 100x100x400mm and cubes 100x100x100mm for determination of concrete strength and deformability.

By the way of the external load application, specimens of each type are divided into series in accordance to the accepted geometrical characteristics of experimental specimens.
The specimens of each series, in their turn, differ one from another by the availability and type of the adhesive-bonded joint.
Therefore, the basic factors are: the geometrical characteristics of structure, concrete strength class, and availability of adhesive-bonded joint. So, all these distinctions can influence the adhesive joint bearing capacity value, as well as the strength and deformability of experimental specimens (beams). Total number of specimens, except of prisms and cubes, is 15 pcs.

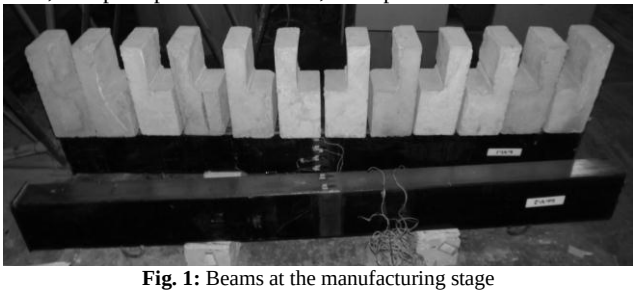


Fig. 1: Beams at the manufacturing stage

Experimental specimens are represented in a form of steel r/c elements (beams), which are strengthened with glued steel plate in the tensile region:

- Shaped tube 200x100x4. GOST 12336-66;
- Channel 20. GOST 8240-89 filled up with concrete.

All the specimens are filled up with concrete mixture of class C20/25 and C25/30. Experimental specimens are represented in a form of steel r/c beams (Fig. 1) BC-1, BC-2, BSC-1, BSC-2.
During experimental investigations procedure it is planned to study the dependence of bearing capacity and deflection of composite steel beams from availability and the adhesive type and way of steel reinforced plates attachment.
The Electronic Universal Testing Machine (MS-100) with maximum capacity of 500 kN is used for normal load test of all specimens. A view of the experimental set-up and the arrangement of the measurement devices are shown in Figure 2.
The load applied to the mid-point of the reaction beam is divided symmetrically into two concentrated loads and applied to the specimens.
The ratio of the shear span length (800 mm) to the effective depth of the beam (200 mm) is the same for all specimens. Specimens are tested under monotonic loading to failure.

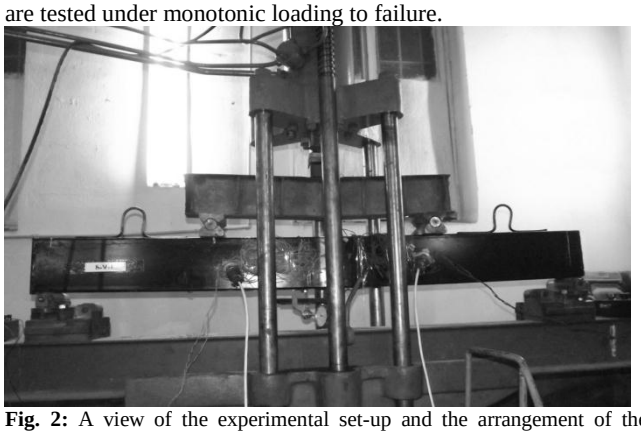


Fig. 2: A view of the experimental set-up and the arrangement of the measurement device

Experimental investigations on determination of bearing capacity of adhesive-bonded joint, as well as strength and deformability of strengthened composite beams, are to be carried out in accordance to the proposed scheme on Figure 3.

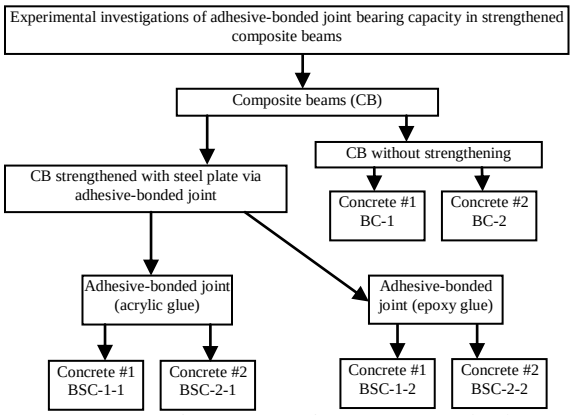


Fig. 3: Scheme of carrying out of experimental study of CB

During experimental investigations procedure it is planned to study the dependence of adhesive-bonded joint bearing capacity from availability and type of the adhesive, as well as its influence on the strength and deformability of experimental steel composite beams.
The specimens were manufactured according to custom design at PJSC «S. Kovalskaya Reinforced-Concrete Products Plant». Specimens are manufactured of premix of concrete, used during formation of SRB, which have been hardened under the same conditions as beams.
Characteristics of prevailing concrete mixture, as strength and deformability of experimental beams, are defined on the result of

testing the control cubical and prism specimens. The specimens for the testing are manufactured by series of 12 pcs in each (6 prisms, and 6 cubes) where 3 cubes and 3 prisms are made from concrete of class C20/25 and other ones – from concrete C25/30.
During the experimentation there were used the next measuring instruments: strain gauges, monometers for loading value control, and Linear Variable Differential Transformers (LVDT's) to measure mid-span deflection of the beam.
There were used two types of adhesives: the epoxy-based adhesive (Sikadur 30), and the acryl-based one.
Sikadur 30 adhesive is used for the structures strengthening. It doesn't contain any solvents; it is thyrotrophic, bicomponent, based on mixture of epoxy resin and special aggregates.
Another adhesive under usage during structure strengthening is the acrylic plastics ASS-T. ASS-T is a high-molecular mixture, which is based on suspension polymer of methylmethacrylate.
Experimental studies of the specimens under investigation are performed during short-time loading, using the multipurpose hydraulic press MS-100, by the pattern of single-bay freely supported beam.
During the experimentation there were used the next measuring instruments: strain gauges, monometers for loading value control, and deflectometers, which record deflections and deformations of the structures.

4. Conclusion

This part of article describes the experimental results of series A (without reinforcement) and series B (with reinforcement) composite steel beams. All the beams are designed to fail in shear even after strengthening with steel plates. The ratio of shear span to effective depth is kept constant throughout the testing of all the beams. The load-deflection behaviour and ultimate load capacity for shear is observed throughout the beams failure testing.
The typical deflection of composite steel beam strengthened with steel plate is shown in Figure 4.

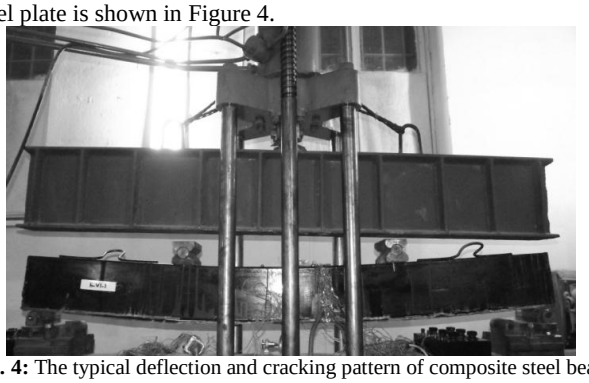


Fig. 4: The typical deflection and cracking pattern of composite steel beam strengthened with steel plate

The cracking pattern of composite steel beams is shown in Figures 5, 6.
The discussion is carried out through comparison between the results determined by the analytical method with those experimentally obtained.

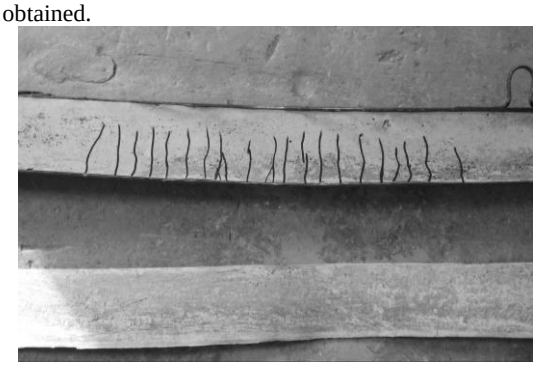


Fig. 5: The cracking pattern of composite steel beam strengthened with steel plate

The load-deflection curve of beams with concrete #1 is shown in Figure 7. It is considered that the deflection of beams increased in comparison with the original beam BC-1.

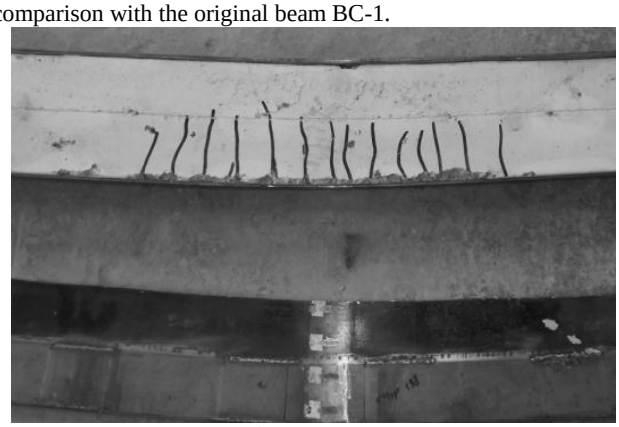


Fig. 6: The cracking pattern of composite steel beams without strengthening

The load-bearing capacity of beams strengthened with steel plate is shown in Figure 8.

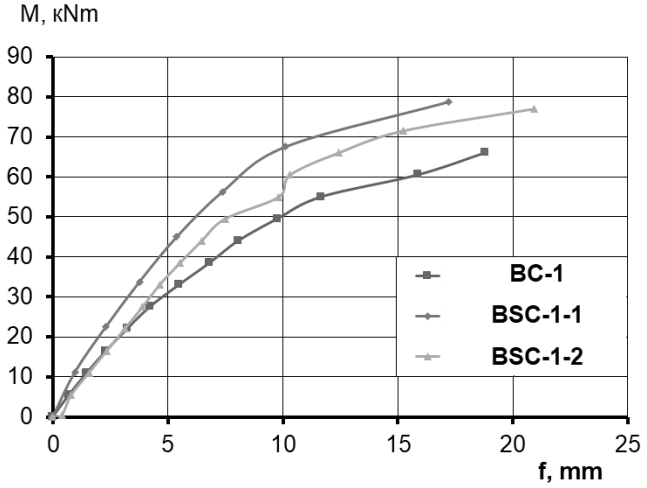


Fig. 7: The load-deflection curve of beams filled concrete #1

The effectiveness of composite steel beams reinforcement with steel plates in tensile zone depends on the type of joint and steel plate thickness. From the obtained results it can be concluded that load-bearing capacity of beams, strengthened with steel plate is increased by 20% comparing with original beam.

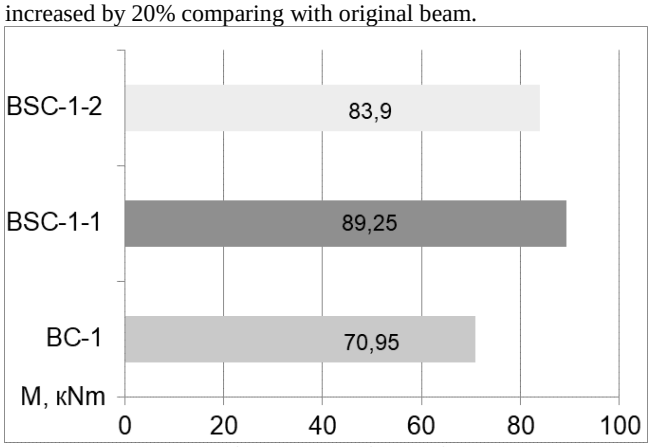


Fig. 8: The load-deflection curve of beams filled concrete #1

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