Strength of reinforced concrete T-beams of bridges reinforced with external reinforcement from fabric polymeric composites

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Abstract. Work is devoted to rehabilitating damaged, injured reinforced concrete T-beams of bridges of carbon fibre-reinforced plastic materials. Estimating beams' resistance at shear depended on the percent of longitudinal working reinforcing- μ, attitudes of flight of shear to a working height of section - a_v/h_o, an interval, quantity, and orientation of CFFM strips. The mechanism of destruction and estimation of bearing ability strengthened damaged and intact T-beams are investigated at shear. Results of deformations of the stretched working and cross-section armature, deformations of concrete on the height of beams and in strips CFFM from loading. The influence of CFFM on the bearing ability and character of the destruction of beams is investigated.

1 Introduction

Polymer fiber materials (PVM) are composite materials made based on exceptionally high-strength and rigid fibers of small diameter (in the form of threads or yarn) included in a matrix of a relatively malleable binder. Such materials abroad are also called advanced (advanced) polymer composites (Advanced Polymer Composites) or reinforced fiber polymers (Fiber Reinforced Polymers). The main purpose of PVM research is to use their effectiveness and potential in construction, although due to their high strength, rigidity, and lightness, they have been widely used in engineering for a long time. PVMs have had a huge impact on the development of aerospace technology. Since the 1960s, the navies of several countries have been using PVM since these materials are antimagnetic in nature and are most suitable in aggressive marine environments. At the same time, they were practically not used as reinforcement for building structures due to their high cost. In recent years, given the higher structural performance of PVM in comparison with steel, they are increasingly being used as a building material. In this regard, they have become the object of intensive research, including solving technical problems related to repairing and reinforcing structures. To safely carry out worldwide load accounting, it is necessary to replace or strengthen the head couplings of intermediate devices during major repairs or reconstruction of reinforced concrete bridges. An effective way to increase the bearing capacity of reinforced concrete beams is the use of modern technologies of interaction with

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FCM. In developed foreign countries, including the USA, Germany, Sweden, Japan, Western European countries, Russia, Canada, and Australia"..... the durability and strength of bridges, roads, and other transport structures are achieved through such promising areas as the use of modern design technologies and technical means". In this regard, developing a methodology for strengthening reinforced concrete bridges with FCM and calculating their strength is necessary.Thousands of reinforced concrete bridges and overpasses of small and medium spans, difficult environmental and climatic conditions under load-bearing conditions. In recent years, there has been a dangerous increase in various damages to structures caused by long periods of their operation on these roads. During the service, their operation modes have changed: speeds, intensity, and load stress have increased, axial loads from rolling stock have increased, the aggressiveness of the environment has increased, etc. Under the influence of operational loads and the environment in the concrete of load-bearing structures, an intensive, often not very noticeable to the eye, accumulation of damage occurs, which entails a slow degradation of the concrete structure, "aging" of the structure, a decrease in its bearing capacity and service life. The development of defects is also influenced by the conditions of the sharp continental climate of the region. The volume of reconstruction and reinforcement of bridge and overpass structures steadily increases yearly. In the reinforced concrete elements of operated bridges and overpasses, many defects of various types occur over time, the uncontrolled development of which can lead to a significant reduction in their service life. Traditional methods of reinforcing reinforced concrete beams are very time-consuming, short-lived, and not always effective. This situation encourages us to promptly develop new, extremely rational solutions for maintaining and restoring their operability. The problems of reinforcement and rehabilitation of reinforced concrete elements have recently acquired great relevance and practical significance due to the large number of buildings and structures in operation. The results of long-term surveys indicate the presence of various defects in load-bearing structures, which, developing over time, can lead to serious consequences. The most serious of these transverse forces are macro cracks in sections located in the area of action. Given the dangerous nature of such defects, when calculating the reinforcement of such elements, it is necessary to have a clearer understanding of their resistance mechanisms, considering shear stresses and displacements in sections with cracks. The practical significance of taking into account these contact stresses and displacements, which are associated with tangential forces of engagement of the banks in cracks, is indicated by some important features in the behavior of reinforced concrete structures containing macro cracks. In the practice of operating structures, various methods of repairing and strengthening reinforced concrete elements with the use of elements made of steel sheets and profiles have been developed. Taking into account the many inconveniences of traditional reinforcement methods, new technologies for reinforcing structures with high-strength polymer fabric materials (made of glass, carbon, and aramid-plastic fibers) are becoming widespread, differing from traditional ones in increased lightness and strength, corrosion resistance, and low labor intensity of application. The approximately 50-year history of using such fibers to strengthen building structures already counts thousands of objects.

2 Methods

Despite the huge number of experimental and theoretical studies conducted recently, the problem of resistance of concrete and reinforced concrete elements to the action of the cut is still far from being solved. These studies are being intensively continued due to the dangerous nature of sudden destruction during cutting and to expand the understanding of the physical aspects of the problem. Due to the large number and complexity of factors affecting the behavior of reinforced concrete elements collapsing from the cut, constructing an appropriate comprehensive theory is associated with great difficulties. This circumstance has been aggravated for a long time by the predominance of an empirical approach to solving the problem without an in-depth study of the fundamental mechanisms and processes underlying the resistance of elements to the action of transverse forces. Each such dependence had limited application despite the large array of experimental data used. First, this refers to the mechanism of manifestation of engagement forces in cracks and the nagel effect of longitudinal reinforcement. For the first time, this concept found serious confirmation in the works. In the works, the role of the contribution of concrete of the compressed zone, the nagel effect of longitudinal reinforcement, and the forces of engagement of the crack banks in the overall load-bearing capacity of beams without transverse reinforcement by transverse force were evaluated. Despite the large contribution of these forces to the shear resistance of beams, the mechanism of their manifestation has been studied very poorly due to the lack of systematic fundamental studies of the effect of the interaction of crack banks in reinforced concrete structures. Depending on the type and scheme of loading, saturation, and location of the longitudinal reinforcement, the features of its anchoring, the geometric characteristics of the beam, the strength of materials, and other factors, various forms of destruction are observed in the bent element. These factors affecting the nature of cracking and destruction of the element, its stress-strain state, can be effectively investigated only in beams without transverse reinforcement, which complicates the picture to varying degrees and does not allow them to be observed in their "pure form". Series T, composed of sixteen T-beams, were reinforced with different amounts of shear reinforcement. Both the main series were tested under the simply supported condition with a shear span to an effective depth ratio of 2.5 and 4.0. Series T was categorized as Group TT and Group TS. Table 1 shows the summary of reinforced concrete beams designation. Figure 1. shows the overall structure of series T.

Table. 1. Marking of reinforced concrete beams.

Main Series	Group	Subgroups	A_v/D
T (T-Beams)	TT	TT1	2.5
		TT2	4.0
	TS	TS1	2.5
		TS2	4.0

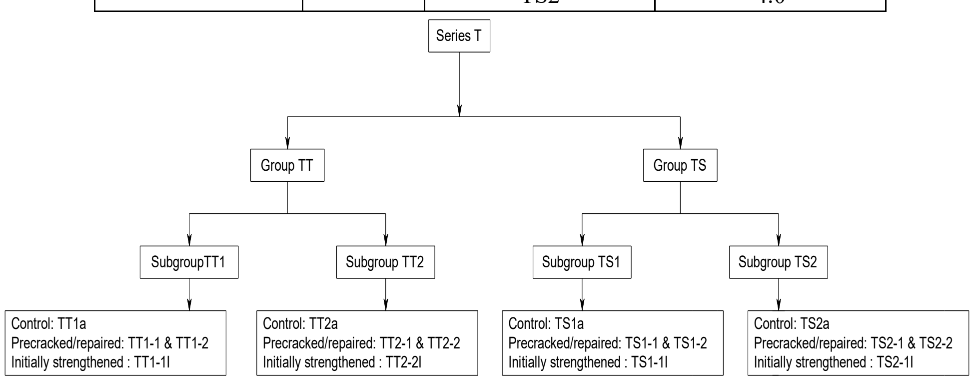

Fig. 1. Overall tree structure of series T (T-beams)

Properties of fittings and parts. The T-series beams were reinforced with steel rods in compressed and stretched zones. The beams of the TT and TS groups were reinforced in the stretched zone with rods with a diameter of 20 and 16 mm, respectively. The beams of the TT1 and TT2 subgroups were reinforced with double clamps with four rods with a diameter of 6 mm in increments of 120 and 90 mm, respectively. For the beams of the TS1 and TS2 subgroups, a pitch of 210 and 145 mm, respectively, were used. The plate's compressed area and all beams' overhangs are reinforced with four high-strength steel rods with a diameter of 12 mm. Reinforcement schemes of TS1, TS2, T1, and T2 subgroups are shown in Fig. 2.

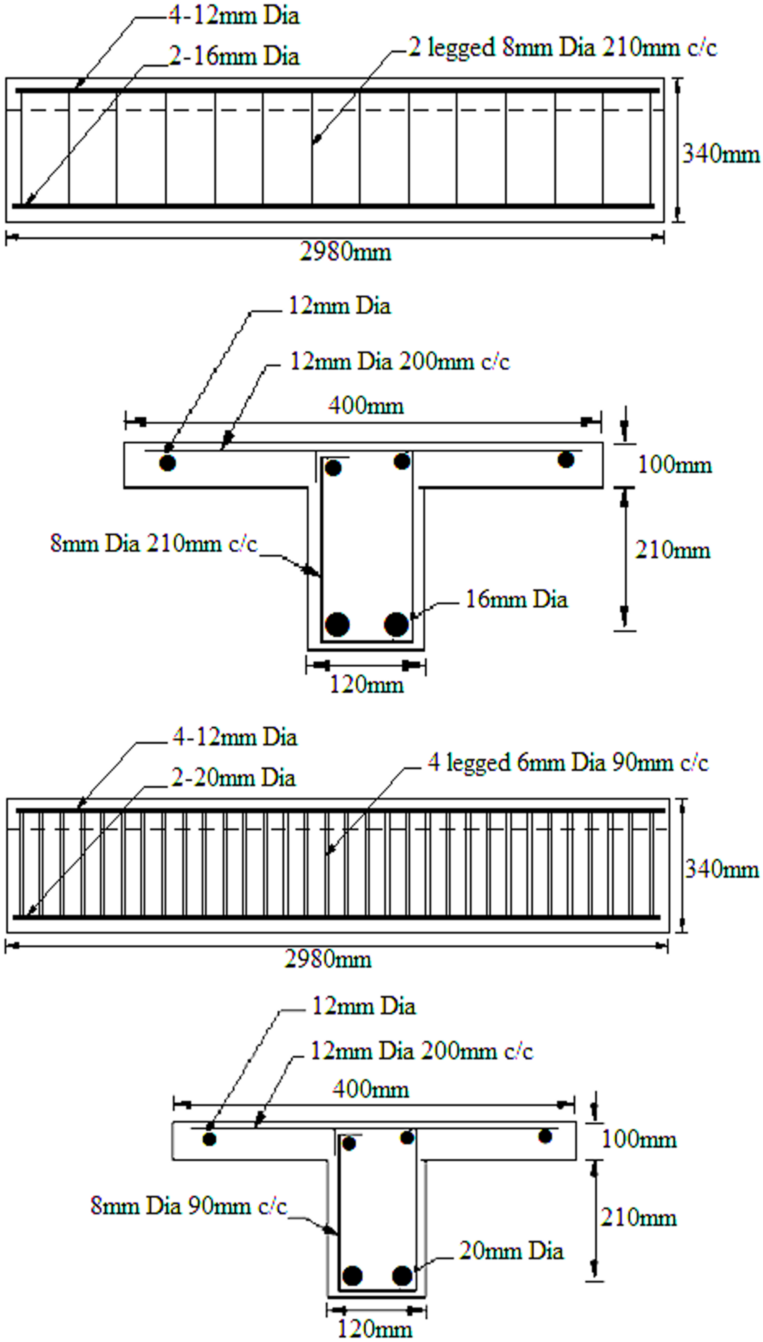

Fig. 2. Reinforcement scheme of beams of the TS1-TS2, TT1-TT2 subgroup

Properties of epoxy resin and fixation of CFFM. In this study, as an external addition to the internal reinforcement system, a reinforcing composite consisting of two main components was used: epoxy resin and sheets of fabric made of carbon fiber material of the Sika Wrap160C trademark (0°/90°). Sikadur-330 epoxy resin was used as an adhesive in the reinforcing composite system. With the help of such a two-component system, the fiber sheets were fixed with epoxy resin on the concrete surface. The properties of epoxy resin are as follows: adhesive strength - 4 MPa; tensile strength - 30 MPa; modulus of elasticity - 3.8 MPa. In the T series, one sample without reinforcement in each subgroup was selected as a control sample, and three beams were externally reinforced with CFFM strips. In each subgroup of reinforced beams, two samples were reinforced after preloading and cracking, and one beam was reinforced without preloading and cracking. The reinforced samples differed in the pitch and orientation of the CFFM bands. Beams of subgroup T1 and TS1. In each subgroup, one sample was used as a control, and the remaining three beams were reinforced by external gluing of CFFM strips. The ratio of the slice span to the working height in these subgroups was 2.5; therefore, the strips were placed only in the slice span. Samples T1-1 and T1-2 were reinforced with vertical U-bands with a step in the center of 150 and 200 mm, respectively. Samples TS 1-1 and T1-2 were reinforced similarly to samples of the T1 subgroup. Samples T1-1 I and S1-1 I were reinforced with U-strips with a step of 150 mm without preloading and cracking. Strips of CFFM with a width of 120 mm and a length of 2480 mm were glued along the lower edge of the ribs of the beams. A detailed description of the samples of subgroups T1 and T1 is shown in Fig. 3. Table 2 shows the details of the reinforcement of the beams of the TT1 and TS1 subgroups, respectively.

Table 2. Strengthening the beams of subgroups T1 and TS1.

Specimen Details		a_v/d	Specification CFRP Strip	
			Orientation	Spacing (mm)
TT1a	Control or Reference	2.5	---	---
TT1-1	Precracked-Repaired	2.5	U-strip (0/90 Degree)	150
TT1-2	Precracked-Repaired	2.5	U-strip (0/90 Degree)	200
TT1-1I	Initially strengthened	2.5	U-strip (0/90 Degree)	150
TS1a	Control or Reference	2.5	---	---
TS1-1	Precracked-Repaired	2.5	U-strip (0/90 Degree)	150
TS1-2	Precracked-Repaired	2.5	U-strip (0/90 Degree)	200
TS1-1I	Initially strengthened	2.5	U-strip (0/90 Degree)	150

Beams of the TF2 and TF2 subgroups. From each subgroup (TT1 and TS1), one beam was left as a control sample without reinforcement, two beams were preloaded and split, and the last beam was reinforced without preliminary cracking. The spacing and width of the strip were 150 and 80 mm, respectively. The TT2-1 and TS2-1 samples were reinforced with vertical U–bands with an orientation of 0°/90°. Similarly, the samples T2-2, T2-2 I, Z2-2, and TS2 were wrapped with the orientation of the strips 45°/135° to the horizontal axis of the beams. Figures 3 show the schemes of wrapping reinforced beams. Table 3 shows the details of the reinforcement of the beams of subgroups T2 and T2.

Table. 3. Strengthening the beams of subgroups T2 and T2.

Specimen Details		a_v/d	Specification CFRP Strip	
			Orientation	Spacing (mm)
TT2a	Control or Reference	2.5	---	---
TT2-1	Precracked-Repaired	2.5	U-Strip (0/90 Degree)	150

TT2-2	Precracked-Repaired	2.5	L-Strip (45/135 Degree)	150
TT2-2I	Initially Strengthened	2.5	L-Strip (45/135 Degree)	150
TS2a	Control or Reference	2.5	---	---
TS2-1	Precracked-Repaired	2.5	U-Strip (0/90 Degree)	150
TS2-2	Precracked-Repaired	2.5	L-Strip (45/135 Degree)	150
TS2-1I	Initially Strengthened	2.5	U-Strip (0/90 Degree)	150

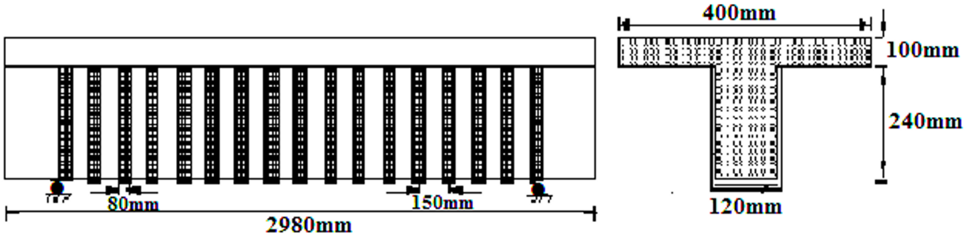

Fig. 3. CFRP U-strip with spacing of 150mm (orientation: 0/90 Degree) for specimens TT2-1, TS2-1, and TS2-1I

2.1 Experimental studies of beams in the post-crack stage

To study the bending elements in the area of transverse forces, it was decided to make two groups of reinforced concrete beams from heavy and light concrete, the destruction of which was supposed to be along inclined sections. All beams were made of rectangular cross-sections with dimensions of 100x400 mm and loaded with one or two concentrated forces at different relative cross-section spans a/h_0 obtained by changing the length of the beams. The type of concrete and the compositions of the concrete mixture was similar to those used for testing special samples for shear. The change in the percentage of longitudinal reinforcement was achieved by varying the diameter of the rods while maintaining the total number of rods equal to two. It amounted to 1.70, 1.08, and 0.60%, respectively; for longitudinal reinforcement of experimental beams, steel of periodic profile A-III with diameters of 12.16 and 20mm and A-1U 5 with a diameter of 16mm were used.

Table. 4. General characteristics of experimental beams

Group of beams	Beam cipher	*b*, mm	h_0, mm	Slice span, mm	a/h_0
I	TB-1	100	370	1230	3,32
	TB-2	100	370	1230	3,32
	TB-3	100	370	1230	3,32
	TB-4	100	370	2180	5,89
	TB-5	100	370	1230	3,32
II	KB-1	100	370	1230	3,32
	KB–2	100	370	1230	3,32
	KB-3	100	370	1230	3,32
	KB-4	100	370	2180	5,89
	KB-5	100	370	1230	3,32

Continuation of table No. 4.

Longitudinal reinforcement	μ_s,%	$\sigma_{0,2}$, MPa	E_sx10^3 MPa	R_b, MPa	R_{bt}, MPa	E_b, MPa
2D20.A–III	1.70	441	201	35.1	3.64	28.0
2D20.A–III	1.09	441	201	30.9	3.73	27.0
2D20.A–III	0.61	441	201	27.7	3.41	28.0
2D20.A–IV	1.09	649	190	31.4	3.12	27.6
2D20.A–IV	1.09	649	190	29.1	3.36	26.1
2D20.A–III	1.70	441	201	23.4	2.19	15.3
2D20.A–III	1.09	441	201	27.2	2.84	16.1
2D20.A–III	0.61	441	201	24.9	2.08	16.0
2D20.A–IV	1.09	649	190	23.7	2.48	16.0
2D20.A–IV	1.09	649	190	23.1	1.94	16.1

In addition to these beams, special beams were tested with an insert in a stretched zone to determine the nagel effect of longitudinal reinforcement, the content of which varied within the same limits. Before testing the beams, as a rule, the strength and modulus of elasticity of concrete and reinforcement were determined on standard type samples. The general characteristics of the experimental beams are given in Table 4. Concreting of the beams was carried out in steel forms with vibration on a vibration platform. The beams were tested using a simple beam scheme with one movable and the other fixed hinge supports.

3 Results

Experiments show that in the limiting state, the beams were destroyed either by bending or shear mechanisms with the rupture of the strips. The number and pitch of steel clamps, the number, pitch, and orientation of CFFM strips, and the ratio of the cut span to the working height affect the effectiveness of reinforced concrete beams. The interval of the CFFM strips also affects the load-bearing capacity of the beam during cutting. In the TT1 subgroup, the load-bearing capacity of the TT1–2 samples (band interval-150 mm) was 15% greater than that of the TT1-1 sample (band interval–200 mm). The reinforced samples of the TS2 and TS1 subgroups showed no increase in load-bearing capacity compared to the "damaged" reinforced samples having a similar orientation to the CFFM bands. The bidirectional strip not only increases the load-bearing capacity when cutting reinforced samples but also prevents the propagation of cracks and the detachment of the strip from the concrete surface, acting as a deformation limiter. Using external reinforcement with the help of FFM sheets for "damaged" beams prevents the development of preliminary cracks at the destruction stage. In connection with the above, we conducted studies of the mechanism of mutual engagement of the crack banks in special reinforced concrete samples reinforced with external reinforcement of carbon fiber fabric materials and evaluated the bearing capacity and stiffness of sections with a crack under the action of shear forces. Special samples were tested in which a crack was created by preliminary splitting. When a shear load is applied along a crack, its banks, mutually shifting, engage with each other due to their roughness, ensuring the transmission of shear stresses arising in the crack through them. According to the methodology developed in [1-4], the nature of the dependence between these stresses and the corresponding shear and normal displacements in the cracks of the samples from the initial loading stages up to destruction was studied, as well as the effect on this dependence of internal and external reinforcement of the samples with steel clamps and fabric polymer material from CFFM.

4 Conclusion

1. The applicability of expression (3) is limited by the cubic strength of concrete in the range of 30 – 40 MPa. The table compares the theoretical and experimental data of the tested samples.

2. However, in the limiting stage, a sudden increase in normal and tangential displacements was observed compared to samples without external amplification. The increase in the shear stress of reinforced samples varies between 7% – 56% compared to samples without external reinforcement (Table 1).

3. The deformation in the steel clamps of the reinforced samples was less than in the non-reinforced ones at the same load. However, the reinforced samples showed greater deformations in the destruction stage than the non-reinforced samples. The nature of the dependence "τ – δ" of reinforced and non-reinforced special samples is approximately the same. The proposed theoretical expression for calculating the shear stress of samples with external amplification can be used, provided there is a sufficient correlation with experimental results. For a wider application of the proposed equation, further research is needed.

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