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Experimental study of reinforced concrete elements reinforced with fiber-reinforced plastics in inclined section under static loading

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ABSTRACT: The results of experimental studies of the strength of inclined sections of bent reinforced concrete elements with fiber-reinforced plastics are presented. Comparative data have been obtained on the use of new types of fiber-reinforced plastics for reinforcing reinforced concrete structures. Experimental studies have been obtained on the value taken into account in the calculations of the limiting deformations of fiber-reinforced plastics under various types of loads.

Keywords: Bending reinforced concrete elements, Beams, Strength of inclined sections, Deformations and cracks, Reinforcements, Fiber-reinforced plastics, Prototypes, Deflections, Tests

1 INTRODUCTION

The need to strengthen reinforced concrete structures during operation arises due to the long-term effect of operational loads or corrosive wear, when errors are eliminated in the design, manufacture, and transportation when the operating conditions become more complicated or not envisaged by the project, the scheme of action and magnitude of loads, the occurrence of various damages, as well as when reconstruction and renovation of the enterprise (EN 2004). An alternative to traditional methods of reinforcing reinforced concrete structures is the use of fiber-reinforced plastics (FRP) - polymers reinforced with fiberglass. Unlike traditional reinforcement methods using steel reinforcement, these methods have high reinforcement efficiency, and do not require overburden and welding, concreting of reinforced elements, they are distinguished by durability, corrosion resistance, low labor intensity, and economic feasibility.

The following types of fibers are commonly used as FRP reinforcement: basalt (B), carbon (C), aramid (A), glass (G), and polyester (Teng et al., 2002).

Reinforcement of reinforced concrete structures with fiber-reinforced plastics (FRP) can be used in the following cases:

– to reinforce undamaged reinforced concrete structures due to increasing loads during the reconstruction of the object (Shilin 2004);
– to strengthen reinforced concrete structures damaged during operation ("shooting off" of the protective layer of concrete, corrosion of reinforcement and concrete, formation and

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development of cracks, excessive deflections, etc.) in order to restore the performance of the elements (Mander et al., 1988);
- to protect against corrosion, increase water resistance, and increase the durability of structures (Mochizuki 2020);
- fiber reinforcement (FAP) is produced by the following methods;
- by impregnation of concrete;
- external reinforcement with fiber-reinforced plastics (FRP)

Reinforcement systems for reinforced concrete structures are made in the form of unidirectional braided sheet coverings or woven unidirectional or bidirectional fibers produced on looms. The most widespread are the following types of fibrous fibers; carbon, aramid and glass. The most common method of reinforcement is external reinforcement with fiber-reinforced plastics (FRP), which is used for longitudinal and transverse reinforcement, as well as for creating reinforcing clips in compressed concrete elements, which prevent the transverse expansion of concrete, creating a triaxial stress state in concrete and can increase the strength of the latter in repeatedly (Samaan 1988, Awwad et al., 2019).

Wrapping reinforced concrete structures with polymer fiber fabrics (FFA) can increase the strength of compressed elements several times by limiting the transverse expansions of concrete and thereby creating a triaxial stress state. Sticking high-strength polymer-fiber tapes (laminate) with unidirectional fibers can significantly increase the strength of tensile reinforcement, and reduce the width of normal cracks (Saafi et al., 1999).

Sticking high-strength polymer-fiber tapes (laminate) with bilaterally directed fibers can significantly increase the strength of the transverse force, reduce the width of the opening of inclined cracks, or significantly increase the bearing capacity of reinforced concrete slabs supported along the contour.

However, comprehensive data on the operation of reinforced concrete structures reinforced in such ways under various operating conditions and the variety of influences of force, temperature, aggression and other factors have not yet been obtained (Miyauchi et al., 2000, Miyauchi et al., 2005).

The purpose of this work is to obtain experimental data on the strength of inclined sections of bent reinforced concrete structures reinforced with fiber-reinforced plastics (Katsumata et al., 1988) under static loading, as well as information on the stress-strain state, strength, stiffness and crack resistance of inclined sections of bent reinforced concrete elements reinforced with high-strength fiber-reinforced plastis.

The implementation of the proposed project will radically improve the technical support and implementation of the strengthening and restoration of building structures, increase the qualifications and potential of workers, reduce noise and environmental pollution due to the rejection of overburden, welding and labor-intensive work, increase the durability and aesthetic appearance of reinforced structures, reduce the time and cost of implementation works.

2 EXPERIMENTAL STUDIES

The strength of inclined sections in terms of the transverse force of bent reinforced concrete elements was tested on 3 batches of prototypes of reinforced concrete beams reinforced in the support zone with fiber-reinforced meshes. The batches of samples differed in the type of fiber-reinforced materials used for reinforcement. The prototypes were tested according to the scheme of a hinged beam with a span of 2.0 m, loaded in the span by two equal concentrated forces at a distance of 1.2 m. At the same time, the ratio between the size of the cut span and the height of the section was providedequallyl to lcp/h = 2.0.

The study of the work of inclined sections of bent reinforced concrete elements, reinforced in the support zone with fiber-reinforced mesh tapes, was carried out on experimental reinforced concrete beams of three batches, tested according to the scheme of a hinged beam with a span of 2.0 m, loaded in the span by two equal concentrated forces at a distance of 1.2 m. In this case, the ratio between the span of the cut and the height of the section lcp/h = 2 was provided.

Three batches of reinforced concrete beams were tested, and the reinforcement of the support zones of which differed in the type of reinforcing material:

– samples of the 1st batch were reinforced with meshes of the S&P C Sheet 240 series 50 mm wide (BASF, Germany);
– samples of the 2nd batch were reinforced with meshes of the FibArm Tape 530/300 series 300 mm wide (HK Composite, Russia);
– samples of batch III were strengthened with meshes of the MBRACE FIB CF 230/4900/530 g/5.100 m series (BASF, Germany).

The prototypes of the 1st batch in the support zone at one end of the beams were reinforced with bent double-shear clamps from Ø6 A-1, installed with a step of 100 mm, and the other end was reinforced in the support zone with vertical or inclined tapes from unidirectional meshes of the S & P C Sheet 240 series 50 mm wide. In addition, the stretched zone was reinforced with S&H Laminate CFR 150/200 50 x 1.2 mm.

Table 1 presents the following experimental data for testing beams of the BI series:

– bending moment at which normal cracks appeared;
– transverse force at which oblique cracks were formed;
– shear force that caused the destruction of the beam;
– bending moment at which the beam failed.

Table 1. Forces at which cracks were formed and the destruction of beams of the BQ-I series occurred.

Beam brand	Transverse reinforcement	$M_{crc,s}$ kNm	$Q_{crc,w}$ kN	M_u kNm	Q_u kN
BQ1-1c	Without clamps	6,38	36,79	15,94	45,53
BQ1-2c		6,87	36,70	18,67	53,44
BQ1-3c	Vertical hair mesh	5,15	31,88	31,76	90,74
BQ1-4c		5,15	41,69	38,63	110,36
BQ1-5c	Inclined mesh strips	5,15	39,24	35,19	100,55
BQ1-6c		6,87	39,24	28,33	80,93

Table 2 presents the following experimental data for testing beams of the BQ-I series:

– the greatest deformations in tension reinforcement;
– the greatest deformations in the compressed reinforcement;
– the greatest deformations in steel collars;
– the greatest deformations in fiber-reinforced meshes;
– the greatest width of opening of normal cracks;
– the largest width of the opening of inclined cracks in the zone of reinforcement with steel clamps;
– the largest crack opening width in the reinforcement zone with fiber-reinforced meshes;
– vertical deflections in the middle of the span of the beam.

Table 2. Deformation parameters of the operation of inclined sections of beams of the BQ-I series.

№	Transverse reinforcement	ε_s ‰	$\varepsilon_{s.1}$ ‰	$\varepsilon_{f,w}$ ‰	$w_{k,s}$ mm	$w_{k,w}$ mm	$w_{k,p}$ mm	a_k mm
1	Without clamps	1,4	0,4	–	0,2	3,5	–	5,82
2		0,96	0,5	1,1	0,16	3,4	–	6,66
3	Vertical stripes made of fiber-reinforced mesh	1,75	0,7	–	0,3	0,6	1,55	14,03
4		1,95	1,4	3,8	0,35	0,9	0,95	15,25
5	Inclined strips of fiber-reinforced mesh	2,0	0,7	2,3	0,3	0,65	0,95	11,12
6		1,9	0,7	2,6	0,25	0,4	1,5	11,14

Let us consider the features of the work of inclined sections in terms of transverse force with their various reinforcement. In beams that do not have transverse reinforcement at the support end, in the process of increasing the vertical load with a bending moment of about 15% of the breaking load, the formation of normal cracks in the zone of pure bending was observed, with an increase in the load by almost 5 times, oblique cracks formed in the support zones. With a further increase in the vertical load, accelerated opening of inclined cracks was observed, and after reaching a crack width of more than 3-3.5 mm, the concrete was destroyed along the inclined zone in the supporting unreinforced zone of the beam. The vertical deflections were about 6 mm, the deformations of the tensile longitudinal reinforcement were about 0,15%, the deformations of the compressed reinforcement were 0,05%, and the opening width of normal cracks was about 0.2 mm. At the opposite end of the beam, reinforced with clamps Ø6 A-1 with a pitch of 100 mm, the width of the opening of inclined cracks did not exceed 0.1 mm, and the deformations in the clamps were about 0,1%.

In beams reinforced in the supporting zone with strips of fiberglass mesh, the strength of inclined sections in terms of transverse force almost doubled. After the formation of normal cracks, which also appeared at a bending moment of about 15% of the breaking load, oblique cracks were formed at a transverse force of about 35-40% of the breaking load. The destruction of the beams was caused by the breaking off of the concrete layer under the glued mesh strips, the switching off of the transverse reinforcement, was accompanied by a loud sound and had a fragile character. At the stage before destruction, inclined cracks reached a value of 1.0–1.5 mm; clamps were about 0.2. The values of vertical deflections were about 11-15 mm, the deformations of the tensile longitudinal reinforcement were about 0.2% of the compressed reinforcement - 0.7-1.0, the opening width of normal cracks was about 0.35 mm.

Prototypes of the BQ-II series of the batch in the form of beams 2.2 m long, had a cross section of 120 × 200 mm and were reinforced with double reinforcement: in the lower zone 2Ø18 A-III and in the upper zone - 2Ø10 A-III. In the support zone, one end of the beams was reinforced with bent double-shear clamps made of Ø6 A-1, installed with a step of 100 mm, and the opposite end did not have transverse reinforcement.

The support zones of the beams of the BQ-II series were reinforced with a sticker of vertical unidirectional meshes of the FibArm Tape 530/300 series 300 mm wide, and the tension zone was reinforced with a FibArm Lamel 12/100 lamella.

The beams were loaded in stages not exceeding 5-8% of the breaking load.

Table 3 presents the following experimental test data for beams of the first batch:

– bending moment at which normal cracks appeared;
– transverse force at which oblique cracks were formed;
– shear force that caused the destruction of the beam;
– bending moment at which the beam failed.

Table 3. Results of testing beams of the second batch BQ-II.

Beam brand	$M_{crc,s}$ kNm	$Q_{crc,w}$ kN	M_u kNm	Q_u kN
BQII-1	13.3	73,3	48.0	120.0
BQII-2	12.0	80	58,0	145,0
BQI1-3	12,0	70	48,0	120,0

With an increase in the transverse load, normal cracks formed in the zone of pure bending, then oblique cracks appeared, after which the destruction of the support zone occurred, accompanied by separation of the concrete protective layer.

Table 4 presents the following experimental data for testing beams of the first batch:

– the greatest deformations in tension reinforcement;
– the greatest deformations in the compressed reinforcement;
– the greatest deformations in fiber-reinforced meshes;

– the greatest width of opening of normal cracks;
– the largest width of the opening of inclined cracks;
– vertical deflections in the middle of the span of the beam;
– vertical deflections under loads.

Table 4. Deformation parameters of inclined sections.

Beam brand	ε_s ‰	$\varepsilon_{s.1}$ ‰	$\varepsilon_{f,w}$ ‰	$w_{k,s}$ mm	$w_{k,w}$ mm	fmax mm	f_o mm
BQI1-1	1,76	–1,44	3,36	0,1	0,30	13,8	7,4
BQI1-1	2,4	–1,52	3,84	0,25	0,30	15,0	9,6
BQI1-1	1,76	–1,6	2,72	0,20	0,30	12,0	8,5

The distribution of tensile strains of fiber fibers along the length of the cut occurs along a convex curve, while the largest strains of mesh fibers reached values of 0,2-0,38%.

Prototypes of beams of the BQ-III series, 2.2 m long, had a cross section of 120 × 200 mm and were reinforced with double reinforcement: in the lower zone 2Ø18 A-III and in the upper zone - 2Ø10 A-III. The stretched area of the beams was reinforced with a sticker of MBRACE LAM CF 165/3000 100x1,4.100m laminate, and the support areas of the beams were reinforced with a sticker of vertical unidirectional meshes of the MBRACE FIB CF 230/4900.530g/5.100m series.

Table 3.10 presents the strength test data for BQ-III series beams:

– bending moment at which normal cracks appeared (Mcrc,s);
– bending moment at which the beam failed (Mu);
– shear force that caused the destruction of the beam (Qu).

Table 5. Forces at which normal cracks were formed and the destruction of BQIII series beams occurred.

Beam brand	$M_{crc,s}$ kNm	M_u kNm	Q_u kN
BQIII-1	5,53	38,2	95,5
BQIII-2	11,1	31,6	78,9
BQIII-3	11,1	34,3	85,8

With an increase in the transverse load, normal cracks were formed in the zone of pure bending, then the delamination of the upper corner of the grids near the zone of application of the transverse force and the separation of the protective layer of concrete began, after which the destruction of the support zone of the beam occurred, accompanied by crushing of the concrete along the inclined strip.

Table 6 presents the following deformation data based on the test results of BQIII series beams:

– the greatest deformations in tension reinforcement (εs);
– the greatest deformations in the compressed reinforcement (εs.1);
– the greatest deformations in the strips of the laminate (εf, lam);
– the largest deformations in the reinforcement grids (εf,w);
– maximum width of normal cracks (ak,s);
– vertical deflections in the middle of the span of the beam (fmax);
– vertical movements under loads (fo).

Thus, the experimental strength in terms of the transverse force of inclined sections of reinforced concrete beams, reinforced in the support zones with fiber-reinforced meshes, exceeds the design strength by an average of 16%.

Table 6. Deformation characteristics of BQIII series beams.

Beam brand	ε_s ‰	$\varepsilon_{s.1}$ ‰	$\varepsilon_{f,lam}$ ‰	$\varepsilon_{f,w}$ ‰	$a_{k,s}$ mm	fmax mm	f_o mm
BQIII-1	–	–1,79	2,62	1,5	0,20	9,2	5,9
BQIII-2	2,18	–1,38	2,51	1,39	0,10	9,1	6,3
BQIII-3	2,18	–1,62	4,05	4,53	0,20	8,9	7,7

Table 7. Comparison of the experimental and design strength of beams in terms of transverse force.

Beam brand	t_f. mm	E_f. GPA	α	s, cm	ε_f. ‰	Q_{design}, кN	$Q_{experimental}$, кN	$Q_{experimental}/Q_{design}$
BQ1-1c					3,1	78,0	100,55	1,33
BQ1-2c	0,176		45°		3,8	80,0	80,93	1,01
BQ1-3c		240		11.2	3,1	77,85	90,74	1,18
BQ1-4c	0,176		90°		3,8	85,96	110,36	1,28
BQII-1c					3,36	108,81	120	1,1
BQII-2c	0.245	245			3,84	117,77	145	1,23
BQII-3c			90°	–	2,72	96,86	120	1,24
BQIII-1c					1,5	73,58	95,5	1,3
BQIII-2c	0,293	230			1,39	71,35	78,9	1,11
BQIII-3c					2,54	94,64	85,8	0,91

3 CONCLUSIONS

1. The results of tests on the transverse force of inclined sections of bent reinforced concrete structures reinforced by gluing in the support zone by surface gluing of various types using carbon fiber plastics showed that reinforcement of beams increases strength by 1.4-2.3 times.
2. The calculated strength of inclined sections of bent reinforced concrete structures reinforced with fiber-reinforced plastics showed a fairly close agreement with the experimental data.

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