Shear Crack Resistance of I-Shaped Concrete Beams with Basalt FRP Stirrups

Sergey Usanov and **Murat Tamov**

Abstract This paper presents the results of experimental research on the shear crack resistance of I-shaped beams with BFRP transverse reinforcement. The tested specimens had equal sizes and different angles of stirrups inclination, web reinforcement ratio, and shear span-to-depth ratio (a/d). The group with $a/d = 2.5$ and 3.2 also included beams with cold-drawn wire transverse reinforcement. The effect of varied parameters on the load of shear crack formation and the width of the cracks is analyzed. The maximum shear crack width in beams with inclined stirrups was slightly lower than that of beams with vertical stirrups. The corresponding difference in the crack width between twin beams differing only in the angle of stirrups inclination was up to 10% and was more pronounced for beams with $a/d = 3.2$. In most cases, the shear crack width for beams with BFRP transverse reinforcement does not exceed the permissible values established by the codes of different countries. The exceptions mainly comprised beams with the lowest web reinforcement ratio.

Keywords Crack resistance · I-shaped beams · Transverse reinforcement · Shear span · Basalt fiber reinforced polymers (BFRP) · Web-shear cracks

1 Introduction

Fiber-reinforced polymer materials have been used in industrial and civil construction for more than 50 years [1]. For a certain period, there was not much demand for the use of FRP due to the long and costly process of its manufacturing. Now a growing amount of research confirms the feasibility of using FRP [2, 3], and more consumption of FRP in the construction industry is forecast [4, 5]. FRP bars are produced using different fibers such as glass (GFRP), basalt (BFRP), carbon (CFRP), aramid (AFRP), and others placed in a polymer matrix. The matrix is a thermoset compound and usually consists of epoxy or vinyl ester. The advantages of FRP over steel include corrosion resistance, light specific gravity, high tensile strength, non-magnetic properties, etc.

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Among the disadvantages are low modulus of elasticity, anisotropy, and the absence of a yield point [6, 7].

The use of FRP as transverse reinforcement instead of traditional steel reinforcement in flexural members affects their shear strength. The reduced modulus of elasticity of FRP leads to an increase of the width of shear cracks. This leads to a decrease of the aggregate mechanical interlock between the cracks and changes the magnitude of forces in the transverse reinforcement [8]. At the same time, it is known that in reinforced concrete beams the magnitude of the aggregate interlock forces is significant and can lie in the range of 33–50% of the shear capacity of uncracked concrete. Anisotropy, high tensile strength and the absence of a yield point also have an impact on the shear behavior of FRP-reinforced concrete members (FRP-RC members).

Most of the shear design methods implemented in building codes for FRP reinforced elements are similar to those used for steel reinforcement. At the same time, in most cases, codes do not contain methods for calculation of the shear cracking load or width of shear cracks only setting a general limit on the width of cracks in a member.

In the design guidelines of the American Concrete Institute (ACI 440.1R-15) for FRP-RC members the width of inclined cracks is limited by the maximum allowable stresses in the transverse reinforcement $E\varepsilon_{f,lim}$ (E is the modulus of elasticity of the FRP, $\varepsilon_{f,lim} = 0.004$ is maximum strain). A similar provision is adopted in the ACI code for the design of reinforced concrete (RC) structures [9].

Due to the absence, both past and present, in ACI 440 of permitted shear cracks width, researchers (for example, in [10]) take the limit set for flexural cracks width (ca. 0.5 mm) as such limit. This is higher than the maximum allowable crack width for RC elements -0.33 mm [9]. For FRP-RC members, a higher value of the maximum crack width is justified due to the high corrosion resistance of FRP and is set only to meet aesthetic requirements [11]. Shekhata et al. [10] showed that the strains of transverse reinforcement corresponding to the inclined cracks width of 0.5 mm are 0.2% for CFRP bars and 0.35% for GFRP bars. Thus it was suggested that the value of 0.2% ought to be accepted as a limit to control the width of shear cracks.

Russian design code SP 295.1325800.2017 also set the maximum tensile strength of FRP stirrups as $0.004E_f$ (also not exceed $0.5R_f$ or 300 MPa). The Institution of Structural Engineers (IstructE) guidance [11], which is a modification of the British codes BS8110 [12] and BS5400 [13], set the limit $\varepsilon_{f,lim}$ for FRP transverse reinforcement at 0.25% [14].

Possible adjustment to $\varepsilon_{f,lim}$ is still a subject of ongoing discussion. Pilakoutas et al. [15], Valivonis et al. [16], and El-Ghandour et al. [17] based on the results of their own and other researchers' tests suggest increasing $\varepsilon_{f,lim}$ up to 0.45%. Ahmed et al. [18] indicated that the measured maximum value of strains of the transverse reinforcement range from 1 to 2% for GFRP and from 0.8 to 1% for CFRP. Based on the test's results [19] Fiko et al. [8] proposed to set the maximum allowable value of $\varepsilon_{f,lim}$ depending on the type of fibers. For AFRP stirrups $\varepsilon_{f,lim}$ should not be taken more than 0.7%, for CFRP and GFRP stirrups – more than 0.35% and 0.85%, respectively.

Experimental researches of FRP RC members mainly include testing beams with a rectangular cross-section [20–23]. In [16] the author tested 4 twin specimens reinforced with GFRP transverse reinforcement. The longitudinal reinforcement of the beams consisted of steel rebars. The tests were carried out by three-point bending with $a/d = 1.4$. During the tests, shear cracks in all cases occurred later than flexural at loading levels in the range of 23.9–34.6% of the failure load. Said et al. [24] tested 10 beams with cross-sectional dimensions 120×300(h) mm and GFRP bars as transverse reinforcement and longitudinal reinforcement of the tension and compression zones.

The stirrups in specimens were set at varying spacing. One of the beams had no transverse reinforcement. Flexural cracks within the zone with the largest bending moment appeared first. Then flexural cracks occurred in the shear span and grew into inclined cracks towards the load with increasing of the latter. The formation of inclined cracks took place within the range of 29.6–50.1% of the shear capacity. Before the failure, the width of the inclined cracks reached 1.5–3.5 mm. The cracking load and the shear capacity of the beams were calculated accurately by FE modeling using ANSYS software package.

Inclined cracks in I-shaped beams generally occur at midheight and subsequently develop towards the flanges. Such cracks are commonly called "web-shear cracks" whereas cracks in rectangular beams developing from tension flange are called "flexure-shear cracks" [25]. The amount of experimental data on the shear crack resistance of I-shaped beams with FRP reinforcement is significantly less than that for rectangular beams. Kurt et al. [26] tested 12 I-shaped beams (24 results for shear spans overall) reinforced with longitudinal and transverse FRP reinforcement. The specimens differed in concrete strength, type, diameter, and spacing of FRP transverse reinforcement. The measurement of the width of the inclined cracks was carried out by a non-contact optical 3D deformation measuring system Aramis and by using crack gauges. The author notes that the cracking pattern in the tested specimens is similar to that observed in RC beams. As the load increased the inclined cracks became flatter. Before the failure, the crack inclination angle ranged from 23 to 40 degrees. The maximum inclined cracks width reached 0.7–3.0 mm and the displacement along the cracks was 0.2–1.7 mm. Other authors [10, 18] carried out tests of T-shaped beams with FRP transverse reinforcement.

This paper studies the shear crack resistance with BFRP transverse reinforcement. To the authors' knowledge, the latter was never previously used for the research of web-shear cracking. In total twenty-eight I-shaped beams were manufactured and tested.
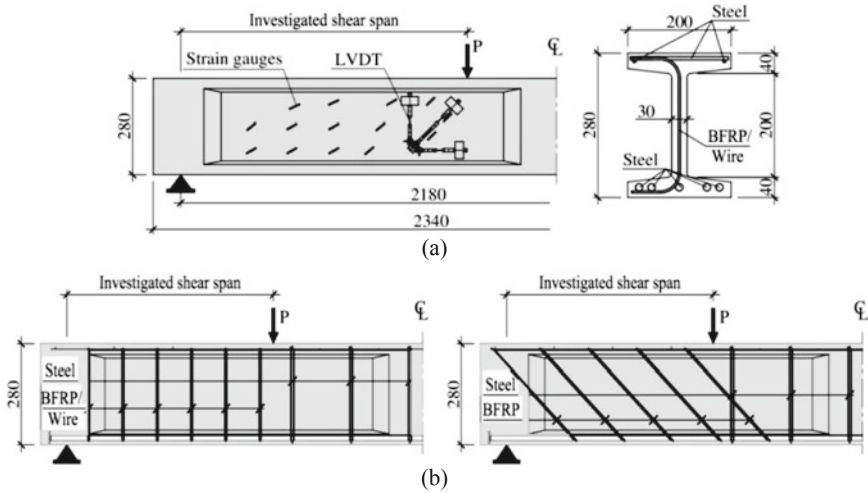
Fig. 1 Details of beams

2 Experimental Program

2.1 Test Specimens

Specimens had the total length 2340 mm (effective span 2180 mm) and total depth h = 280 mm (effective depth d = 260 mm). The flange width of the beams was 200 mm and the web width was 30 mm (Fig. 1a). The shear reinforcement of beams consisted of single bars anchored into the bottom and top flanges. Shear reinforcement was tied to longitudinal bars to form reinforcement cages. The beams differed in the angle of inclination of transverse FRP bars α_{sw} to the longitudinal axis and spacing of shear reinforcement (i.e. shear reinforcement ratio μ_{sw}). The group with shear span ratio a/d = 2.5 and 3.2 also included specimens with cold-drawn wire transverse reinforcement. Longitudinal reinforcement was identical for all beams (Fig. 1b). It consisted of steel bars Grade A500C in the amount sufficient to avoid flexural failure. Beams were tested in four-point bending with an a/d ratio equal to 1.6, 2.5, and 3.2. The list of beams, failure loads, and some parameters of crack resistance of beams are given in Table 1.

2.2 Material Properties

The beams were cast from normal strength concrete made of the M500 Portland cement (JSC "Verkhnebakansky cement plant", Novorossiysk). To ensure the good compaction of concrete for the web with small thickness, coarse aggregate with a

Table 1 Parameters of beams and shear test results

Beam	Type of stirrups	Q_{crc}, kN	α_{crc}, deg.	$\alpha_{crc\ cr}$, deg.	l_s, cm	$a_{crc\ ult}$, mm	Q_{ult}, kN	Mode of failure
B1.6-V-0.4	BFRP	7.7	33–39	39	3.9	0.46	54.9	WC
B1.6-V-0.7		7.5	32–39	35	3.1	0.48	57.6	WC
B1.6-V-1.0		14.7	41–43	41	3.5	0.44	77.4	WC
B1.6-V-1.3		16.4	36–42	36	3.1	0.63	71.5	WC
B1.6-N-0.4		13.6	40–42	40	4.8	0.78	61.7	WC
B1.6-N-0.7		13.1	44–48	45	3.2	0.33	62.1	WC
B1.6-N-1.0		14.5	38–41	38	3.4	0.44	76.2	WC
B1.6-N-1.3		13.4	44–47	44	3.1	0.39	70.5	WC
B2.5-V-0.4	BFRP	14.1	27–58	34	7.9	0.87	42.7	WC
B2.5-V-0.7		15.1	26–46	28	6.2	0.57	47.1	WC
B2.5-V-1.0		13.8	19–43	27	7.0	0.77	51.2	WC
B2.5-V-1.3		13.1	19–43	33	5.5	0.65	57.1	SR
B2.5-N-0.4		10.1	24–42	42	5.9	0.55	48.1	WC
B2.5-N-0.7		13.6	33–48	36	5.6	0.65	50.3	WC
B2.5-N-1.0		4.9	17–54	38	4.5	0.75	44.8	SR
B2.5-N-1.3		8.9	21–57	39	4.1	0.72	55.4	WC
BS2.5–1.0	Wire Vr500	15.6	33–46	35	5.0	0.35	65.1	WC
BS2.5–1.3		20.9	36–54	43	4.2	0.27	74.5	WC
B3.2-V-0.4	BFRP	6.8	24–48	25	4.5	0.98	42.5	SR
B3.2-V-0.7		11.2	28–49	42	3.6	0.60	48.7	WC/SR
B3.2-V-1.0		9.0	17–45	22	6.0	0.87	47.2	SR
B3.2-V-1.3		12.3	25–58	43	4.6	0.55	47.4	SR
B3.2-N-0.4		11.1	26–42	33	5.9	1.18	42.8	WC
B3.2-N-0.7		16.0	20–55	29	3.9	0.57	50.1	SR
B3.2-N-1.0		11.1	21–46	39	6.1	0.60	46.3	WC
B3.2-N-1.3		15.2	29–46	37	4.5	0.37	56.2	WC/SR
BS3.2–1.0		15.6	31–39	39	5.1	0.47	62.5	WC
BS3.2–1.3		19.8	32–45	40	4.1	0.30	70.8	WC

Note: α_{crc} – range of shear cracks angle; $\alpha_{crc\ cr}$ – angle of critical shear crack, l_s – average distance between shear cracks, WC - web crushing, SR – stirrups rupture

size of 3–10 mm was used for a concrete mix. The sand size modulus was 2.3, the content of clay and organic particles did not exceed 1.2%. The compressive strength of concrete was determined by testing prisms with the dimensions of $100 \times 100 \times 400$ mm at the age of 28 days and was in the range of $R_b = 24.1 \div 30.7$ MPa.

Basalt fiber-reinforced polymer bars with a diameter of 4 and 6 mm and cold-drawn wire with a diameter of 4.0 mm were used as transverse reinforcement of

specimens. For BFRP bars standard tensile tests were carried out according to GOST 31,938-2012 with the calculation of the ultimate strength σ_t, the modulus of elasticity E_f, and the elongation at fracture ε_t. Tested samples were straight BFRP bars with steel couplings on their ends designed for clamping these couplings with the grips of the tensile testing machine (Fig. 2). The elongation of the bars was measured with strain gauges. Obtained mechanical characteristics of BFRP bars are summarized in Table 2.

Bending of FRP rebars is possible only during their manufacturing. Precast C-shaped shear BFRP reinforcement with a diameter of 4 and 6 mm for our experiment was provided by LLC "NZK" (Nizhny Novgorod). It is known that a small mandrel diameter of FRP rods can lead to their premature rupture in the bent zones [15].

According to ACI 440.1R-15 [1], the radius of the bend should not be less than 3 diameters d_b of the bar. In Russian building code SP 295.1325800.2017, a similar minimum is set as $6d_b$. Some researchers recommend that the bending radius of the FRP should be at least $4d_b$, but not less than 50 mm [10]. In our research C-shaped BFRP bars (Fig. 3) had a bending radius equal to 35 mm, i.e. not less than the value specified by the aforementioned codes. As a result, the rupture of transverse reinforcement in the bent zone did not happen in any of the tested beams.

Fig. 2 BFRP rods before and after standard tensile tests

Table 2 Mechanical properties of BFRP bars

Bar diameter, mm	Tensile strength σ_t, MPa	Tensile strain ε_t, %, not less than	Modulus of elasticity E_f, MPa
4	1305	1.98	65,916
6	1377	2.07	66,524

Fig. 3 C-shaped BFRP transverse reinforcement

Table 3 Mechanical properties of wire Vr500 bars

Bar diameter, mm	Proof strength $\sigma_{0.2}$, MPa	Tensile strength σ_{vr}, MPa	Elongation per unit length, %, not less than	Var. coeff. of tensile strength ν_{vr}, MPa	Modulus of elasticity E_f, MPa
4.0	664	706	2.6	0.078	$2.01 \cdot 10^5$

Mechanical characteristics of wire Vr500 were determined according to GOST 12,004-81. For testing 15 samples were taken from the same bundle, which meets the requirements of GOST 6727-80. The average values of the mechanical characteristics of wire are given in Table 3.

2.3 Instrumentation, Test Setup and Procedure

The beams were tested in a closed load-bearing frame in the structural laboratory of the Department of building structures of Kuban State Technological University. The specimens were placed with compressed flange down which made the control of formation and development of cracks more convenient. The load was provided by a hydraulic jack connected to a pump station. The magnitude of the support reaction was monitored by load cells. Deflections of beams on supports and in the middle of the span were measured by high-sensitivity strain gauge displacement transducers. Concrete strains within the shear span were measured with strain gauges glued along the assumed direction of principal compressive stresses. Three LVDT sensors were attached in the form of a rosette at the expected location of an inclined crack on one side of the beams for measuring strains. Another LVDT sensor on the opposite side of the beam measured the displacement along the shear crack. All measuring devices were connected to the TDS-530 data logger (TML).

3 Results and Discussion

No relationship between the shear force at first cracking Q_{crc} and the angle of inclination α_{sw} of the transverse reinforcement was found (Fig. 4). For both vertical and inclined shear reinforcement (Fig. 4a and 4b), Q_{crc} was about 10–33% of the failure load Q_{ult}. For beams with steel reinforcement (Fig. 4c) Q_{crc} was 15.6–20.9 kN (24–28.1% of Q_{ult}).

Analysis of the test results revealed the following patterns for the Q_{crc} value:

- with an equal value of μ_{sw} inclined cracks in beams with steel transverse reinforcement occurred at higher loads than in FRP RC beams. On average, for beams with steel transverse reinforcement Q_{crc} was 54% larger;
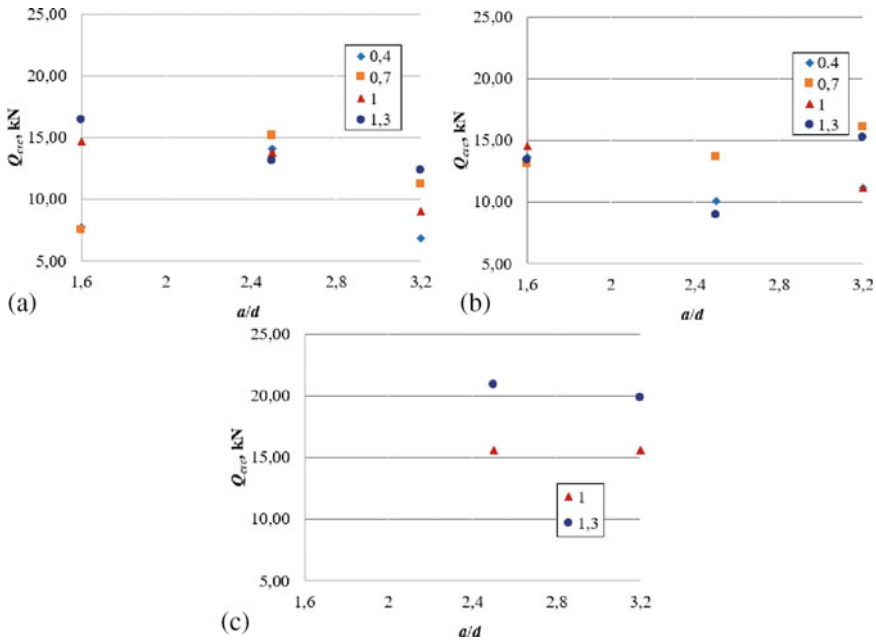
Fig. 4 Shear force at first web cracking for the FRP RC beams with inclined (a) and vertical (b) stirrups and for the RC beams (c)

– with an increase in *a/d* the Q_{crc} decreased. When *a/d* changes from 1.6 to 2.5, the decrease of Q_{crc} is more evident than when in the range of *a/d* from 2.5 to 3.2 for all angles of inclination of the FRP stirrups. In the latter case, for samples with inclined FRP stirrups, there is virtually no decrease of the Q_{crc}.

Cracks in specimens with FRP transverse reinforcement formed mainly at the midheight and propagated to the flanges (web-shear cracks). In most cases, the first shear cracks were located in the middle of the shear span, less often in areas close to the load. As a rule, cracks reached the flanges of the beams several steps after their emergence, but in some cases, they immediately propagated through the entire height of the web. One to three cracks in the shear span initially occurred, the total number of cracks in the shear span in most cases did not exceed 6–8.

During loading with a small shear span (*a/d* = 1.6) cracks occurred parallel to each other, forming 1–2 concrete struts in the direction between the load and the support. In specimens with *a/d* = 2.5 and 3.2 in the areas close to the supports and the loading points, cracks had a fan-shaped pattern, and in the middle of the shear span, the cracks were parallel to each other.

Some crack resistance characteristics of beams are shown in Table 1. The range of values for the maximum shear crack width $a_{crc,ult}$ before the failure was 0.44–0.98 mm for beams with vertical FRP stirrups, 0.33–1.18 mm for inclined FRP stirrups, and 0.27–0.47 mm for specimens with steel stirrups (Fig. 5).
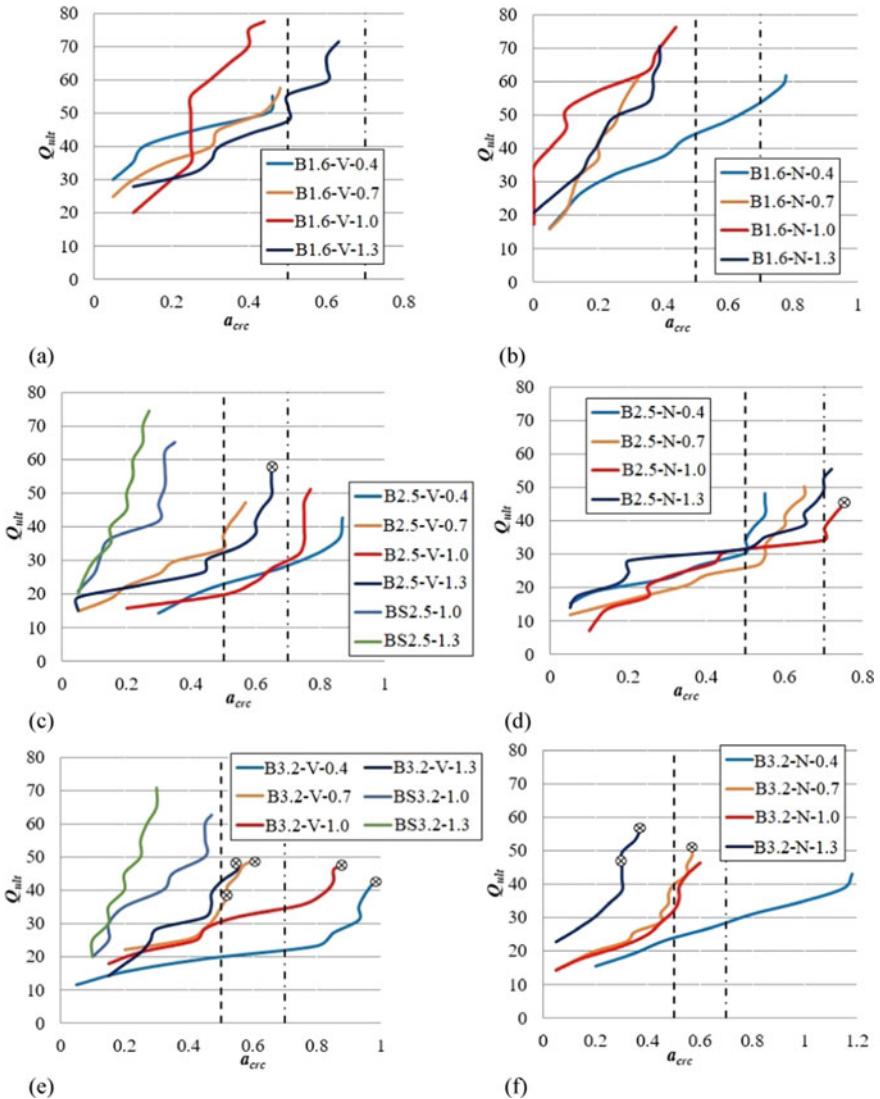
Fig. 5 Shear crack widths of the specimens

The shear crack spacings decreased with an increase in the percentage of transverse reinforcement and ranged from 3.1 to 7.9 cm for FRP RC beams and from 4.1 to 5.1 cm for steel RC members.

As can be seen from Table 1, the angle of the shear cracks' inclination to the longitudinal axis of the FRP RC beams was in the relatively wide range of 17–58 degrees. Critical shear cracks formed at an angle of 22–45 degrees. For specimens with steel transverse reinforcement, these angles were in the range of 31–54 degrees

and 35–43 degrees, respectively. Thus, the angles of inclination of the critical shear cracks correspond to the values provided by the truss analogy adopted in the standards of the American Concrete Institute [1, 9] and Eurocode [27].

The previous research conducted in KubSTU showed that the crack width in I-shaped beams with steel and mesh shear reinforcement increased with increasing the shear span, and the relationship was nonlinear [28]. For our beams, with the change shear span from $1.6d$ to $2.5d$ maximum crack width increased on average 1.47 and 1.84 times for the vertical and inclined FRP transverse reinforcement respectively. With a further increase of shear span up to $3.2d$, the growth of maximum crack width $a_{crc,ult}$ was less noticeable, and in one case, for beam B3.2-N-1.3, the $a_{crc,ult}$ was smaller than for a similar beam tested with a smaller shear span $2.5d$.

The values of $a_{crc,ult}$ in beams with inclined stirrups were slightly lower than those of the specimens with vertical stirrups. The corresponding difference of $a_{crc,ult}$ between twin beams differing only in α_{sw} was up to 10% and was more pronounced for beams with $a/d = 3.2$. This is explained by the fact that with an inclined arrangement of shear reinforcement, its angle with respect to the web cracks approaches 90º, and thus the development of tensile strains is better restrained.

In Fig. 5 it can be seen that the maximum crack width for FRP RC specimens, most times did not exceed 0.8 mm, in some tests reaching a value of 1–1.2 mm. In latter cases, the failure occurred mainly due to the rupture of the stirrups. Beams with wire transverse reinforcement showed a smaller value of the $a_{crc,ult}$, averaging 0.35 mm with a maximum value of about 0.5 mm.

4   Conclusion

There is no unified approach in different building codes for FRP-RC members to assign the allowable crack width. The Russian SP 295.1325800.2017 "Concrete structures reinforced with fiber-reinforced polymer bars. Design rules" establishes the following allowable values of crack width: for short-term opening 0.7 mm, for long-term opening −0.5 mm (shown with vertical lines in Fig. 5). In Japanese [29] and Italian [30] codes, the allowable crack width is set at 0.5 mm. Canadian guidelines [31] the limit is 0.5 mm for structures exposed to harsh conditions and 0.7 mm for other cases. These requirements are mainly aimed at restricting the width of flexural cracks. The values of the maximum web-shear cracks width of the tested I-shaped FRP-RC beams demonstrate that even at high loads $a_{crc,ult}$ in most cases is less than the specified limit values. Significant (up to 30%) exceedance of those limits are cracks in beams with the lowest shear reinforcement ratio. Taking into account also the fact that the crack resistance calculations are made for the service loads, the openings of the inclined cracks observed in our tests can be considered acceptable. Thus, the relatively lower elastic modulus of FRP should not be considered a shortcoming hampering its use as shear reinforcement of I-shaped beams.

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