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CRACK RESISTANCE OF RC COLUMNS STRENGTHENED BY CFRP UNDER 30% OF ULS LOADING

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Abstract: Nowadays, among many existing reinforced concrete (RC) columns, it is impossible to find samples that work only as centrally compressed members – their vast majority work as eccentrically compressed members. On the other hand, the significant volumes of reconstruction in Ukraine will require studies of the work of various RC structures strengthened under different load levels. In addition to choosing the method of strengthening itself, the relevant tasks will be studies of bearing capacity, crack resistance, reliability (including residual resource) of structures, etc. This article presents the method of crack resistance experimental study of eccentrically compressed RC members. The proposed method was tested on unstrengthened (ordinary) and strengthened (in a stretched zone) RC columns; the results of experimental studies for ordinary and strengthened samples were also obtained. The columns were strengthened with a composite material (from many carbon-fiber-reinforced polymers) – the Sika Carbodur S512 strip. The feature of the crack resistance study of columns was that they were strengthened under the initial load level of 30 %. As a result of experimental research on the samples strengthened under load, we stated that the width of the crack decreased on average by about 36 % (at the comparable values of the active load). In turn, the average maximum length of cracks decreased to about 50 % of the height of the cross-section (for unstrengthened samples, this value was approximately 80 %), and the eccentric compressive ultimate load was increased by about 33 %.
Keywords: CFRP strip, crack resistance, strengthening, initial load level, RC column.

1. INTRODUCTION

Among many existing RC columns, it is practically impossible to find samples that work only as centrally compressed members – their vast majority work as eccentrically compressed members (Vatulia et al., 2020; Yakovenko et al., 2022). For some eccentricity values, the stretched zone can reach sufficiently large sizes, which makes it necessary to add new reinforcement when strengthening members; furthermore, the large volumes of reconstruction in Ukraine (heavily destroyed by military actions) will require studies of the work of various RC structures strengthened under different load levels (Dmytrenko et al., 2016; Krynke, 2019; Dmytrenko et al., 2023, Semko et al., 2023).

Today, the fundamental issues of studying the characteristics and design of the concrete composition, corrosion rate, distribution of microcracks in steel members, and approaches to the RC structures' reconstruction are described and analyzed in many works (Blikharskyy et al., 2021a, 2021d; Lenkovskiy et al., 2017; Helbrych, 2021; Kobaka and Katzer, 2022; Ostash et al., 2011; Koteš et al., 2023; Lipiński, 2021; Lipiński and Wach, 2020; Zahuranec et al., 2023; Czajkowska et al., 2023; Popławski, 2020; Nikolić, 2020; Ulewicz et al. 2013). In the case of the need for reinforcement of various RC structures (Blikharskyy et al., 2019; Blikharskyy et al 2021c; Kos et al., 2017; Vegera et al., 2021; Ilnytskyy et al., 2019; Selejdak et al., 2018, Katunský et al., 2015), one of the methods is to increase the stretched reinforcement percentage (Andriichuk et al., 2021; Bobalo et al., 2021; Kolchunov et al., 2016). Nowadays, RC jacketing (Krainskyi et al., 2020) is often used for columns at strengthening – but this method has several disadvantages, particularly in terms of jacket arrangement technology. The technique of installation of a layer of fibre reinforced concrete is also widely used today (Koteš et al., 2020; Koteš et al., 2022).

There are many proposals for high-strength, lightweight, and easy-to-mount materials used on the market recently (most often for RC structures strengthening). One such method of strengthening is reinforcement using composite materials (Pham et al., 2013; Selejdak et al., 2021; Torabian and Mostofinejad, 2017). This method describes the arrangement of composite reinforcement (in the strip form) on the outer stretched face of the slab, beam, or column using high-strength paste and anchoring devices if necessary. The simultaneous action issue of steel reinforcement and CFRP strip is currently insufficiently studied – mainly due to the problem of various deformability of these materials.

In our case, during the theoretical calculation of the strengthened structure, many points require additional studies, including the main one – the impact of joint work of both the steel reinforcement and the external CFRP strip on the dynamics of opening and the distribution's nature of cracks. This is one of the reasons for the limited number of studies in the work field of compressed and eccentrically compressed RC members strengthened with external composite materials (Benzaid and Mesbah, 2013; Blikharskyy et al., 2018; Gajdosova and Bilcik, 2013; Hadi, 2010; Selejdak et al., 2020). However, it should be noted that some works are also devoted to the problems of assessing the non-failure and durability of RC structures (including strengthened ones) (Khmil et al., 2021; Tytarenko et al., 2023).

The equally important issue that needs further study is the influence on the RC member's operation of the actual load level during strengthening – after all, in real conditions, all structures at strengthening carry some operational load.

Based on the above, we state the topic relevance and formulate the following goals of our study:

- to compare the crack resistance of RC samples of columns – unstrengthened and strengthened with CFRP system (the Sika Carbodur S512 strip);

- to identify the effectiveness of strengthening by the carbon strip (under the initial load level of 30 % at the moment of strengthening) in comparison with the ordinary (unstrengthened) samples.

2. METHODOLOGY OF RESEARCH

Experimental samples of columns (2200x180x140 mm in size) were made to achieve the aim. At the ends of columns, cantilevers were designed to transmit vertical load eccentrically (in our study, the accepted eccentricity was equal to 150 mm). During the production period, the specific bonds were attached to reinforcing bars, which, in turn, were assigned to mechanical devices fastening (to determine the steel reinforcement deformations). The reinforcing bars were also tested (Blikharskyy et al., 2021b). The test samples' construction with steel reinforcement is demonstrated in Fig. 1.

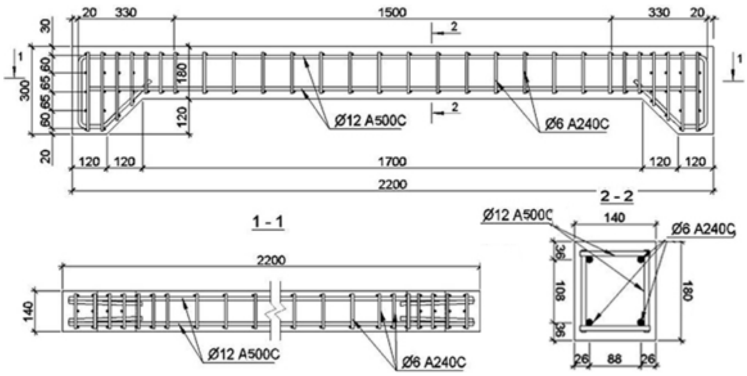

Fig. 1. The test samples' construction with steel reinforcement

The carbon strip was fastened to the column's stretched face (under the initial load level of 30 % at the moment of strengthening). Before pasting, the prepared wrap and strip were "activated" via pre-cleaning their surfaces with "Colma Reinger" specific liquid solution (activation time was equal to 30 min.). To provide the strip fixing, two layers of SikaWrap 230 fabric were applied within the cantilever zones (see Fig. 2).

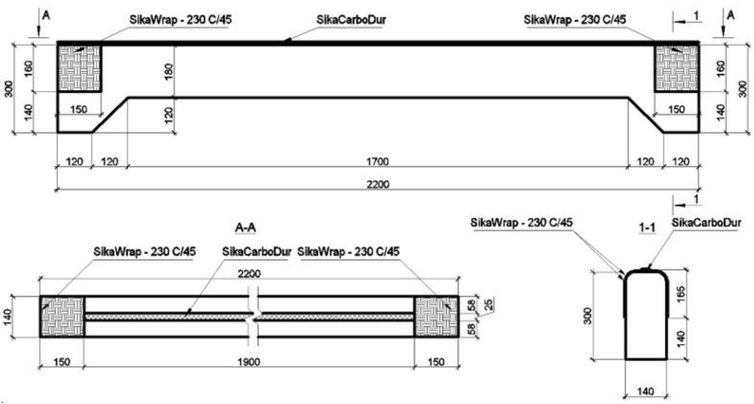

Fig. 2. The test samples' construction, strengthened by the CFRP system

In turn, for pasting Sika Wrap 230 fabric to columns, we used two-component epoxy-based thixotropic Sikadur 330 impregnating resin, consisting of A and B parts (the proportion A/B = 4/1). We mixed the parts for 3 minutes using a mixing spindle, connected to a slow-speed electric drill (maximum 600 rpm.) – till the material became a uniform grey color. After applying the Sikadur 330 paste on the surface with a trowel, we placed the SikaWrap 230 fabric in the needed direction; then, parallel to the fiber direction, we carefully pushed the fabric in the resin using a roller – till the resin penetrated through and between the fiber of the fabric.

Further, for pasting the Sika Carbodur S512 strip to columns, we used two-component epoxy-based thixotropic Sikadur 30 impregnating resin, consisting of A and B parts (in this case, the proportion A/B = 3/1). Then, we mixed the parts (by analogy, as for Sikadur 330 resin) and applied the Sikadur 30 paste along the column's length (from the side of the stretched face) with a trowel. After this, we placed the Sika Carbodur S512 strip in the needed direction (on top of the Sikadur 30) and pressed the strip to the sample (using a roller). Finally, after picking up excess resin with a trowel, the second layer of SikaWrap 230 fabric was applied one day later using the described above technique. Thus, using this way, all experimental samples were strengthened (under the initial load level of 30 %) by the Sika Carbodur S512 strip.

The strip's parameters were as follows:

- for strength and deformability – f_{fk} = 3.0×10^3 MPa, ε_{fuk} = 1.70 %, f_{fd} = 2.08×10^3 MPa, ε_{fuk} = 1.30 %, and E_S = 1.6×10^5 MPa;
- for geometry – width b = 25.0 mm, thickness t = 12.0 mm, and cross-sectional area A_S = 30.0 mm^2.

The marking for test samples was chosen: column ordinary (unstrengthened) – C (or CU); column strengthened under load with a carbon strip – CS. The 1st digit in the numbering of samples determines the batch number, the 2nd digit – the sample's number in the batch, and the number after the hyphen – determines the load level at the moment of strengthening.

According to the experimental research program, four columns were tested: two unstrengthened samples (CU-0.1, CU-0.2) and two samples strengthened under load by CFRP (CS-1.5-0.3, CS-1.6-0.3).

Strengthened columns were tested till failure. The load, in turn, was transferred by the hydraulic jack (loading control was carried out with a mechanical dynamometer). Loading was transferred by 10 kN steps (time between steps – 15 minutes). All columns were tested in the horizontal placement (see Fig. 3).

Fig. 3. Test stand with eccentrically compressed RC column

During the test, the cracks' occurrence was fixed at each step, and their opening width was also identified (using a microscope of MPB-2M mark).

3. RESULTS

The nature of the cracks' formation and distribution for unstrengthened columns (CU-0.1, CU-0.2) are demonstrated in Fig. 4. Cracks were determined at the level of the stretched reinforcing bars. The maximum value of crack width was 0.25 mm (that doesn't exceed the normative limit values). The cracking moment was at a load of about 40 kN.

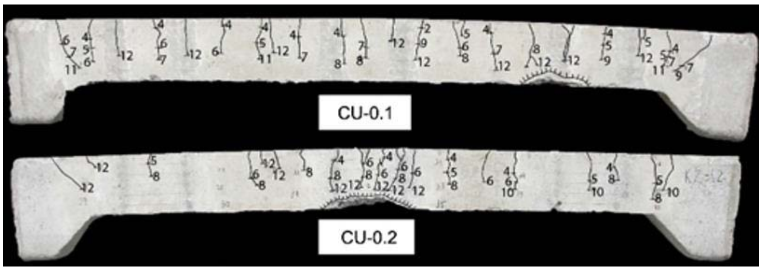

Fig. 4. The nature of the cracks' formation of the null batch samples

In Fig. 5, the numbers from 4 to 12 marked the load step (at which the cracks were distributed). Cracks were distributed along the samples' length almost evenly. The cracks' maximum length (at the columns' destruction moment) was about 80 % of the height of the cross-section.

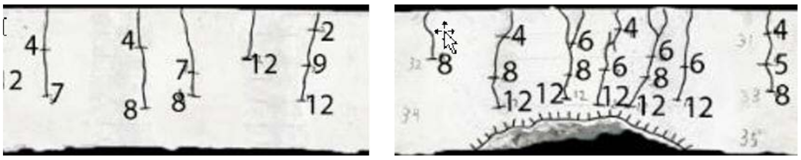

Fig. 5. The nature of the cracks' formation in the central zone of the samples of the null batch – CU-0.1, CU-0.2 (left and right in accordance)

Samples of columns of the 1st batch (strip width is 25 mm) – CS-1.5-0.3, CS-1.6-0.3 marks – strengthened under the initial load level of 0.3 (30 %). In the case of testing columns strengthened under load, the nature of the cracks' distribution and opening was different – after strengthening, the development of cracks occurred with a lower intensity (see Fig. 6).

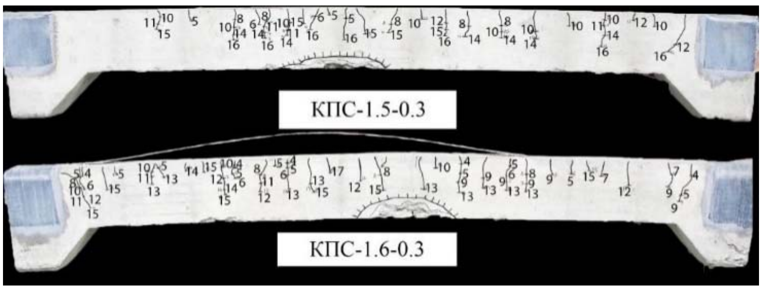

Fig. 6. The nature of the cracks' formation of the 1st batch samples (strengthened by CFRP under the initial load level of 30 %)

As in the case described above (for unstrengthened columns), cracks here were also determined at the level of the stretched reinforcing bars. The cracks' maximum length was less – about 50 % of the height of the cross-section.

In strengthened samples of columns (CS-1.5-0.3, CS-1.6-0.3), the maximum value of crack width was 0.30 mm (vs. 25 mm in unstrengthened samples), but at a higher level of ultimate load (160 kN vs. 120 kN).
In the comparative Table 1 below, we summarized the basic parameters of crack resistance for unstrengthened and strengthened (with a carbon strip under the initial load level of 30 %) samples of columns (by the experimental data).

Table 1
Comparison of the basic parameters of crack resistance for unstrengthened and strengthened (with a carbon strip under the initial load level of 30 %) samples of columns (by the experimental data)

Load [kN]	**Limit crack width w_k for the column's sample [mm]**						**Effect of strengthening [%]**
	CU-0.1	**CU-0.2**	**CU-0 (aver.)**	**CS-1.5-0.3**	**CS-1.6-0.3**	**CS-1 (aver.)**	
0.0	-	-	-	-	-	-	-
20.0	-	-	-	-	-	-	-
40.0	0.050	0.050	0.050	**0.050**	**0.050**	**0.050**	-
60.0	0.100	0.100	0.100	0.100	0.100	0.100	0
80.0	0.150	0.150	0.150	0.050	0.100	0.075	50
100.0	0.200	0.150	0.175	0.050	0.150	0.100	43
120.0	0.250	0.250	0.250	0.100	0.150	0.125	50
140.0	-	-	-	0.150	0.200	0.175	-
160.0	-	-	-	0.150	0.300	0.225	-

Note to the Table. 1: the width of the cracks opening in the test samples at the moment of their strengthening with a carbon strip is highlighted in bold.

The dependence of the crack width on the active load for test samples is also demonstrated on the graph (see Fig. 7).

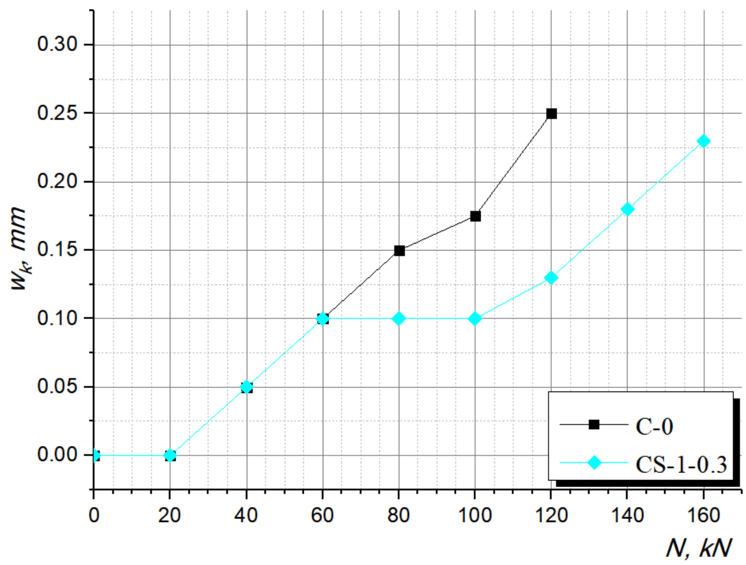

Fig. 7. The crack width of the columns' samples for the null and 1st batches (depending on the active load)

4. DISCUSSION

In the test samples of columns strengthened under the initial load level of 0.3 (30 %), the moment of crack formation occurred at the active load of about 40 kN – this is approximately the same value at which cracks opened in unstrengthened samples (explained by the fact that the test sample was brought to the load of 40 kN without pasting the strip).

After strengthening, the distribution of cracks occurred with lower intensity (in comparison with the identical load steps of unstrengthened samples) (see Fig. 4–6, Table 1) – this is typical for all strengthened test samples. At higher load levels, the maximum width of the crack decreased – for example, at the load of 120 kN, the limit width in unstrengthened samples was 0.25 mm, and in strengthened ones under the initial load level of 0.3, it was 0.15 mm (primarily, this is explained by the effective inclusion of the carbon strip in work). The average maximum length of cracks decreased to about 50 % of the height of the samples' cross-section (for unstrengthened samples, this value was approximately 80 %), and the eccentric compressive ultimate load was increased by about 33 % – from 120 to 160 kN (see Table 1).

5. CONCLUSION

- Strengthening the eccentrically compressed RC columns with the different CFRP systems (in our case, the Sika CarboDur carbon strip) can give positive results: the study found that the carbon strip begins to work almost simultaneously with the main steel reinforcing bars.
- When strengthening columns with the Sika CarboDur carbon strip (under the initial load level of 0.3), the width of the crack decreased on average by about 36 % – at the comparable values of the active load. The eccentric compressive ultimate load was also increased for strengthened columns (160 kN vs. 120 kN).
- The strengthening carbon strip has a noticeable deterrent effect: not only do the cracks near the strip not appear, but the limit width of the crack is moved from the outer face. In addition, the intensity of the possible influence of an aggressive environment via cracks on the column's steel reinforcing bars is also reduced.
- Based on the above, we recommend using composite reinforcement (including CFRP systems) as strengthening in further studies of the load-bearing capacity, crack resistance, or reliability of RC compressed-bent members.

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