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STRENGTHENING OF SLAB-COLUMN CONNECTIONS WITH CFRP STRIPS

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The paper describes experimental research of slab-column connections examined on specimen designed as a part of reinforced concrete structure with flat slabs. The aim of the research was to verify the efficiency of slab reinforcement concept against punching shear by increasing slab's mechanical reinforcement ratio by applying additional external reinforcement in the form of carbon fiber reinforced polymer (CFRP) strips.

The capacity enhancement in comparison to unstrengthened slab obtained 36%.

Key words: concrete, punching, slab, CFRP, strengthening, external reinforcement.

1. INTRODUCTION

Structures with flat concrete slabs have been commonly used in civil engineering for the last few decades. This type of structure has many advantages, which are the reason of its popularity and noticeable success, such as freedom in arranging buildings' interiors or simplicity of structure construction. The scale of the structure causes rising danger and great possibility of mistakes that occur during the design and construction process.. A practical example of this problem was described in paper [1]. Moreover, many of completed buildings already need rebuilding or strengthening because of changing of their function and purpose, which also involves upgrading them to the latest, usually more rigorous, codes and standards. All mentioned above problems gather rising interest of designers and researchers to the methods of strengthening flat concrete slabs against punching shear failure.

Support area is the most exhausted zone of the whole slab and the punching issue is the key problem of the safety of the structure. Usually, punching strength decides about the load carrying capacity of the whole slab and all failures mostly initiate in the support area.

The punching issue in the reinforced concrete structures is very complex, depending on many factors. The most significant are geometrical proportions of a slab-column connection (d/c), concrete and steel characteristics (f_c, f_y), slab reinforcement ratio (ρ_l),

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presence of transverse reinforcement (ρ_w), etc. A choice of the strengthening technique is conditioned by above mentioned parameters and technical abilities of the field work. Suggestions in this matter were introduced in papers [2, 3, 4], where different approaches and techniques of strengthening of the slab-column connections were described. While the strengthening method using flat steel as additional external reinforcement was presented in paper [5].

As one of the first publications in the field of strengthening flat reinforced concrete slabs against punching shear failure was presented in the paper by *Hassanzadeh* and *Sundqvist* in 1998 [6]. The authors introduced three different techniques of strengthening of reinforced concrete slabs against punching shear failure, because of lack of the transversal reinforcement (see Fig. 1).

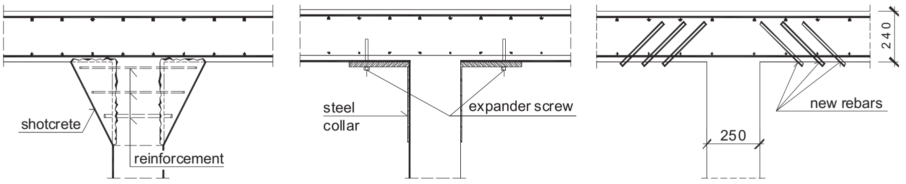

Fig. 1. The techniques of strengthening against punching shear failure proposed by *Hassanzadeh* and *Sundqvist* [6].
Rys. 1. Sposoby wzmacniania płyt na przebicie zaproponowane przez *Hassanzadeh* i *Sundqvist* [6]

The following investigation in the raised issue of strengthening was the paper of *Ebead* and *Marzouk* in 2002 [7], which introduced the method of strengthening of the internal slab-column connection by steel plates and screws (see Fig. 2).

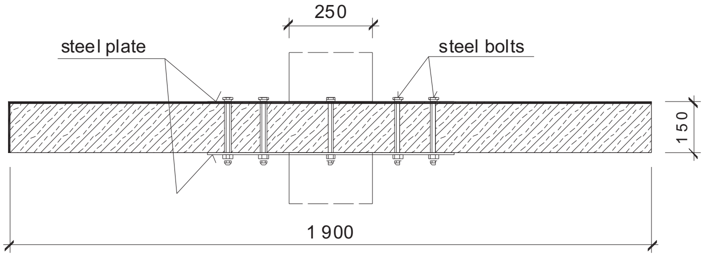

Fig. 2. The strengthening of flat concrete slabs against punching shear by *Ebead* and *Marzouk* [7].
Rys. 2. Wzmocnienie płyty żelbetowej na przebicie wg *Ebead* i *Marzouk* [7]

Polak *et al.* [8, 9] introduced a new technique of slab-column connections strengthening against punching shear by shear bolts placed in the previously drilled openings in the support zone. The idea of this solution is presented in Fig. 3. The results of the experimental research, for the edge column and internal slab-column connections, were published in 2003 [8] and in 2005 [9], respectively.

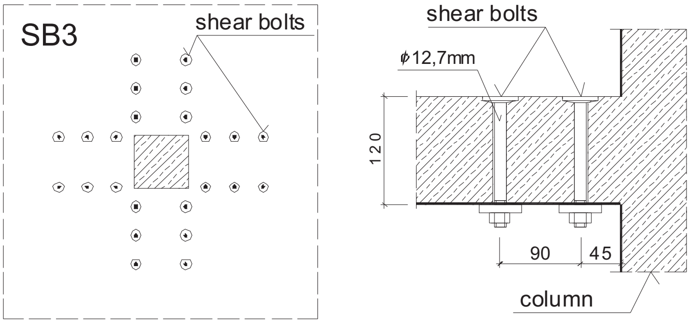

Fig. 3. A method of strengthening of slab-column connection against punching shear by transverse reinforcement [8] and [9].
Rys. 3. Metoda wzmacniania połączeń płyta-słup na przebicie za pomocą zbrojenia poprzecznego [8] i [9]

Recently, composite materials are often used for strengthening of reinforced concrete structures. A special consideration in this matter deserve carbon fiber reinforced polymer (CFRP) strips. One of the latest tests using this material for strengthening of the support areas was carried out by SOUDKI and VAN ZWOL [10], and BINICI *et al.* [11, 12, 13]. Figure 4 shows the RC specimens strengthened with CFRP strips [10].

According to the authors' report, all test specimens failed abruptly, which is characteristic failure mode for punching shear. The specimens strengthened with CFRP strips provided an increased punching shear resistance in the range from $2,2$ up to $29,1\%$ over the reference slab. The largest increase in the load carrying capacity was registered for Slab 4. The CFRP application in the offset to column face configuration resulted in a greater increase of punching shear resistance than that for the specimen with CFRP strips adjacent to the column outline.

The interesting outcome from the research are the strain measured in the CFRP strips during ultimate load. The maximal registered strain in the Slab 4 reached $3,55^0/_{00}$ and in the remaining models the maximal CFRP strain was approximately $2,85^0/_{00}$, which is about $0,15$ of the CFRP tensile strain.

Binici and *Bayrak* in the research published in 2003 [11] and in 2005 [12] presented an idea of using CFRP materials as a transversal reinforcement for strengthening of the support areas of the existing slab-column connections. Their solution consisted of internal stirrups made of CFRP tow sheet, as it is shown in Fig. 5.

2. THE PROGRAM OF OWN INVESTIGATION

Presented study was undertaken to evaluate the possibility of increasing two-way shear capacity of the internal slab-column connection by increasing the mechanical reinforcement ratio ($\rho_l\ f_y\ /\ f_c$) through adding additional external CFRP strips. Assumption for

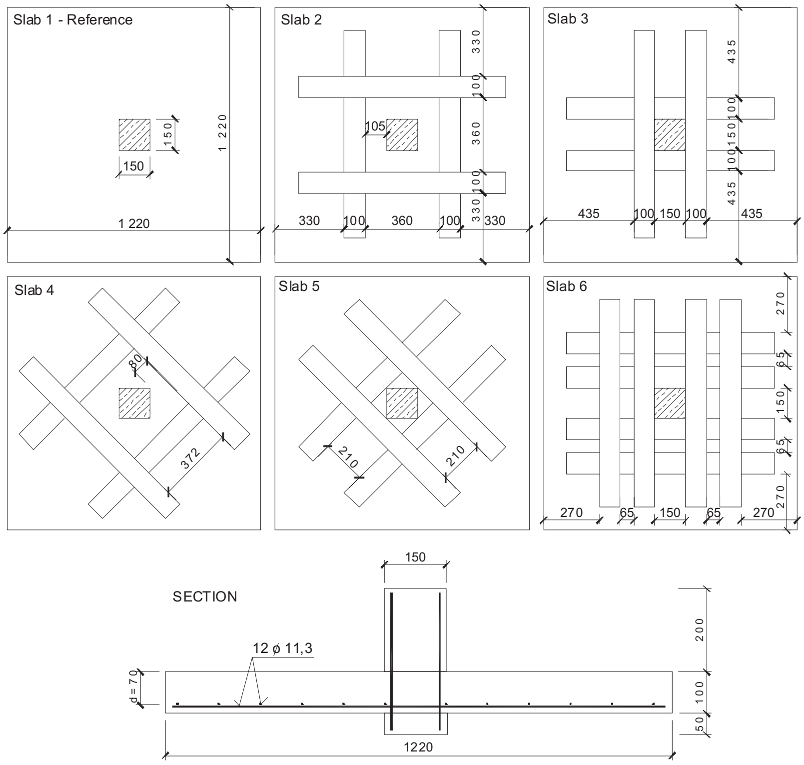

Fig. 4. The test model [10].
Rys. 4. Model badawczy [10]

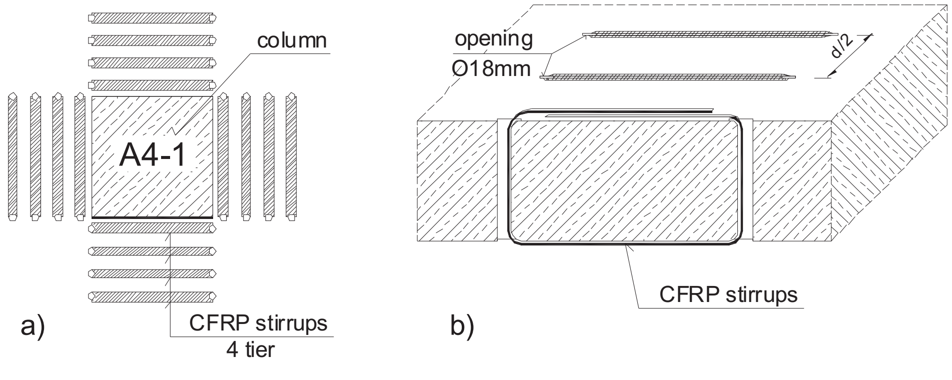

Fig. 5. An idea of CFRP stirrups according to *Binici* and *Bayrak* [11, 12]: a) an example of stirrup location around the column, b) a stirrup detail.
Rys. 5. Idea strzemion CFRP według *Binici* i *Bayrak* [11, 12]: a) przykład usytuowania strzemion wokół słupa, b) detal strzemienia

this method of strengthening is based on a numerous experimental results, shown in Fig. 6. In the publication [3], the relation between punching resistance and ($\rho_l\ f_y\ /\ f_c$) was proven. The punching shear stress along the control section depends on reinforcement ratio for longitudinal reinforcement (ρ_l), which therefore shows the influence of the main reinforcement on punching shear resistance. Taking this fact into consideration, the authors tried to implement a strengthening technique for flat reinforced concrete slabs against punching shear failure by increasing the reinforcement ratio. According to Fig. 6, the efficiency of this concept is more significant in case of slabs with low reinforcement ratio for main longitudinal reinforcement (low mechanical reinforcement ratio $\rho_l\ f_y\ /\ f_c$).

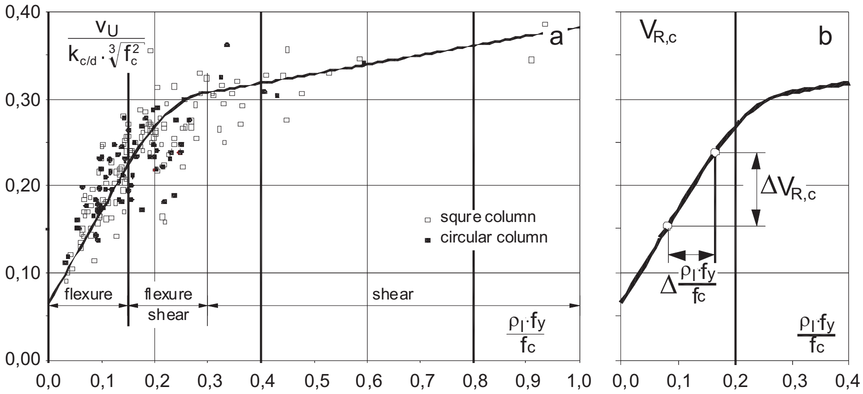

Fig. 6. Punching versus reinforcement mechanical ratio: a) standardized critical stresses v_u in calculated section (distance of $d/2$ from column face) versus reinforcement mechanical ratio according to [3], b) the rule of strengthening for punching shear with the increase of reinforcement mechanical ratio.

Rys. 6. Przebicie w funkcji mechanicznego stopnia zbrojenia: a) standaryzowane naprężenia krytyczne v_u w przekroju krytycznym (w odległości $d/2$ od lica słupa) w funkcji mechanicznego stopnia zbrojenia według [3], b) zasada wzmacniania na przebicie poprzez zwiększenie mechanicznego stopnia zbrojenia

Figure 7 shows a typical reference specimen before strengthening.

Experimental schedule consisted of 4 RC specimens casted from the same batch of concrete and with identical amount of reinforcement bars. Each specimen was cast as a square slab with the overall dimensions of 2,3m by 2,3m and 180mm thick. Additionally, each slab was bonded to a small fragment of a square column on the compression side of the slab.

Steel reinforcement was made of the A-IIIN class steel. Bottom reinforcement mesh was composed of Ø8 steel bars, whereas the top reinforcement mesh was made of Ø12 bars. Both top and bottom reinforcement had identical axial spacing of 150mm. Geometrical reinforcement ratio of the slab was about 0,5%.

Table 1 shows the configuration of external reinforcement applied during investigation.

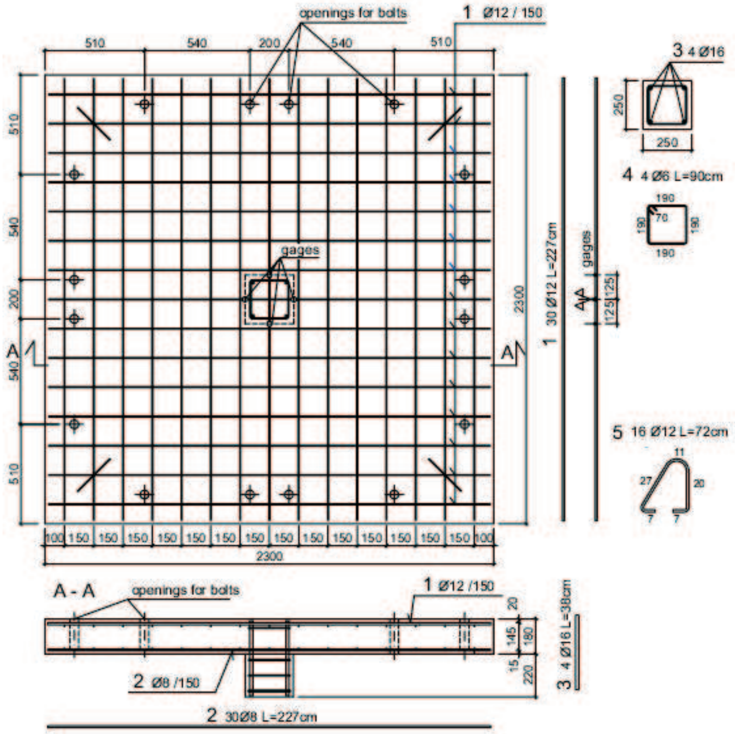

Fig. 7. The model before strengthening
Rys. 7. Zbrojenie modeli przed wzmocnieniem

Table 1

The configuration of external reinforcement applied during investigation.
Specyfikacja zbrojenia zewnętrznego

Specimen	Number of CFRP strips	Type of external reinforcement
S-2	–	–
WT-CF-8	8	strips bonded to the slab
WT-CF-K-8	8	strips bonded to the slab and additional M10 anchoring bolts
WT-CF-K-16	16	two layers of strips bonded to the slab and additional M10 anchoring bolts

Specimen dimensions were chosen to simulate a part of the real structure with the location for the radial moment equal zero.

All four analysed specimens were casted at the same time. The first tested slab was WT-CF-8 (257 days after casting), whereas the last tested specimen was WT-CF-K-16

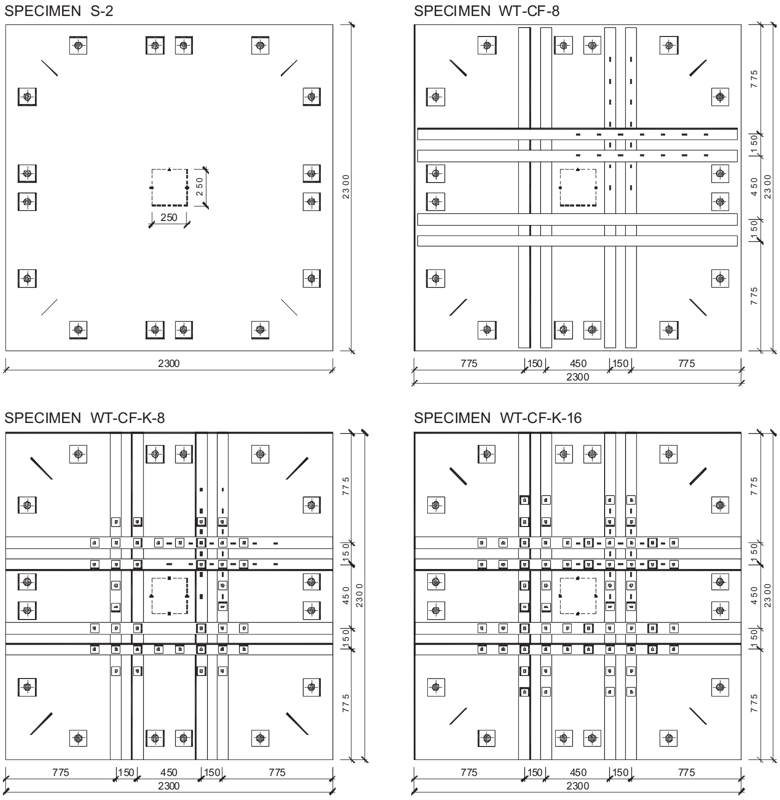

Fig. 8. Configuration of the CFRP strips.
Rys. 8. Widok lokalizacji taśm CFRP na modelach badawczych

(357 days after casting). Although there was a notable time gap between testings, no major difference in concrete strength was observed. The average concrete characteristics for the whole series was described by: $f_{c,cube}$ = 48,3 MPa, f_{cm} = 38,8 MPa, $f_{ct,sp}$ = 3,42 MPa, E_{cm} = 25,7 GPa. Steel reinforcement bars of Ø12 had the following characteristics: A_{sm} = 1,113 cm^2, $f_{y,h}$ = 580,8 MPa, $f_{y,l}$ = 565,6 MPa, f_{ym} = 573,2 MPa. CFRP strips of 90 x 1,4mm cross-section used in the test as external reinforcement were characterised by following values (specified by the manufacturer): A_{CFRP} = 1,26 cm^2, $f_{t,CFRP}$ = 3100 MPa, E_{CFRP} = 174 GPa (test value).

Figure 8 shows the location of the CFRP strips on test specimens.

Three specimens were strengthened with CFRP strips 90mm wide and 1,4mm in thickness, with a cross-sectional area of 126mm^2. The first element WT-CF-8 was strengthened with 8 strips placed in two perpendicular directions and bonded to the slab's surface with epoxy adhesive. Next specimen WT-CF-K-8 was also strengthened with 8 external strips, however, apart from bonding with epoxy there were additional anchoring bolts M10 applied. Finally, to strengthen the last specimen WT-CF-K-16, 16 CFRP strips fixed in two layers were used. In this case anchoring bolts were also applied to improve the bonding of strips to the slab's surface – but their number increased to 80 units. In both specimens a depth of the bolt inside the slab was 100mm. Fig. 8 shows the location of anchoring bolts in the specimen.

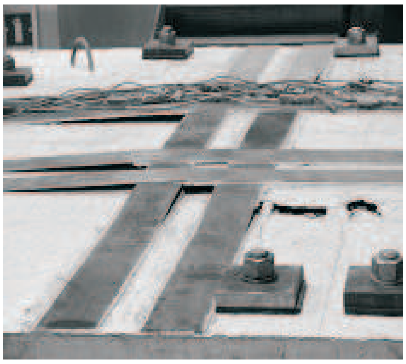

Fig. 9. Specimen WT-CF-8 after punching failure.
Rys. 9. Widok modelu WT-CF-8 po zniszczeniu

3. Experimental results

3.1. Load carrying capacity of experimental models

Table 2 shows the ultimate loads (V_{exp}) obtained during the test.

Table 2

The ultimate load capacity obtained during the experimental research
Nośność eksperymentalna

Specimen	V_{exp} [kN]	Ratio V_{exp}/V_{expS-2}	Load-carrying increase [%]
S-2	495	–	–
WT-CF-8	550	1.11	11.1
WT-CF-K-8	625	1.26	26.3
WT-CF-K-16	675	1.36	36.4

The table above indicates that strengthening of concrete slab with external CFRP strips leads to moderate increase in punching shear capacity in comparison to the unstrengthened reference specimen S-2. Fixing strips to the slab's surface only with adhesive resulted in the lowest increase in the load carrying capacity, which is similar to the results obtained by Canadian researchers [10]. Additional anchoring of CFRP strips by steel bolts doubles the strengthening efficiency.

Specimen S-2 failed abruptly under the load of 495 kN, in the explosive way. Punching shear failure of the WT-CF-8 specimen had the similar mode. Two consecutive specimens WT-CF-K-8 and WT-CF-K-16, with additional anchoring bolts were applied, failed more softly – which was especially exhibited by the specimen with a double number of the strips. This effect was probably influenced by anchoring bolts, which pulled out of the concrete below the diagonal shear crack during the punching failure.

As listed in Table 2, CFRP strip efficiency is relatively low and CFRP tensile strength is utilized only in a small percentage. This fact can be explained by:

- low modulus of elasticity, e.g. in comparison to steel (CFRP strips used in the investigation had a modulus of elasticity of 174 GPa),
- small cross sectional area of CFRP strips ($90 \times 1{,}4 = 126$ mm^2),
- a unique mode of failure, leading to the debonding of CFRP strips on the edge of a shear crack as a result of the transverse movement of concrete on either sides of the crack – which might be compared to the debonding due to vertical displacement (see Fig. 9 and 11).

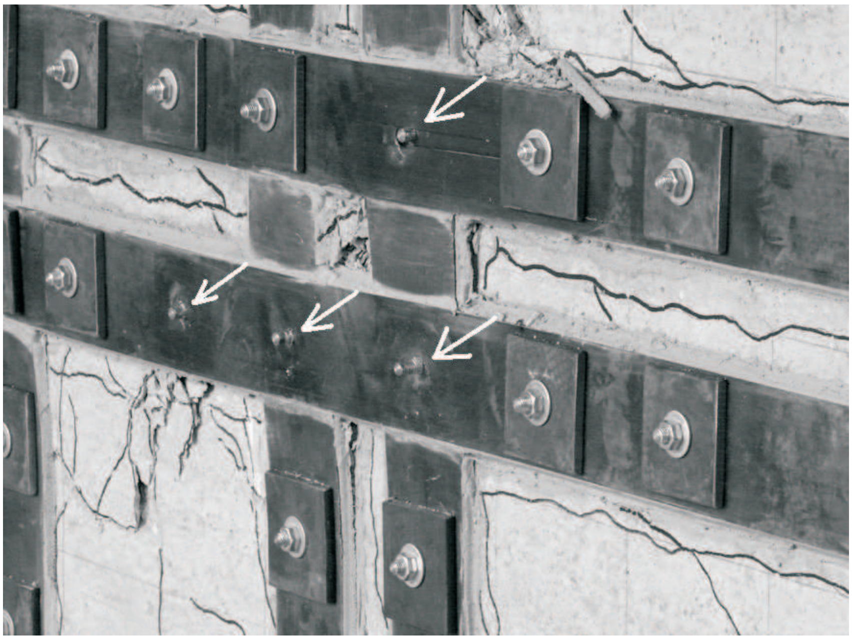

Fig. 10. A fragment of WT-CF-K-16 specimen after failure with marked broken screw-threads.
Rys. 10. Fragment płyty modelu WT-CF-K-16 po zniszczeniu z zaznaczonymi śrubami z zerwanym gwintem

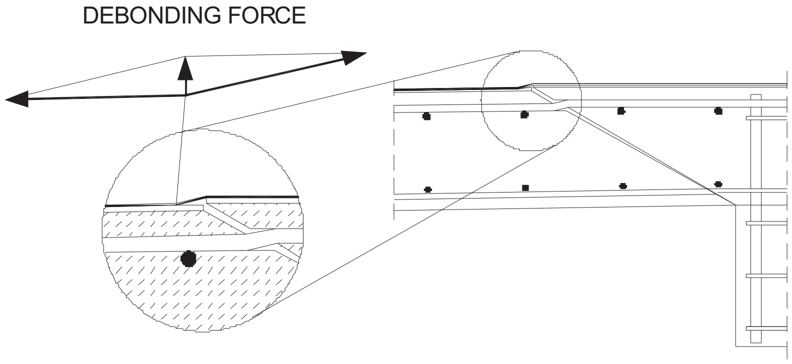

Fig. 11. The mechanism of strip's debonding near the diagonal shear crack.
Rys. 11. Mechanizm odspajania się taśm na wylocie rysy ukośnej

To prevent a negative effect of strip debonding, additional anchoring bolts were used in specimen WT-CF-K-8 and WT-CF-K-16. Mechanism of bolts' action is shown in Fig. 12. Test results of those slabs proves of this action. Specimen WT-CF-K-8 increased its load carrying capacity about 75 kN over the slab WT-CF-8 with the same number of strengthening strips, but without anchoring bolts. Specimens with anchoring bolts failed by breaking of the screw-threads. Figure 10 shows a part of WT-CF-K-16 after punching failure with marked broken bolts.

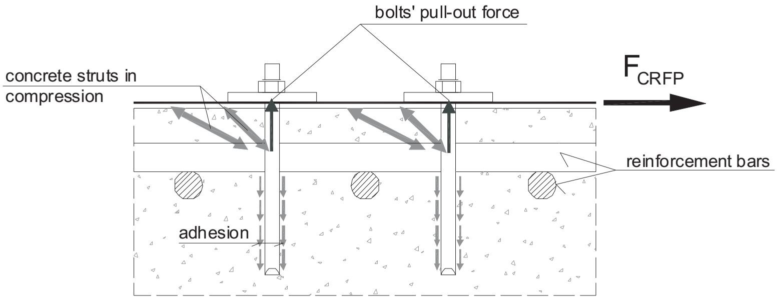

Fig. 12. The mechanism of additional anchoring of external reinforcement by bolts.
Rys. 12. Mechanizm dodatkowego kotwienia zbrojenia zewnętrznego za pomocą śrub

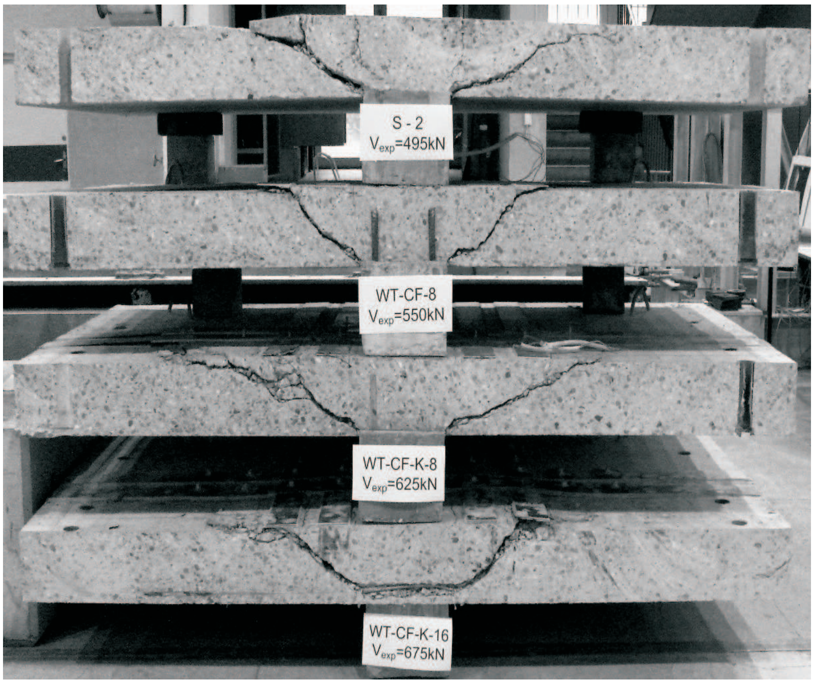

Fig. 13. The section of the experimental specimens appeared in the column face.
Rys. 13. Modele po przecięciu płyty w licu słupa

View of shear cracks, which propagated away from the column face inside the specimen, are shown in Fig. 13, that illustrates the section appeared next to the column face.

3.2. Crack development observations

During experimental testing, cracks propagation was registered on each level of applied load and for selected cracks, their width was measured using 25x magnification microscope. The largest cracks usually appeared right next to the column's outline. Fig. 14 shows a plot illustrating development of the largest measured cracks versus applied load. Horizontal line represents the largest crack's width allowed by Polish standard amount to 0,3 mm. An unstrengthened specimen exceeded that limit right after the load of 150 kN. For slabs WT-CF-K-8 and WT-CF-K-16 strengthened with CFRP strips and anchoring bolts, cracks of maximum allowed width were registered under the load of 250 kN and 300 kN. Whereas for the last specimen WT-CF-8, shrinkage cracks exceeding 0,3 mm were already observed before testing. However, these cracks were registered in a small number, which did not influence the investigation.

A comparison of specimens strengthened with 8 strips indicates that application of additional strip fixing by anchoring bolts has no significant effect on cracks' width – plots for both slabs are similar (see Fig. 14).

Utilization of CFRP reinforcement provided a considerably smal number of cracks appearing on the slab's surface. A comparison of the unstrengthened specimen S-2 and WT-CF-K-16 after failure is shown in Fig. 15.

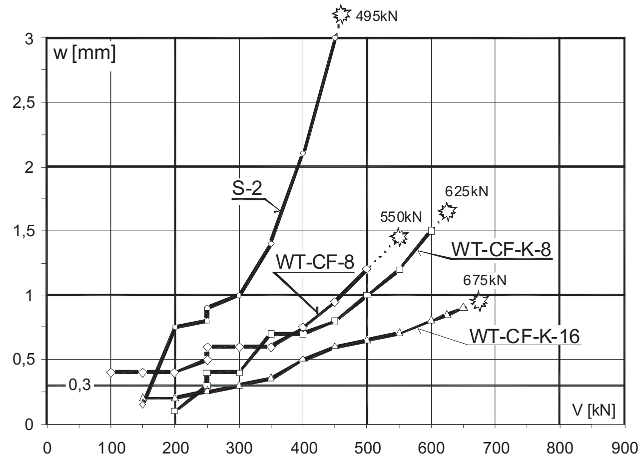

Fig. 14. The comparison of cracks with the maximum width.
Rys. 14. Porównanie rys o największej szerokości rozwarcia

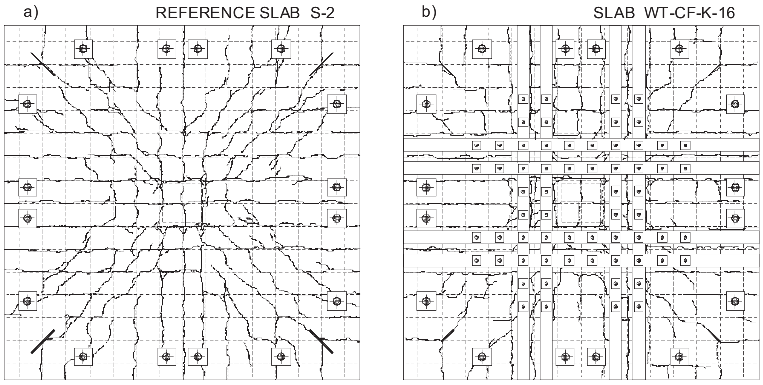

Fig. 15. The view of crack surface after failure: a) specimen S-2, b) specimen WT-CF-K-16.
Rys. 15. Widok zarysowanej powierzchni rozciąganej po zniszczeniu: a) model S-2, b) model WT-CF-K-16

3.3. Deflection results

The deflection versus load curves for all specimens are compared in Fig. 16. The significant influence of external reinforcement on the slab's stiffness is observed – stiffness of the CFRP strengthened slabs is considerably greater than the reference slab. Application of additional anchoring bolts does not effect the slab's stiffness (for specimen WT-CF-8 and WT-CF-K-8). The same time application of the CFRP strips and anchoring bolts (specimen WT-CF-K-16) resulted in further increase of slab's stiffness and lower vertical deflections.

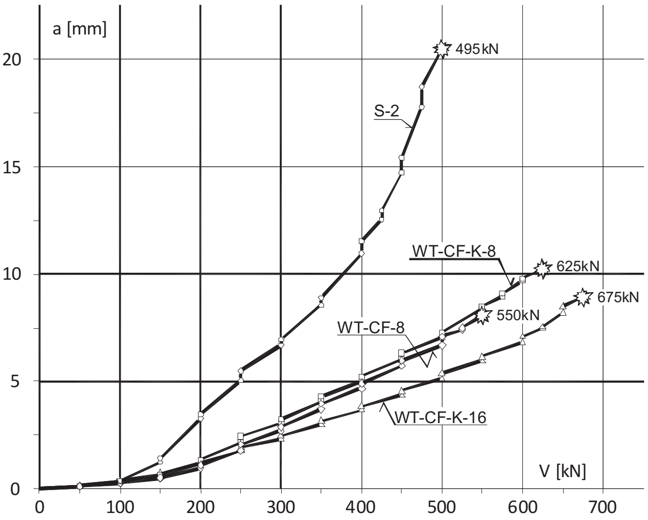

Fig. 16. The comparison of the slabs' deflection.
Rys. 16. Porównanie ugięcia płyt

3.4. Strain of the steel reinforcement bars

Figure 17 shows the progress of main steel reinforcement bars strain measured in the intersection with column's edge. The horizontal line ε_y represents the yield steel strain. Specimen S-2 reached steel yielding under the load of approximately 270 kN. Slabs strengthened with external CFRP strips WT-CF-8 and WT-CF-K-8 exceeded the yield stress of steel bars above the load of 475kN, whereas in the last specimen WT-CF-K-16 steel reinforcement bars never reached the yield stress. Presented strain of the main reinforcement bars prove the efficiency of the CFRP strips. A significant strain reduction is observed while applying external CFRP reinforcement.

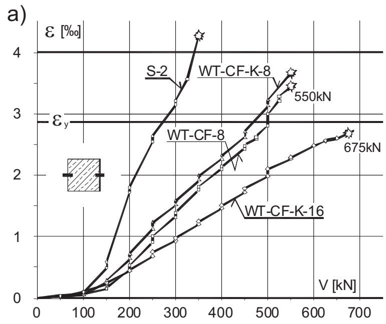

Fig. 17. The comparison of strain of the main reinforcement: a) the bottom bars of the mesh, b) the upper bars of the mesh.

Rys. 17. Porównanie odkształceń zbrojenia głównego płyt: a) dolna siatka zbrojeniowa, b) górna siatka zbrojeniowa

3.5. Test results of strain of the external reinforcement

The comparison of specimens with the same number of CFRP strips shows the increase in the strain due to application of the additional mechanical anchoring bolts in the model WT-CF-K-8 (see Fig. 18).

In the specimen WT-CF-K-16 with a double number of strips (see Fig. 19), the maximum strain of the external reinforcement was registered by electric resistance strain gauge (extensometer) W-3, which was located on the specimen's diagonal line. It is obvious, because of a theoretical yield line being formed along the slab's diagonal line.

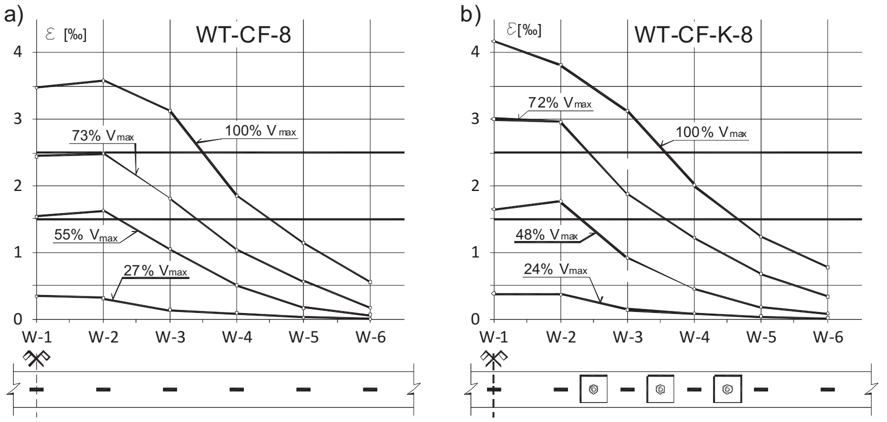

Fig. 18. Strain of the CFRP strips located near the column: a) specimen WT-CF-8, b) specimen WT-CF-K-8.

Rys. 18. Odkształcenia taśm CFRP zlokalizowanych bliżej słupa: a) model WT-CF-8, b) model WT-CF-K-8

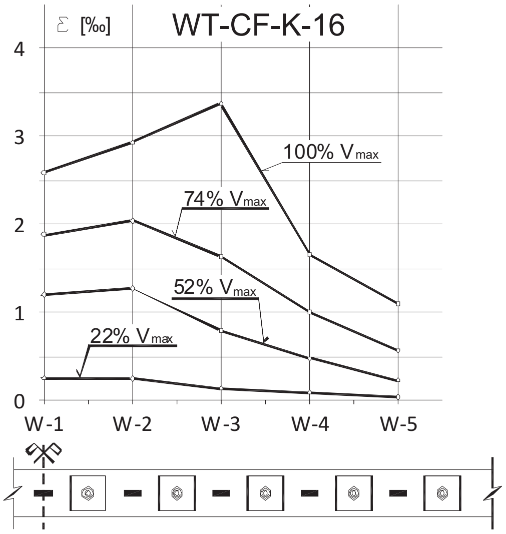

Fig. 19. Strain of the CFRP strips located near the column in specimen WT-CF-K-16.
Rys. 19. Odkształcenia taśm CFRP zlokalizowanych bliżej słupa w modelu WT-CF-K-16

4. PUNCHING STRENGTH PREDICTION USING EC2 PROCEDURE

Test results were compared with the analytical calculations, recommended by the European Standard EN 1992-1-1 for the ultimate punching shear load capacity. The EC2 procedure was modified in order to take into consideration the external reinforcement by calculating a new effective depth of a cross-section d_{eff} and reinforcement ratio which considers either longitudinal slab's reinforcement and external reinforcement. Differences between the characteristics of the main steel reinforcement and the external one, resulting mainly from the lower modulus of elasticity of CFRP strips, were included by determining an effective cross-section area of external reinforcement converted into steel reinforcement as a product of the strips' actual cross-section area and a quotient of CFRP and steel modulus of elasticity ($A_{CFRP} \cdot E_{CFRP}/E_s$). Modulus of elasticity of CFRP strips used in the research was calculated as equal E_{CFRP} = 174 GPa. Assuming that the modulus of steel bars is equal E_s = 200 GPa (no laboratory testing executed), the ratio is $E_{CFRP}/E_s = 0,87$.

As mentioned in section 2, the value of f_{cm} for the whole series was set equal 38,8 MPa and for further analysis was assessed as identical with f_{ck}. The punching shear resistance of reinforced concrete slab without shear reinforcement should be verified for the basic control section according to Eq. (4.1).

$$v_c = 0,18 \cdot k \cdot \sqrt[3]{100 \cdot \rho_l \cdot f_{ck}} \geq v_{\min} \tag{4.1}$$

where:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2,0 \tag{4.2}$$

For specimen WT-CF-8 an effective depth of a cross-section for internal steel bars is d= 150 mm. Therefore substituting this value to Eq. (4.2) equation, it gives k= 2,0.

In accordance to EC2 the reinforcement ratio for main longitudinal reinforcement to calculate design shear stresses should be determined for a width b_s, according to Eq. (4.3).

$$b_s = c + 6 \cdot d = 115cm \tag{4.3}$$

The cross sectional area of steel reinforcement Eq. (4.4) equals:

$$A_s = A_{sm} \cdot \frac{b_s}{s} = 1.113 \cdot \frac{115}{15} = 8.53cm^2 \tag{4.4}$$

where: s = 15 cm – axial spacing of the steel reinforcement bars,
c = 25 cm – length of column's side.

Minimal shear stress in the basic control section can be assessed from:

$$v_{\min} = 0.035 \cdot k^{3/2} \cdot f_{ck}^{1/2} = 0.035 \cdot 2^{3/2} \cdot 38.8^{1/2} = 0.617MPa$$

Specimen WT-CF-8 was strengthened with 8 strips of cross sectional area of A_{CFRP} = 1.26 cm^2, for which the effective depth of a cross-section equals d_{CFRP} =180 mm. It allows to determine the effective cross sectional area of external reinforcement Eq. (4.5), and next, the new effective depth of a cross-section Eq. (4.6).

$$A'_{CFRP} = \frac{E_{CFRP}}{E_S} A_{CFRP} = 0.87 \cdot 4 \cdot 1.26 = 4.38cm^2 \tag{4.5}$$

$$d_{eff} = \frac{A_S \cdot d + A'_{CFRP} \cdot d_{CFRP}}{A_S + A'_{CFRP}} = \frac{8.53 \cdot 15.0 + 4.38 \cdot 18.0}{8.53 + 4.38} = 16.02cm \tag{4.6}$$

For the strengthened specimens a slab width slightly increases and takes form of Eq. (4.7).

Therefore the slab's geometric reinforcement ratio taking into account the main steel reinforcement and the external reinforcement for a width Eq. (4.7) is Eq. (4.8).

$$b_m = c + 6 \cdot d_{eff} = 25 + 6 \cdot 16.02 = 121.12cm \tag{4.7}$$

$$\rho_l = \frac{A_s + A'_{CFRP}}{b_m \cdot d_{eff}} = \frac{8.53 + 4.38}{121.12 \cdot 16.02} = 0.00665 \tag{4.8}$$

The limit stress in the control cross-section according to Eq. (4.1) equals:

$$v_c = 0.18 \cdot 2 \cdot \sqrt[3]{100 \cdot 0.00665 \cdot 38.8} = 1.064\,MPa \geq 0.617\,MPa = v_{\min}$$

The control perimeter:

$$u_1 = 4c + 2\pi \cdot (2d_{eff}) = 4 \cdot 0.25 + 4\pi \cdot 0.1602 = 3.013m$$

Therefore the value of punching shear resistance:

$$V_c = v_c \cdot u_1 \cdot d_{eff} = 1064 \cdot 3.013 \cdot 0.1602 = 513.6kN$$

Summarizing, the ultimate punching load capacity according to EC2 for WT-CF-8 specimen equals V_{calc} = 514 kN, whereas the experimental value is V_{exp} = 550 kN. The ratio of those two punching shear strengths amount to V_{exp}/V_{calc} = 1.07. The sum-up of obtained results (for characteristic values) for all specimens is shown in Table 3. Results for identical reference slabs S-1 and S-3 from other experimental series are also included [14].

Table 3

The comparison of experimental and theoretical values.
Porównanie wartości eksperymentalnych z teoretycznymi

Specimen	d [mm]	f_{ck} [MPa]	V_{exp} [kN]	ρ_l [%]	d_{eff} [mm]	V_{calc} [kN]	V_{exp}/V_{calc}
S-1	147	45.3	500	0.505	–	428	1.17
S-3	147	38.9	475	0.505	–	406	1.17
S-2	145	38.8	495	0.512	–	399	1.24
WT-CF-8	150		550	0.665	160	514	1.07
WT-CF-K-8	148		625	0.670	159	508	1.23
WT-CF-K-16	149		675	0.846	165	583	1.16

5. CONCLUSION

Research studies presented in the paper show the possibility of strengthening flat RC slabs against punching shear failure with external CFRP reinforcement. Applying bonded CFRP strips only, provides moderate gain of the punching shear resistance, not much more than *10%* over the unstrengthened specimen. This effect is adequate to the results obtained by other researchers [10]. Better utilization of the CFRP strips might be expected when apart from bonding them to the slab with epoxy adhesive, additional anchoring bolts are used to improve the CFRP-to-concrete bond.

The analytical procedure introduced in the paper, created on the basis of EC2 for assessing the value of punching shear resistance, including CFRP strips as external reinforcement, in all cases provide the results on the “safe side”. The experimental load capacity reserves, in the reference to the theoretical value, ranges from 7 to *23%*.

Analytical results indicate that utilization of the CFRP strips without additional anchoring bolts, leads to the decrease of safety in relation to the reference specimen. Introduction of additional anchoring bolts results in a comparable degree of safety as for the unstrengthened specimens.

Presence of anchoring bolts to externally bonded CFRP strips was not included in the theoretical procedure, because they did not meet the constructional principles for the transverse reinforcement. Nevertheless, a positive effect of their presence was observed consisting of the increase of the load carrying capacity and an upgrade of failure mode, from abrupt to more ductile.

Taking above statements into consideration, the EC2 procedure modified by the authors, can be recommended for the practical use.

SELECTED SYMBOLS

A_s – cross sectional area of tension steel,
A_{sm} – cross sectional area of a single steel bar,
A_{CFRP} – cross sectional area of a single CFRP strip,
E_{cm} – modulus elasticity of concrete,
E_s – modulus elasticity of steel,
E_{CFRP} – modulus elasticity of CFRP,
$V_{R,c}$ – punching capacity of slab without shear reinforcement (theoretical),
V_{exp} – experimental punching capacity,
c – size of column side,
d – effective depth of cross-section for mean steel reinforcement,
d_{eff} – effective depth of cross-section which considers either mean steel reinforcement and external reinforcement (CFRP),
f_{ck} – characteristic value of concrete compressive strength,
f_{cm} – mean value of concrete cylinder compressive strength,
$f_{c,cube}$ – mean value of concrete cube compressive strength,
$f_{ct,sp}$ – mean value of splitting tensile strength of concrete,
f_{ym} – mean value of yield strength of steel reinforcement,
$f_{y,h}$ – upper yield strength of steel reinforcement,

$f_{y,l}$ – lower yield strength of steel reinforcement,
$f_{t,CFRP}$ – tensile strength of CFRP,
$v_{R,c}$ – punching shear resistance for basic control section ($d \bullet u_1$),
u_1 – control perimeter,
ε_y – yield steel strain,
ρ_l – average reinforcement ratio of longitudinal reinforcement, for two directions,
ρ_w – reinforcement ratio of shear reinforcement.

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WZMACNIANIE POŁĄCZEŃ PŁYTA-SŁUP ZA POMOCĄ TAŚM CFRP

Streszczenie

Artykuł przedstawia badania doświadczalne płyt żelbetowych, przyjętych jako fragment realnej konstrukcji żelbetowej z płaskimi stropami. Celem badań była weryfikacja efektywności wzmocnienia połączenia płyty ze słupem na przebicie poprzez zwiększenie mechanicznego stopnia zbrojenia (mocy zbrojenia) za pomocą dodatkowych zewnętrznych taśm karbodurowych (CFRP).

Uzyskano wzrost nośności na przebicie do 36% względem modelu odniesienia.

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