

EXPERIMENTAL INVESTIGATIONS ON PUNCHING SHEAR OF FLAT SLABS MADE FROM LIGHTWEIGHT AGGREGATE CONCRETE

M. GOŁDYN¹, Ł. KRAWCZYK², W. RYŻYŃSKI³,
T. URBAN⁴

In the paper the results of experimental investigations concerning flat slabs made from reinforced lightweight concrete with sintered fly ash aggregate CERTYD were presented. In the research program 6 models made in a natural scale were included. The main variable parameter was slab longitudinal reinforcement ratio. The aim of investigation was the experimental verification of efficiency of double-headed studs as punching shear reinforcement. In the existing technical approvals such kind of reinforcement was allowed only in normal concrete slabs. It was demonstrated that double-headed studs can be an effective transverse reinforcement of lightweight aggregate concrete slabs. The use of double-headed studs resulted in increase in the ultimate load from 19% to 44%, depending on the slab reinforcement ratio which ranged from 0.5% to 1.2%. The comparative analysis showed that the Eurocode 2 provisions were conservative in relation to the experimental results, which were on average 42% higher than the theoretical ones however with a very low 7% coefficient of variation.

Keywords: punching shear, lightweight aggregate concrete, fly ash, shear stress, double-headed studs

¹ PhD., Eng., Lodz University of Technology, Faculty of Civil Engineering, Architecture and Environmental Engineering, al. Politechniki 6, 90-924 Łódź, Poland, e-mail: michal.goldyn@p.lodz.pl, corresponding author

² PhD., Eng., Lodz University of Technology, Faculty of Civil Engineering, Architecture and Environmental Engineering, al. Politechniki 6, 90-924 Łódź, Poland, e-mail: lukasz.krawczyk@p.lodz.pl

³ PhD., Eng., State Higher Vocational School in Suwałki, Faculty of Technology, Institute of Civil Engineering, ul. Noniewicza 10, 16-400 Suwałki, e-mail: biuro@ryzynski.pl

⁴ Prof. PhD., Eng., Lodz University of Technology, Faculty of Civil Engineering, Architecture and Environmental Engineering, al. Politechniki 6, 90-924 Łódź, Poland, e-mail: tadeusz.urban@p.lodz.pl

1. INTRODUCTION

Lightweight concrete based on natural aggregates such as crushed tuff or pumice was known and used as building material in ancient times. It found application not only as a filling and finishing material but also as a construction material used for erecting of walls and vaults. Well-known historic objects from the ancient Rome time that have survived to the modern times, such as the Colosseum or the Pantheon, well testify to the strength and durability of lightweight concrete. A sharp progress in the technology of modern lightweight concretes took place mainly in the second half of the 20th century. LWA concretes were used essentially in the construction of high-rise buildings. Due to reduction in the self-weight construction of several additional storeys was enabled without the need to enlarge the cross-section of columns, walls and foundations.

The widespread use of column-and-slab structures was a reason for undertaking the experimental investigations concerning punching shear of LWAC slabs. The first work, which aim was to adapt the design procedures adequate for normal weight concretes also for lightweight concretes, were experimental studies by *Hognestad et al.* [8]. This issue was also continued by *Ivy et al.* [9] who tested a total of 14 lightweight concrete slabs and then proposed changes in the American standard ACI 318-63 [1]. Experimental instigations of *Corley and Hawkins* [4], covering 9 lightweight concrete slabs, demonstrated that use of rigid steel heads could increase the load carrying capacity up to 45% with respect to slabs without punching shear reinforcement. The results of experimental investigations conducted from 2000 by the *Marzouk et al.*, including three series of axially [12], eccentrically [10] and cyclic [11] loaded slabs, showed that high-strength lightweight aggregate concrete slabs (compressive strength of about 70 MPa) exhibited similar behavior to slabs made from normal density and strength concrete of about 35 MPa. Recently, punching shear of LWAC flat slabs has been the subject of research i.e. *Youm et al.* [15], who managed to reproduce the behavior of test specimens by means of finite element method in the ABAQUS analysis system. *Carmo et al.* [3], tested 6 slabs made from lightweight aggregate concrete with strength of 29, 42 and 52 MPa and a density of about 1940 kg/m³. The obtained experimental results were analyzed in the light of EN 1992-1-1 [5] and fib Model Code 2010 [7] provisions. *Caratelli et al.* [2] found [7] rules as conservative if the aggregate particles did not break and aggregate interlock is possible. They suggested introduction of a factor accounting a partial break of the particles instead of assuming aggregate diameter equal to zero as is suggested in [7] by calculating k_{dg} coefficient.

2. EXPERIMENTAL PROGRAM

2.1. TEST SPECIMENS

The experimental program consisted of 6 models of flat slabs made in a natural scale and dimensions in a plane of $2400 \times 2400 \times 200$ mm. The elements were casted with bottom and top column stubs with a section of 250×250 mm and a height of 150 mm. The main variable parameter was the slab longitudinal reinforcement ratio ρ_l , equal intentionally to 0,47, 0,86 and 1,23%. One of the pair of models was the reference element for the specimen with punching shear reinforcement. Main longitudinal reinforcement consisted in $\varnothing 12$ or $\varnothing 16$ bars at spacing of 100 or 150 mm – accordingly to the assumed reinforcement ratio. Bottom reinforcement was made of $\varnothing 10$ mm bars at 200 or 300 mm except $2\varnothing 16$ within column area posing integrity reinforcement against progressive collapse. Main reinforcement was anchored mechanically by welding to the peripheral bars. Transverse reinforcement consisting of 16 sets of double-headed studs was arranged symmetrically on two perimeters (see Fig. 1b). By arranging the punching shear reinforcement the principles of technical approval [6], which demands to transfer 100% of load by the transverse reinforcement, were followed.

2.2. MATERIALS

The specimens were made of lightweight concrete with CERTYD aggregate produced by LSA sp. z o.o. from Białystok. The aggregate was made from fly ash accumulated in electrostatic precipitators and ash-slag mixture from wet furnace waste removal produced in the process of burning hard coal in thermal-electric power station. Ash collected in the slag heaps in Sowłany near Białystok as well as current waste from the power plant EC-2 for this purpose were used. All slabs were casted from the same batch of ready-mixed concrete. Strength properties were determined on standard samples: cylinders (compressive strength f_{cm} and secant modulus of elasticity E_{lcm}) and cubes (tensile splitting strength $f_{ct,spm}$) on the day of the test. The age of concrete during the tests was in range of 55 ÷ 80 days. Due to technical possibilities, the test were conducted within 25 days, however, no significant differences in the concrete characteristics were found at that time. Therefore the average values from all samples were taken in the further analysis. After completing the tests additional samples – drilling cores of $\varnothing 100$ mm were cut off in order to check the homogeneity and density of the casted concrete. The obtained strengths were similar ($f_{lcm,core} = 55,7$ MPa). The mean density ρ

after drying, equal to approximately 1780 kg/m^3 , allowed to classify the slab concrete to the density class 1.8 according to EN 1992-1-1 [5]. The features of concrete were listed in Table 1.

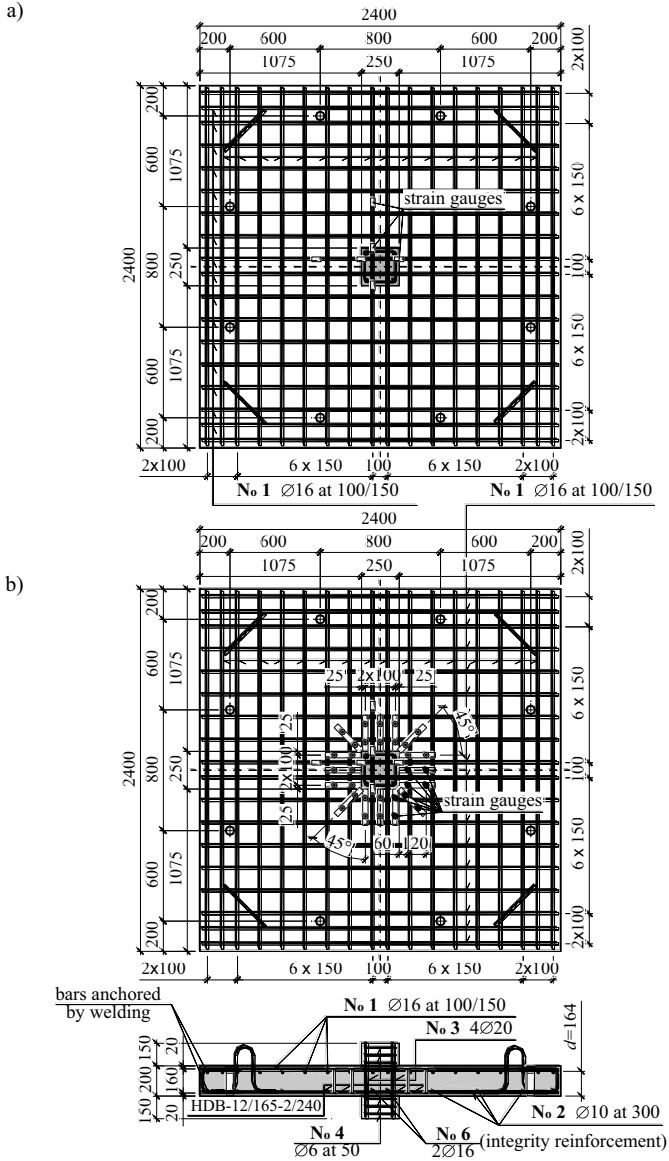


Fig. 1. Reinforcement of the test specimens: a) LC-0.86-0, b) LC-0.86-Z

Table 1. Features of the slab concrete

	Compressive strength f_{ic} [MPa]	Tensile splitting strength $f_{ict.sp}$ [MPa]	Secant modulus of elasticity E_{ic} [GPa]	Density ρ [kg/m ³]	
				(surface saturated dry)	(dry)
Mean	49,9	2,79	21,6	1934	1780
Standard deviation	2,5	0,25	1,1	25	15

Longitudinal and transverse reinforcement were made of 500 MPa steel grade, characterized by a pronounced yield point. Geometric and strength parameters – cross-sectional area A_{sw} , yield strength f_{ym} and ultimate strength f_{um} , were summarized in Table 2.

Table 2. Features of the reinforcement

Longitudinal reinforcement						Double-headed studs		
Ø12			Ø16			Ø12		
A_{sw} [mm ²]	f_{ym} [MPa]	f_{um} [MPa]	A_{sw} [mm ²]	f_{ym} [MPa]	f_{um} [MPa]	A_{sw} [mm ²]	f_{ym} [MPa]	f_{um} [MPa]
113,4	537,7	634,6	202,4	578,8	691,3	112,5	591,1	639,5

2.3. TEST SETUP AND TEST PROCEDURE

The tests were carried out in the test setup shown in Figure 2a. The specimens were tested in a natural position and anchored to the test frame by 8 bolts embedded in sleeves cast in the slabs (see Fig. 2a). The load was applied on the bottom column by four hydraulic jacks, connected by one piston with a maximum pressure of 1600 kN,.

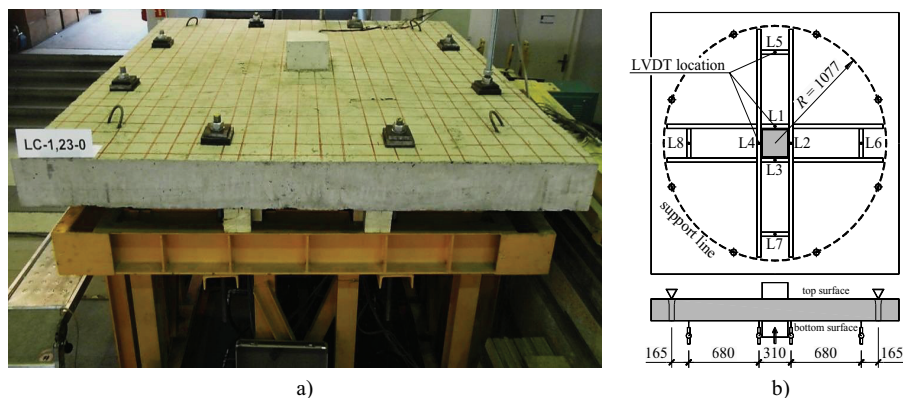


Fig. 2. Test setup: a) side view, b) location of the LVDT devices

During the tests strains of longitudinal and transverse reinforcement as well as concrete on the bottom slab surface were carried out by means of the strain gauges. In order to measure deflections of the slab LVDT were used. The devices were placed in a special steel frame which enabled to measure the deformations in the column vicinity and edge of the slab – see Fig. 2b. The load was increased gradually by approximately 40 kN. The load was held constant for about 5 minutes while current crack pattern was stocktaken and crack widths were measured. By approaching the ultimate load, what was indicated by the strain readings, load increase rate was reduced to 20 kN every 5 min.

3. TEST RESULTS

3.1. CRACK PATTERN

In the initial phase of the test, the development of cracks resulting from bending was observed. The first cracks appeared on the perimeter of the top column, while the subsequent – in its vicinity. Their course corresponded to direction of top reinforcement bars. At higher load level of about 60% of destructive force, visible radial cracks were formed. They were propagating gradually from the column to the edge of the slab. In the Figure 3 the cross-sections of selected models made after the test were showed. In the specimens without transverse reinforcement, the angle of the critical shear cracks was in range $\theta = 20 \div 40^\circ$ and was similar to that observed in the tests of normal concrete slabs [13, 14]. The use of punching shear reinforcement caused that the critical cracks were formed always outside the reinforced zone. The angle of these cracks was approximately $\theta = 15 \div 20^\circ$ and smaller than angle of cracks coming directly from the column edge.

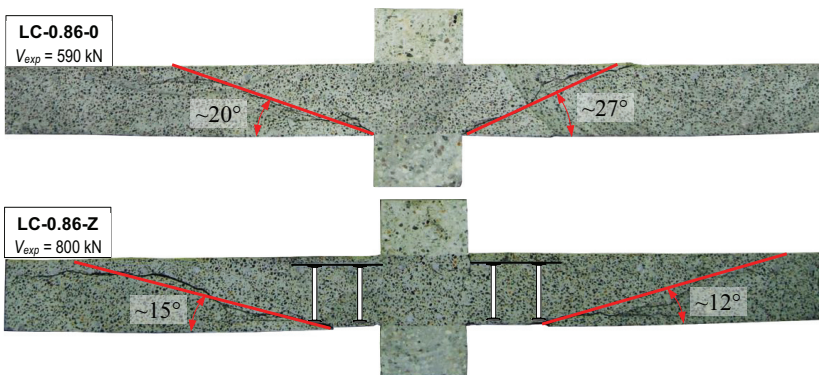


Fig. 3. Cross-sections of the specimens after failure

The beginning of the critical cracks was visible in the vicinity of the heads of studs located on the second perimeter of the punching shear reinforcement. By comparing the photographs showing bottom surfaces of the specimens (see Fig. 4) could be noticed that introduction of double-headed studs resulted in similar way to observed by increasing dimensions of the column. Transverse reinforcement has determined the range of the “new head”. In all cases the column or head were moved up relative to the bottom slab surface what was associated with the push-out of the punching cone.

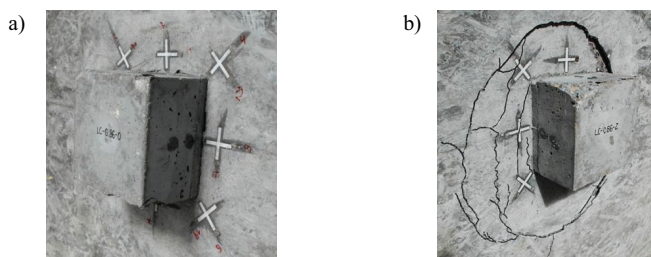


Fig. 4. Detail of the bottom column stub after failure of the specimen: a) LC-0.86-0, b) LC-0.86-Z

3.2. ULTIMATE SHEAR STRESSES

In the figure 5 the relation between the actual shear stresses v in the basic control section (located at the distance of $2d$ from the column edge) and the slab reinforcement ratio ρ_l was presented. By increasing the slab reinforcement ratio, an increase in the shear ultimate stresses was observed. The effect was more pronounced in case of punching shear reinforced elements. Considering the regression curves shown in Fig. 5, it could be noticed that use of transverse reinforcement resulted in an increase in ultimate shear stress by 28% at the longitudinal reinforcement ratio $\rho_l \approx 0.5\%$, against 40% when $\rho_l \approx 1.3\%$. It could be stated that the effectiveness of double-headed studs is proportional and dependent on the slab longitudinal reinforcement ratio.

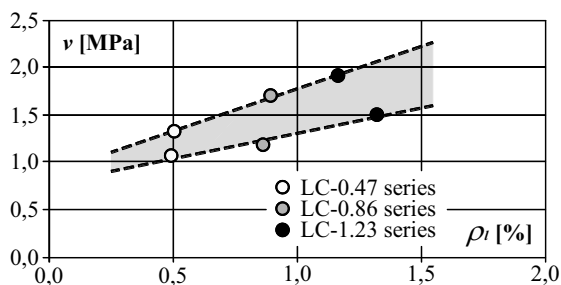


Fig. 5. Relation between ultimate shear stresses and slab longitudinal reinforcement ratio

4. TEST RESULTS IN THE LIGHT OF EUROCODE 2 PROVISIONS

The ultimate shear stress $v_{Rd,c}$ of lightweight aggregate concrete can be determined analogically as for normal concrete slabs, however by applying the reduction factor η_1 , depending on the concrete density, and by reducing the factor $C_{Rk,c}$ by 17% – from 0,18 to 0,15:

$$(4.1) \quad v_{Rd,c} = \max \left(C_{Rd,c} k \eta_1 \sqrt[3]{100 \rho_l f_{lck}} ; \eta_1 v_{l,\min} = \eta_1 \cdot 0,028 \sqrt{k^3 f_{lck}} \right)$$

where:

$C_{Rd,c}$ – empirical factor equal to $0,15/\gamma_c$, k – size effect factor: $k = \min[1 + (200/d)^{0,5}; 2,0]$,
 d – effective depth of the slab, η_1 – coefficient depending on density of LWAC: $\eta_1 = 0,4 + 0,6\rho/2200$,
 ρ – upper limit of the oven dry density for the relevant LWAC class, ρ_l – slab longitudinal reinforcement ratio (not more than 0,02), f_{lck} – characteristic compressive strength of LWAC.

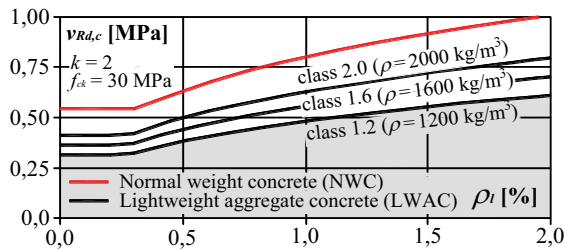


Fig. 6. Ultimate shear stress with respect to reinforcement ratio depending on concrete type and density

In the Figure 6 the relationship between ultimate shear stress $v_{Rd,c}$ and slab reinforcement ratio were presented. Considering the curves it can be stated about 20 ÷ 40% decrease in ultimate shear stress, depending of density class, should be expected if lightweight aggregate concrete instead of normal weight concrete of equal strength was used. In the Table 3 experimental and theoretical load carrying capacities determined in accordance with the principles of EN 1992-1-1 [5] and the European technical approval [6] relating to normal concrete, are listed. In case of the second document, punching shear capacity $V_{calc}(cs)$ is calculated by assuming yielding of the entire transverse reinforcement (all studs were placed in zone C) and omitting contribution of concrete strength. Load capacity outside the punching shear reinforced area $V_{calc}(u_{out})$ was determined analogically as in case of normal concrete, however by reducing the empirical factor corresponding to outer perimeter: $C_{Rd,c} = 0,15/\gamma_c \cdot 0,15/0,18$. The critical values, corresponding to the ultimate, theoretical load capacities V_{calc} , were bolded.

Table 3. Comparison between results of the tests and calculations according to EN 1992-1-1 [5] and modified technical approval provisions [6]

Specimen	ρ_l [%]	d [mm]	u_1 [mm]	u_0 [mm]	u_{out} [mm]	$f_{sw,ef}$ [MPa]	V_{exp} [kN]	EN 1992-1-1 [5]						ETA-12/0454 [6]				
								$V_{calc}(u_1)$ [kN]	$V_{calc}(u_{out})$ [kN]	$V_{calc}(cs)$ [kN]	$V_{calc,max}(u_1)$ [kN]	$V_{calc,max}(u_0)$ [kN]	V_{exp}/V_{calc}	$V_{calc}(u_{out})$ [kN]	$V_{calc}(cs)$ [kN]	$V_{calc,max}(u_1)$ [kN]	V_{exp}/V_{calc}	
LC-0.47-0	0,49	162	3036	1000	-	-	520	378,8	-	-	1,37	-	-	-	-	-	-	
LC-0.47-Z	0,50	158	2985		3579	289,5	620	439,2	1304,2	549,6	1162,2	1,41	366,0	2129,6	718,1	1,69	-	-
LC-0.86-0	0,86	164	3061		-	-	590	466,7	-	-	-	1,26	-	-	-	-	-	-
LC-0.86-Z	0,89	158	2985		3579	289,5	800	532,3	1362,5	666,0	1162,2	1,50	443,6	2129,6	870,3	1,80	-	-
LC-1.23-0	1,32	149	2872		-	-	640	458,8	-	-	-	1,40	-	-	-	-	-	-
LC-1.23-Z	1,16	160	3011		3598	290,0	920	592,1	1415,8	743,1	1176,9	1,55	493,4	2129,6	971,0	1,86	-	-
								Mean		Coefficient of variation								
Designations:		ρ_l	- actual longitudinal reinforcement ratio	V_{exp}	- ultimate test load													
d	- actual effective depth (measured after the test)	$V_{calc}(u_1)$	- theoretical load carrying capacity corresponding to basic perimeter															
u_1	- length of the basic control perimeter	$V_{calc}(u_{out})$	- theoretical load carrying capacity corresponding to outer perimeter															
u_0	- length of the shortest control perimeter	$V_{calc}(cs)$	- theoretical load carrying capacity of slab with transverse reinforcement															
u_{out}	- length of the outer control perimeter	$V_{calc,max}(u_1)$	- maximal theoretical load carrying capacity corresponding to the basic perimeter															
$f_{sw,ef}$	- effective stress in the punching shear reinforcement	$V_{calc,max}(u_0)$	- maximal theoretical load carrying capacity corresponding to the shortest perimeter															

It was stated that EN 1992-1-1 [5] provisions were conservative in the light of author's test results – see Table 3. The average ratio of experimental to theoretical load was $V_{exp}/V_{calc} = 1,42$ with a low coefficient of variation of 7%. However if the rules relating to normal density concrete slabs were applied, the results of the tests and calculations were similar – an average ratio $V_{exp}/V_{calc} = 1,05$ with 7% coefficient of variation was obtained. Despite the mentioned differences failure modes were determined correctly. In the case of all of the punching shear reinforced specimens the load carrying capacity $V_{calc}(u_{out})$, corresponding to the outer perimeter, was decisive. In the tests all of these elements were damaged outside the transverse reinforced zone. The load carrying capacity corresponding to the studs $V_{calc}(cs)$ was on average more than 2-3 times higher than experimental loads. It demonstrated that the punching shear reinforcement was too heavy to use the full capacity of the studs.

5. CONCLUSIONS

The results of authors' investigations demonstrated that double-headed studs may be an effective punching shear reinforcement of lightweight aggregate concrete slabs. Depending on the flexural reinforcement ratio an increase in load capacity of more than 40% was obtained. The failure of punching shear reinforced specimens came outside the transverse reinforced zone. Critical cracks visible at the intersections did not run from the edge of the column but started from the heads of the studs located on the last reinforcement perimeter. Load carrying capacities calculated in accordance with the EN 1992-1-1 [5] provisions relating to lightweight aggregate concretes proved to be conservative in relation to the authors' results – an average ratio of experimental V_{exp} to theoretical V_{calc} load equal to 1,42 was obtained. By using the principles for normal weight concretes, the difference between the results of the test and calculations turned out to be small. An average V_{exp}/V_{calc} ratio of 1,05 was obtained. This may suggest that in case of slabs made from lightweight concrete with "CERTYD" aggregate applying rules relating to normal concretes may be appropriate. Thus, it would not be necessary to reduce the punching shear capacity while limiting the density of concrete and the self-weight of the floor slab.

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EXPERIMENTAL INVESTIGATIONS ON PUNCHING SHEAR OF FLAT SLABS MADE FROM LIGHTWEIGHT AGGREGATE CONCRETE

Keywords: punching shear, lightweight aggregate concrete, fly ash, shear stress, double-headed studs

SUMMARY:

In the paper the results of authors' experimental investigations concerning punching shear of flat slabs made from lightweight concrete with "CERTYD" aggregate were presented. This aggregate is manufactured from fly ash accumulated in electrostatic precipitators and ash-slag mixture from wet furnace waste generated in the process of burning hard coal in a combined heat and power plant.

A total of six specimens with dimensions of $2400 \times 2400 \times 200$ mm were tested. The slabs were connected with short fragments of columns of a cross-section of 250×250 mm and a height of 150 mm. The main variable parameter was slab longitudinal reinforcement ratio ρ_l , equal to 0.47, 0.86 and 1.23% intentionally. One of the pair of models with the same longitudinal reinforcement was the control specimen and did not contain shear reinforcement.

The failure of all of the specimens took place in a violent manner, characteristic for punching shear. On the upper surface of the specimens a base of the punching cone was clearly visible. After end of the tests the models were cut to determine the course of shear cracks. In case of the elements without transverse reinforcement, the inclination of the diagonal cracks was in the range $\theta = 20 \div 40^\circ$ and therefore was similar to that observed in ordinary concrete slabs. The introduction of double-headed studs resulted in strengthening of the support zone and forced the formation of critical shear cracks outside the shear reinforced zone. A new effective "head" was observed on the bottom, compressed side of the slab. The base of the head was determined by the last perimeter of punching shear reinforcement. The inclination of the critical shear cracks forming outside shear reinforced zone was smaller and equal to about $\theta = 15 \div 20^\circ$.

Increasing the longitudinal reinforcement ratio ρ_l from about 0.5% to 1.2% resulted in an increase in ultimate shear stresses v by about 35 and 50%, respectively in models with and without transverse reinforcement. The effectiveness of double-headed studs was proportional to longitudinal reinforcement ratio.

The comparison between results of the tests and calculations according to EN 1992-1-1 and the procedure referring to the technical approval ETA-12/0454 indicated that design provisions are conservative. The mean ratio of the experimental to theoretical load carrying capacity according to EN 1992-1-1 was equal to $V_{exp}/V_{calc} = 1.42$, with a relatively low coefficient of variation of 7%. In the case of the procedure referring to ETA-12/0454, the difference between the actual and experimental load capacities was even greater – the average ratio $V_{exp}/V_{calc} = 1.79$ was obtained. It is worth noting that a very good agreement between results of the test and calculations according to EN 1992-1-1 was obtained, however, by applying the rules for ordinary concrete. The ratio $V_{exp}/V_{calc} = 1.05$ was obtained. For this reason it can be concluded that the reduction in the load carrying capacities of slabs made from "CERTYD" lightweight aggregate concrete may be lower than it would appear from the general provisions of EN 1992-1-1 for other types of lightweight aggregate concretes.

It was stated that double-headed studs can be an effective type of shear reinforcement of flat slabs made from lightweight aggregate concretes – although such applications have not been included in the relevant technical approvals. Depending on the slab longitudinal reinforcement ratio, the application of double-headed studs allowed for increasing punching shear carrying capacity by more than 40% with respect to the control specimens.

BADANIA EKSPERYMENTALNE PRZEBICIA PŁYT PŁASKICH WYKONANYCH Z LEKKIEGO BETONU KRUSZYWOWEGO

Słowa kluczowe: przebicie, lekki beton kruszywowy, popiół lotny, naprężenia styczne, trzpienie dwugłówkowe

STRESZCZENIE:

W pracy przedstawiono wyniki własnych badań eksperymentalnych dotyczących przebicia płaskich płyt z betonu lekkiego, wykonanego na kruszywie „CERTYD”, produkowane przez firmę LSA sp. z o.o. z Białegostoku. Kruszywo to powstaje z popiołów lotnych zgromadzonych w elektrofiltrach i mieszanki popiołowo-żużlowej z mokrego usuwania odpadów piecowych, wytwarzanych w procesie spalania węgla kamiennego w elektrociepłowni.

Zbadano 6 modeli płyt płaskich o wymiarach $2400 \times 2400 \times 200$ mm, połączonych z krótkimi fragmentami słupów o przekroju 250×250 mm i wysokości 150 mm. Głównym parametrem zmiennym był stopień zbrojenia podłużnego ρ_l , równy w zmierzeniu 0,47, 0,86 oraz 1,23%. Jeden z pary modeli o tym samym stopniu zbrojenia stanowił element odniesienia dla modelu zbrojonego na przebicie.

Zniszczenie wszystkich elementów nastąpiło w sposób gwałtowny, charakterystyczny dla przebicia. Na górnej powierzchni płyty widoczna była podstawa stożka przebicia. Po zakończeniu badań modele przecięto w celu ustalenia przebiegu rys ukośnych wewnątrz płyty. W przypadku modeli bez zbrojenia poprzecznego kąt nachylenia rys ukośnych zawierał się w przedziale $\theta = 20 \div 40^\circ$ i był zbliżony do obserwowanego w płytach płaskich z betonów zwykłych. Zastosowanie trzpieni dwugłówkowych skutkowało wzmocnieniem strefy podporowej i wymusiło formowanie się krytycznych rys ukośnych poza strefą zbrojenia na przebicie. Na dolnej, ściskanej powierzchni płyty obserwowano nową, zastępującą głowicę. Jej podstawa wyznaczona była ostatnim obwodem zbrojenia na przebicie. Kąt nachylenia krytycznych rys ukośnych był mniejszy i wynosił około $\theta = 15 \div 20^\circ$.

Zwiększenie stopnia zbrojenia podłużnego ρ_l z około 0,5% do 1,2% skutkowało wzrostem naprężeń stycznych v o około 35 i 50%, odpowiednio w przypadku modeli zbrojonych trzpieniami dwugłówkowymi i bez zbrojenia na przebicie. Efektywność wzmocnienia trzpieniami dwugłówkowymi była proporcjonalna do stopnia zbrojenia podłużnego płyty.

W artykule porównano wyniki badań z rezultatami obliczeń według EN 1992-1-1 oraz procedury nawiązującej do aprobaty technicznej ETA-12/0454. W świetle wyników badań reguły EN 1992-1-1 okazały się zachowawcze. Uzyskano średni stosunek nośności eksperymentalnej do teoretycznej równy $V_{exp}/V_{calc} = 1,42$, przy stosunkowo niedużym współczynniku zmienności wynoszącym 7%. W przypadku procedury nawiązującej do ETA-12/0454 różnica pomiędzy rzeczywistymi i eksperymentalnymi nośnościami modeli zbrojonych na przebicie była jeszcze większa – uzyskano średni stosunek $V_{exp}/V_{calc} = 1,79$. Warto przy tym zauważyć, iż uzyskano bardzo dobrą zgodność pomiędzy wynikami badań i obliczeń według EN 1992-1-1 jednak przy założeniu reguł dotyczących betonu zwykłego. Uzyskano bowiem stosunek $V_{exp}/V_{calc} = 1,05$. Może to prowadzić do wniosku, że w przypadku stosowania kruszywa „CERTYD” nie ma konieczności tak znacznej redukcji nośności na przebicie, jak wynikałoby to z ogólnych zapisów EN 1992-1-1, dotyczących wszystkich rodzajów lekkich betonów kruszywowych.

Trzpienie dwugłówkowe mogą stanowić skuteczny sposób zbrojenia na przebicie płyt płaskich z lekkich betonów kruszywowych – mimo iż takowe zastosowanie nie zostało ujęte w odpowiednich aprobatkach technicznych. W zależności od stopnia zbrojenia podłużnego płyt uzyskiwano wzrost nośności sięgający ponad 40% względem modeli odniesienia.