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CARRYING CAPACITY OF AXIALLY LOADED HSC COLUMNS INTERSECTED BY NSC SLAB

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Abstract

There are presented and commented in this paper existing code provisions and empirical relationships in a view of results of own experimental investigations. The load transmission mechanism between high strength concrete columns intersected by weaker slab concrete has been considered. Slabs of the specimens were made of normal and lightweight aggregate concrete. One of the examined parameters was an effort grade of the concrete slab in punching shear on the column load carrying capacity. No significant effect of this factor was found. However, considerable effect of concrete type of which slab was made was noted. Even similar concrete strengths of slabs and columns of models, higher load carrying capacity was obtained in case of specimen with normal concrete slab.

Streszczenie

W artykule przedstawiono i skomentowano wyniki własnych badań eksperymentalnych w świetle obowiązujących przepisów normowych i formuł empirycznych. Rozważano mechanizm przekazywania oddziaływań pomiędzy słupami z betonu o wysokiej wytrzymałości przewarstwionymi słabszym betonem płyty. Płyty badanych modeli wykonane zostały z betonu zwykłego oraz lekkiego betonu kruszywowego. Jeden z rozpatrywanych parametrów stanowił stopień wytężenia płyty stropowej na przebicie na nośność słupa w obrębie połączenia. Stwierdzono brak istotnego wpływu tego czynnika. Zauważono natomiast wpływ rodzaju betonu płyty na nośność badanych modeli. Mimo zbliżonych wytrzymałości betonów płyt i słupów modeli, większą nośność zarejestrowano w przypadku elementu z płytą z betonu zwykłego.

Keywords: **Column; Column-slab connection; Concrete slab; Effective concrete strength; High-strength concrete; Lightweight aggregate concrete; Load carrying capacity.**

1. INTRODUCTION

Reason to undertake the subject presented in this paper was the practice of designing and constructing. Due to the significant progress that has been made recently in the field of concrete technology, it is possible to manufacture concrete of significant strength. High-strength concrete of 100 MPa is applied especially in tall buildings. Due to the large gravitational forces resulting mainly from dead as well as live loads, it becomes necessary to design load-carrying structures of considerable size. Introduction of high-strength concretes to the widespread use led to a significant restriction of the cross-sectional size of the columns and thus increase the profitability of constructed facilities by increasing the usable space. This solution is very beneficial from an economic perspective, however, it makes considerable difficulties in creating connections with the floor slab. In order to optimize the use of material strength properties, slabs are

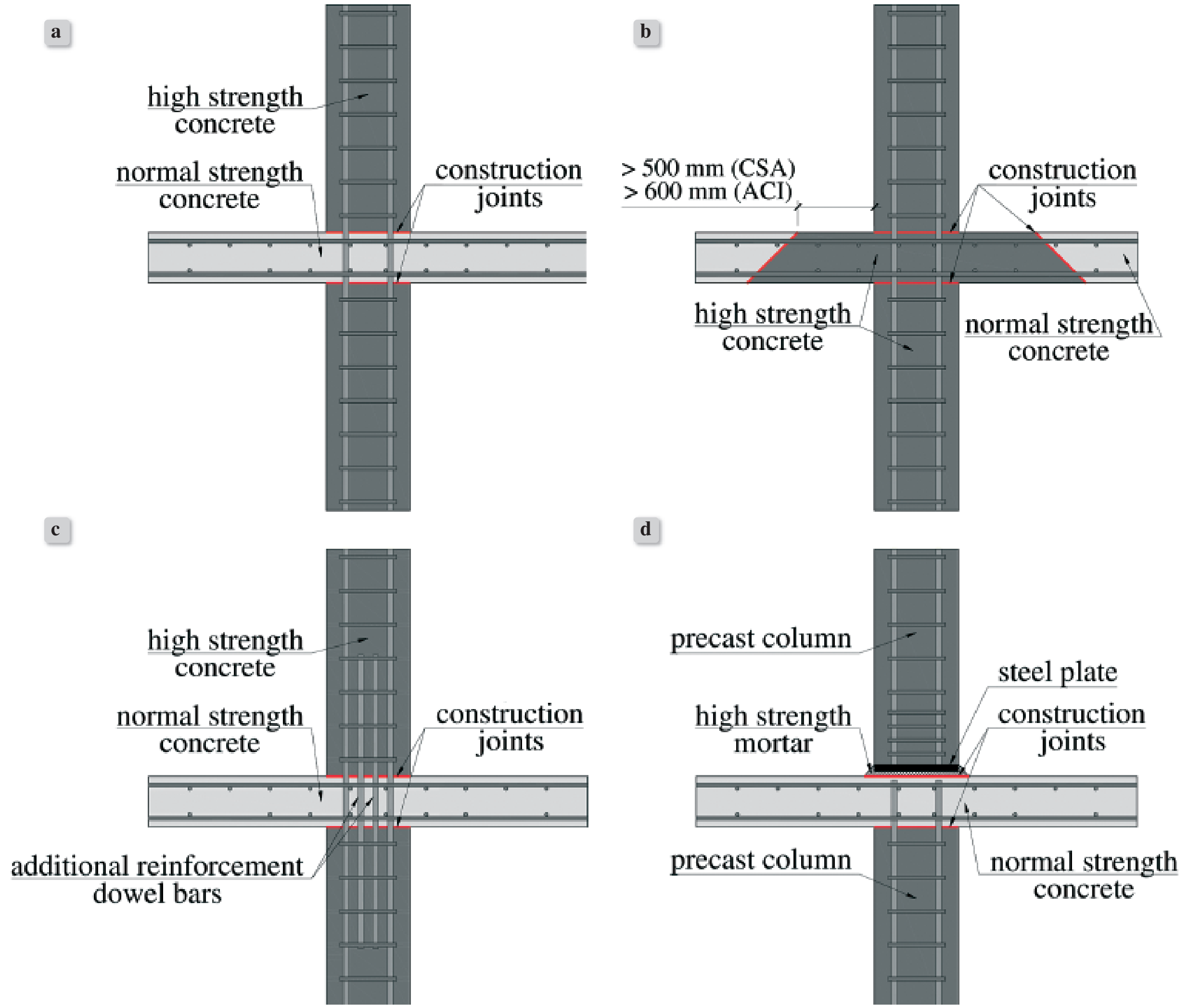

Figure 1.
Types of column-slab connection

made of normal strength concrete (NSC) or lightweight aggregate concrete (LWAC). For this reason, concretes of markedly various strength parameters comes into contact. A significant problem is thus taking into account the effect of intersection of high-strength concrete column by weaker slab concrete.

2. BACKGROUND

2.1. Code provisions

In none of the existing European codes the problem of load carrying capacity of columns intersected by weaker slab concrete was solved. This issue was presented only in the standards of the America ACI 318-11 [1], Australia AS 3600-2001 [2] and the Canada CSA A23.3-04 [3]. Despite some differences these codes present similar solutions on the calculation and design of column-slab connections. The basic parameter of the considered connections is the ratio of the column concrete strength $f_{c,c}$ to strength of slab concrete $f_{c,s}$. For internal connections, when the joint is surrounded on all sides by a slab, the effect of the intersection by weaker slab concrete on column load carrying capacity is not taken into account when the $f_{c,c}/f_{c,s}$ is not more than 1.4. If this quotient is greater then by dimensioning of the column strength of slab concrete should be taken. The solution of the homogeneous formation of the slab (see Fig. 1a) it is convenient from the point of view of technology, however, it may limit possibility to use full column concrete strength properties. When used as described below, additional technological actions the effect of intersection by weaker slab concrete can be ignored in the calculation.

One of the proposed solutions by the ACI [1], as shown schematically on Fig. 1b, is "puddling" which consists in putting high strength concrete within connection zone. The remaining area of the slab is made from normal strength concrete. The recommended coverage area made of high-strength concrete should be equal at least 600 mm (according to ACI 318 – 11 [1]) or 500 mm (CSA A23.3 – 04 [3]) measured from the edge of the column. It is also noted that the contact zones of concrete of different strengths should be outside the zone of significant bending moments. Both concretes should be properly compacted to ensure good integration. This solution allows for appropriate load transmission between the columns, however, it requires high carefulness and proper coordination of work. Due to the possibility of some mistakes it is recommended first to place high-strength concrete in connection zones.

Another solution is to compensate for decrease of concrete strength by applying an additional longitudinal reinforcement, which should be properly anchored to the upper and bottom column (see Fig. 1c). This solution, convenient from the point of view of construction, is relatively limited due to the maximum possible amount of the reinforcement – for columns should not exceed 0.04 of concrete cross-section area A_c ($0.08A_c$ within the lapped joints).

The solution in a slightly modified form is used for the construction of objects built in precast technology. Fig. 1d shows the method of realizing column-slab constructions, when precast columns are used and the slab is made in monolithic technology. Loads are transmitted from the top column mostly via longitudinal reinforcement. Rigid steel plate base crowning the upper column on high-strength mortar allows to uniform load transmission, limiting at the same time the transverse strains of column.

2.2. Literature survey

First, the relatively extensive studies have been carried out starting since the 1960s by *Bianchini et al.* [4]. These included models which represented all types of column-slab connections. 11 models corresponding to internal connections were investigated. The main purpose of the study was to determine the effect of intersection by weaker slab concrete on load carrying capacity of the column. The authors focused on the determination of column to slab concrete strength aspect ratio, below which the effect of heterogeneity can be neglected. For the first time, they introduced the concept of the effective concrete strength $f_{c,e}$ which is a measure of real concrete strength within the connection zone.

The main considered parameter was the ratio of column to slab concrete strength ($f_{c,c}/f_{c,s}$). Geometry and reinforcement of the investigated models were the same. It was noted an effect of $f_{c,c}/f_{c,s}$ aspect ratio on load carrying capacity of the column. It was stated that the limiting value of these ratio, above which the decrease load carrying capacity of internal column has to be considered it is equal to 1.5.

Comparing the results obtained for edge and corner connections they found a significant effect of confinement by concrete slab on the strength of joint concrete. On the basis of these investigations, the following formula has been developed to describe the effective concrete strength $f_{c,e}$:

$$f_{c,e} = \begin{cases} f_{c,c} & \text{when } f_{c,c}/f_{c,s} \le 1.5 \\ 1.5f_{c,s} + 0.75\left(f_{c,c} - 1.5f_{c,s}\right) & \text{when } f_{c,c}/f_{c,s} > 1.5 \end{cases} \quad (1)$$

The continuation of this work were investigations of *Gamble and Klinar* [5]. Use of concrete of considerable for those times strength of up to 105 MPa made possible experimental verification of effective concrete strength formula $f_{c,e}$ at higher $f_{c,c}/f_{c,s}$ ratios. The study confirmed the observations made by Bianchini et al. [4]. The authors found that the effect of concrete strength on the column load carrying capacity depends only on the ratio $f_{c,c}/f_{c,s}$, regardless of the concrete strengths at which it is obtained.

Another study carried out in the early 1990s by *Shu and Hawkins* [6] included 54 models of isolated columns, intersected by weaker concrete. The considered parameters in these study were: the $f_{c,c}/f_{c,s}$ ratio of 1.0÷5.6, the slab thickness h to the column width c ratio in the range of 0.17÷3.0 and the ratio of column longitudinal reinforcement.

The elements with a low h/c ratio were damaged in similar way to columns made entirely of high strength concrete. Destruction of models with a weaker concrete layer of considerable thickness started with the rise of cracks within the node. The authors concluded a clear effect of the h/c aspect ratio on the load carrying capacity of the column which decreased by increase of h/c. The authors presented design formula which allows to determine the effective joint concrete strength of edge and corner connections:

$$f_{c,e} = f_{c,s} + \frac{f_{c,c} - f_{c,s}}{0.4 + 2.66\,h/c} \quad (2)$$

A significant contribution to the current state of knowledge brought experimental investigations of *Ospina and Alexander* [7]. They included all types of column-slab connections. In contrast to previous studies, slabs of test specimens were loaded during the tests. Due to bending moments the upper part of the slab was subjected to tension, what resulted in a decrease of confining effect of joint concrete by surrounding slab. For this reason, these models were characterized by lower load carrying capacities than specimens investigated by *Bianchini et al.* and *Gamble and Klinar* when the slabs remained unloaded started.

The authors reaffirmed the earlier observations on the effect of $f_{c,c}/f_{c,s}$ and h/c aspect ratios on load carrying capacities of columns intersected by weaker concrete. They proposed their own relationship defining the effective concrete strength:

$$f_{c,e} = \begin{cases} f_{c,c} & \text{when } f_{c,c}/f_{c,s} \le 1.4 \\ \dfrac{0.25}{h/c} f_{c,c} + \left(1.40 - \dfrac{0.35}{h/c}\right) f_{c,s} & \text{when } f_{c,c}/f_{c,s} > 1.4 \end{cases} \quad (3)$$

The empirical formula developed by *Ospina and Alexander* is a special case the basis of the expression used in the Canadian CSA Standard A23.3 – 04 [3] which describes effective strength of internal column-slab connection joints:

$$f_{c,e} = \begin{cases} f_{c,c} & \text{when } f_{c,c}/f_{c,s} \le 1.4 \\ 0.25 f_{c,c} + 1.05 f_{c,s} & \text{when } f_{c,c}/f_{c,s} > 1.4 \end{cases} \quad (4)$$

The internal column-slab connections were also the subject of investigations conducted by *Viet Tue et al.* [8]. The main considered parameters were slab thickness h to column width c ratio and slab longitudinal reinforcement ratio. On the basis of obtained results the authors proposed a new relationship used for description of the effective concrete strength, in which the slab reinforcement ratio as a factor affecting the confinement of joint concrete was taken into consideration.

In recent years several works (such as *Lee and Mendis* [9], *Lee and Yoon* [10]), which present the results of experimental investigations of columns intersected by weaker concrete were published. There were presented new relationships describing the effective concrete strength of column-slab connection joints, which were developed on the basis of an analogy to masonry structures.

3. OWN INVESTIGATIONS

3.1. Test setup and experimental programme

The experimental investigations of column-slab connections were initiated in 2011. The tests were conducted on a press setup with a maximum thrust of a hydraulic jack equal to 6000 kN. The slab was loaded point-wise in the corners through the steel beams connected to a hydraulic jack with a maximum thrust of 100 kN. Test setup with therein the model is shown in the Fig. 2.

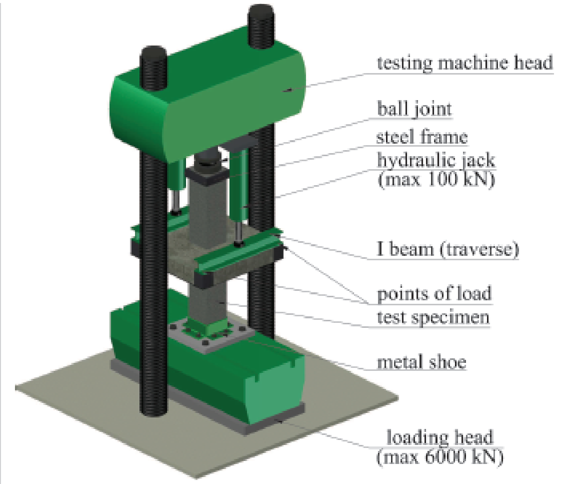

Figure 2.
Test setup

In order to check the proper operation of the test stand the three pilot models were made. They were characterized by the same geometry. The only variable parameter was the strength of the slab concrete. The columns of the models were made of high strength concrete while slabs of normal strength concrete. One of the specimens (M60/20/1) was the comparison-model for second series models with the slabs of lightweight aggregate concrete. After tuning the test setup the next stage of the work began. Three ML-Series specimens were manufactured in the scale of 1 : 2 (because of the technical possibilities of the test bench). They were made in three stages: first casting concrete of the bottom columns, then the next day after setting the form placing the concrete of the slab was begun. At the end concrete of the top column was cast. In addition, comparison-models which represented bottom and top columns were made. They were made of the same concrete and were reinforced in the same way as the columns of basic specimens. It was assumed to obtain column concrete strength equal to 80 MPa. The slabs of models were

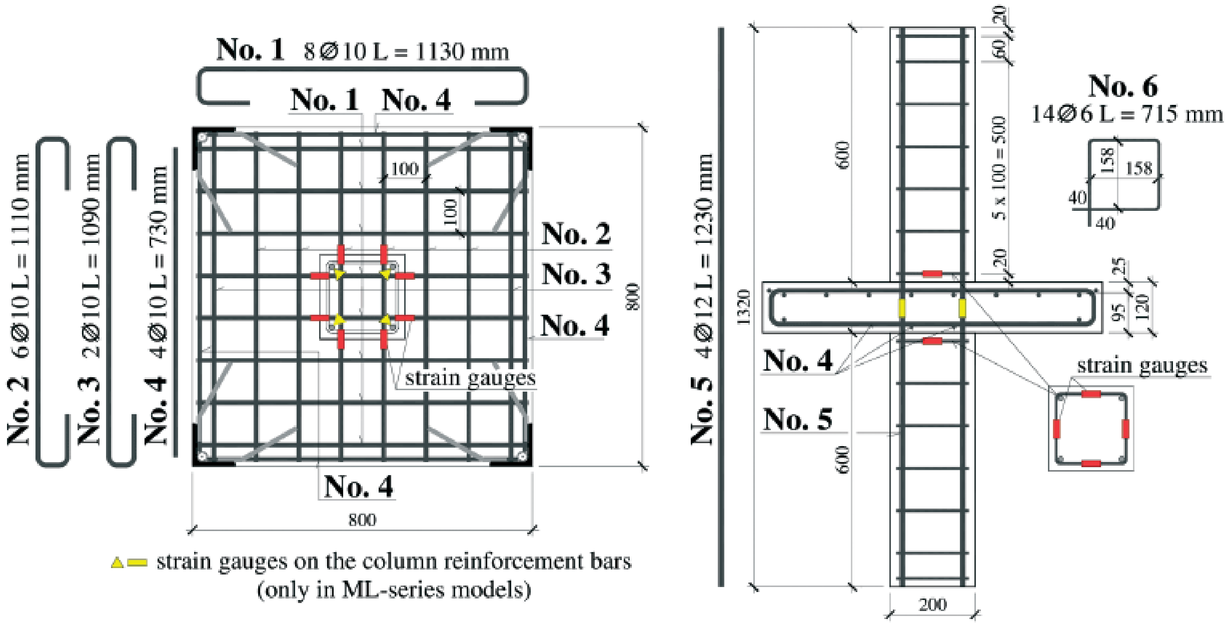

Figure 3.
Reinforcement of test specimens and location of strain gauges

made of lightweight aggregate concrete with a grain diameter of 10 mm and the assumed compressive strength of 25 MPa.

Reinforcement of the models was shown in Fig. 3. Pilot and basic series models were reinforced in the same way. During the test measurements of deformation of the column and slab longitudinal reinforcement, as well as the stirrups were carried out by strain gauges. Their location is shown in Fig. 3. In addition, the strains were measured on the surface of the concrete.

Strength of concrete was determined in the test day on the prepared cylindrical samples with a diameter of 150 mm and a height of 300 mm. After completion of the test series, no significant differences between the strengths of concrete from one concrete cast were noted. Therefore, the mean value of concrete strength f_{cm} was taken for the further analysis. In the following Tables 1 and 2 the strength parameters of the M and ML series models are summarized.

Table 1.
Properties of used concrete

Specimen	Bottom column		Top column		Slab		
	f_{cm} [MPa]	E_{cm} [GPa]	f_{cm} [MPa]	E_{cm} [GPa]	f_{cm} [MPa]	E_{cm} [GPa]	ρ [kg/m^3]
M60/20/1	72.8	–	75.1	–	26.9	–	2207
ML – 1	89.8	32.2	88.4	33.3	33.0	13.9	1722
ML – 2					28.8	13.3	1705
ML – 3					24.6	12.6	1688

f_{cm} – mean value of concrete cylinder compressive strength, E_{cm} – secant modulus of elasticity, ρ – bulk density

Table 2.
Properties of used steel

Specimen	Longitudinal reinforcement						Stirrups		
	Column			Slab					
	Ø [mm]	f_{ym} [MPa]	E_s [GPa]	Ø [mm]	f_{ym} [MPa]	E_s [GPa]	Ø [mm]	f_{ym} [MPa]	E_s [GPa]
M60/20/1	12	540.4	194.5	10	544.4	203.1	6	640.2	199.6
ML – 1		594.2	209.8		539.5	211.5		586.4	215.7
ML – 2									
ML – 3									

f_{ym} – mean value of yield strength of reinforcement, E_s – modulus of elasticity of reinforcing steel

3.2. Main observations and behaviour of test specimens

Figure 4a shows the average strains of the longitudinal slab reinforcement in the two orthogonal directions. It could be seen clear increase in strains caused by slab load, which was between 50 and 150 kN, depending on the investigated specimen. Increase of the load transmitted to the column resulted in a slight decrease in strains in the slab reinforcement. Above a certain level of the column load it was recorded a sharp increase in strains of the slab reinforcement,

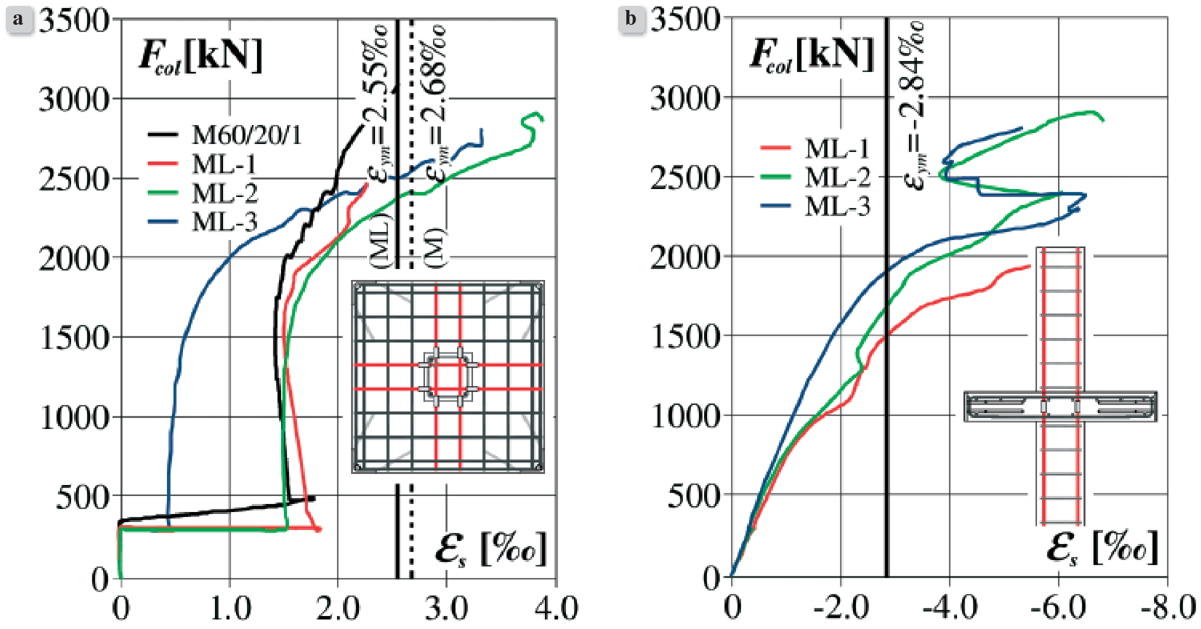

Figure 4.
Mean strains and location of strain gauges: a) on slab b) on column reinforcement

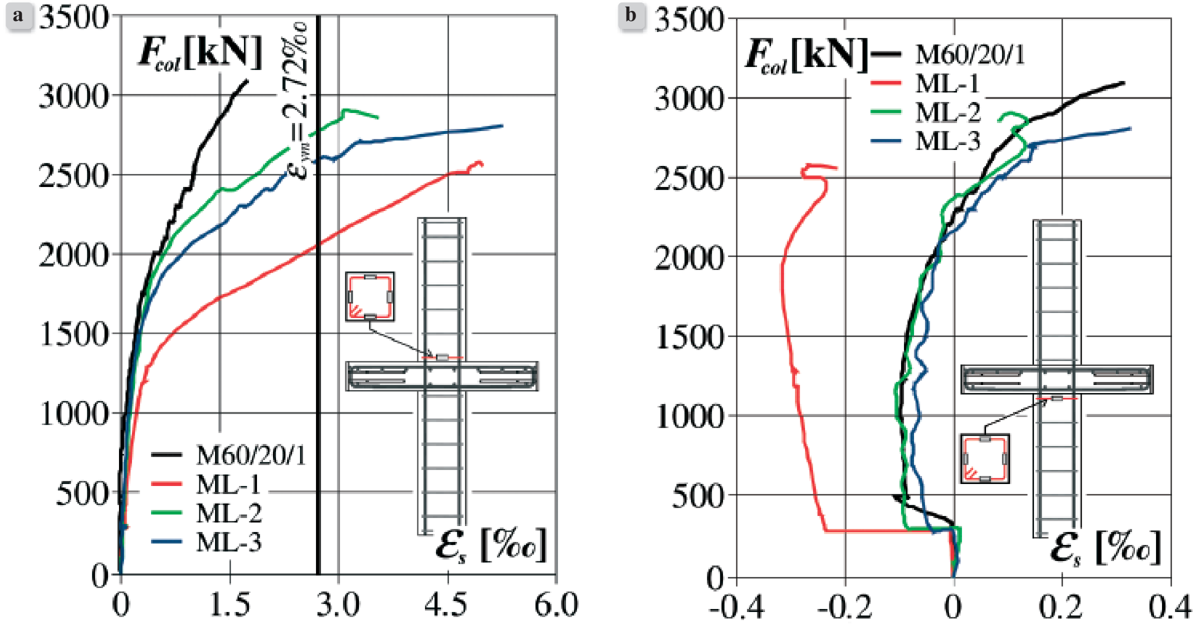

Figure 5.
Mean strains of transverse reinforcement: a) upper stirrup, b) bottom stirrup

even though the slab load remained unchanged. This observation is explained by the deformation of the joint concrete that caused spreading of the surrounding slab. Strain raising rate was dependent on the modulus of elasticity of concrete. By the M60/20/1 specimen with normal strength concrete slab it was observed slower growth of strains. Registered strains suggested yielding of the column longitudinal reinforcement.

Readings of strain gauges placed on the column reinforcement of ML series models, which are shown in Fig. 4b, provided the relevant information about the load transmission mechanism within the connection joint. After reaching the yield point, the deforma-

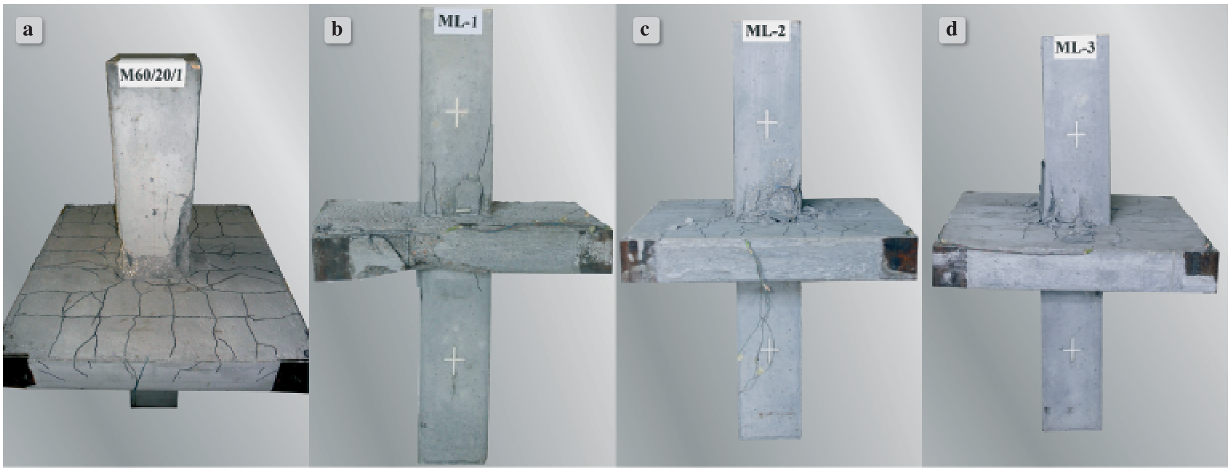

Figure 6.
Test specimens after failure: a) M60/20/1, b) ML – 1, c) ML – 2, d) ML – 3

tions have been significantly increased. At load equal to about 75% of the destructive force it was began to record significant variability of deformations. This observation may testify buckling of the column longitudinal bars due to significant destruction of joint concrete.

Analyzing strains of stirrups located at a distance of about 20 mm from the slab surfaces (Fig. 5a and 5b) a clear effect of slab load can be seen. In the initial phase of the test in the bottom stirrup compressive stresses only compressive stresses were recorded. An increase in the column load caused a change in the nature of stress, however, the maximal strains did not exceed 0.4‰. The discrepancy between the readings for the ML – 1 and the other models may result from a break in the test due to failure of a hydraulic press.

Throughout the test in the top stirrup only tensile stresses were recorded. It is clear that the rate of their growth is related to the deformation of slab surrounding the joint. An increase in the growth rate of strains in the stirrups was accompanied by an increase in strains of slab longitudinal reinforcement, which resulted from the significant lateral deformation of joint concrete. For ML series specimens yielding of upper stirrups was recorded while for model M60/20/1 stresses were only close to the yield point.

In the Fig. 6 are presented forms of the destruction of all described specimens. Destruction of ML – 1 model was initiated by a damage of the slab. Other specimens have been destroyed in a violent manner, which was related to the damage of top and bottom column near the slab surface.

4. LOAD CARRYING CAPACITY OF COLUMN – SLAB CONNECTIONS

One of the parameters considered in the study was the effect of an effort grade in punching shear on load carrying capacity of the specimen. The theoretical punching shear resistance was determined in accordance with the principles of Eurocode 2 [11] (designations are explained in Table 3):

$$v_{R,c} = \begin{cases} C_{R,c}\, k \sqrt[3]{100 \rho_l f_{cm}} & \text{for NSC} \\ C_{Rl,c}\, k\, \eta_1 \sqrt[3]{100 \rho_l f_{cm}} & \text{for LWAC} \end{cases} \tag{5}$$

where $C_{R,c} = 0.18$ and $C_{Rl,c} = 0.15$

Table 3.
Punching shear effort of slab

Specimen	d [mm]	ρ_l [%]	u_1 [mm]	η_1 [-]	k [-]	V_E [kN]	v_E [MPa]	$v_{R,c}$ [MPa]	$v_E/v_{R,c}$ [-]
M60/20/1	95	0.83	1994	–	2.0	100	0.53	1.01	0.52
ML – 1				0.87		150	0.79	0.79	1.00
ML – 2				0.86		100	0.53	0.75	0.71
ML – 3				0.86		50	0.26	0.71	0.37

d – effective depth of slab, ρ_l – longitudinal reinforcement ratio, u_1 – length of control perimeter, η_1 – factor for lightweight aggregate concrete equal $0.40 + 0.60\rho/2200$ (ρ – density of slab concrete), k – scale factor, v_E – shear stress on control perimeter, $v_{R,c}$ – punching shear resistance

The obtained results clearly shows that the effort grade in punching shear does not affect significantly the load carrying capacity of the column. Regardless of the applied slab load, the load carrying capacity of ML series specimens was about 20% lower than the capacity of the comparison models. Therefore this indicates a significant effect of intersection by weaker slab concrete on load carrying capacity of the column. Although the slabs of M and ML series models were made of similar strength concrete, only load carrying capacity of M60/20/1 was close to theoretical.

5. EFFECTIVE COMPRESSIVE STRENGTH

The analysis of the test results was also made to verify the existing code provisions and empirical relationships. Effective concrete strength is defined in the ACI 318-11 [1] as follows:

$$f_{c,e} = \begin{cases} f_{c,c} & \text{when } f_{c,c}/f_{c,s} \le 1.4 \\ 0.75 f_{c,c} + 0.35 f_{c,s} & \text{when } 1.4 < f_{c,c}/f_{c,s} \le 2.5 \\ 2.225 f_{c,c} & \text{when } f_{c,c}/f_{c,s} > 2.5 \end{cases} \qquad (6)$$

Effective concrete strength according to the Canadian standard CSA A23.3-04 [3] was calculated by the expression (4), to *Bianchini et al.* [4] by (1), and by *Ospina and Alexander* [7] in accordance with equation (3). Table 4 lists the obtained results. The strengths of joint concretes of considered specimens were determined according to the following relationship:

$$f_{c,e} = \frac{F_{exp} - A_s f_{ym}}{A_{col} - A_s} \qquad (7)$$

where F_{exp} is load carrying capacity, A_s is area of column longitudinal reinforcement and A_{col} is the gross area of column.

Table 4.
Effective strengths of joint concrete

Specimen	F_{exp} [kN]	$f_{c,c}/f_{c,s}$	$f_{c,e}/f_{c,s}$ acc. to [1]	acc. to [2]	acc. to [4]	acc. to [7]	experiment.
M60/20/1	3180	2.75	2.225	1.738	2.438	1.963	2.759
ML – 1	2720	2.70	**2.225**	1.726	**2.400**	**1.943**	1.884
ML – 2	3000	2.99	2.225	1.798	**2.618**	2.064	2.323
ML – 3	2850	3.55	2.225	1.938	**3.038**	2.297	2.607

unsafe results were **bold** (theoretical values higher than experimental)

6. CONCLUSIONS

In view of test results of internal column-slab connections there is no important effect of an effort grade in punching shear on column load carrying capacity. However, an important influence of type of slab concrete on the load carrying capacity should be noted. Column concrete strength of ML – 2 was about 16% higher than of M60/20/1 model. The slab concretes of both specimens were of a similar strength. Even so, load carrying capacity higher by about 9% was registered in case of M60/20/1 model, whose slab was made of normal concrete of higher secant modulus of elasticity.

Comparing the test results with code provisions and empirical relationships, which are illustrated in Fig. 7, it can be noted that only the CSA A23.3-04 [3] sets in a safe manner effective strengths of column – slab connection joints. All of concerned procedures predict in a safe manner capacity of M60/20/1 model with normal concrete slab. It is therefore necessary to draw attention to the need for further analysis of the lightweight aggregate concrete column-slab connectionjoints, since all of the presented procedures have been developed basing on the test results of models with normal concrete slab.

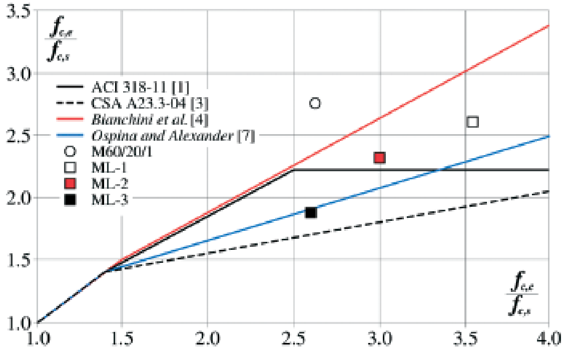

Figure 7.
Comparison of test results with existing code and empirical provisions

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