JOURNAL OF SCIENCE OF THE MILITARY ACADEMY OF LAND FORCES

Volume 48 Number 1 (179) 2016

DOI: 10.5604/17318157.1201746

CONSTRUCTION DISASTERS CAUSED BY PUNCHING IN THE SUPPORT ZONE OF REINFORCED CONCRETE SLAB-AND-COLUMN CEILINGS AS WELL AS MEANS OF THEIR REPAIR AND REINFORCEMENT

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Received on January 15th 2015; accepted after revision in April 2015

Abstract:

Slab-and-column ceilings are widely used because of the considerable savings that they allow to obtain in the total construction cost. However, this structural system has a weak feature that consists of vulnerability to punching in a ceiling slab around its connection to a column. This paper describes several examples of disasters caused by slab punching and gives conclusions resulting therefrom. In order to eliminate the problem of punching, in the world there are used various types of shear reinforcement in a slab around a column, which are characterised by malleability and puncture resistance, thereby preventing a disaster. Examples of such reinforcement of ceiling slabs around columns are also shown in the work.

Keywords:

disaster, building structure, punching in the support zone, slab-and-column ceiling , reinforcement

INTRODUCTION

Bidirectionally reinforced ceiling slabs of uniform thickness, which are directly supported by columns, prove to be very economical when used to small spans and not too large loads as they are easy to apply and do not have ribs that reduce the useful height of a ceiling. However, the negative feature of these floor ceilings is susceptibility to punching by shearing in the vicinity of a slab-column connection, which may lead to the chain mechanism of damage resulting from brittle crack [6]. In flat slabs covering floors the concentration of stresses occur in connections around truncated cone shaped columns and they break due to punching by shearing rather than scratching during bending, particularly when the high level of reinforcement is provided (Figure 1). In floor slabs there is stress concentration in the concrete, which may lead to punching in the support zone, the character of which depends on the reinforcement layer in a slab (including the direction and the level of reinforcement Figure 1).

a) b)

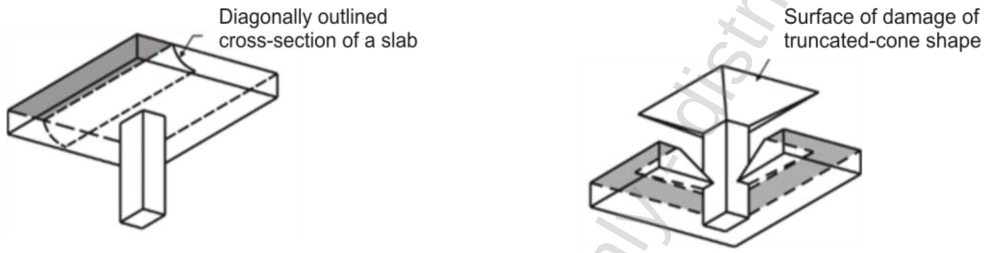

Fig. 1. Punching of reinforced slabs [16a]: (a) unidirectionally; (b) bidirectionally

Below there are described collapses caused by such errors on examples of buildings: 2000 Commonwealth Avenue, Bailey Crossroads Building, Virginia, New York Coliseum and a multi-storey car park, Pipers Row Car Park, Wolverhampton. The characteristics of repairs and reinforcements of slab-and-column ceilings are given in the conclusion.

1. FAILURES AND DISASTERS CAUSED BY PUNCHING IN THE SUPPORT ZONE OF SLAB-AND-COLUMN CEILINGS

1.1. The collapse of the 16-storey building 2000 Commonwealth Avenue, Boston, 5th January 1971

The collapse of the building with two-way reinforced slab ceilings of uniform thickness, supported by columns, took place during its construction. In Figure 2 there is shown the view of the ceiling and the scale of its collapse. The resistance to punching by shearing depends on loads, the useful thickness of the slab and the surface of the punching plane around the column (Figure 3). According to [10], [13] factors that contributed to the disaster in Boston include the premature removal of stamps before reaching the designed strength of concrete, which was additionally reduced by low temperature.

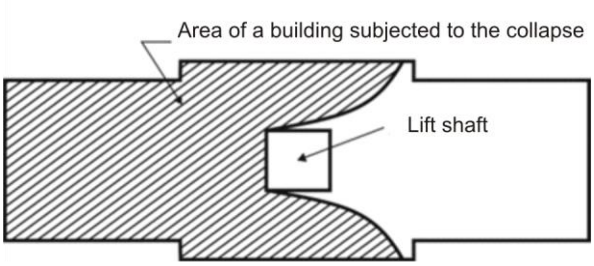

Fig. 2. The view of the ceiling structure and its collapse [10]

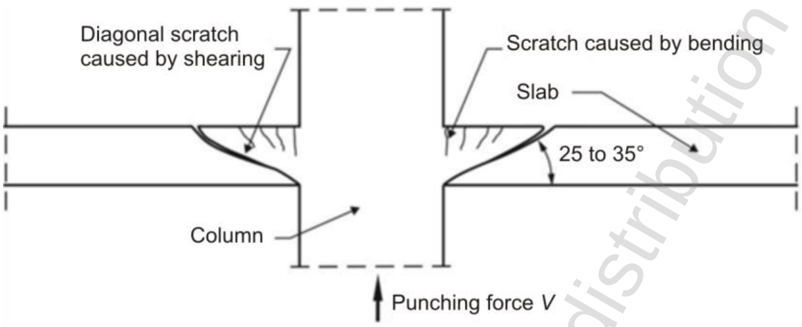

Fig. 3. Scratches caused by bending and shearing in the slab around its connection to the column

1.2. The collapse of the residential building Skyline Plaza, Bailey Crossroads in Fairfax, Virginia

The similar well-known case of the premature removal of formwork took place in the residential building Skyline Plaza, Bailey Crossroads Building on 3rd February 1973, 14:30 [20]. This kind of an error is one of the most common causes of a failure that can lead to a progressive collapse, thus it is extremely dangerous [14].

This building was almost entirely erected when the damage occurred. While the concrete was being laid on the 24th floor, the formwork on the 22nd floor was removed. Thus, the fresh concrete was based entirely on the 23rd floor, where the concrete had been laid only five days before. The weight of the concrete on the 24th floor was too large due to the shear resistance of the slab around a single column, which caused the collapse involving the entire height of the building. All the slabs were 200mm thick, the height of floors was equal to 3 m.

14 construction workers lost their lives, 35 others suffered injuries [20]. Figure 4 shows the building after the disaster.

Fig. 4. The view of the Skyline Plaza building in Virginia after the progressive partial collapse of its central part as a result of punching in support zones of flat ceiling slabs

Photo by Nick Carino of National Institute of Standards Technology

Conclusions drawn from the collapse of the Skyline Plaza building [14], [23]:

- the designed rigidity of the structure was sufficient to prevent the progressive collapse;
- loads occurring in the construction phase should always be estimated and included in the project design;
- the strength of concrete must be determined before removing the formwork;
- the correctness of formworks of the above ceilings as well as of the currently implemented one should be checked especially in slab-and-column systems.

1.3. The collapse of the ceiling of New York Coliseum, 1955

In 1955 the main coffered ceiling of Coliseum collapsed with no previous indications (Figure 5). The ceiling had constituted the exhibition space while the concrete was being laid with the use of 8 motor-driven cars, each weighing about 1.5t, moving at a speed of 20 km/h. By the collapse 380m^3 of the concrete had been laid. The ceiling covered the floor of the height of 6.7m, which was supported by two-storey stamps.

After-failure investigations [17] evidenced that if diagonal and horizontal frameworks of the temporary support structure had been applied, the collapse would not have taken place. The framework was particularly significant due to horizontal forces caused by the cars.

Sometimes a formwork fails or gets damaged if stamping moves / subsides due to vibrations caused by:

- traffic;
- the concrete compaction;
- the movement of workers or the equipment across the formwork.

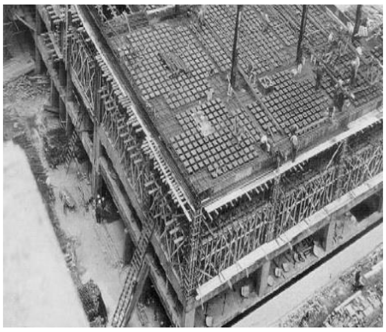
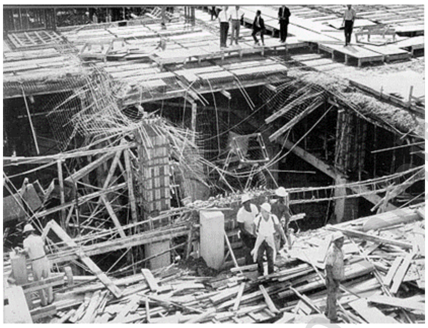

Fig. 5. The view of the ceiling of the Coliseum before and after the collapse [12]

1.4. The partial collapse of the multi-storey car park Pipers Row Car Park, Wolverhampton, 20th March 1997

The part of the roof of the fourth floor collapsed under its own weight (Figure 6). It was of the area of 15m × 15m and the weight of 120t and it fell down due to the puncture of slabs on one of the columns that led to the progressive collapse also caused by punching of the slab on 8 adjacent columns [3], [25]. Luckily the parking lot was empty and no accidents happened there, however the decision was taken to close the car park for 400 cars and to begin the demolition of the parking lot. Shortcomings of the project design and the maintenance process (negligence in the ceiling repair technology) were the reasons for the collapse of the upper ceiling, which had been realised in 1965 and weighed 120t.

a)

b)

Fig. 6. The view of the collapsed flat ceiling of the car park Pipers Row Car Park, Wolverhampton: a) the general view; b) the view of the column after being punched

Photo by HSE, the UK

2. CONSTRUCTION OF THE FLAT SLAB-COLUMN CONNECTION IN THE LIGHT OF PUNCHING BY SHEARING

In order to increase the punching shear capacity of slabs there are used different systems of designing slab-and-column connections (see Figure 7)

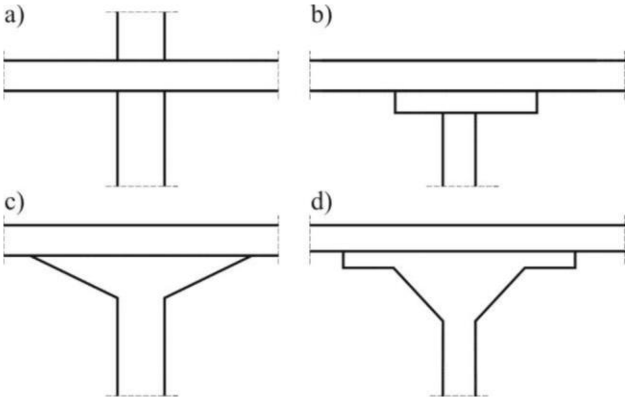

Fig. 7. Connections of slabs and columns in slab-and-column ceilings: a) the slab ceiling of constant thickness; b) the slab ceiling with a head plate; c) the slab ceiling with a head (mushroom-shaped); d) the slab ceiling with a head plate and a mushroom head

Flat slabs allow an architect to reduce the height of a floor and enable the easy and quick construction in particular with the usage of advanced reinforcement techniques. However, flat slabs according to their structural characteristics (concrete strength, a reinforcement layout, a slab thickness etc.) are susceptible to punching by shearing around the cross-section of columns especially with a larger slab span (*l*s) and a payload > 5– 8 kN/m^2. Therefore, particularly in industrial buildings the right solution of a slab-column connection is required. Most often this can be achieved through thickening of the support zone. Another way to increase the capacity is the adoption of a head over a column. The width of a slab of the increased thickness is taken 1/3 of the slab span, while thickening is 1/4 of the flat slab thickness *(h)*. For larger loads, it may be necessary to adopt larger dimensions. For economic reasons, slabs of the same dimensions are applied within a building, and it is recommended to take thickening equal to the timber standard dimension. With the use of heads (conical or pyramidal ones) over columns, their width should be 8 to 10 of a slab thickness, and the height of minimum half the width of the half of an upper head.

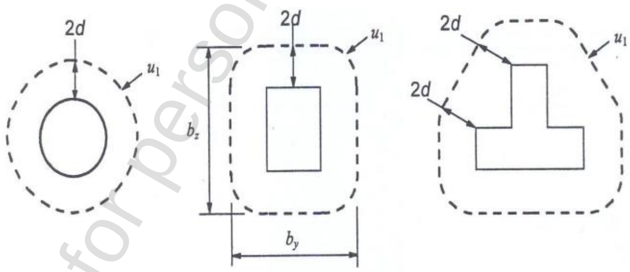

Fig. 8. Typical basic control circuits around load areas [21]

A bidirectionally-reinforced slab gets punched along a truncated cone (Figure 1b). According to the EC 2, the verification of the punching resistance involves the comparison of alternative shear stresses occurring during punching with concrete strength parametres [21]. Alternative shear stresses are calculated on the basis of loads acting on the control circuit. This critical cross-section is located within 2*d* from the load area [21]; the control circuit should be determined in such a way that minimises its length (Figure 8).

Figures 9-16 show different types of reinforcement in the form of pins, stirrups and bent rods that connect flat slabs with columns. Shear reinforcement is being increasingly used in flat slabs due to load capacity and malleability. The strength is nearly doubled compared to the attempts without shear reinforcement, as evidenced by tests conducted by Muttoni et al. [18]. Similarly, limit deformations are much higher (even more than tripled) than in slabs without shear reinforcement. The application of two-headed pins as the reinforcement against punching pursuant to the rules specified in EC2 [8], as well as the method of calculating them according to European Technical Approvals are presented in the work [15].

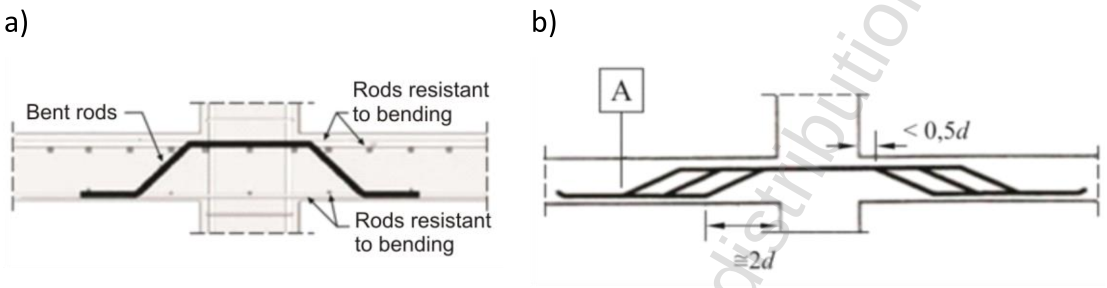

Fig. 9. Reinforcement with bent rods: a) the cross-section of the slab-column system according to [19]; b) the cross-section of the slab-column system according to [21], A – the external control circuit requiring shear reinforcement

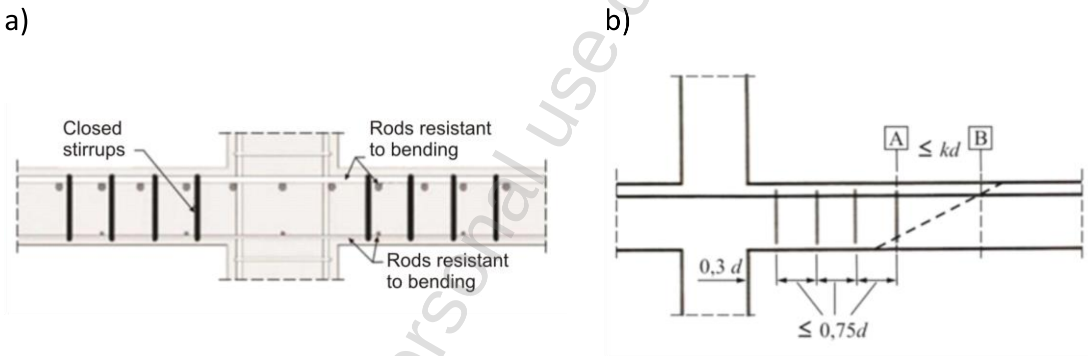

Fig. 10. Reinforcement with closed stirrups: a) the cross-section of the slab–column system [19]; b) stirrup spacing, A – the external control circuit, requiring shear reinforcement, B -the first control circuit, beyond which shear reinforcement is not required, *d* represents the average of useful heights of two orthogonal directions [21]

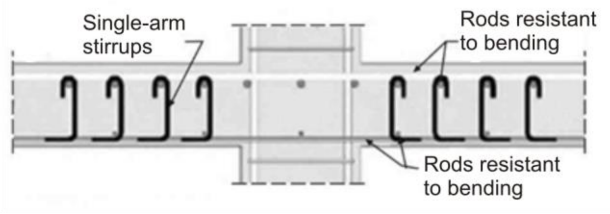

Fig. 11. Reinforcement with single-arm stirrups [19]

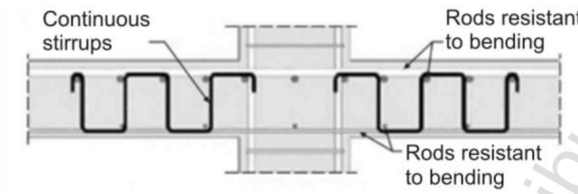

Fig. 12. Reinforcement with continuous stirrups [19]

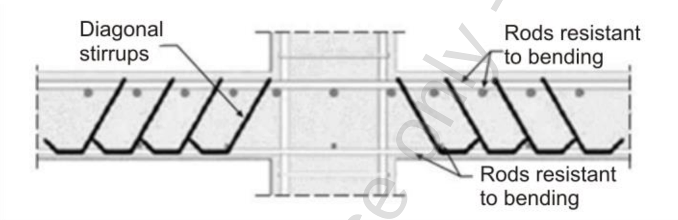

Fig. 13. Reinforcement with diagonal stirrups [19]

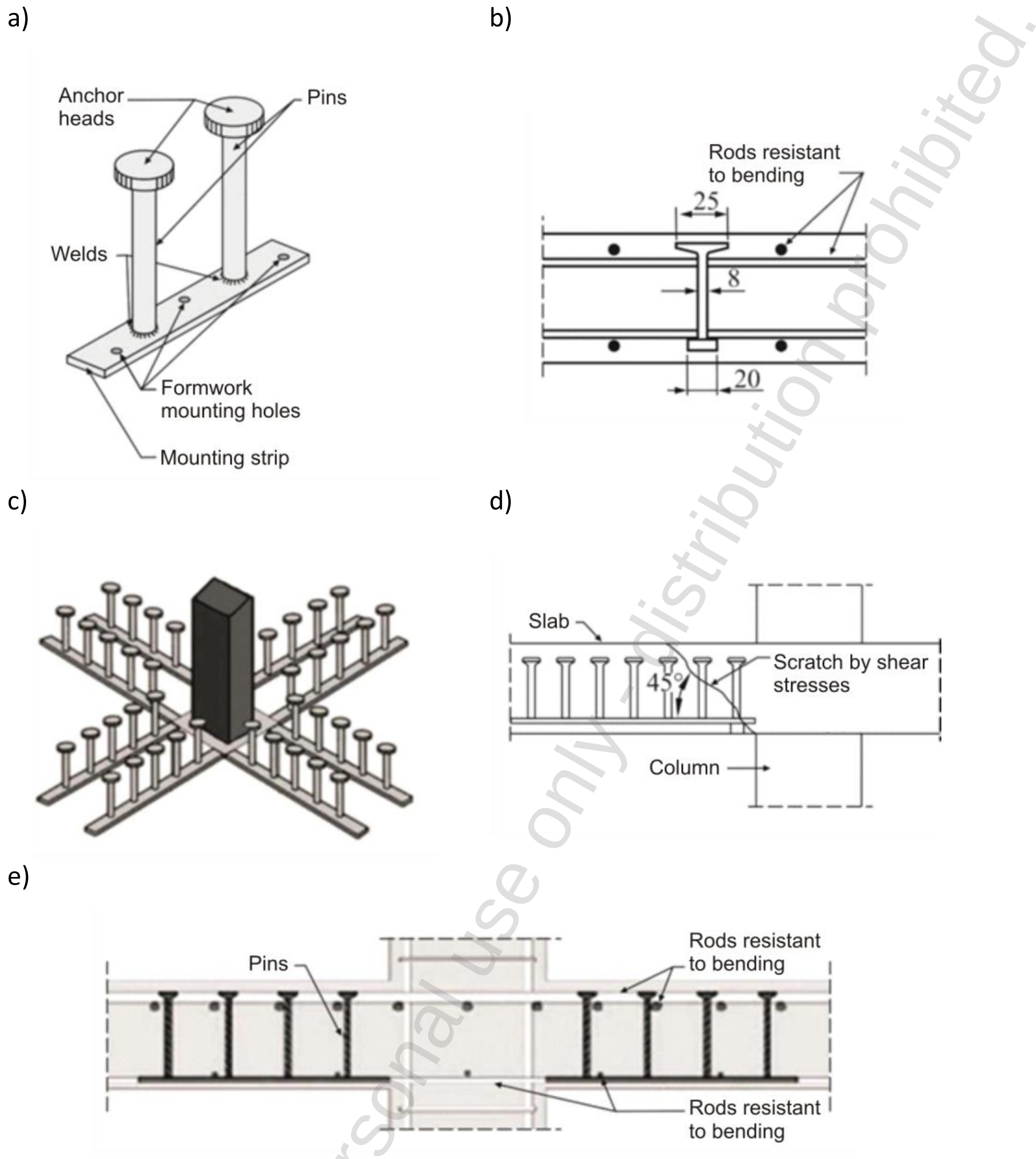

Fig. 14. Reinforcement to punching by means of one-headed metal pins: a) the view of steel pins; b) the location of the pin in the slab [27]; c) the scheme of the arrangement of one-headed reinforcement elements [27]; d) the view of the slab after punching; e) the cross-section of the slab-column system [19]

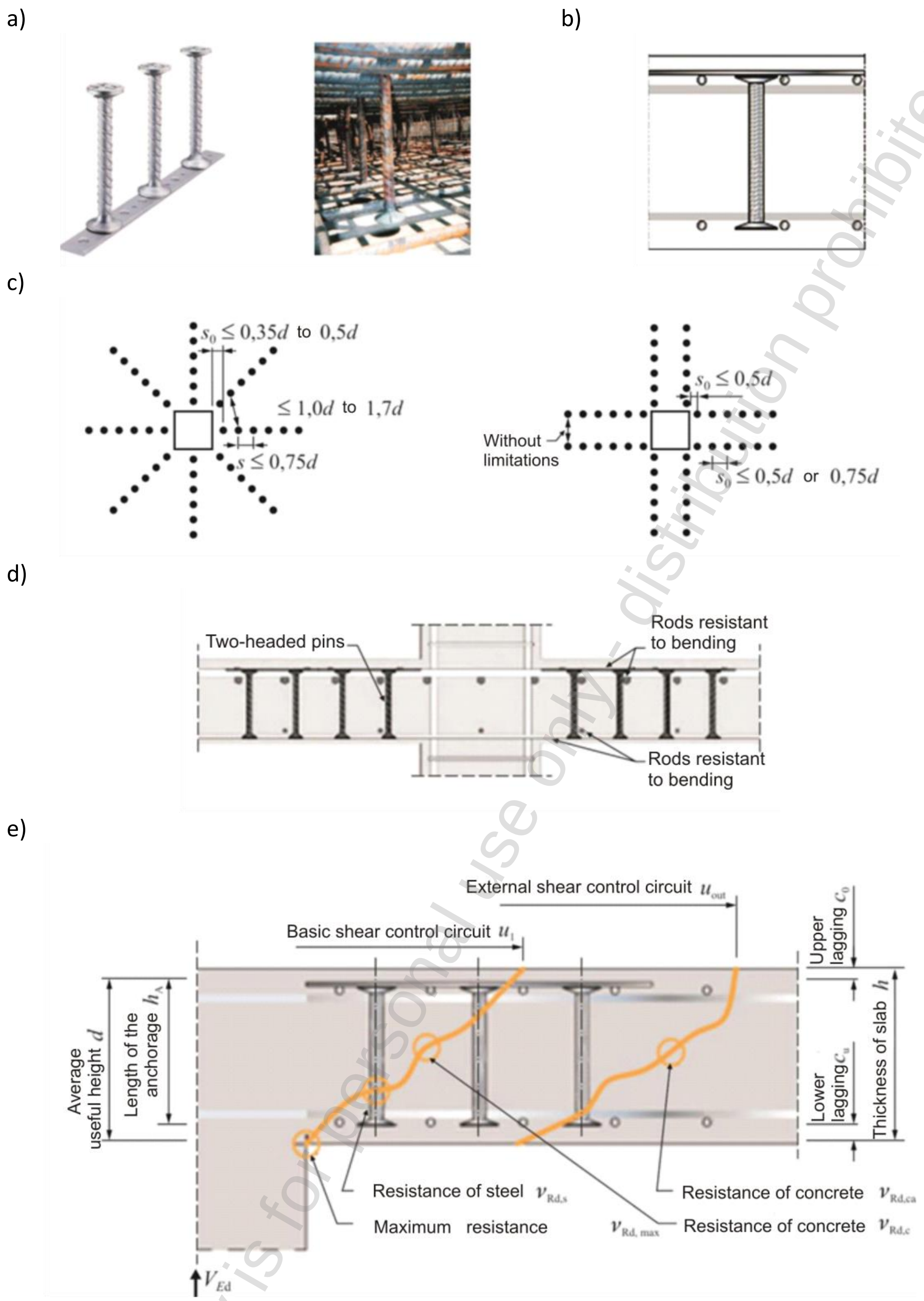

Fig. 15. Reinforcement of flat slabs with two-headed steel pins: a) the example of the inbuilt standard element [15]; b) the pin incorporated into the slab and typical dimensions; c) the distribution according to Halfen [1], [26] and the distribution according to the Canadian Standard [5]; d) the cross-section of the flat slab reinforced with two-headed pins [19]; e) the main design assumptions in the calculation of pins by ETA-13/0136, a- denotes the distance from the edge of the column to the considered control circuit [28]

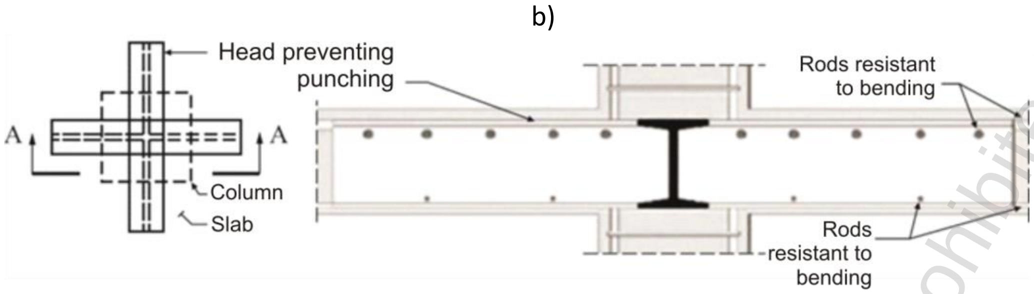

Fig. 16. The head with rigid reinforcement: a) the horizontal projection of the rigid reinforcement (bending reinforcement not shown); b) the cross-section A-A [19]

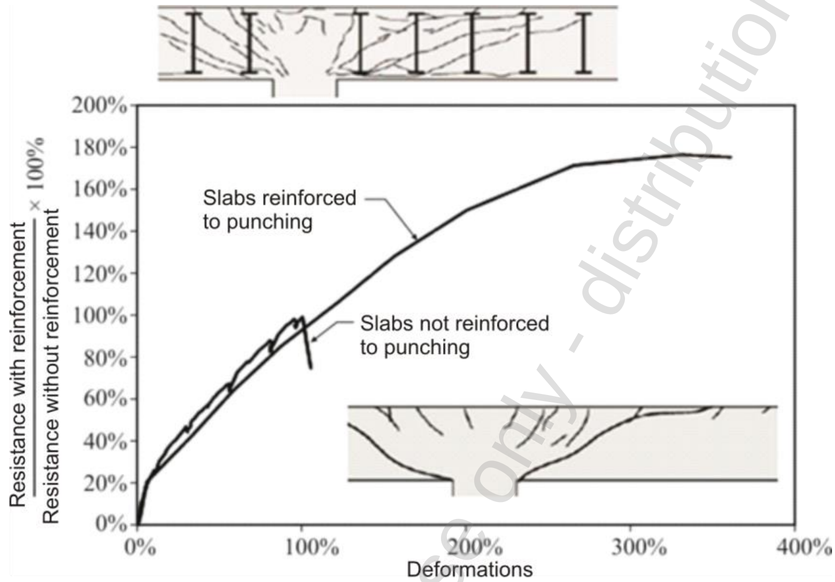

Fig. 17. The comparison of the behavior and resistance of two slabs with reinforcement and without reinforcement to punching by shearing [18], [9]

Should it be necessary, the puncture resistance of existing structures can be enhanced through the modernisation of slab-column connections involving the increase of the cross-section of a column in the head part by using shotcrete or by the injection method, or the use of a steel flange glued to the structure [24]. Another way to strengthen the resistance is the usage of pins placed in pre-drilled holes. Solutions of this type of reinforcements (see Figure 18) were developed by Hassanzadeh and Sundquist [11] (see [24]), Mary Polak and El-Salakawy [7], [22].

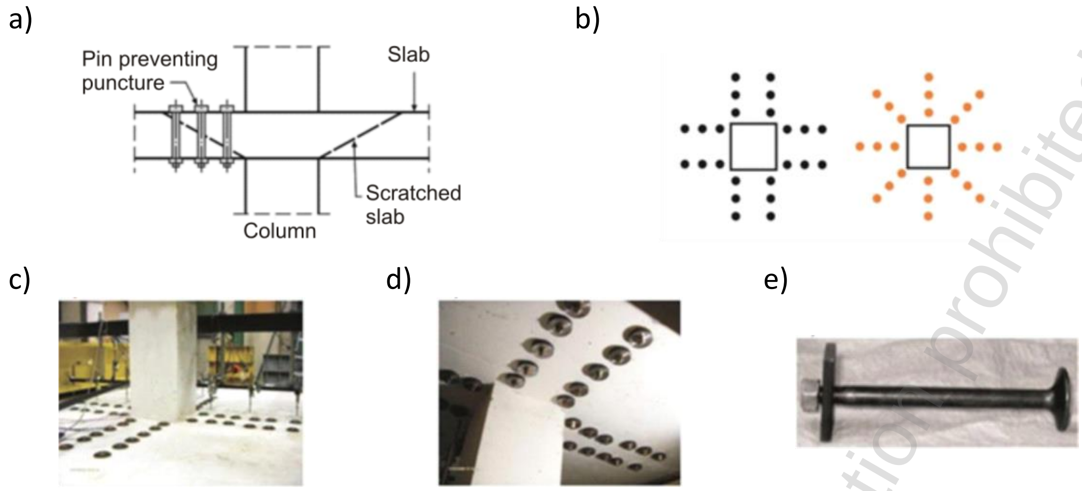

Fig. 18. Strengthening reinforced concrete slabs against punching with the use of metal two-headed pins [4]: a) pins in the area of the slab scratch; b) orthogonal and radial systems of pins in the slab around the column; c) the slab top view of steel pins in the orthogonal system; d) the slab bottom view of steel pins in the orthogonal system; e) the view of the two-headed steel pin

Figure 19 shows the way of strengthening the flat slab-column system using the carbon fiber reinforcement.

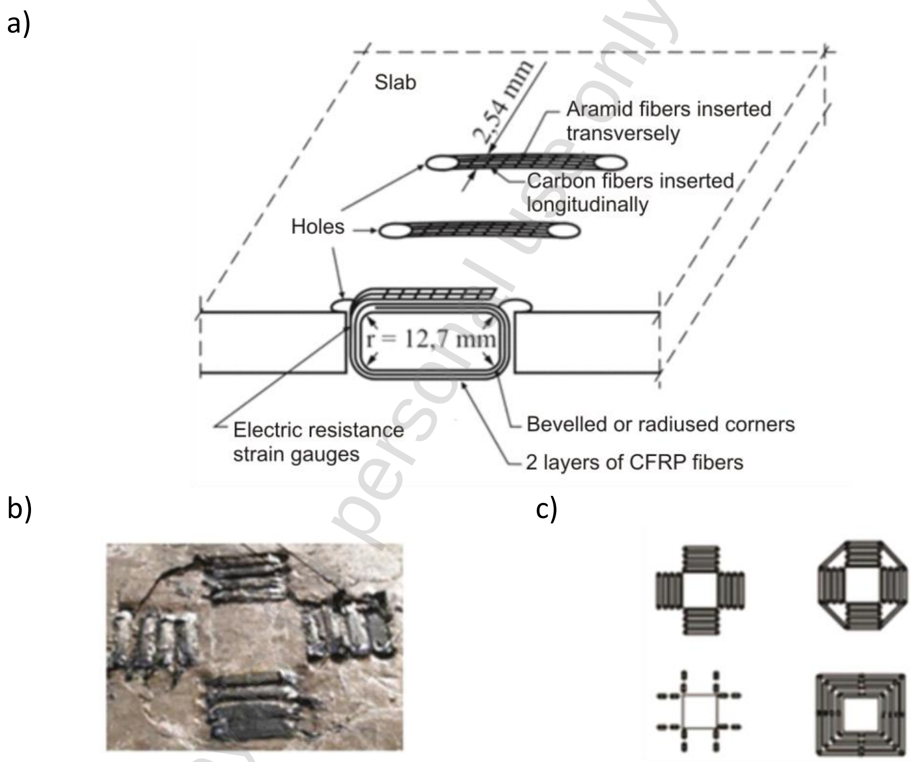

Fig. 19. Reinforcement with stirrups made of materials (one, two and four-layer ones): carbon fiber (longitudinal) and aramid (transverse) according the Binici's study [2]: a) the concept of the reinforcement against punching with strips of wound CFRP stitches passing through the holes, thus creating closed stirrups with the152.5 mm margin, b) the location of the stirrups and the marked line of the crack during the test, c) the studied systems of stirrups distribution.

CONCLUSION

The paper provides basic information on disasters caused by errors during the execution and design of reinforced concrete slab-and-column ceilings and different types of shear reinforcement used in a slab around a column to increase the bearing capacity of ceiling systems of this type.

In order to avoid this kind of disasters, the following conclusions can be drawn:

- when designing a slab-and-rib ceiling, one should check the puncture resistance as well as control whether a slab thickness is sufficient in view of the requirements concerning the ultimate states of resistance and usage; while at the implementation phase it is necessary to check if the reinforcement is stacked properly, i.e. it does not reduce slab resistance;
- the reinforcement being of prime importance as the protection against a progressive collapse should be placed on the perimeter of a column;
- additional elements in the form of frames or structural walls should be used so as to transfer horizontal loads;
- resistance of older slab-and-column systems must be checked, in particular the possible need to strengthen support zones, to reduce useful loads or span slabs, or to increase a slab thickness;
- loads occurring in the construction phase, especially horizontal and eccentric forces in the concrete during the fast delivery in the case of high formworks should always be estimated and taken into account in the design project;
- plans for laying concrete, formwork projects and a schedule of formwork removal or restamping should be determined in consultation with a general contractor;
- before removing formwork the current concrete resistance ought to be determined;
- the correctness of formwork of above ceilings as well as the currently implemented one must be monitored especially in slab-and-column systems;
- diagonal and horizontal frameworks of a temporary support structure are to be used;
- the complete building permit should be ensured;
- requirements for the concrete quality have to be met and appropriate methods for determining a concrete resistance in cold weather must be applied;
- adequate construction supervision is obligatory to be ensured;
- favourable and unfavourable weather conditions should be taken into account before drawing up final construction or expansion plans.

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HOW TO CITE THIS PAPER

Kobielak S., Hutnik E., Zamiar Z., (2016). Construction disasters caused by punching in the support zone of reinforced concrete slab-and-column ceilings as well as means of their repair and reinforcement. *Zeszyty Naukowe Wyższa Szkoła Oficerska Wojsk Lądowych im. gen. Tadeusza Kościuszki Journal of Science of the gen. Tadeusz Kosciuszko Military Academy of Land Forces*, 48 (1), p.151-167. http://dx.doi.org/10.5604/17318157.1201746