Tailor Made Concrete Structures – Walraven & Stoelhorst (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-47535-8

Enhanced safety with post-installed punching shear reinforcement

J. Kunz
Hilti Corp., Schaan, Liechtenstein

M. Fernández Ruiz & A. Muttoni
Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

ABSTRACT: A considerable number of flat slabs supported by columns need to be strengthened against punching shear. Reasons are increasing loads, construction or design errors, but also more stringent code requirements due to the increased knowledge gained in the past years. This paper shows the effects of bonding post-installed shear reinforcement into inclined holes drilled from the bottom of the slab. Laboratory tests have shown that this method not only increases the slab strength but also adds significant deformation capacity. The evaluation of the tests has resulted in a clear design concept based on the critical shear crack theory. First practical implementations have proved that the system can be installed economically at a total cost which is below that of other strengthening methods.

1 INTRODUCTION

Several tragic incidents have shown that a certain part of the existing building stock does not provide adequate safety against punching shear failure. This type of failure is particularly dangerous because of its brittleness. As there is no pre-warning to punching shear, collapses due to this mode of failure often result in fatalities. Two examples are shown in figure 1: The piper's row car park deck in Wolverhampton (GB) failed due to insufficient maintenance; the parking garage in Gretzenbach (CH) did not resist the exceptional load case fire.

Many such accidents could be avoided, if the concrete slabs were strengthened properly. There is a number of reasons for this: planning errors, execution errors, load increase during the lifetime of the structures and modification of the building codes due to increased knowledge on the topic.

Figure 1. Accidents due to punching shear: Wolverhampton (l), Gretzenbach (r).

2 STRENGTHENING SLABS WITH POST-INSTALLED SHEAR REINFORCEMENT

2.1 *Strengthening methods*

A number of parameters determine the resistance of a slab without shear reinforcement against punching shear. Most models take into account the sizes of the column and the slab as well as the concrete quality. Further important influences are the amount of tensile reinforcement, the size effect (decreasing nominal strength with increasing size of the member) and the aggregate size.

In case insufficient punching shear strength is estimated for a slab, shear reinforcement can be provided. Dimensioning of such reinforcement can be performed according to available models and codes of practice. However, there is currently no general agreement on the interaction between the concrete and shear reinforcement contributions to the shear strength. Thus, different codes propose different models.

Existing slabs of cured concrete can also be strengthened: by increasing the size of the slab or the column, by adding tensile reinforcement e.g. as glued laminates or by adding post-installed shear reinforcement. Obvious advantages of the latter method are that the original geometry can be maintained, that the installation work can be carried out from the lower side of the slab and that the intervention remains invisible.

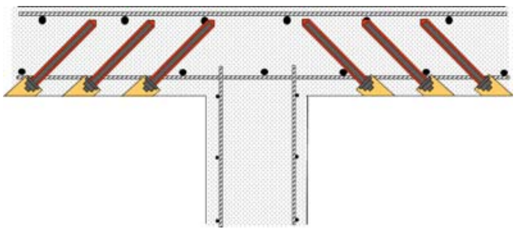

Figure 2. Post-installed punching shear reinforcement.

Figure 3. Strengthening anchor Hilti HZA-P.

2.2 *System description*

Special anchors in combination with an adhesive mortar are used to install punching shear reinforcement into already hardened concrete, see Figure 2. Inclined holes are hammer drilled from the bottom into the concrete slab under an angle of 45° and in the direction towards the column. The length of the drilled holes should be at least such that they reach the lowest level of the upper (tensile) reinforcement, but preferably, the holes should end only at the level between the tensile reinforcements in the two directions. Adhesive mortar is injected into the drilled holes and the special strengthening anchors Hilti HZA-P are set into the mortar filled holes. The special anchors consist of a reinforcement bar of diameter 16 mm or 20 mm in the upper part (see Fig. 3). The lower part is a smooth shaft with a thread at the end. For the design, the strength of the reinforcement bar is decisive since the smooth shaft and thread are made of a steel of higher strength than that of the reinforcement bar.

After curing of the adhesive mortar, the lower anchor head is installed. It consists of an injection washer, a spherical washer to eliminate bending of the bar and a nut. To ensure a slip free anchorage, the annular gaps and the interface between washer and concrete surface are injected with adhesive mortar through the injection washer.

The anchor head is installed in an enlarged part of the drilled hole. The embedded anchorage has the advantage that it can be covered with a fire protection mortar and is not visible after the installation.

3 PUNCHING SHEAR TESTS

3.1 *Description of the tests*

The efficiency of strengthening concrete slabs against punching shear with post-installed shear reinforcement was checked by a series of tests. Slabs of $3 \times 3 \times 0.25$ m with varying amounts of tensile and shear reinforcement were subjected to monotonically increasing punching shear load, see Figure 4. Measurements during the tests were the load, the vertical deformation of the slab, the strains in the central tensile reinforcement bar, the strains on the concrete on the compression side and, where applicable, the longitudinal strain of a part of the reinforcement anchors. The concrete quality for all tests was C25/30 (maximum aggregate size equal to 16 mm) with only small variations observed over the entire series. The average compressive strength on cubes of 150 mm side length was 40.3 N/mm^2. The effective depth of the slab was 210 mm for all tests. The column was simulated by a square steel plate of 260 mm side length.

The load was applied from bottom to top by a hydraulic cylinder on which the steel plate was positioned. The slab was held down on eight points of a circular section (diameter 3120 mm) on its outer limit. The load from two points was taken up by a steel beam which in turn transferred it to one of four prestressing steel bars which were themselves anchored in the strong floor.

The strengthening anchors were installed in radii around the piston (column). Figure 5 shows the arrangement of the starting points for the drilled holes for the example of test V2.

Table 1. Test parameters, f_y: yield strength of flexural reinforcement, ρ: flexural reinforcement ratio; $f_{cc,m}$: average concrete strength measured in cubes

	Tensile reinforcement		Concrete	Strengthening anchors 16 mm		
Test	f_y N/mm^2	ρ %	$f_{cc,m}$ N/mm^2	Radii [–]	Anchors / radius [–]	Dist.-column anchors [mm]
V1	709	1.5	42.2	–	–	
V2	709	1.5	42.2	8	3	200
V3	709	1.5	42.2	12	3	150
V6	505	0.6	39.4	8	4	150
V7	505	0.6	39.4	8	4	150
V8	505	0.6	39.4	4	4	150

Figure 4. Test setup.

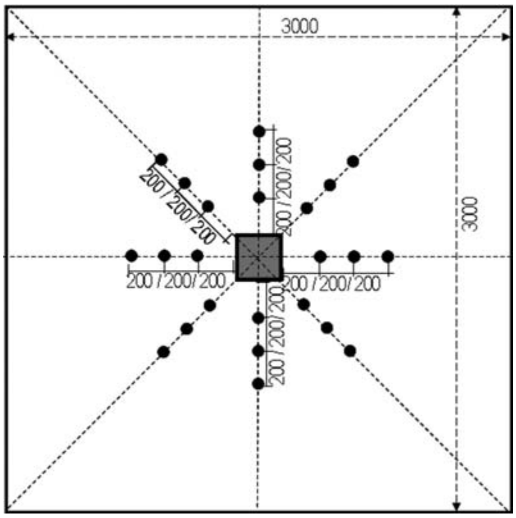

Figure 5. Arrangement of strengthening anchors in test V2.

Table 2. Failure loads.

Test	ρ %	$f_{cc,m}$ N/mm^2	Strengthening anchors total [–]	Failure load [kN]
V1	1.5	42.2	–	974
V2	1.5	42.2	24	1383
V3	1.5	42.2	36	1577
V6	0.6	39.4	32	850
V7	0.6	39.4	32	854
V8	0.6	39.4	16	833

The vertical displacement relative to the strong floor was measured on the lower side of the slab at the points where the pre-stressing rods penetrated it. The true deformation of the slab under loading was evaluated by deducting this displacement (corresponding to the elongation of the pre-stressing bars) from the vertical displacements (relative to the strong floor again) measured on top of the slab.

3.2 *Failure loads*

The failure loads measured for the six tests are given in Table 2. It can be noted that a significant increase on the failure load develops for series V1-3 ($\rho = 1.5\%$) as post-installed shear reinforcement is placed and as its amount is increased. Thus, for tests V2 and V3 the strengthening anchors permitted to increase the failure load from 974 kN to 1383 and 1577 kN, respectively with failure modes inside or outside the area with shear reinforcement. In tests V6 to V8, the post-installed shear reinforcement led to the development of a punching shear failure after development of large plastic strains in the flexural reinforcement.

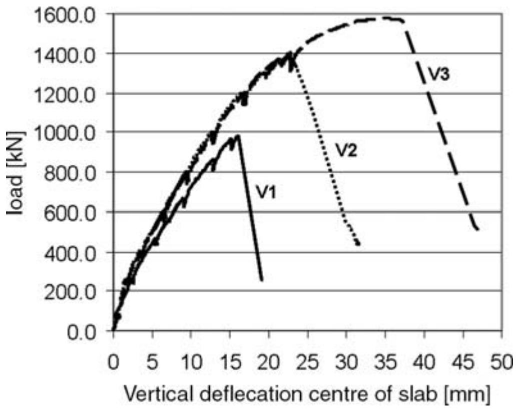

Figure 6. load-displacement curves of V1 to V3.

3.3 *Deformation Capacity*

With respect to structural reliability, the main problem of punching shear is that it is a brittle failure mode. Thus, a progressive collapse of a whole flat slab (Fig. 1) may develop after punching of a single column. Therefore it is important to investigate also the influence of the post-installed shear reinforcement on the deformation capacity of the slab.

Figure 6 shows the piston (column) load versus the vertical deflection of the slab centre for tests V1 to V3. It can be noted a significant increase on the rotation capacity is developed for slabs with post-installed punching shear reinforcement (slabs V2 and V3). According to figure 6, the total displacement of V1 at 900 kN was 15.5 mm. For V3 it was 30.5 mm at a load of 1500 kN. For a load increase of 67% the increase of deformation was almost 100%, i.e. there was a more-than-proportional increase of deformation capacity with increasing resistance.

Figures 7, 8 show the vertical deformations of the upper side of the slab for V1 (no shear reinforcement) and V3 (strengthened with 36 anchors) on a line parallel to the side of the slab and through its centre. The displacement was measured at nine positions on this line. The comparison of the two diagrams shows that the main rotation of the slab clearly takes place between the two points closest to the centre of the slab. These displacement transducers were positioned at 230 mm from the slab centre which is at 100 mm from the column end.

4 DESIGN METHOD

4.1 *Basis: critical shear crack theory*

The basis of the design method for the post-installed punching shear reinforcement presented in this paper

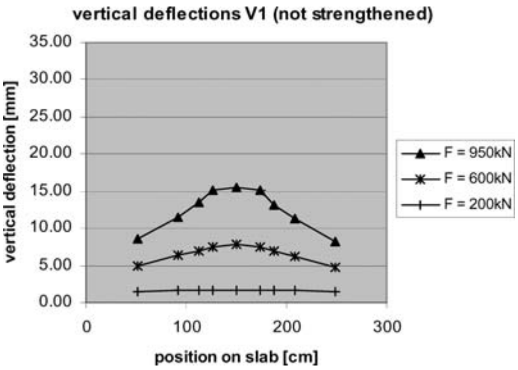

Figure 7. Vertical deflections test V1.

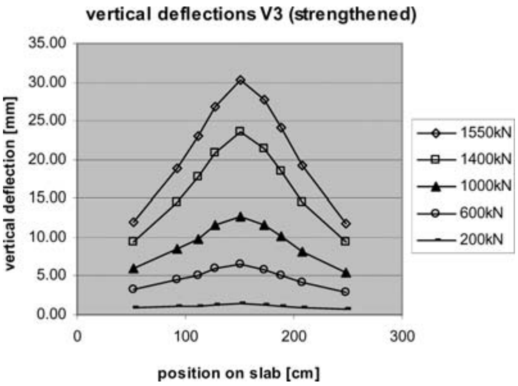

Figure 8. Vertical deflections test V3.

is the critical shear crack theory as described by Muttoni (2007) and Muttoni and Fernández Ruiz (2008). This theory stipulates that the rotation of the slab under load will open a shear crack inside. According to this theory, the rotation ψ_d of the slab can be expressed as a function of the column load V_d by the load-rotation relationship (see Fig. 9):

$$\psi_d = \frac{0.22 \cdot \ell}{d} \cdot \frac{f_{yd}}{E_s} \left(\frac{V_d}{a \cdot m_{Rd}} \right)^{3/2} \tag{1}$$

with: ℓ span [m]
- d effective depth [m]
- f_{yd} design yield strength of flexural reinforcement [N/mm^2]
- E_s modulus of elasticity of flexural reinforcement [N/mm^2]
- m_{Rd} bending resistance of the slab [kNm/m]
- a factor for column position (interior, edge or corner) [–]

where $a \cdot m_{Rd} = V_{flex}$ is an approximation of the column force at which the flexural resistance of the slab

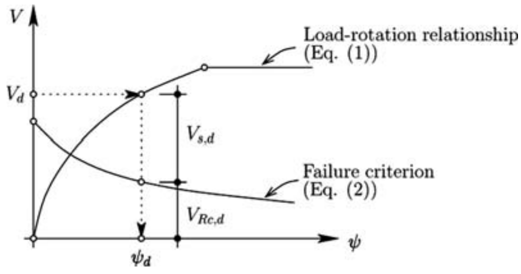

Figure 9. load-rotation relationship and failure criterion.

is reached. The smallest value of V_{flex} resulting from the different checks has to be considered:

- interior columns: $a = 8 \rightarrow$ check upper reinforcement in both directions
- edge columns: $a = 4 \rightarrow$ check upper reinforcement parallel to edge
  $a = 8 \rightarrow$ check upper and lower reinforcement perpendicular to edge
- corner columns: $a = 2 \rightarrow$ check upper and lower reinforcement in both directions

If the rotation ψ_d opens a crack of a critical width, shear failure develops. The function connecting the rotation of the slab and its punching shear resistance is called the failure criterion. For a given rotation of the slab, the design failure criterion can be expressed as (Muttoni 2007):

$$V_{Rd,c} = \frac{2}{3\gamma_c} \cdot \frac{b_0 \cdot d \cdot \sqrt{f_{ck}}}{1 + 20 \cdot \frac{\psi_d \cdot d}{d_{g0} + d_g}} \tag{2}$$

where b_0 is the control perimeter set at $d/2$ from the border of the column, f_{ck} is the characteristic cylinder strength of the concrete, d_g is the maximum aggregate size and d_{g0} is a reference value for the aggregate size (=16 mm).

4.2 *Concrete and reinforcement contributions*

For an existing slab the parameters ℓ, d, f_{yd}, E_s, f_{ck} and d_g need to be evaluated from original drawings or by measurements on site. Then the rotation of the slab corresponding to the design column load V_d is calculated using Equation (1). The contribution of concrete at failure can then be estimated with Equation (2). The rest of the design load V_d is assumed to be carried by the contribution of the shear reinforcement, see figure 9:

$$V_{s,d} = V_d - V_{Rd,c} \tag{3}$$

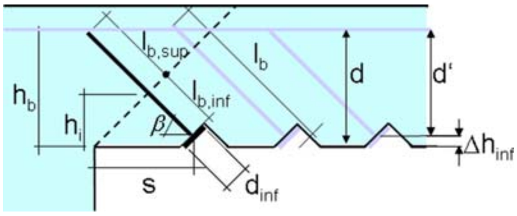

Figure 10. Geometry of the post-installed shear reinforcement.

4.3 *Post-installed shear reinforcement*

The post-installed shear reinforcement is placed around the column in radii. A number of detailing rules prescribe for example that the angle between radii should not be larger than 45° or that the radial distance between anchors in a radius should not be larger than $0.75d$; for further details refer to Muttoni and Fernández Ruiz (2007).

The shear reinforcement must satisfy the following condition:

$$V_{s,d} \leq \sum_{i=1}^{n} N_{si,d} \cdot \sin \beta_i \tag{4}$$

with $N_{si,d}$ being the design resistance to tensile load of one specific strengthening anchor and β_i is the angle at which the shear reinforcement is installed (see Fig. 10, usually 45°). $N_{si,d}$ is equal to the minimum of the following four values:

$$N_{si,d} = \min[N_{si,el,d}; N_{si,pl,d}; N_{si,b,d}; N_{si,p,d}] \tag{5}$$

where (see details in Muttoni and Fernández Ruiz 2007):

1. $N_{si,el,d}$ is the force in the shear reinforcement that can be activated assuming an elastic behavior of the bar.
2. $N_{si,pl,d}$ is the plastic strength of the anchor
3. $N_{si,b,d}$ is the maximum force that can be developed by bond in the shear reinforcement
4. $N_{si,p,d}$ is the maximum force that can be developed due to pullout of the lower anchorage

4.4 *Evaluation*

Muttoni and Fernández Ruiz (2007) have compared this design concept to the tests shown in section 3 as well as to a similar test series performed by Hassanzadeh (1996). The ratio of predicted resistance to the measured resistance was computed for each test. For every test, the ratio was larger than 1.0 (safe results), the average for the nine tests is 1.2 with a coefficient of variation of only 7%. Based on this evaluation it can be confirmed that the proposed design model yields an excellent prediction of the resistance that is reached with the post-installed shear reinforcement. Therefore, a structure which is designed according to the proposed model and strengthened with the strengthening anchors presented in section 2 can be upgraded to the level of safety required by the applicable structural design code.

5 CONCLUSIONS

5.1 *Advantages*

The strengthening of concrete slabs by bonding shear reinforcement anchors into inclined drill holes from the bottom of the slab has a number of advantages compared to other strengthening methods:

- The fact that work is carried out from one side of the slab can help to significantly improve the construction process.
- The size of columns and slab are not modified and therefore, the traffic space is not reduced, which may be critical in parking decks. Moreover, waterproofing systems need not be crossed.
- The lower anchorage plate is installed in a widening of the drilled hole inside the slab. Thus, in the end the anchor plate can be covered with a fire protection mortar. In general, no additional fire protection is then required and the slab remains flat which is also an esthetic advantage (Figs 2, 12).
- Adding steel collars to the column or adding new layers of concrete either to the column or to the slab will increase the strength of the system but not improve its brittleness. The tests have shown that post-installed shear reinforcement significantly improves the deformation capacity of the slab.
- The clear and accurate design concept allows to plan strengthening measures to a defined level of safety.

5.2 *Implementation*

The proposed method has been implemented in a number of construction projects in Switzerland, see figure 11. Thus, the suitability of the method for the practice on construction sites has already been proved.

The experience has shown that in some cases the hole cannot be drilled as long as required because it is hitting e.g. the support of the upper reinforcement layers. Shortened anchors should be installed into such a hole in order to close it and a correct anchor should be installed beside it. As there is no possibility to check the shear reinforcement a posteriori (Fig. 12), it is recommended to require a setting protocol from the contractor.

The completed projects have also shown that slabs can be strengthened with post-installed shear reinforcement at a cost which is below that of other methods like adding steel collars or additional concrete.

Figure 11. Drilling holes and installation of the anchors.

Figure 12. smooth surface of strengthened slab.

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