Punching Shear and Critical Shear Crack Theory In Existing Column-Supported RC Slabs

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ABSTRACT: Punching shear failure is the major cause for brittle and sudden progressive collapse of column-supported reinforced concrete (RC) slabs. Insufficient safety develops from increased loads, reduced load-bearing capacity or deficiencies due to bad design or execution.

The present paper documents the authors' experience in structural assessments of existing concrete slabs with a special focus on parking garages, including numerous punching shear reinforcement systems used in Switzerland from the 1960s to present.

Furthermore, common issues in the assessment of existing buildings are discussed and explained using examples from daily business.

1 INTRODUCTION

Punching shear has been deeply investigated in recent decades, leading to new design rules in modern codes which allow more detailed analysis of punching shear behaviour, but are far more conservative than older rules in many cases. With the introduction of the critical shear crack theory, slab rotation has become a governing parameter for punching shear resistance.

In practice, code development has led to more reliable new structures, whereas many existing parking garages show major deficiencies after today's codes, even if they were in accordance with past standards. In many cases, structural safety is further impaired by deterioration of the structure, mostly due to ambient influences or increased loads.

With the frequent lack of engineering plans the assessment process requires a huge effort. Therefore, an overview on investigation methods for existing structures is given, mainly focussing on parking garages. Non-destructive evaluation techniques exploit the latest technological developments enhancing conventional destructive methods to detect hidden structural damages. Highly optimised diagnostic procedures combining destructive and non-destructive on-site investigations as well as laboratory tests are therefore presented as a well-recommended manner to obtain the required governing key parameters for the structural analysis while at the same time reducing cost and impact for the customer.

Issues regarding the application of the critical shear crack theory are discussed in later sections. Various calculation tools commonly used in Switzerland are compared in an example calculation, and the discrepancies are discussed.

All of the investigated parking garages are located in Switzerland, and SIA 262 (similar to fib Model Code 2010) is therefore used for structural analysis.

2 INVESTIGATION TECHNIQUES

2.1 General

Economic considerations usually result in multi-stage methods which prioritise structures exhibiting higher risk potential among others in a group of structures in a portfolio. Therefore, the procedures shown below are recommended only in well-justified cases. While most investigation techniques are well-known, the key challenge on structural investigations is to find the optimum combination of all available methods and technologies for each single case.

2.2 Plan studies

Plans allow considerable reduction of structural detection and thus reduce cost for an analysis. Without plans, considerable research effort is required to obtain the required data. Still, often no plans or architectural plans only are available, causing major investigation effort. With plans available, further investigations can be limited to sample verifications on whether plans are appropriate and execution quality is sufficient, apart from durability and deterioration aspects.

2.3 Visual inspection

Visual inspections aim to identify the potential risk e.g. from increased load requirements, excessive soil cover or decreased load-bearing capacity due to durability problems.

2.4 Non-destructive investigations

Tools such as ferromagnetic and radar scanner or ultrasonic systems enable scanning of large areas without any emissions. The findings are used to identify patterns and analogies concerning the load-bearing structure. Further, damages due to destructive methods are minimised.

2.4.1 Ferromagnetic scanning

Extensive ferromagnetic scans help to obtain a very quick overview on the location of the rebars close to the concrete surface. Still, diameter analyses remain unreliable without calibration from minimal destructive tests. Typical applications are the detection of rebar cover for fire safety analysis or a line scan to identify girder strips – both of which can be performed within minutes.

2.4.2 Radar scanning

Radar scans allow detection of steel items, voids and cracks among others in greater depths at lower resolutions, whereas the actual depth and resolution limitations are frequency-dependent. Typical devices for concrete inspection reach 30-100 cm at resolutions from 1 to 5 cm. Even with plans available, radar scans are an indispensable tool for verification of plan information, since faults such e.g. as a missing shear reinforcement element are easily detected.

Apart from execution errors such as severely misplaced rebars (Figure 1), numerous types of punching shear are located using radar scans (Figure 2).

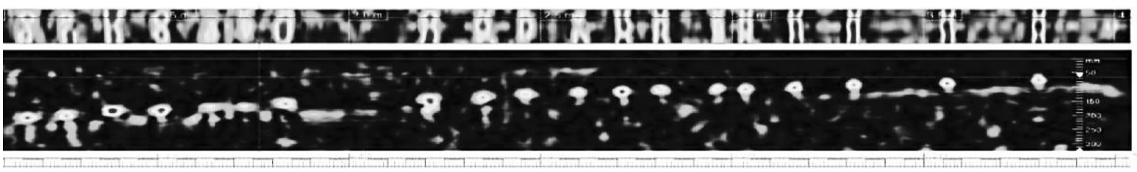

Figure 1. Radar image of too low lying reinforcement, generated from a line scan [recontec.ch (2016)].

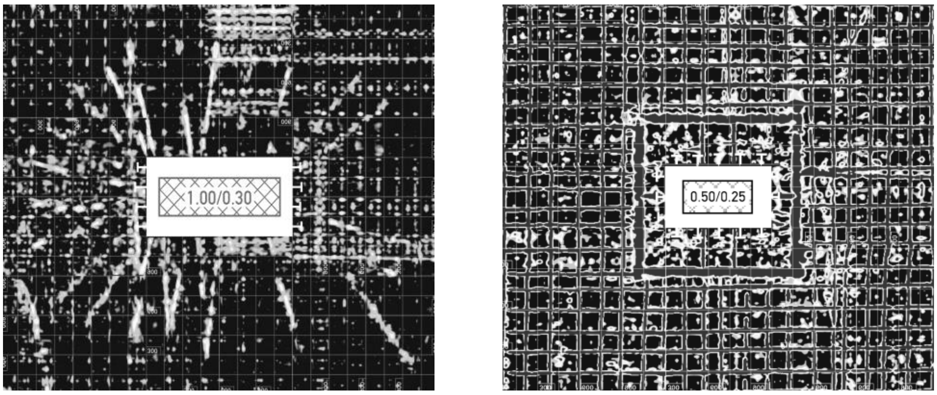

Figure 2. Radar images of punching shear reinforcement systems (left: Riss-Stern, right: steel shear head, generated from several image scans [recontec.ch (2016)].

2.5 Geodesic investigations

Landscaped areas on parking garages require special attention, as excessive soil load has been identified as the most common source of structural safety issues in parking garages, as traditionally terrain shapes were frequently formed without sufficient structural considerations. Further, concentrated loads from heavy objects, trees or playground equipment are known to develop radial forces around support members which need to be considered for punching shear.

2.6 Destructive investigations

2.6.1 Pick hammer investigations

With plans missing destructive tests and even more pick hammer investigations are the common way to collect significant information such as reinforcement or material properties. As picking can impair the bearing resistance of a member, picking spots must be selected carefully whereas maximum gain of information and minimum damage to the structure must be balanced.

For the upper reinforcement over columns the evaluated section must cover the whole width of the girder strip (usually 1.5 to 2 m) in each direction (Figure 3) in order to give reliable information to be considered in punching shear analysis. This allows accurate estimation of the reinforcement area and hence the bending resistance, whereas with the small investigation windows often found in practice bending resistance is often severely overestimated.

Figure 3. Probe stripe length covering the girder strip in both directions.

2.6.2 Material tests

In column-supported slabs concrete compressive strength is a governing parameter, even more without punching shear reinforcement. Compressive lab tests on drill core samples are an appropriate way to obtain this data in accordance with SIA 269/2. The same drill cores can be used to determine carbonation depth.

Further analyses regarding chloride-contamination are mostly performed on drilling dust as a basis for durability considerations.

3 PARAMETERS FOR PUNCHING SHEAR ANALYSIS

3.1 General

Detailed information on most important parameters for punching shear analysis is given in SIA (2008). Based on extensive practice in the field, selected comments on a choice of parameters are discussed.

3.2 Steel yield strength

Steel yield strength of the bending reinforcement is a governing parameter for the bending resistance of concrete slabs but has usually limited effect on punching shear resistance. Still, in inclined reinforcing bars and shear reinforcement, it strongly affects punching shear resistance.

Older reinforcing steels are known to show a considerable scatter among different production lots. Therefore, determination of steel yield strength of reinforcing steel from laboratory tests is only worth in specific cases, primarily for inclined or vertical bars. Usually, determination of the steel quality using the steel database provided by ASTRA (2015) is more accurate and economical, but requires local pick hammer investigations.

3.3 Concrete compressive strength

Concrete compressive strength has usually limited influence on the bending resistance of concrete slabs, but is decisive for its punching shear resistance. Therefore, the cost for lab tests allowing reliable determination of the concrete compressive strength is well-justified, even though estimations are possible using the temporal development curve in SIA 262.

3.4 Bonding depth

As the inner lever in a slab decisively governs punching shear resistance, deviations due to execution faults such as precast columns or steel shear heads installed too high or walls and columns cast too high are among the most frequent sources of fatal structural failures.

3.5 Reinforcement cover

If the upper reinforcement lies far too low, the inner lever is strongly reduced, leading to similar fatal effects as excessive bonding depth.

Experience shows that the upper reinforcement is frequently lying a few centimetres lower than planned while excessive deviations are generally rare. If excessive deviations are found on a spot in a structure, such deviations are very probable in many more spots of the same project, as such deviations usually originate from installing far too few high chairs or treating the reinforcement with excessive violence before and during casting the concrete.

4 COMPARATIVE APPROACH

4.1 Comparison of common punching shear design software used in Switzerland

Various suppliers of punching shear reinforcement systems offer free design tools for their products. Even though they are made for the design of new structures they are often used for the assessment of existing structures without shear reinforcement or with shear reinforcement of the type the software was designed for, which is feasible in many cases, but shows its limitations.

In order to compare such design tools, different products were fed with identical input parameters of a slab without shear reinforcement.

In accordance with SIA 269/2 for existing structures, level of approximation III was used to determine the punching shear resistance, and all analyses were performed strictly according to SIA 262 code rules. Since various software do not offer the same level of detail grade concerning input variables, a simplified scenario of an inner column was analysed (Table 1).

Table 1. Input parameters

Parameter	
V_d	650 kN
Materials [N/mm²]	f_{cd} = 28 f_{sd} = 435
Slab depth	300 mm
Column dimension	300 x 300 mm
Concrete cover	35 mm top and bottom
Upper reinforcement	ϕ14/100 each direction
Moment contraflexure	1600 mm each direction
Bending moment	100 kNm/m
Coefficient k_e	0.90

Table 2. Comparison of numerical results

Software used	V_{Rd} (Deviation from mean value)
Software A	774 kN (+4%)
Software B	743 kN (<1%)
Software C	739 kN (<1%)
Software D	752 kN (<1%)
Software E	717 kN (-4%)
Manual analysis	720 kN (-3%)

As highlighted in Table 2, the results from different suppliers' software differ. This may occur due to software faults or due to proprietary interpretation of the existing code rules. Still, the results are sufficiently close to each other. In practice, deficiencies in modelling of actions and structural properties will inflict the results much more than the accuracy of the software tools.

4.2 Practical experience regarding critical shear crack theory and modelling assumptions

In daily practice of performing safety assessment or formulating second opinion for public or private owners many situations with contradictory interpretation of method details occur as well as challenges in applying the theory in non-standard cases. While simple misapplication of the critical shear crack theory is often observed, discussions on the interpretation of input variables are often justified, even more in non-standard cases. Some of the frequent sources as seen in practice are listed below:

- The slab rotation given in SIA 262 is based on the rotation under existing loads, but it is often falsely interpreted as the governing rotation (rotation at the event of a failure) to obtain the punching shear resistance. However, an iterative approach is required, setting V_{Rd} equal to V_d to obtain the governing rotation for the punching shear resistance.

- The maximum punching resistance considering the bearing capacity of concrete struts as given in SIA 262 is set by the system factor k_{sys}, which equals to 2 in general (unless the coefficient can be increased if the systems are experimentally verified). This factor is often interpreted as if a slab with punching shear reinforcement could transfer double shear loads than one without shear reinforcement. In fact, the system factor k_{sys} bases on the concrete contribution failure criterion, thus the gain in shear resistance between a slab with and without punching shear reinforcement is significantly lower than k_{sys}.
- Often, the bending moments considered for punching shear design and verification are maximum peak values taken from finite element calculations in spots with singularities. Still, this interpretation is strongly conservative. In accordance with SIA 262, the average bending moment m_{Ed} acting in the girder strip should be considered instead.
- The location of the moment contraflexure is generally vague, even more as often envelope curves are evaluated solely. Further, in finite element models the location strongly depends on the mesh size used. As the location of the moment contraflexure also effects the width of the girder strip considered for the analysis, variations in the location of the moment contraflexure lead to over- or underestimation of the reinforcement to be considered and thus inflicts both average bending resistance m_{Rd} and the average bending moment m_{Ed}.

5 PUNCHING SHEAR REINFORCEMENT SYSTEMS

5.1 General

A choice of common punching shear systems used in Switzerland from 1960s to present is discussed below with their key properties from today's perspective. All examples are gathered from recent investigation projects.

5.2 Riss-Stern

Riss-Stern systems were very popular at the time, but in the meantime research has shown that these systems are far less effective than considered at the time when they were installed. According to SIA 262, only reinforcing elements in an region between 0.35 d_v and d_v from the face of support can be considered (Figure 4) which causes large parts of the system to be ineffective. Further, in ultimate load state the reinforcement strength is exploited only by about 20%. Therefore, only a limited gain of punching shear resistance is achieved with these systems.

Further, this system is incapable to increase progressive collapse safety compared to an unreinforced slab as it cannot help suspending the slab after an initial punching failure.

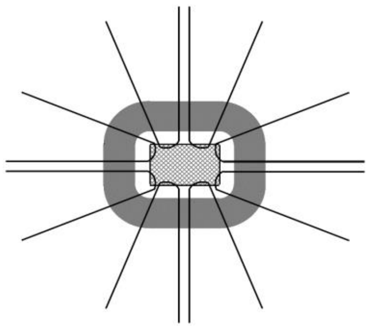

Figure 4. Cross-hatched area shows the region where the shear reinforcement can be considered.

5.3 Stirrups

Stirrups can be installed as prefabricated cages or individual stirrups.

Stirrup cages are placed in different amounts and positions depending on governing failure mechanism. For an inner column as example, one stirrup cage can be placed centrally on the top of the support, exhibiting a higher shear reinforcement ratio, whereas several cages distributed around column can cover a larger area (Figure 5).

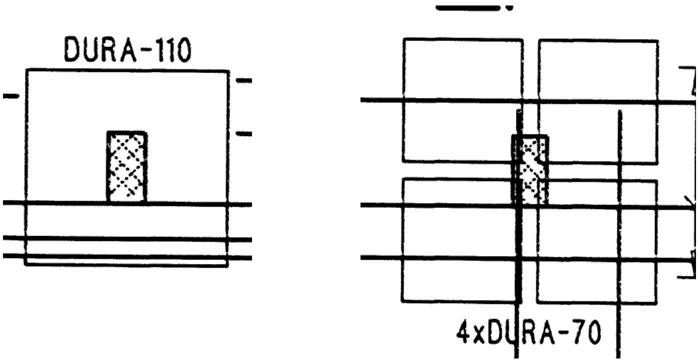

Figure 5. DURA stirrup cages by Aschwanden AG.

Figure 6 shows two slab surfaces near a column with differently-distributed stirrups, taken from different storeys of the same object.

For punching shear verification, uniquely shear reinforcement located within the zone between $0.35d_v$ and d_v from the edge of the column can be considered. As on left side of Figure 6, overlaid effects of low slab depth and the stirrups distributed perpendicularly to the larger column face avoid any possible consideration of stirrups, since all of them are placed outside the activated zone. However, the shear activated zone of the slab on the right side of Figure 6 covers the whole stirrup area, thanks to the optimum layout.

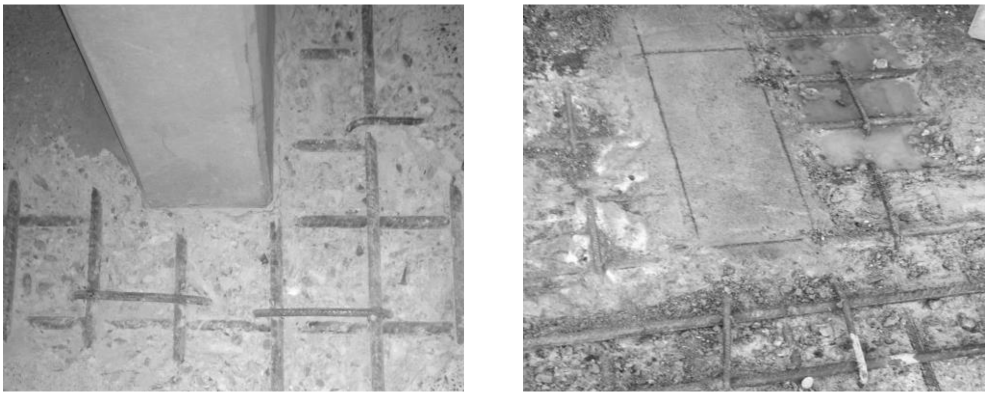

Figure 6. Stirrups perpendicular (left) and parallel (right) to the larger face of the column.

5.4 Steel shear heads

Shear heads have been often preferred with higher loads. In general, steel shear heads offer a wide support area which can be considered as a close-to-rigid body.

Typical punching shear deficiencies arise from improper installation at too high level causing a drastic decrease of punching shear resistance.

In numerous retrofitting projects, post-installed steel shear heads are placed on the top of the column underneath the slab. This system moves the bending moment curve further away from the column, requiring an increased anchorage length for the upper reinforcement. Often, the present upper reinforcement is too short and must therefore be complemented by additional upper reinforcement. Furthermore, load history of a slab to be retrofitted with post-installed shear heads must be considered as presented in detail by Kenel et al (2016).

5.5 Bent-up bars

Bent-up bars were popular in Switzerland before the 1970s. Such, the same bars were used for bending and punching shear resistance, helping to prevent a total collapse triggered by the loss of a local member (chain reaction).

Extensive numerical analyses performed on existing column-supported RC slabs show that punching shear resistance outside the bent-up bars or failure of the activated bent-up bars are usually the governing failure modes, as addressed by Tassinari et al (2011). Further, failures due to limited anchorage length are common.

6 CONCLUSION

This paper documents frequent issues concerning the assessment of existing column-supported RC slabs with focus on parking garages, based on the authors' vast experience in daily business.

Using the commercial design tools is adequate for the design of new structures. However, the verification of structural safety requires very detailed analysis and all possible efforts towards close-to-realistic analysis since non-fulfilment of safety requirements lead to costly retrofitting or even demolition of the structure.

7 OUTLOOK

The authors' commitment in the assessment and rehabilitation of hundreds of existing column-supported reinforced concrete slabs is still ongoing. In this context, the authors are working on a generalised software which can consider numerous punching shear systems, used in Switzerland from 1960s to present. The software has been experienced to be accurate and helpful and remains under close supervision and further development. Still, open communication between experts in practice, research and industry will be a decisive step towards safe and economical existing and new buildings in the future.

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