Research Plan

Post-Punching Behavior of Flat Slabs Supported by Columns

PhD Candidate: Yaser Mirzaei

Thesis director: Prof. Dr Aurelio Muttoni

Director of the Doctoral school: Prof. Dr Eugen Brühwiler
## Contents

1. Summary ............................................................... 3

2. Introduction and research significance .......................... 4

3. State of the research ............................................... 6

4. Contents and goals of the proposed research .................. 7
   - Study of the local and global post-critical behaviour .... 7
   - Study of the constructive solutions .......................... 7

5. Planning ............................................................. 8

6. References .......................................................... 8
Summary

Flat plates are a very common and competitive structural system for cast in place slabs in buildings since no beam is involved. That means that the formwork is very simple and economic. Using this type of structure presents however a serious disadvantage because of the risk of a brittle punching failure at the column.

Large scientific efforts have been done in the past to predict the punching shear strength of the slab-column connection. However, some punching failures that occurred during the past decades showed that it is necessary to improve the design methods to avoid this type of failure. In most cases the failure of horizontally reinforced concrete slabs or beams in bending is ductile, and the failure causes only limited redistribution of loading. Punching failure of flat slabs without shear reinforcement is an exception, because the drop in resistance at failure can be large and give rise to a redistribution of effects, which can trigger failure at adjacent columns and eventually lead to progressive collapse of large parts of the structure.

One of the objects of this research is finding a practical constructive solution to improve the post-punching behavior of the slab-column connection to avoid progressive collapse as it happened in some dramatic punching collapses in Switzerland (Figs. 1-3).

Key words: punching shear, post-punching, slab-column connection, ultimate strength, progressive collapse, membrane effect, dowel action, bent-up-bars, mechanical model

Figure 1 : Shopping center « Serfontana » at Morbio Inferiore (TI), at the end of 70’s. The punching failure of one slab during the construction phase led to the progressive collapse of a large part of the structure.
Introduction and research significance

More than 90 years ago, Talbot [1] proposed a method to determine the punching strength of slabs by comparing the nominal shear stress with an admissible shear stress (defined as a property of concrete). This nominal shear stress is calculated by dividing the punching load by the area of a cylindrical control surface normal to the plane of the slab. Based on Talbot’s method, various modifications were proposed in which the control surfaces, considered depth of the slab and distribution of the shear stress over the thickness are modified. Similarly, extensions of the method were suggested by introducing empirical factors that depend on reinforcement ratio, size of the slab, shape of the column, and so on. The resulting methods are simple and were consequently adopted
by most code recommendations around the world. They are mostly based on empirical factors.

Kinnunen and Nylander [2] developed another approach to compute the punching strength based on mechanical observations. They described the punching resistance as a function of rigid segments located outside the punching cone, and a compressed truncated conical shell extending from the column to the tip of the punching crack. The failure criterion is expressed in terms of a limitation of the inclined radial compressive stress and a limitation of the tangential compressive strain at the shear crack.

The theory of plasticity can be used to determine an upper bound value of the punching load [3]. Braestrup [4] assumed a failure mechanism in which the deformation is concentrated in a rotationally symmetric surface representing the punching crack. The obtained punching load is an upper-bound value. Another simplified upper-bound value for the punching load was derived by Marti and Thürlimann [5]. However, for particular cases such as thick slabs or high reinforcement ratios, the obtained safety levels are inconsistent. In addition, the contribution from the dowel effect (shear transferred by reinforcing bars crossing a concrete crack), stirrups, shear head, and pre-stressing tendons are not considered in a unified treatment of the strength.

Menétrey proposed an analytical expression to compute the punching strength of reinforced concrete based on the integration of the tensile strength of concrete and reinforcement along the punching crack, as suggested by the results of numerical simulation of the punching failure phenomenon [6, 7].

Muttoni suggested a failure criterion for slabs without shear reinforcement which can determine the punching strength mainly as a function of the radial rotation of the slab in the vicinity of the slab-column connection [8-11]. Guandalini proposed a computational model for the flexural behaviour of concrete slabs and merged his computational model with the failure criterion proposed by Muttoni to develop a new physical model. This physical model is able to determine the punching strength of symmetrical slabs with any flexural reinforcement layout. Also, by applying this model, it is possible to predict the punching strength in the particular cases such as temperature effects or the failure of a foundation plate [12].

The prediction of the punching strength was the main object of research on the punching shear, leading to the development of reliable design rules with an acceptable level of safety to be used in design codes [13-18]. The behaviour of plates after a punching failure and circumstances in which it can lead to a progressive collapse were not considered [19, 20].

In principle, a local failure should not lead to the progressive collapse of the significant portion of a structure. There is question whether flat plates designed according to current structural concrete codes really fulfil this basic requirement for structural integrity [21, 22].
It is therefore striking that the Eurocode 2 [23] and ACI 318-05 [24] for instance, require a minimum shear reinforcement in main beams to prevent a brittle shear failure, but no ductility requirement is exists for flat plates despite the fact that a punching failure may lead to worse consequences than the shear failure of a beam.

State of research

As described above, most research in the past was about predicting the punching shear strength and strengthening the slab by using shear reinforcement to prevent punching failure and have a more ductile behavior. The literature on the subject of post-punching is thus limited. Because of this lack of information and experimental data related to the behavior of the slab-column connection after a punching failure, two preliminary test series were performed as shown the table 1. Also, a first mechanical model was developed to describe the post-punching behavior of the slab-column connection and to identify the various parameters governing this behavior.

The experimental work shows that bottom bars crossing through a column and anchored in the slab on both sides of it can be highly effective in increasing the post-punching strength of a slab-column connection. The final resistance provided by the bottom bars appears to be governed either by the crushing of the concrete where they are anchored in the slab or by the fracture of the bars.

Table 1: Preliminary test series

<table>
<thead>
<tr>
<th>Test</th>
<th>Tensile reinforcement</th>
<th>Compressive reinforcement</th>
<th>Type of failure</th>
<th>$V_{post-punching}$/${V_{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM - 1</td>
<td>Ø8 @ 200 mm</td>
<td>-</td>
<td>punching</td>
<td>0.19</td>
</tr>
<tr>
<td>PM - 2</td>
<td>Ø8 @ 100 mm</td>
<td>-</td>
<td>punching</td>
<td>0.29</td>
</tr>
<tr>
<td>PM - 3</td>
<td>Ø8 @ 60mm</td>
<td>-</td>
<td>punching</td>
<td>0.36</td>
</tr>
<tr>
<td>PM - 4</td>
<td>Ø8 @ 35 mm</td>
<td>-</td>
<td>punching</td>
<td>0.36</td>
</tr>
<tr>
<td>PM - 5</td>
<td>Ø8 @ 75 mm</td>
<td>4Ø12</td>
<td>punching+flexural failure</td>
<td>0.19</td>
</tr>
<tr>
<td>PM - 6</td>
<td>Ø8 @ 75 mm</td>
<td>4Ø16</td>
<td>punching+flexural failure</td>
<td>0.21</td>
</tr>
<tr>
<td>PM - 7</td>
<td>Ø8 @ 75 mm</td>
<td>4Ø20</td>
<td>punching+flexural failure</td>
<td>0.30</td>
</tr>
<tr>
<td>PM - 8</td>
<td>Ø8 @ 75 mm</td>
<td>4Ø15.2 (strand)</td>
<td>punching+flexural failure</td>
<td>0.16</td>
</tr>
<tr>
<td>PM - 9</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø8</td>
<td>punching</td>
<td>0.55</td>
</tr>
<tr>
<td>PM - 10</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø10</td>
<td>punching</td>
<td>0.70</td>
</tr>
<tr>
<td>PM - 11</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø12</td>
<td>punching</td>
<td>0.98</td>
</tr>
<tr>
<td>PM - 12</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø14</td>
<td>punching</td>
<td>0.99</td>
</tr>
<tr>
<td>PM – 13</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø8 (bent-up bars)</td>
<td>punching</td>
<td>0.46</td>
</tr>
<tr>
<td>PM – 14</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø10 (bent-up bars)</td>
<td>punching</td>
<td>0.52</td>
</tr>
<tr>
<td>PM – 15</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø12 (bent-up bars)</td>
<td>punching</td>
<td>0.64</td>
</tr>
<tr>
<td>PM - 16</td>
<td>Ø8 @ 60 mm</td>
<td>4Ø14 (bent-up bars)</td>
<td>punching</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Contents and goals of the proposed research

In spite of its importance for the progressive collapse of the flat slabs, the post-critical behavior (the behavior of the structure after punching of a column) was little studied until now. The goal of the present research is to investigate the post-punching behavior of flat slabs and its consequences. To that end, the research is structured as follows:

I. Study of the local and global post-critical behaviour

- Study of the local behaviour of a slab element after punching, and establish a load-deformation relationship as a function of the top and bottom reinforcement (phase A of table 2). To investigate the effect of tensile reinforcement and compressive reinforcement in the post-punching behaviour, a test was performed and some experimental data was obtained (B). Using available data, a model will be developed to describe the local post-punching behaviour including the effect of top and bottom reinforcement (C). Normal straight and bent-up-bars will be used to investigate the effect of various shapes and bars layout. To observe the effect of shear reinforcement on the local post-punching behaviour, a second series of small specimens will be tested.

- Study of the global system and identification of the main parameters (span, slenderness of the slab, reinforcement ratio, load level…) for which the failure propagates to the adjacent columns (D). This theoretical part is crucial to understand the relationship between local punching failure and progressive collapse. To predict the global behaviour of the structure, a physical model will be developed (E). A series of full scale experimental tests will be needed to demonstrate the results obtained by physical model (G).

II. Study of the constructive solutions

In principle, the aim of this research is to decrease the vulnerability of the flat slabs to serious accidents while preserving their economic advantages and simplicity and to establish the bases for the design of economic solutions and easy of construction (F). To that end, practically applicable constructive details will be developed. Their efficiency will be checked in an additional test series.
Planning

Table 2: Planning of the activities

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References:


