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Punching Shear Tests on RC Slabs with Different Initial Crack Patterns

L. C. HOANG\textsuperscript{1a}

\textsuperscript{1}Department of Industrial and Civil Engineering, University of Southern Denmark, Denmark

Abstract

The objective of this paper is to investigate the influence of initial cracking on the punching shear behavior of reinforced concrete slabs. For this purpose, a series of punching tests has been conducted at the University of Southern Denmark. The slabs were quadratic with span of 1050 mm. Slab thickness was 150 mm. The initial crack patterns were created by mechanical tension, uniaxial as well as biaxial. The slabs were pre-cracked up to 0.55 mm. After cracking and prior to punching testing, the axial loads were removed. The obtained test results show no significant strength reduction compared to the strength of initially uncracked slabs. This indicates that as far as punching strength is concerned, no precaution needs to be taken for slabs suffering axial cracking.

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Keywords: Concrete slabs; punching shear; initial cracking.

1. INTRODUCTION

Reinforced concrete structures without shear reinforcement are widely used in practice, for instance as top and bottom slabs in rainwater reservoirs and tunnels or as retaining walls. Enhanced by the frictional restraints from the soil, this type of structure often experiences initial macro cracking due to temperature gradients, shrinkage and creep. The cracks may develop at an early stage before application of the static loads.

The extent of initial cracking is not known in the design phase. Therefore, when analyzing the strength and stiffness of such structures, the designers often assume that the tensile strength has disappeared completely. For designers who strictly follow the codes rules, this assumption also means that the shear

\textsuperscript{a}Presenter and corresponding author: Email: lch@ib.sdu.dk
and punching shear strength cannot be verified as the code formulas in this regards depend on the concrete tensile strength. Often, this problem is solved by adding shear reinforcement. Naturally, slabs with initial cracking do not lose their shear and punching strength completely. The interesting question is, however, to what extent initial cracking affects the shear and punching strength? To this end, a series of punching tests on concrete slabs has been conducted at the University of Southern Denmark. The slabs were pre-cracked up to 0.55 mm in uniaxial as well as in biaxial tension. The punching tests show no significant strength reduction compared to the strength of initially uncracked slabs. This indicates that as far as punching strength is concerned, no precaution needs to be taken for slabs suffering axial cracking (due to temperature and shrinkage).

The test results are compared with analytical calculations. Good agreement has been found.

2. EXPERIMENTAL INVESTIGATION

2.1. Test Specimens

The test specimens were quadratic with side lengths of 1200 mm and depth of 150 mm, as shown in Fig. 1. The average cylinder concrete strength was $f_c = 49$ MPa. At the top and the bottom face, the slabs were reinforced with Ø15mm thread bars at 120 mm in both directions. Dywidag bars with yield strength 900 MPa were used to ensure that all specimens would fail in punching and not in flexure. Further, the high strength reinforcement was chosen to obtain sufficiently large crack widths when subjecting the specimens to tension prior to the punching tests. To prevent local anchorage failures, the thread bars were provided with anchorage plates and bolts, as shown in Fig. 1.

Six identical specimens were produced. The reference specimen P2 was subjected to punching test without pre-cracking. The remaining specimens P1 and P3 – P6 were pre-cracked by tension (in one or two directions) prior to punching test. For specimen P4, the pre-cracking process went out of control with indications of breaking of reinforcement. This specimen was therefore excluded. Further details can be found in Goldschmidt and Fugloe (2008).
2.2. Test Set-up and Testing Procedure

The test setup for pre-cracking of the specimens is schematically shown in Fig. 2 (left). Basically 2x5 hydraulic jacks (shown as red cylinders in the figure) were used to provide pressure on 5 steel diaphragms, each one mechanically attached to four thread bars with bolts. In this way, tension was transferred to the concrete specimen and a system of tensile cracks could be created. The level of tension was controlled by monitoring the stresses applied to the thread bars. Information on the level of tension and crack widths for the pre-cracked specimens are shown in Table 1. The tension applied has been given as reinforcement stresses in the table. These reinforcement stresses can be transformed into smeared stresses by multiplying with the reinforcement ratio $\rho = 0.020$. For specimen P6, the applied smeared stresses reached 8.7 MPa. This means that no residual tensile strength can be assumed to exist in the crack after the pre-cracking process. The listed crack widths are measurements obtained at the peak of the applied tension.

As can be seen, specimens P1, P3 and P6 were pre-cracked in both reinforcement directions while specimen P5 was only pre-cracked in one direction.

Table 1: Level of tension and crack widths in pre-cracked specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Level of tension given as reinforcement stress [MPa]</th>
<th>Crack widths [mm]</th>
</tr>
</thead>
</table>
| P1       | $\sigma_{xx}$ 849  
           | $\sigma_{yy}$ 808 | 0.35 - 0.45       |
| P2       | $\sigma_{xx}$ 0  
           | $\sigma_{yy}$ 0   | 0                 |
| P3       | $\sigma_{xx}$ 950  
           | $\sigma_{yy}$ 950 | 0.45 - 0.55       |
| P5       | $\sigma_{xx}$ 850  
           | $\sigma_{yy}$ 0   | 0.40 - 0.50       |
| P6       | $\sigma_{xx}$ 437  
           | $\sigma_{yy}$ 436 | 0.20 - 0.30       |

After the pre-cracking process, the specimens were installed into a testing frame schematically shown in Fig. 2 (right). The punching load (red hydraulic jack in the figure) was applied to the slab via a quadratic loading plate with dimensions $b = 150$ mm and $t = 30$ mm. The slabs were supported on all four sides by the steel frame. The span of the slabs was $L = (b + 2a) = 1050$ mm, Fig. 1.
2.3. Punching test results

All specimens suffered pure punching shear failure. For illustration, photos of the crack patterns on the bottom face of specimens P1 and P2 are shown in Fig. 3. The cracks shown as black lines are those created by tension as described in section 2.2. The red lines correspond to cracks developed during the punching shear tests. In order to study the shape of the punching failure surface, test specimens were sawn up (crosswise and diagonally). As can be seen in Fig. 3, the geometry of the punching failure surface for the pre-cracked specimen does not differ significantly from the failure surface observed in the reference specimen P2.

Fig. 4 shows the load-deflection response of the specimens. As can be seen, specimen P2 exhibits larger initial stiffness than the other specimens. This is expected, as P2 was un-cracked before tested in punching.

The experimental ultimate punching loads are shown in Table 2. It can be seen that the punching strength of the pre-cracked specimens is similar to the strength of the reference specimen P2. The results indicate, that pre-cracking and thus removal of concrete tensile strength in the cross sectional directions does not have any impact on the punching strength.
Figure 3: Crack pattern and punching failure surface for specimens P1 and P2.

Figure 4: Punching load vs. midpoint deformation of test specimens
3. CALCULATIONS BY THE CRACK SLIDING MODEL

Calculations have been conducted to predict the punching shear strength of the test specimens. The model adopted is based on the so-called Crack Sliding Model, which originally was formulated by Zhang (1997), see also Nielsen (1999), for shear strength prediction of beams without stirrups. The model has been extended by Hoang (2006) to deal with punching shear strength of slabs.

In the model, punching failure is assumed to take place as sliding in four inclined crack planes. The horizontal projection of the crack planes is denoted as \(x\), and may be determined from the following cubic equation:

\[
\left(\frac{x}{h}\right)^4 + \frac{3 \cdot b}{4 \cdot h} \left(\frac{x}{h}\right)^3 + \left(\frac{3 \cdot b}{4 \cdot h} + \frac{3}{2} \cdot \frac{\tau_c}{f_{\text{ref}}} \cdot \frac{a}{h} - \frac{3 \cdot \tau_c}{f_{\text{ref}}} \cdot \frac{b}{h} \cdot \frac{a}{h}\right) \cdot \frac{x}{h} - \frac{3 \cdot \tau_c}{f_{\text{ref}}} \cdot \frac{b}{h} = 0
\]  

(1)

Here, \(h\) is the depth of the slab, \(a\) and \(b\) are the parameters shown in Fig. 1 and \(\tau_c\) and \(f_{\text{ref}}\) are given below:

\[
f_{\text{ref}} = 0.156 f_c^{2/3} \left(\frac{h}{0.1}\right)^{-0.3}; \quad \tau_c = 0.059 \nu_f f_c; \quad \nu_f = \frac{0.88}{\sqrt{f_c}} \left(1 + \frac{1}{\sqrt{h}}\right)(1 + 26 \rho_t) \leq 1.0
\]  

(2)

where \(f_c\) is inserted in MPa and \(h\) in meters. When \(x/h\) has been determined by mean of Equation (1), the punching load can be calculated as:

\[
P_u = 8 \cdot \frac{\tau_c}{x} \cdot (b + x) \cdot h
\]  

(3)

The calculated result has been compared with tests in Table 2 and in Fig. 5. The agreement is seen to be good. This may indicate that the diagonal crack planes, which in the model is assume to experience sliding failure, can be formed even in the present of a fully developed system of tension cracks.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Experimental punching strength, (P_{u,\text{test}}) [kN]</th>
<th>Calculated Punching strength, (P_{u,\text{theory}}) [kN]</th>
<th>(P_{u,\text{theory}}/P_{u,\text{test}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>445</td>
<td>465</td>
<td>1.04</td>
</tr>
<tr>
<td>P2</td>
<td>443</td>
<td>465</td>
<td>1.05</td>
</tr>
<tr>
<td>P3</td>
<td>421</td>
<td>465</td>
<td>1.10</td>
</tr>
<tr>
<td>P5</td>
<td>444</td>
<td>465</td>
<td>1.05</td>
</tr>
<tr>
<td>P6</td>
<td>418</td>
<td>465</td>
<td>1.11</td>
</tr>
<tr>
<td>Mean value</td>
<td>445.5</td>
<td>465</td>
<td>1.07</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. CONCLUSION

A series of punching shear tests on pre-cracked reinforced concrete slabs has been reported. The cracks were induced to the specimens by uniaxial tension as well as biaxial tension. The crack widths at the peak of the applied tension were between 0.20 – 0.55mm. No significant reduction in the punching capacity was observed. The results indicate that pre-cracking and thus removal of concrete tensile strength in the cross sectional directions does not have any impact on the punching shear strength of reinforced concrete slabs.

REFERENCES


