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Review article

Punching shear of RC flat slabs – Review of analytical models for new and strengthening of existing slabs

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A B S T R A C T

The conversion of existing buildings, development of standards, material deterioration and detailing deficiencies have led to a need for strengthening an increasing number of concrete flat slabs against brittle punching shear failure. However, existing analytical and design models do not yet take into account the specific aspects of strengthening slabs against punching shear. More than 40 models exist for predicting the punching shear strength of new slabs. A three-level classification is proposed to provide a consistent overview of the wide range of approaches adopted for resistance calculation. Based on this classification, models are evaluated with regard to their applicability for problems specific to the strengthening of existing slabs, such as pre-damage of existing slabs, insufficient anchorage lengths of tensile reinforcement outside the punching zone, new openings in slabs within the punching zone, and the prestressing of post-installed shear reinforcement. The efficiency of current strengthening solutions is evaluated, suggesting local prestressing as a promising method.

Contents

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1. Introduction

The structural concepts of buildings often comprise concrete flat slabs locally supported by columns. One advantage of this concept is easier construction compared to ribbed or mushroom slabs. Additionally, it generates greater flexibility in the disposition of rooms that are simply enclosed by easily removable non-structural walls. The disadvantage, however, is the combination of locally high negative bending moments and shear forces around the columns, which increases the sensitivity of this zone to brittle punching failure. In this failure mode, the slab collapses around a truncated cone above the column and this abrupt failure is followed by a drop in the load-bearing capacity of the slab which may eventually lead to a progressive collapse of the entire structure.

In the recent past, tragic examples of this hazardous failure mode have raised public awareness in this respect [1–3]. Not only because of these failures but also generally due to the increasing number of aging structures, the need for the strengthening of existing concrete flat slabs against punching shear is significantly increasing. In Europe, already around one third [4] of construction costs involve the strengthening and upgrading of existing structures. This includes the reorganization of buildings after a certain service life and a change in the purpose of the building often leads to higher permitted live loads. Poor detailing and pre-damage in slabs, as well as durability problems like deterioration or rebar corrosion, are additional reasons for strengthening.

Although various methods to strengthen flat slabs exist (cf. Section 2.3), corresponding analytical and design models have not yet been developed which can take into account effects such as poor detailing or local prestressing as used in some strengthening methods. The question arises whether the models developed for new slabs are also suitable for strengthening applications. This paper reviews over 40 models concerning the punching shear of interior, edge and corner columns that have been published in the last decades and evaluates their applicability for the punching shear strengthening of existing flat slabs. Suggestions are given for adjusting the available formulae accordingly.

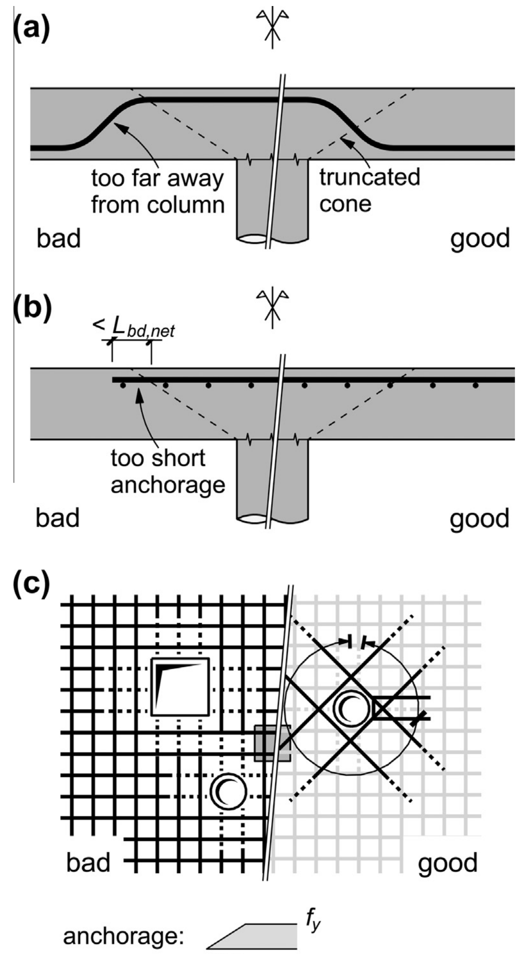

Fig. 1. Detailing deficiencies: (a) shear reinforcement outside the truncated cone; (b) insufficient anchorage length of top reinforcement; and (c) cut rebars for openings.

2. Strengthening against punching

2.1. Detailing deficiencies of existing slabs

Based on the knowledge developed in recent years regarding the punching shear problem, numerous existing flat slabs no longer meet detailing requirements for sufficient punching shear strength. Thin slabs are common and are often built without shear reinforcement around the columns. When shear reinforcement was installed, bent-up bars were often used, as shown in Fig. 1a, where the top longitudinal reinforcement in the support area continued as bottom reinforcement at midspan or was anchored at the lower side of the plate. This procedure minimized the amount of steel rebars necessary; at midspan the upper reinforcement was often omitted (discontinuous upper longitudinal reinforcement). One critical point is the location of the inclined part relative to the punching cone: if the latter is not crossed by the rebar (left case in Fig. 1a), the rebar is ineffective as punching reinforcement. Fig. 1b shows another typical problem: to effectively contribute to punching shear strength, the top reinforcement has to be fully anchored outside the punching cone ($L_{bd,net}$ denotes the required length for full anchorage), which is often not the case. This problem either dates back to when the structure was built (too short rebars) or results from strengthening methods that enlarge the punching cone (e.g. by widening of the column or adding mushrooms), as will be discussed in Section 2.3. The Pipers Row Car Park collapse is one example where deterioration of the concrete and rebar corrosion together with insufficient repair work resulted in an insufficient anchorage of the top reinforcement around the two columns where punching shear failure was probably initiated [2]. Note that sufficient anchorage is also needed for the bent-up bars on the right side of Fig. 1a. Large openings next to the column disturb the distribution of forces and therefore have a negative effect on punching strength, especially when correct detailing around the holes is lacking, i.e. rebars are cut for subsequently drilled holes, as shown in Fig. 1c. The dashed lines denote the anchorage length of the rebars and f_y denotes their yield strength.

2.2. Pre-damage in existing slabs

Fig. 2 illustrates how the shear force V increases with increasing slab rotation ψ, (angle between deformed slab and horizontal axis, as shown in Fig. 2) until (theoretically) reaching the ultimate (flexural) strength, V_{flex}, of the slab. When a failure criterion according to Muttoni [5] is assumed, where punching shear strength decreases with increasing slab rotation (also shown in Fig. 2), the intersection between the curves denotes the (real) ultimate (punching) strength, V_{R0}. The service loads, V_{ser}, of properly designed slabs are normally about 70% of V_{R0}, while the first cracks around the supported area already appear at around one third [6–9] of the ultimate load at V_{cr} (with considerable scatter).