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Fracture kinematics of reinforced concrete slabs failing in punching

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ABSTRACT

Over the past decades, a large number of punching shear resistance models with different backgrounds have been developed. Among them, punching shear resistance models based on kinematic failure mechanisms have been found to be in good agreement with punching tests on slender slabs. The existing kinematic models generally determine the punching strength based on suitable failure criteria relating punching failure to a certain slab rotation. Hence, slab deformations are assumed to occur as a result of flexural deformations only. Yet, measurements taken from recent punching tests with varying slenderness reveal differences between fracture kinematics of slender slabs (e.g. flat slabs) and compact slabs (e.g. column bases). In this context, the deformation behavior of compact slabs is rather governed by translational deformations. Consequently, a general application of the existing models to both slender and compact slabs might yield inconsistent results.

In this paper, the punching shear behavior of reinforced concrete flat slabs and column bases is investigated in detail. Based on measurements from tests and theoretical investigations, the fracture kinematics of slabs failing in punching are analyzed. The investigations verify that the total deformation of compact slabs at punching failure is significantly underestimated by considering the slab rotation as single degree of freedom (DOF). A more general description of the deformation behavior of both slender and compact slabs is possible by introducing a second DOF considering translational deformations. Based on the aforementioned observations, a general kinematic model is introduced to describe the fracture kinematics of reinforced concrete slabs by means of two DOFs. The proposed model is verified by means of measurements taken from punching tests.

1. Introduction

The problem of punching shear in reinforced concrete slabs has been investigated extensively in the past decades (e.g. [1–5]). As a result of these investigations, various punching shear models with different backgrounds have been proposed. While semi-empirical models (e.g. [6,7]) can be easily applied, they are generally limited to predict the punching shear resistance. To allow for a more general description of the punching shear behavior including the deformation behavior of reinforced concrete slabs, various models based on kinematic failure mechanisms have been developed.

One of the probably most well-known kinematic punching shear model was developed by Kinnunen and Nylander [8,9] in the 1960s. Considering their test results, they assumed that the hogging moment area (area between column and line of contraflexure) of a loaded flat slab can be described by a truncated cone, which is confined by a shear crack and the slab portion outside the crack. Under load action, radial cracks occur leading to a separation of the outer slab portion into segments. Each segment is considered as a rigid body rotating about a center of rotation located in the root of the crack. Because of its clarity and transparency in explaining the fracture kinematics of reinforced concrete slabs failing in punching, the model by Kinnunen and Nylander attracted attention by many researchers, who used the theoretical framework of the model as a basis for further investigations (e.g. [10–16]).

The existing kinematic punching shear models have been verified by systematic test series on slender reinforced concrete slabs (usually isolated flat slab specimens). Nevertheless, since the available kinematic models so far only consider flexural deformations, their applicability to more compact slabs (e.g. footings and ground slabs) is at least questionable, since the deformation behavior of these slabs is rather governed by translational deformations (shear deformation and column penetration) than by flexural deformations [17–20]. In this paper, systematic punching tests on reinforced concrete slabs with varying slenderness are used to investigate the failure mechanism more in detail. Based on the results of these investigations, a general two-

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Nomenclature

Roman lower case letters

a_λ	shear span
d	effective depth
h	depth
l	length
l_k	length over which δ_t develops
l_t	length over which $\varepsilon_{t,avg}$ is averaged
s_{cr}	average spacing of flexural cracks
t_{CR}	projected distance between center of rotation and intersection between slab soffit and edge
x	x-coordinate
z	z-coordinate

Roman upper case letters

V	shear force
V_{max}	shear force at punching failure

Greek letters

α	inclination of shear crack
βcr	angle between length t_{CR} and plane of slab
δ	deformation
δ_c	column penetration
δ_f	flexural deformation
δ_h	horizontal deformation
δ_{max}	deformation at punching failure
δ_r	measured horizontal deformation
δ_s	shear deformation
δ_t	translational deformation (DOF of kinematic model)
δ_{total}	total vertical deformation
δ_w	measured vertical deformation
δ_x	deformation in x-direction
δ_z	deformation in z-direction
ε	strain
$\varepsilon_{t,avg}$	average strain in flexural reinforcement (DOF of kinematic model)
σ_g	ground pressure
ψ	slab rotation

Other symbols

Ø	diameter of flexural reinforcement

parameter kinematic model is derived to describe the fracture kinematics of reinforced concrete slabs failing in punching under symmetric loading conditions.

2. Information from tests

2.1. General

While previous investigations [8,14,21] clearly verify that the punching shear behavior of slender reinforced concrete slabs is strongly influenced by the slab rotation (flexural deformation), punching tests on reinforced concrete footings with varying flexural reinforcement ratio indicate that this influence is less pronounced, especially in very compact slabs [22]. It is therefore assumed that the failure mechanism of compact slabs is governed by translational deformations (shear deformation and column penetration) and, thus, differs significantly from slender slabs.

To investigate the fracture kinematics of reinforced concrete slabs more in detail, inner crack patterns and measured changes in thickness can be used. In this context, Fig. 1(a) shows the saw-cut and the measured changes in thickness of flat slab specimen PG3 [23]. The saw-cut supports the assumption that the slab portion outside the shear crack remains uncracked, since flexural cracks mainly formed in the region of the column. The measured changes in thickness increase with increasing distance from the column edge. The fact that the measured changes in thickness close to the edge of the column are very small even at failure indicates that the failure mechanism is only slightly influenced by translational deformations. Hence, it can be assumed that the fracture kinematics of slender slabs is governed by flexural deformations.

The saw-cut and the measured changes in thickness of footing specimen PS11 [20] is shown in Fig. 1(b). Compared to specimen PG3, the formation of flexural cracks in the region of the column is less pronounced. Also, the measured changes in thickness decrease slightly with increasing distance from the column edge. Thus, the failure mechanism of the footing seems to be influenced by both flexural and translational deformations. The fact that the measured changes in thickness are very large at the edge of the column can be explained by crushing of concrete near the column due to the column penetrating into the footing.

Similar observations can be made for the compact footing specimen PS13 [20] (Fig. 1(c)). Nevertheless, the fact that no flexural cracks are visible in the region of the column indicates that the flexural deformations are very small and that the failure mechanism is governed by translational deformations.

Based on the evaluation of the punching tests (Fig. 1), it can be postulated that the fracture kinematics of reinforced concrete slabs can be described by both flexural and translational deformations. While the failure mechanism of slender slabs is dominated by flexural deformations, the failure mechanism of very compact slabs is governed by translational deformations. In the transition region between very compact and slender slabs, the deformation behavior can be described by both deformation components. Similar observations were also made for slender and compact beams failing in shear (e.g. [24,25]).

2.2. Evaluation of deformation components

For a detailed investigation of the deformation behavior of reinforced concrete footings failing in punching, specimens DF_N8 ($a_\lambda/d = 1.25$), DF_N0N ($a_\lambda/d = 2.00$), and DF_N9 ($a_\lambda/d = 3.00$) with varying shear span-depth ratio can be evaluated [26,27]. The specimens were reinforced with a novel type of shear reinforcement. During the tests, several linear variable differential transformers (LVDTs) were used to investigate the fracture kinematics of the specimens. An extract of the arrangement of LVDT measurements of the specimens is shown in Fig. 2(a). The separation of the deformation components into flexural deformations and translational deformations (shear deformations and column penetration) can be performed following the procedure described in [20] (Fig. 2(b) and (c)).

The slab rotation ψ is calculated by means of the measured horizontal deformations $\delta_{r,top}$ and $\delta_{r,bot}$ at the footing edge:

$$\psi = \arctan\left(\frac{(\delta_{r,top} - \delta_{r,bot})}{h_\psi}\right) \quad (1)$$

Since the slab rotation ψ is directly related to the flexural deformation of the specimens, the flexural deformation δ_f (Fig. 2(b) and (c)) can be calculated as: