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Compressive membrane action in progressive collapse resistance of RC flat plates

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ABSTRACT

In this paper, a new finite element modeling technique is developed to simulate punching and post-punching behavior of flat plates, which is verified against an available punching experiment. The experiment did not impose lateral restraints on the slab, however, the punching strength of the same experiment accounting for the effects of lateral restraint is numerically investigated. It is observed that punching strength is considerably enhanced by lateral restraining of the isolated slab. This is due to the formation of compressive membrane forces in the slab as a result of its tendency to grow in-plane as it deforms vertically. These compressive membrane forces and the resulting friction shear are the source of punching strength enhancement. Although the compressive membrane force is an important contributor to the punching shear strength of flat slabs, current design codes and guidelines ignore this action, and therefore underestimate the punching strength. The progressive collapse potential of a sixteen-column flat slab is numerically investigated, using the techniques developed. Ignoring the effects of compressive membrane forces led to the propagation of the punching failure through the slab, while including the compressive membrane force helped resist progressive collapse. It is shown that in flat slab structures the lateral restraint is provided by the slab itself and there is no need for restraining of the slab edges. The contribution of the non-continuous tensile reinforcing bars at the location of the columns to the post-punching strength is found to be negligible compared to the integrity bars.

1. Introduction

Progressive collapse is likely to occur in a flat plate structure if punching shear failure occurs in the slab at the location of an interior column [1–5]. Progressive collapse is defined as the spread of an initial local failure from element to element, which eventually results in the collapse of an entire structure or a disproportionately large part of it [6]. The chain reaction of failures will continue until the structure comes to equilibrium by finding a stable alternative load path [7]. Progressive collapse has been investigated on different types of structural systems over the past decades [8–11]. Some structural collapses have been reported over the past decades due to punching failure at a column [12–15]. A punching failure over a column can overload the system and initiate punching shear failure in the neighboring columns and lead to a partial or total collapse of the structure. It is important to identify the collapse resisting mechanisms and more reliably evaluate structural response following initial damage. Direct and indirect design methods are suggested by different guidelines for investigations of the potential for progressive collapse [16,17]. The direct design method explicitly investigates the ability of the structure to arrest the initial damage propagation by the Alternative Load Path method (ALP) [17]. In the ALP method, some of the primary structural elements, commonly a column, are eliminated and the capability of the structure to bridge over the initial damage is investigated which is a threat independent method.

Since 1921, researchers have reported an increase in the ultimate load carrying capacity of laterally restrained slabs on a single column or flat plate structures than that of Isolated and Simply Supported (ISS) slabs [18–26]. The compressive membrane action in the slab is known to contribute to the enhancement of punching strength and load carrying capacity, which in turn can help prevent or limit progressive collapse in flat plates [20,24,25,27–29].

Over the past 50 years, researchers and guidelines have proposed various analytical/empirical methods to predict the punching strength of flat plate floors [30,31,23,32,33,2,34]. The majority of these methods were based on the experimental results of ISS slabs that did not account for the compressive membrane action [35,31,23–26]. Thus, predicting the punching shear strength of flat plates based on the behavior of ISS slabs underestimates the ultimate load carrying capacity of floor systems and/or laterally restrained isolated slabs [22].

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Despite the studies on the finite element modeling of punching failure in flat plate and slab structures [36–40], the progressive collapse potential of RC flat plates following punching is rarely investigated using Finite Element Methods (FEMs). This is due to the complexity of modeling punching failure, including the effects of the compressive membrane forces and dowel action on the punching shear strength. In the first section of the present study, a new technique is developed to explicitly simulate the punching failure of an isolated slab–column specimen. The effects of dowel action, critical shear crack formation, critical shear crack widening during punching, and post-punching response are investigated. The results are compared with the available experimental results. The effects of the boundary conditions on the punching strength of the isolated slab–column specimen are then numerically investigated by improving the proposed technique. In the second section, the system-level response after a column loss of an RC flat plate floor system with and without the effects of membrane forces is presented.

2. Punching failure in flat plates

Under monotonically increasing load, tangential flexural cracks form around columns [41,2]. The propagation of the flexural cracks in the slab in combination with shear cracks forms a diagonal critical shear crack. After the formation of the shear crack, and prior to punching shear failure, aggregate interlocking and dowel action are the main shear transfer mechanisms from the slab to the column [2]. Once the shear crack crosses the bottom reinforcement, reinforcing bars contribute to the shear transfer by dowel action. A truncated punching cone around the column forms as the column punches through the slab (see Fig. 1). The punching shear failure occurs with very little warning. After punching shear failure, the only connection between the slab and the truncated cone is the flexural and integrity reinforcement, in the absence of shear reinforcement. Note that the slab bottom reinforcement passing directly over the column is called the integrity reinforcement, which may be under compressive stress before punching failure. Slabs with only top reinforcement at the location of the column have little post-punching strength and deformation capacity to redistribute the load from the damaged column to the adjacent columns [42,5]. The top flexural reinforcement tends to break the concrete cover and tear out as the slab moves downwards with respect to the column. According to ACI 318-11, Section 13.3.8.5, at least two integrity (bottom) reinforcing bars, which are continuous through the column and well anchored at the supports, are required to increase the redundancy, ductility, and integrity of two-way slabs. The integrity reinforcement will act in a hammock-like fashion to prevent the slab from falling down and triggering a progressive collapse [43]. After punching, the integrity reinforcing bars can almost recover the pre-punching strength of the slab if sufficient integrity reinforcing bars are used [35].

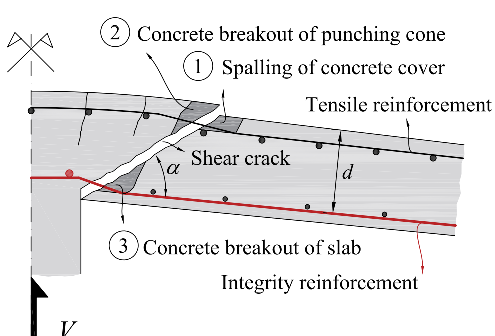

Fig. 1. Truncated punching cone, tensile and integrity reinforcing bars and failure zones of slab, cone and connectors.

Three failure zones can be defined during punching failure of the slabs with integrity reinforcing bars (Fig. 1). As the column punches through the slab, the tensile reinforcement tears out of the concrete slab in zone 1 causing concrete spalling, and the integrity and tensile reinforcing bars break concrete in zones 2 and 3. When the thickness of the concrete is enough to prevent the breakouts of zones 2 and 3, concrete failure stops [3].

3. Experimental and analytical response of isolated and simply-supported (ISS) slab

A large number of experiments have been conducted to study the punching shear strength over the past decades. The dimensions of most of the specimens were bounded by the lines of contraflexure at a radial distance of about 0.22*L* from the supports, where *L* is the center-to-center span of the slab. ISS slabs are individual panels with the dimensions discussed above and no restraints against lateral (in-plane) movement around the edges. One of the specimens tested by Mirzaei and Muttoni [35] was chosen for the numerical simulation in this section. The test was carried out on a half-scale, ISS RC slab specimen (PM-11) under monotonically increasing displacement at the center of the specimen. Fig. 2c, shows a quarter of the test specimen after punching. The specimen, with uniformly distributed tensile reinforcement (ϕ8@60 mm top), two integrity reinforcing bars (ϕ12) in each normal direction, and dimensions of $1.5 \times 1.5 \times 0.125$ m, represented a slab with 7 m center-to-center spans. The tensile and integrity reinforcing bars were well anchored at the ends representing the continuity of the top and bottom bars over the entire span.

Due to the symmetry and to simplify the analysis, a quarter FE model was developed using Abaqus v.6.9-2 (see Fig. 2a and b). Fig. 2a shows the final mesh layout of the ISS slab. The finite element mesh used in this study is primarily determined by considering the following factors: (1) Given that the integrity and tensile reinforcing bars crossing the punching cone are modeled explicitly and need to attach to the slab, these reinforcing bars are aligned with the boundary of finite elements and the slab nodes; (2) A proper number of Slab-Cone Connectors (SCCs) connecting the nodes on the mid-height of the slab to the corresponding nodes on the mid-height of the cone, is required to model the slab punching strength; and (3) The state of stress and strain in the slab need to be reliably represented. The results of a sensitivity study demonstrated that increasing the number of Slab-Cone Connectors by a factor of two and the number of elements by a factor of four leads to less than 1% change in the punching strength of the slab and the vertical displacement at which punching occurs. Furthermore, the post-punching response of the slab changes insignificantly as a result of increasing the number of elements. Therefore, the finite element mesh presented in Fig. 2a is considered reliable. S4R general-purpose shell elements with quadrilateral finite-membrane-strain were used for the slab. An explicit time integration method was used to perform a nonlinear displacement-controlled quasi-static analysis which was compared with the experimental results.

3.1. Material properties

The tensile and cylindrical compressive strengths of the concrete were 2.5 MPa and 30 MPa, respectively. The yield and ultimate strengths of reinforcing bars were 548 MPa and 625 MPa, respectively. The concrete and steel moduli of elasticity were 26 GPa and 200 GPa, respectively.