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Probabilistic assessment of the ultimate load-bearing capacity in laterally restrained two-way reinforced concrete slabs

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ABSTRACT

In the last two decades, the problem of compressive membrane action (CMA) in laterally restrained reinforced concrete (RC) slabs has been widely under research due to significant strength enhancement and reserve strength it can provide in resisting progressive collapse. Besides, it is well known that reliability of a structure subjected to extreme loading scenarios is a function of uncertainty propagation in the ultimate load-bearing capacity of structural components. This paper is concerned with probabilistic assessment of the ultimate load-bearing capacity of laterally restrained RC slabs considering the contribution of CMA. Using global variance-based sensitivity analysis, uncertainties in material properties, geometrical properties and mechanical properties are studied. Moreover, the influence of different modeling strategies on uncertainty propagation is investigated for the available analytical and numerical approaches to provide a basis in terms of probabilistic model quality. Mesh sensitivity and parametric studies are also performed to shed light on the influence of finite element discretization, reinforcing steel configuration, and in-plan aspect ratio on uncertainty propagation in the ultimate load-bearing capacity. Following the sensitivity studies, non-influential parameters are fixed at their mean values, and the probability of failure is estimated for the investigated modeling strategies using a full-probabilistic approach.

1. Introduction

The yield-line theory proposed by Johansen [1] has been used since 1943 in assessing the ultimate load-bearing capacity of reinforced concrete (RC) slabs. However, following the full-scale collapse test done by Ockleston in 1955 [2], where he found the collapse load to be more than twice the load predicted by the classical yield-line approach, the topic of compressive membrane action (CMA) in laterally restrained RC slabs gained interest among researchers. When an RC slab is loaded beyond the cracking load, the neutral axis shifts towards the compressive zone at critically loaded sections, resulting in a net tensile strain at mid-depth of the member and, in turn, elongation of the element. However, if such an elongation is restrained as it normally occurs in multi-span framed RC structures due to in-plane stiffness of neighboring elements, compressive forces will develop to satisfy the axial displacement compatibility. Such a physical phenomenon is called compressive membrane action (CMA) in two-way RC slabs. Fig. 1 schematically shows the load-displacement relationship of a laterally restrained RC slab under the influence of CMA. Experimental studies such as [3–6] confirmed that CMA significantly increases the collapse load particularly when the laterally restrained RC member is under-reinforced. The second wave of interest in this research field appeared in the 1970s, when researchers worked to develop efficient analytical solutions for quantifying the contribution of CMA. Proposed analytical approaches were mainly based on either using the two-part approach analogy or using the rigid-perfectly plastic theory [7]. Examples of two-part approaches can be found in works done by Christiansen [3] and Rankin [8,9]. As for the rigid-plastic approaches, Park's method [4,10] has been widely used as a basis in other research works. The aforementioned analytical approaches are examined and improved in a series of published works such as [11–13]. The third wave of interest in further investigating the CMA is tightly connected to the problem of progressive collapse of RC structures. Progressive collapse is a structural-level problem that indicates a situation where a triggering local failure provokes a chain reaction of failures, which results in the collapse of the entire structure or a large part of it, which is disproportionate to the triggering action [14]. The ultimate load-bearing capacity of structural members is a key element in the collapse resistance of the whole structure. Therefore, in the last two decades, the CMA in laterally restrained RC slabs was significantly under research due to considerable reserve strength it can provide in resisting progressive collapse. Three-dimensional

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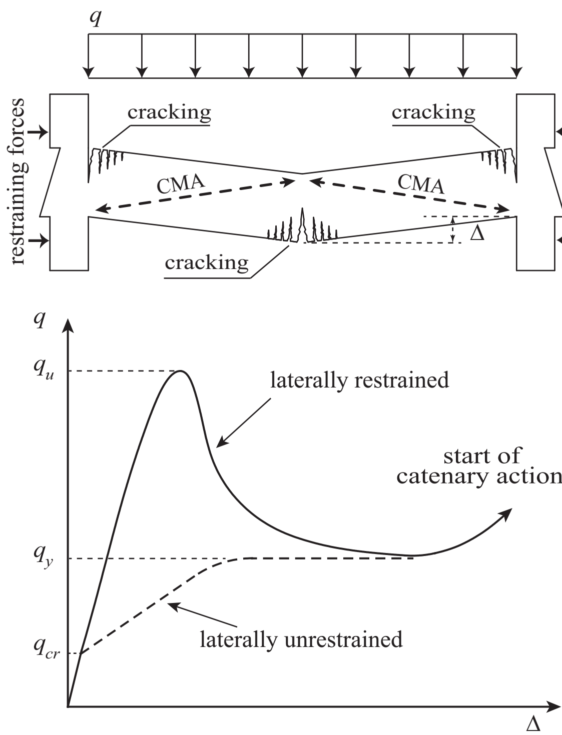

Fig. 1. Development of CMA in a laterally restrained RC slab (side-view), and its influence on the load-displacement relationship, q_{cr} is the cracking load, q_y is the ultimate flexural load for laterally unrestrained RC slab, and q_u is the ultimate load-bearing capacity due to interaction of flexural action and CMA.

numerical and experimental studies such as [15–19] revealed that the development of CMA in beams and slabs can significantly help the structure to redistribute the amplified gravity loads and, in turn, resist progressive collapse. Several attempts such as [20,13,21] were also made to improve previous analytical approaches accompanied with laboratory test verification. As for the numerical studies, two general approaches of using nonlinear multi-layered shell elements and grillage of nonlinear fiber-based beam elements are used in the quantification of CMA's contribution in two-way laterally restrained RC slabs [16,22,23,18,24].

Despite extensive research works on mechanism interpretation as well as quantification of CMA in laterally restrained RC slabs, recent works have mainly tried to either improve and generalize previous analytical approaches or to investigate such a beneficial collapse resisting mechanism using numerical approaches in a deterministic sense. However, reliability of a structure subjected to extreme loading scenarios is a function of uncertainty propagation in the ultimate load-bearing capacity of structural components. This paper studies the major sources of uncertainty in the ultimate load-bearing capacity of two-way laterally restrained RC slabs. Uncertainties in material properties, geometrical properties and mechanical properties are studied using variance-based global sensitivity analysis, where the influence of CMA on uncertainty propagation is addressed. In addition, the influence of different modeling strategies on uncertainty propagation is comprehensively discussed for the existing analytical and numerical approaches. Mesh sensitivity and parametric studies are also performed to shed light on the influence of finite element discretization, reinforcing steel configuration, and in-plan aspect ratio on uncertainty propagation in the ultimate load-bearing capacity. Finally, following the sensitivity analyses, non-influential parameters are fixed at their mean values, and the probability of failure is estimated for the investigated modeling approaches.

2. Analytical and numerical approaches

2.1. Overview

One of the major questions that we try to answer in this paper is how modeling approaches affect the uncertainty propagation for the specific problem of the ultimate load-bearing capacity in laterally restrained RC slabs. To this end, a comprehensive probabilistic study is made for the commonly used analytical and numerical approaches. The majority of proposed analytical approaches for the problem of CMA are founded on either rigid-perfectly plastic approaches or on two-part approaches. While a combined stress state of moment and axial force is assumed in rigid-perfectly plastic approaches, the contribution of CMA is calculated separately from the flexural strength in two-part approaches. In this paper, Keenan's theoretical model [25], which is a modified extension of Park's rigid-perfectly plastic approach [10] for laterally restrained square RC slabs is accepted as the analytical benchmark solution. Rankin's model [8] is also taken as a representative for two-part approaches. As for the numerical approaches, two general modeling strategies of using nonlinear multi-layered shell elements and using a grillage of nonlinear fiber-based beam elements are studied. The investigated analytical and numerical approaches are briefly explained in this section.

2.2. Keenan's rigid-perfectly plastic approach

For a reinforced concrete slab under a uniform static pressure, the slab mechanism can be decomposed into longitudinal and transverse strips [10], where mechanical behavior of each strip is influenced by the so-called yield-line pattern. The static ultimate resistance can then be determined by summing up the loads carried by each slab strip. A typical strip with plastic hinges formed at critically loaded sections is depicted in Fig. 2. Assuming a rigid behavior for the slab strip under a vertical deflection u of the central portion, one can compute the forces acting on the strip by considering stress-strain properties of concrete and steel as well as geometric restraints. Keenan [25] proposed that restraining thrust N_u and moment M_u can be determined using a failure interaction diagram. An idealized failure interaction diagram is depicted in

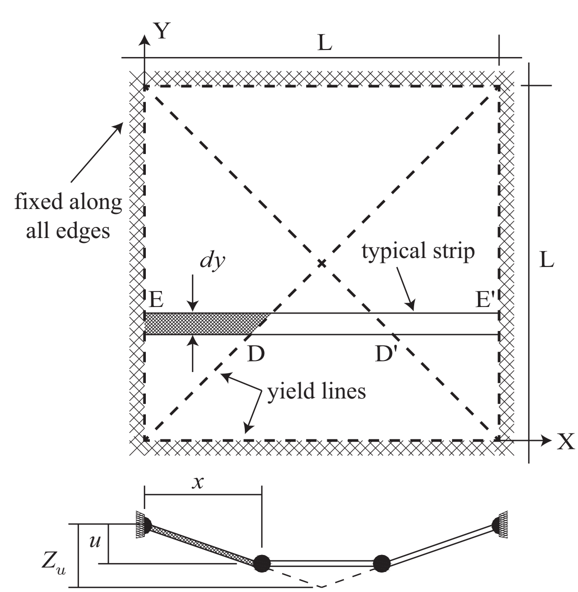

Fig. 2. Collapse mechanism, formation of plastic hinges, and a typical deflected strip under a vertical displacement u in a laterally restrained square slab, where Z_u is the ultimate deflection at collapse initiation, reproduced after [25].