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Experimental investigation of shear strength of full-scale concrete slabs subjected to concentrated loads in nuclear buildings

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The following study analyzes the shear behavior of full-scale slabs without shear reinforcement (the design of slabs used in nuclear buildings) under a concentrated load near a linear support. Experimental tests were conducted to quantify the shear strength and the associated failure modes. We addressed the influence of several variables, such as bottom longitudinal reinforcement, bottom transverse reinforcement, compressive strength, concrete aggregate size, and influence of the slab depth. A series of ten tests on nine full-scale slabs (one slab of $3.2\ m \times 2.9\ m \times 0.3\ m$; six slabs of $4\ m \times 2.6\ m \times 0.3\ m$; one slab of $4\ m \times 2.6\ m \times 0.35\ m$; one slab of $4\ m \times 2.6\ m \times 0.4\ m$) are presented. Realistic boundary conditions with the slabs supported on all four sides were used. The experiments are firstly used to evaluate the pertinence of Eurocode 2 for the shear design of reinforced concrete slabs without shear reinforcement in comparison with the French approach, and then to make comparisons with the ACI 318-14 code. We also studied the verification of a new proposal for the extension of Eurocode 2 proposed by Lantsoght et al. (2015).

1. Introduction

The resistance of reinforced concrete fabrications under out of plane shear forces remains a non-consensual topic, with divergent international practices. This is especially the case for reinforced concrete slabs subjected to concentrated loads near to supports. As the shear provisions are sufficient for normal buildings, little research has been conducted, and the design codes are relatively unchanging. In nuclear buildings, situations such as localized heavy loads from equipment, slabs loaded by walls or columns, and dynamic loading (seismic, drop loads), are commonly found. For constructability and cost-effectiveness reasons, shear reinforcement of concrete is an important issue in a new nuclear plant project.

In reinforced concrete members, after cracking due to bending, shear can be transferred by a number of potential actions, thereby leading to failure. A summary of shear-transfer actions can be found in ASCE-ACI Committee 445 report from 1998 [1], with the actions defined as: shear stresses in uncracked concrete, interface shear transfer (or aggregate interlock), the dowel action, residual tensile stresses, and arch action.

Shear behavior in slabs can be divided into two types: one- or two-way shear. The latter behavior can result in shear failure, for example in punching under a concentrated load, which is generally smaller than the flexural failure load calculated by theories such as the yield line theory [2]. Failure occurs with a potential diagonal crack following the surface of a truncated cone around the loading area. The problem with this failure mode is the brittle nature of concrete and its subsequent inability to support the large tensile stresses that develop. One-way shear behavior is defined by the presence of a distinct shear crack on a single side. This occurs with loading from either line loads or concentrated loads. The slab's behavior under line loads can generally be assumed to be equivalent to a beam's behavior. A number of experimental studies conducted on slabs or wide beams under line loads have confirmed this tendency, such as in [3–7]. The shear behavior of concrete beams has long been the subject of investigations, and a review of the studies published on shear behavior of concrete beams over the past 60 years can be found in [8].

Currently, contrary to the study of shear behavior in beams, only a few tests have been conducted to study the one-way shear behavior of slabs without shear reinforcement under concentrated loads [9–15,33]. Most of these studies addressed structures used in slab bridges. All of these listed studies on the shear behavior of slab bridges conducted tests on slabs supported on one (cantilever slab) or two sides, to model real deck slabs in bridge structures. However, in concrete floor structures the slabs may also be

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Nomenclature

a_v	clear shear span: face-to-face distance between the load and the support
b	member width
b_w	smallest width of the cross-section in the tensile area
b_{eff}	effective width in shear
d	effective depth of the cross-section
d_l	effective depth to the longitudinal reinforcement
d_t	effective depth to the transverse reinforcement
f_{ck}	nominal characteristic cylinder compressive strength (MPa)
$f_{cm,meas}$	measured cylinder compressive strength of the concrete at the age of testing
$f_{ctm,meas}$	measured cylinder tensile strength of the concrete at the age of testing
A_{sl}	tensile reinforcement (mm^2)
σ_{cp}	the average normal concrete stress over the cross section, positive in compression
$V_{Rd,c}$	design value of the shear capacity according to NEN-EN 1992-1-1:2005
ρ_l	ratio of flexural reinforcement in the longitudinal direction
ρ_t	ratio of flexural reinforcement in the transverse direction
K	factor taking into account the size effect in shear
$C_{Rd,c}$	empirical factor for characteristic shear capacity
M_{exp}	ultimate bending moment at the location of the concentrated load
P_u	measured peak load in an experiment
V_{EC2}	shear capacity calculated according to NEN-EN 1992-1-1:2005
V_{France}	shear capacity calculated according to French National Annex
$V_{Lantsoght}$	shear capacity calculated according to formula proposed by Lantsoght et al.
V_{ACI}	shear capacity calculated according to ACI 318-14
V_{exp}	shear force at failure in the experiment
B	reduction factor for the contribution of loads close to the support to the shear force
γ_c	partial safety factor for concrete
l_{sup}	supported length

supported on all four sides. These different boundary conditions can produce different shear behaviors due to the influence of the two supported lateral sides, as in punching shear. We previously [16] tested similar slabs supported along either the entire perimeter or on only two opposite edges. The resulting crack pattern was different for each slab. The slabs supported along the whole perimeter showed a stiffer behavior than the slabs supported on two edges, with the failure load being higher. This demonstrated that for one-way shear, the different boundary conditions occurring when slabs are supported on all four sides should also be studied. This study examines the one-way shear capacity of slabs under concentrated load with simple support on all four sides instead of two, for which no previous experiments have been performed.

One parameter that can be particularly pertinent for the shear strength of slabs is the longitudinal reinforcement ratio. Lubell et al. [4] showed that the longitudinal reinforcement details will influence shear from the transfer of force in uncracked compression block, aggregate interlock along the diagonal crack surface, and dowel action of the longitudinal reinforcement. For example, increased reinforcement strains will correspond to wider cracks and therefore reduced aggregate interlock. Hence, it is necessary to determine the influence of longitudinal reinforcement on the shear strength of reinforced concrete members. In the formulation of Eurocode 2, an empirical formulation for shear capacity based on longitudinal reinforcement was adopted. However, this formulation was calibrated and validated using experimental tests in beams, but not in slabs.

The influence of transverse reinforcement was assessed in this study. Sherwood et al. [6] and Gurutzeaga et al. [3] confirmed that transverse flexural reinforcement does not influence the shear stress in failure of one-way slabs under line loads. The behavior of one-way slabs under line loads can be assumed to be the same as in beams. However, in one-way slabs under concentrated loads, moments occur in the span and transverse directions, therefore, a one-way slab under concentrated loads does not behave like a beam. Most of the international codes such as ACI-318-14 [17] and Model code 2010 [18] for design provisions, do not take into account the influence of transverse reinforcement. In the French National Annex [19] for Eurocode 2 [20], a different approach is used to evaluate the shear strength of slabs with transverse redistribution of load. In this annex, for beams and for other types of slab, the shear stress is calculated as $v_{min} = 0.035k^{3/2}\sqrt{f_{ck}}$, but for slabs with transverse redistribution of loads, the shear stress is calculated by another approach $v_{min} = 0.23\sqrt{f_{ck}}$. Nonetheless, it is not made clear how the transverse reinforcement influences the shear strength. The effect of transverse redistribution can be obtained by all factors that contribute to two-way functioning of a slab. Two such examples are: (a) when the boundary conditions permit functioning in the manner of a plate and not a beam, for example with slabs supported on three or four sides; (b) when a slab that works primarily in one direction has a width sufficient for lateral transfer to be possible. These two examples assume the existence of reinforcement in the transverse direction corresponding to at least 1/5 of that in the main direction.

Other parameters that can influence the shear resistance of reinforced concrete slabs without shear reinforcement include the compressive concrete strength, clear shear-span-to-depth ratio a_v/d, and the maximum aggregate size; these are also considered in this study.

Finally, the experimental results are compared to the recommended values in EN 1992-1-1:2005 (EC2), and those used in the French National Annex. These approaches were also compared to ACI 318-14, and the extension to EC2 proposed by [21]. In EC2, the design value for the shear resistance $V_{Rd,c}$ of members without shear reinforcement was evaluated empirically from experimental data collected worldwide [22]. These experimental results are from a large number of beams, which were mostly small, simply supported, and subjected to two point loads. In the study of [12], an extensive literature review showed that the EC2 approach to estimate the shear capacity of RC beams results in substantial variation, which results in a large safety coefficient. In particular, the shear design rules for slabs are mostly derived from shear tests on beams and lead to an underestimation of the shear resistance of one-way slabs [23]. Currently, the shear tests performed on slabs under concentrated loads, which have been considered for the calibration and validation of design rules, have been little studied. There is only a single recent research article [21] proposing to extend the existing Eurocode for one-way shear capacity in slabs. Therefore, further experimental tests to estimate the shear capacity of one-way slabs are required.