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Influence of uniaxial tension and compression on shear strength of concrete slabs without shear reinforcement under concentrated loads

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HIGHLIGHTS

- A database of experimental tests of RC slabs under concentrated load was addressed.
- Influence of the axial compression/tension load on the shear strength was studied.
- Axial tension forces equal to $0.28f_{ctm}$ reduced the shear capacity up to 30%.
- Experimental tests were compared to Eurocode 2, ACI 318-14 and AFCEN ETC-C.

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ABSTRACT

Under the shear load, reinforced concrete structures may be simultaneously subjected to the axial tensile or compressive forces due to shrinkage in restrained members, earthquake, tornado, and so on. Until now, no experiment addressing the effect of the uniaxial load on the shear resistance of reinforced concrete slab has been reported in the literature. All the experimental tests found in the literature were conducted on panel and beam (or wide beam) specimens. The current shear design provisions with axial load (ACI 318 and Eurocode 2) were developed based solely on panel and beam tests and not slab tests. Therefore, the current shear design codes applied to slab structures under the effect of axial forces urgently need revision. The present research studies the shear strength tests of slabs under the concentrated load simply supported on four sides. The effect of the tension/compression forces on the shear capacity was studied on full-scale slabs without shear reinforcement, a design similar to the slabs used in nuclear buildings, under a concentrated load near support. Experimental tests were conducted to quantify the shear capacity and the associated failure modes with the influence of axial forces. In this study, a series of seven tests on seven full-scale slabs measuring 4 m × 2.6 m × 0.3 m is presented. The experiments were used to evaluate the pertinence of Eurocode 2 in terms of shear in reinforced concrete slabs with axial load, to compare these results to the AFCEN ETC-C code used for nuclear buildings, and to compare them to the ACI 318 code. The results showed that the axial tension forces equal to $0.28f_{ctm}$ (average concrete tensile capacity) reduced the shear capacity up to 30% in the concrete slab experiments conducted.

1. Introduction

The collapse of a part of the AMC warehouse (August 1955) followed difficulties in buildings at other locations with similar warehouse designs. The ACI building code permitted a service load of 3% compressive strength (equivalent to 0.6 MPa for C20/25 grade concrete) for beams without shear reinforcement. However, in the AMC warehouse, the beams were destroyed in shear at a lower shear value of 0.5 MPa. An experimental investigation into the causes of failure in a rigid frame warehouse was conducted by the Portland Cement Association [9]. The type of diagonal cracking that caused the failure was reproduced in the laboratory with a 1:3 ratio model scale of the collapsed part of the warehouse. Their tests showed that 1.4 MPa axial tension strength in the reinforced concrete section used in the AMC warehouse could reduce the shear capacity by up to 50%. Although more research is necessary to understand the fundamental mechanism of failure completely, it seems that the failure was created by shear under the dead weight

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Nomenclature

a_v	horizontal distance of the section from the face of the support
a	distance between the center of the support and the center of the load
A_{sl}	tensile reinforcement
A_g	area of concrete section
b	member width
b_w	width of the cross-section in the tensile zone
b_{eff}	effective width in shear
$C_{Rd,c}$	empirical factor for characteristic shear capacity
d	effective depth of the cross section
d_l	effective depth for the longitudinal reinforcement
d_t	effective depth for the transverse reinforcement
f_{ck}	nominal characteristic cylinder compressive strength
$f_{cm,cyl}$	measured cylinder compressive strength at the age of testing the concrete
$f_{ctm,cyl}$	measured cylinder tensile strength at the age of testing the concrete
f_y	yield strength of reinforcement
σ_{cp}	the average normal concrete stress over the cross section, positive in compression
ρ_l	flexural reinforcement ratio in the longitudinal direction
ρ_t	flexural reinforcement ratio in the transverse direction
k	factor taking into account the size effect in shear
N_u	axial load in the cross section
P_u	measured peak load in an experiment
V_{EC2}	shear strength calculated according to EN 1992-1-1:2005
V_{France}	shear strength calculated according to the French National Annex
V_{ACI}	shear strength calculated according to ACI 318-14
$V_{ETC\text{-}C}$	shear strength calculated according to AFCEN ETC-C
V_{exp}	shear strength at failure in the experiment
γ_c	partial safety factor for concrete

(service load) combined with the axial tension force due to changing temperature and shrinkage.

Under the shear load, reinforced concrete structures may be simultaneously subjected to axial tensile or compressive forces due to shrinkage in restrained members, earthquake, tornado, etc. It is clear that the axial compressive effect increases the shear capacity and the axial tensile effect reduces the shear resistance of reinforced concrete structures without shear reinforcement. Cracks will be delayed by compression forces, giving structures greater shear capacity. On the other hand, the compression areas will be reduced by the axial tension effect and decrease the shear strength of the structures. However, until now, it has not been clear how much the shear strength can be affected under axial forces, and also their influence on the ductility of reinforced concrete structures. Therefore, the effects of axial tension and axial compression on strength and stiffness need to be accounted for appropriately.

When diagonal cracking first occurs, reinforced concrete structures without shear reinforcement under shear loading with a high axial compressive stress value can be destroyed by brittle failure [4]. The failure of the Sleipner offshore platform triggered extensive experimental research on the design procedures of heavily reinforced concrete structures under associated compression and shear in Gupta and Collins [13]. The tests indicated that the method detailed by the ACI provided an unconservative design for members under very high compression and shear. The ACI simplified method provided a more consistent and safe design for elements under various levels of compression and shear. It should be noted that within ACI 318-14, different estimates of the increase in shear capacity caused by compression are obtained depending on whether or not axial stress is assumed to result from prestressing from an externally applied axial load. However, the ACI 318M-95 provisions for structures combining tension and shear may be very conservative [4] for structures involving a relevant longitudinal reinforcement. Although designed to be applied to high axial tensile stress, ACI 318M-95 provisions were based on experiments on structures with low longitudinal reinforcement [7].

Compared to the database of the number of tests in which the concrete members failed in shear without the axial load, the number of shear tests with the axial loads is limited. In particular, the effect of the axial tension load on shear resistance was studied far less than the influence of compressive loads. In a literature review, two categories of tests to evaluate the effect of the axial load on the shear capacity exist: panel tests and beam tests.

First, panel tests of reinforced concrete elements under different combinations of uniaxial stress and shear stress have been found to be a better way to evaluate the fundamental shear response of reinforced concrete as compared to beam tests, because the stress and strain conditions in panel tests are generally uniform and therefore easier to interpret. In particular, it is useful to first understand the influence of axial load on the shear behavior of structures not subjected to moment. In Bhide and Collins [7], 24 panels of reinforced concrete with the reinforcement only in the longitudinal direction were tested under various uniaxial tension and shear levels (including tests of pure shear and direct tension). The experiments showed that the ACI provision for calculating the shear strength is very conservative with regard to the effect of the axial tensile force applied to the reinforced concrete structure with the high level of longitudinal reinforcement. Recently, in Xie et al. [34], six reinforced concrete panels were tested to determine the influence of different longitudinal reinforcements on shear capacity ratios. The tests demonstrated that more accurate estimates of the influence of axial compression on shear strength are given by the simple expression of the ACI code. The simple expression for the effect of axial tensile force on shear strength greatly overestimates the detrimental effect of tension.

Second, the beam tests, despite their complexity for analysis of fundamental shear behavior, enable the complete loading geometry and the construction details of real structural members to be reproduced and are the most straightforward way to evaluate any analytical and design method. Tests to study the effect of axial tension forces on the beams' shear resistance can be found in Refs. [20,14,2,23,12], and the effect of compression loads was investigated in Gupta and Collins [13]. How to determine shear strength in these beams under the combination of tension and flexion is very difficult to clarify. In 12 experiments on reinforced concrete beams, Quast and Los [23] showed that if the formation of shear cracks is accompanied by longitudinal tensile stresses, steeper shear cracks are produced. This consequently reduces strength if these steeper primary cracks become so wide that no secondary cracks are formed. The same conclusions were found in Adebar and Collins [2] from the results of tests on 27 narrow wall structures. These elements had the large quantity of longitudinal reinforcement, but there was no or very little shear reinforcement. When a structure is under a large axial tensile stress, the first cracks were very steep (angle near 90 degrees), extending especially over the complete depth of the element. When the force