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Load-carrying capacity of axially-loaded RC members with circular openings

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ABSTRACT

Core drilling is today one of the most used technique among the group of partially destructive testing methods in reinforced concrete (RC) members. Even if the engineering practice provided to extract cores only in beams, taking samples from columns could be often necessary. In this case, the presence of the hole introduced a geometrical discontinuity in the member, creating a disturbed region. Consequently, compressive stresses will disperse in lateral direction as they have to avoid the drilled area. A bursting tensile force will develop, in orthogonal direction to the column axis, and if no sufficient reinforcement was arranged, a vertical crack will form, leading to the concrete splitting. Such a failure mode was related to the tensile strength of concrete and consequently it could be weak and dangerous. In the last years a very poor amount of works was carried out on the behavior of drilled compressive members. Among them, most of studies investigated from an experimental point of view. In this paper, an analytical model is presented able to predict the load-carrying capacity of RC columns with core holes. The model is constituted by two parts: the first part is based on a continuum approach and it allows to find the position and the intensity of the bursting (or splitting) force; the second part is an equilibrium-based model able to design the reinforcement. Results obtained analytically are compared with those obtained by non-linear F.E. analysis and with experimental data available in the literature. Results are discussed and design considerations are made.

1. Introduction

Nowadays core-drilling is the most common test performed in existing reinforced concrete structures due to the fact that it allowed to estimate concrete strength by standard specimens. Its application was essential to assess the safety of a building and allowed also to evaluate the results obtained with other non-destructive testing techniques or with numerical simulations.

As well-known, the technique provided to cut a circular hole into the concrete in a structural member in order to extract a cylindrical concrete sample. The obtained specimens allowed to determine different concrete properties by means of laboratory tests as compressive and split-cylinder tests for strength evaluation or phenolphthalein test for carbonation measurement. However different aspects, as the damaging effect of the hole saw, long term effects, environment, moisture and so on, had to be taken into account when evaluating the concrete strength by testing an extracted core. Concrete strength determination by drilled specimens had been studied in some works [1–4], while by contrast, a few of studies were carried-out on the effects of circular holes on the strength of structural members. It was well-known from engineering practice that cores had to be extracted preferably from beams, avoiding to introduce localized damages in the columns. In fact, as illustrated by Mansur et al. [5] by test evidence, in the case of pure bending, placement of an opening completely within the tension zone did not change the load-carrying mechanism of the beam because concrete there would have cracked anyway in flexure at ultimate. Thus, the ultimate moment capacity of the beam was not affected by the presence of an opening as long as the minimum depth of the compression chord was greater than or equal to the depth of ultimate compressive stress block.

However, taking cores from columns could be often unavoidable, and strictly rules concerning the opening position and dimension should be applied. In spite of such an important application, a poor amount of research work had been addressed about the evaluation of load-carrying capacity of compressive members with openings, and most of studies investigated mainly from an experimental point of view.

Zhu et al. [6] performed compressive tests on nine full-scale RC columns, with different hole locations and reinforcement arrangement. They found reductions of the load-carrying capacity varying from 5.63% to 22.14%, also showing that such strength loss could be limited to 4% by repairing the hole with slight-expansion high-strength concrete.

In Campione et al. [7] an experimental investigation about the application of the over-coring technique in reinforced concrete structures was presented. The authors also evaluated the

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Nomenclature

a	half-length of the bearing plate in Sahoo et al.'s [9] model
A_l	total area of longitudinal reinforcement
b	half-width of the column's side
d	diameter of the hole
F	total axial compressive load
f	applied load per unit length of column width = $F/2b$
f_c	cylinder compressive strength of concrete
f_{ct}	split-cylinder tensile strength of concrete
f_{yl}	yield stress of longitudinal reinforcement
f_{ys}	yield stress of transverse reinforcement
l	y-coordinate of the isostatic line of compression for $x = 0$
n	y-coordinate of the isostatic line of compression for $x = x_o$
x_o	x-coordinate of the center of the hole
y_O	y-coordinate of the center of the hole
$y(x)$	function defining the generic isostatic line of compression
T	bursting tensile force
t	thickness of the column
ρ_l	geometrical ratio of longitudinal reinforcement
ρ_{st}	geometrical ratio of transverse reinforcement

load-carrying capacity of drilled members after the over-coring tests and found reductions in the range between 6% and 20%.

Campione and Minafò [8] investigated on bottle-shaped struts and members with openings by testing twenty specimens in both reinforced and plain concrete. Among them, eight in presence of a circular opening, which was created in the specimens by core-drilling. Recorded reductions of load-carrying capacity were 32% for plain concrete specimens and 40% for RC columns. In the same work, the authors also proposed an extended version of the Sahoo et al.'s [9] model to evaluate the ultimate capacity of drilled specimens.

It has to be noted that even if a few of experimental researches were addressed on the behavior of RC columns with drilled core holes, different studies investigated on the effect of ungrouted post-tensioning ducts on the strength of shear-induced compression struts in bridge girders. Muttoni et al. [10] tested sixteen panels in compression with various types of ducts, finding a maximum strength reduction of about 37% (for the case of plastic duct). The authors also resumed all the different experimental results available in the literature.

In the following sections an analytical model is presented, able to predict the axial capacity of drilled columns. The model is presented in two parts. The first part is based on a continuum approach and it extends and refines the model proposed in [8]. The model allows to draw the isostatic lines of compression in a compressive member with a circular opening and to calculate position and intensity of the bursting tensile force. The model takes into account the effect of position and diameter of the hole and it allows to formulate provisions in terms of maximum allowable core diameter. On the basis of considerations made by the continuum analysis, a strut-and-tie model is derived. This is a simple design method based on equilibrium and it also allows to formulate practical considerations for design of reinforcement.

Comparisons are made with experimental results available in the literature and with non-linear finite element analysis carried out with the software ATENA-2D [11].

2. Theoretical background

The presence of the hole in an axially-loaded member modified the existing stress state. A dispersion of compressive stress trajectories occurred, due to the presence of the opening (Fig. 1a); a geometrical discontinuity was introduced in the column and consequently a disturbed region (D-region) could be individuated along the member. The total extent of the disturbed zone could be determined by means of St. Venant's principle which stated that the stress distribution due to an applied disturbance (geometric or statical) approached a uniform stress distribution as the distance between the applied disturbance and the cross-section in question increased. On such basis, if the width of the member was $2b$ and the diameter of the hole was d, the total length of the disturbed region had to be equal to $4b + d$.

Consequently to the trend of the compressive stress trajectories, a bursting tensile force developed in orthogonal direction to the axis of the column, analogously to the case of classical bottle-shaped struts. The presence of tensile stresses could lead to the formation of vertical cracks along the column axis, and if no sufficient transverse reinforcement was provided, splitting failure could be reached. Due to its dependence on the concrete tensile strength, splitting failure was brittle and similar to the failure mode developing in a split-cylinder test. Furthermore it has to be noted that often in columns of old existing structures, the transverse reinforcement arrangement could not dealt with seismic codes and therefore the bursting force development could be very critical.

2.1. Strength of bottle-shaped struts

Splitting failure was typical in bottle-shaped struts [8,9], which could be individuated in members loaded across a reduced portion of their cross-section (Fig. 1b). Different analytical models are currently available to predict the splitting strength of bottle-shaped struts. The case was initially studied by Guyon [12] to evaluate the strength of the anchorage zone of prestressed reinforced concrete beams and afterwards a lot of studies were addressed on this field [8,9,12–15]. In general the theoretical relation between the bursting tensile force T and the applied axial load F can be expressed by:

$$T = k \cdot F \cdot \left(1 - \frac{a}{b}\right) \tag{1}$$

where a was the length of the bearing zone, b was the member width and k is a coefficient that depends on the model (e.g. 0.32 for Guyon's model [12]).

Among the different expressions for the k coefficient, Sahoo et al. [9] recently suggested an analogous formula given by Eq. (1), which was obtained studying the dispersion of compression in bottle-shaped struts by assuming a shape of isostatic lines of compression (ILC). Adopting a plane model, Sahoo et al. [9] obtained the expression for ILC by imposing specific boundary conditions. A fifth order polynomial expression was obtained: