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# Experimental investigation on the aerodynamic behavior of square cylinders with rounded corners

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ABSTRACT

The influence of corner shaping on the aerodynamic behavior of square cylinders is studied through wind tunnel tests. Beside the sharp-edge corner condition considered as a benchmark, two different rounded-corner radii (r/b=1/15 and 2/15) are studied. Global forces and surface pressure are simultaneously measured in the Reynolds number range between $1.7\times10^4$ and $2.3\times10^5$. The measurements are extended to angles of incidence between 0° and 45°, but the analysis and the discussion presented herein is focused on the low angle of incidence range. It is found that the critical angle of incidence, corresponding to the flow reattachment on the lateral face exposed to the flow, decreases as r/b increases and that an intermittent flow condition exists. In the case of turbulent incoming flow, two different aerodynamic regimes governed by the Reynolds number have been recognized.


## 1. Introduction

A careful modeling of the corners shape of building and structural elements has become a major objective for a wind-response-oriented optimal design. The introduction of rounded or chamfered corners has often the positive effect of reducing the drag force and the fluctuation of the transversal force due to vortex shedding (e.g. Kwok et al., 1988; Tamura and Miyagi, 1999); on the other hand, it can produce a more complicated aerodynamic behavior whose physical or numerical modeling may be challenging at design stage for wind engineers. As a matter of fact, in contrast to sharp-edge bodies, the rounding or the chamfering of the corners may lead to the absence of fixed separation points, and a significant dependency on both the Reynolds number and the characteristics of the incoming flow (e.g. Delany and Sorensen, 1953; Tamura and Miyagi, 1999; Tamura et al., 1998; Larose and D'Auteuil, 2008).

The square cylinder is probably the simplest sharp-edge body and probably the most commonly investigated in aerodynamics; it is therefore the natural candidate to investigate the effect of corner shaping on the aerodynamic behavior of bluff bodies. With the twofold purpose of investigating the basic behavior of rounded corners and providing technical information useful for wind engineers, a wind-tunnel tests campaign has been carried out on square cylinders with rounded corners. Beside the sharp-corner case, rigid models of cylinders with two corner radii ($r/b=1/15$ and 2/15) have been realized and tested. The global forces and the pressure field along the mid-span cross-section have been measured in the Reynolds number range between $1.7\times10^4$ and $2.3\times10^5$. Two levels of turbulence intensity (0.2% and 5%) have been considered.

Section 2 provides a brief review of the current knowledge on the aerodynamic behavior of sharp-edge square cylinders, with particular reference to the qualitative modification of the flow field with the variation of angles of incidence.

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These concepts are then used as a guide for the interpretation of the experimental results presented in Section 3 and discussed in Section 4.

The discussion is focused on two specific phenomena: (1) the intermittence of the vortex-shedding regime at the critical angle of incidence in smooth flow and (2) the transition from subcritical to supercritical Reynolds number regime in turbulent flow, with the inversion of the steady lift coefficient slope at zero angle of incidence.

## 2. Aerodynamic behavior of sharp-corner square cylinders: the dependency on the angle of incidence

Sharp-edge square cylinders have been studied by several researchers who focused their attention on numerous aerodynamic parameters including pressure distribution, drag and lift forces, vortex shedding properties, as well as near wake velocity field (e.g. Vickery, 1966; Lee, 1975; Okajima, 1982; Igarashi, 1984; Nakamura and Ohya, 1984). The flow pattern around a square cylinder is strongly dependent on the angle of incidence $\alpha$, and at least two characteristic flow regimes are clearly identified and separated by a critical angle $\alpha_{cr}$ located about 12–15° (Igarashi, 1984). The boundary layer is completely separated from both the lateral faces for $\alpha < \alpha_{cr}$, whereas the flow reattaches on the side exposed to the wind forming a separation bubble for $\alpha > \alpha_{cr}$ (e.g. Huang et al., 2010; Huang and Lin, 2011). A further sub-classification of the two regimes could be mentioned (Igarashi, 1984), but is not relevant in the present context. The subcritical regime ($\alpha < \alpha_{cr}$) is characterized by negative slope of the lift coefficient, which sharply changes to positive as $\alpha$ becomes greater than $\alpha_{cr}$.

Besides, the transition from the subcritical to the supercritical regime produces a rapid increment of the Strouhal number that corresponds to the reduction of the wake width due to the flow reattachment (Lee, 1975). In the critical regime both the drag coefficient and the fluctuating lift coefficient have a minimum value. This scenario is somehow dependent on the Reynolds number (Yen and Yang, 2011), as well as on the characteristics of the incoming flow. In particular, the thickening of the shear layers due to a small-scale free-stream turbulence promotes the formation of the separation bubble, which tends to appear for smaller angle of incidence and to shrink towards the leading edge (Lee, 1975).

## 3. Experimental results

The experimental tests have been carried out in the closed-circuit wind tunnel at the University of Genova, whose cross section is $1640 \times 1350\ \text{mm}^2$. The models have span length $l = 500$ mm; they are fabricated through the assemblage of aluminum plates and machined to reduce geometrical imperfections below 0.1% of the cross-section size $b$. The angle of incidence of the prisms is measured through a digital protractor with resolution 0.1°. End plates are installed at the extremities of the models. A force balance realized by six resistive load cells is employed to measure global forces. The mid-span cross section of the models is instrumented by a ring of $N$ pressure taps ($N$ ranges from 20 to 44 for different models) connected through short tubes to pressure scanners mounted inside the model. Beside the sharp-edge square cross section used as a benchmark test, two rounded-corner configurations with $r/b = 1/15$ and $2/15$ ($r$ being the corner radius) are considered. Fig. 1 shows the cross section of the tested cylinders and the reference system used for the presentation of the results.

The force balance measurements are analyzed calculating the steady aerodynamic drag and lift coefficients ($C_D$ and $C_L$), the Strouhal number (St) and the fluctuating lift coefficient ($\tilde{C}_L$) defined as

$$C_D = \frac{E[D]}{0.5\rho b l U^2}, \quad C_L = \frac{E[L]}{0.5\rho b l U^2}, \quad \text{St} = \frac{n_s b}{U}, \quad \tilde{C}_L = \frac{\sqrt{E[L^2] - E[L]^2}}{0.5\rho b l U^2}, \tag{1}$$

where $D$ and $L$ are, respectively, the measured drag and lift forces (Fig. 1); $\rho$ is the air density estimated on the basis of the temperature measured inside the wind tunnel; $U$ is the free stream mean velocity measured through a static-Pitot tube installed upstream the test section; $E[\bullet]$ is the statistic average operator that is implemented as a time average adopting the hypothesis of ergodic behavior; $n_s$ is the vortex shedding peak frequency. The vortex shedding frequency is estimated by fitting the power spectral density function of $L$ through a Gaussian function in the neighborhood of the vortex shedding peak. The spectral analysis of $L$ was carried out separately for the two concurrent flow configurations when a clear intermittent behavior was observed. Similar analyses carried out on the velocity recorded in the wake were used for verification purpose.

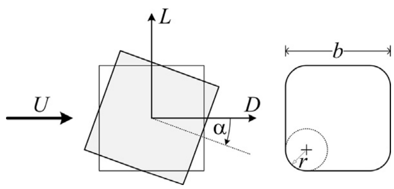


**Fig. 1.** Experimental setup.