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Experimental investigation of the aerodynamic stability of the "Endless Column", Romania

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ABSTRACT

Wind tunnel tests have been performed on several models of the "Endless Column", a 30 m tall sculpture, created by C. Brancusi in 1938. In spite of its slenderness, the Column, located in Targul Jiu, Romania, has shown a great stability against wind. In order to clarify if the symmetric, original shape has influence upon its stability, we have carried out tests on section models of "Endless Column" shape (EC models) and square shape (SQ models), of various *Sc* numbers. Across-wind response was determined in smooth flow for wind speeds in wind tunnel of 1–10 m/s ($Re = 4000$–46,000) for angles of attack 0°, 10° and 45°. Furthermore, an aerolastic full model was created and tests under smooth and turbulent flow conditions were performed for angles of attack between 0° and 45°. For low wind speeds, in the area of vortex-induced vibrations, the EC models had similar response with the SQ models; however, for higher wind speeds the EC models proved to be more stable. Based on measurements of aerodynamic drag and lift coefficients and by a verification of Glauert den Hartog criterion, it could be concluded that is a very low possibility for EC model to encounter galloping; for extremely high wind speeds though, this might not be impossible.

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1. Introduction

Wind tunnel experiments have been performed for investigating the aerodynamic stability of the "Endless Column", a slender sculpture existing in the city of Targul Jiu, Romania, which was created by the famous sculptor C. Brancusi. The sculpture has 29.7 m height and consists of a vertical addition of 15 modules and 2 half modules at each end, as it can be seen in Fig. 1. The modules have an interesting shape obtained by joining base to base two identical cones of pyramid and dubbing a 2% outer curvature on the connecting corners. Each module has dimensions, of 180 cm (height), 45 cm (small base) and 90 cm (big base), which confer a pleasant structural symmetry; the elevated row of modules gives an aspect of endlessly raising to the sky, especially if the Column is viewed from its base upward (Fig. 1). Inside, the Column has an iron shaft of square section, which supports the row of modules on its entire height. At the lower end, the shaft is extended underground, being pinned into a concrete block foundation of 4.5 m × 5 m, as shown in the details of Fig. 1.

The first concern regarding the Column's structural integrity was corrosion, as the sculpture is made from metal: modules are made of cast iron and the inner square section shaft is made from steel. Therefore a restoration project was undertaken and with this occasion the natural frequencies and damping ratios were provided by in situ measurements by Lungu et al. (2002).

Considering its unusual height ($H = 29.7$ m) and slenderness ($H/B = 44$), Column's stability against wind was questioned. Based on wind tunnel experiments for a rigid sectional model of three modules segment of the "Endless Column", scaled by a factor of 1:6, Solari et al. (2002) have revealed aerodynamic force coefficients of $C_L = -0.35$ to 0.25 and $C_D = 0.8$ to 1.5 for various angles of attack, $\alpha = -55^\circ$ to 55°; C_M registered negligible values. Details regarding the reference area considered for determining aerodynamic coefficients were not provided by Solari et al. (2002). The same wind tunnel study concluded that the Column is aerodynamically stable and galloping have not been encountered, but just predicted to occur for wind speeds of 260 m/s at the tip of the Column. The exact cause of this stability was not clarified though. Other researchers (Safta, 2003; Sofronie, 2001) considered the Column as being immune to wind effect due to its shape characteristics and symmetry, defining it as "aerolastic indifferent to wind". Gabbai (2007) has studied the "aerolastic indifference" of the "Endless Column", from the vortex-induced vibrations point of view, considering the calculation as per a circular shape, and

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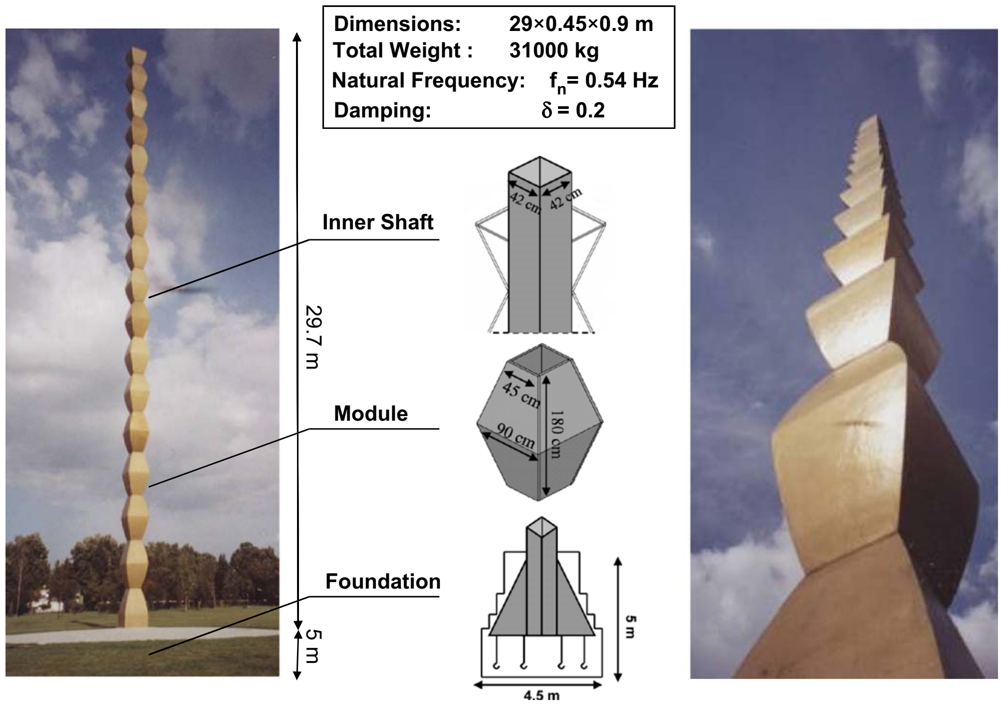

Fig. 1. The Endless Column monument from Targul Jiu, Romania.

galloping point of view, considering the calculation as per a square shape and found out that both responses are negligible due to the high damping and mass; therefore the analytical investigation concluded that the "Endless Column" would have an "excellent" aerolastic behavior even as a circular or square cylinder.

It should be mentioned that the "Endless Column" of Tg. Jiu, Romania, has not only a unique shape but also a very high weight: 31,000 kg, almost 1 ton/m, which can have a decisive influence upon its aerodynamic stability.

In order to clarify the influence of sculpture's pyramidal shape and the effect of its extraordinary weight upon aerodynamic stability of the "Endless Column", a series of detailed wind tunnel experiments on models of various *Sc* numbers and shapes were performed and obtained results are reported herewith. In general, the experiments focused on identification of vortex-induced vibrations, which occur at relatively low wind speeds, due to "lock-in" phenomenon (Sakai et al., 2002; Simiu and Scanlan, 1996) and on divergent vibrations, which occur at higher wind speeds and might degenerate into galloping (Blevins, 1990; Naudascher et al., 1981). Both aerodynamic instabilities are discussed in regard to their effect on the models of the "Endless Column".

2. Experimental set-up

Experiments were carried out in the closed circuit wind tunnel of Yokohama National University, which has the testing chamber of 1.8 m × 1.8 m section and a total length of 17.7 m. A maximum wind speed of 37 m/s can be achieved.

2.1. Aerolastic section model tests

An aerolastic section model of six modules and two halves at the ends was constructed from wood, by scaling 1:10.16 a segment of the "Endless Column" (Fig. 2(a)), in respect to the aerodynamic similarity conditions (Simiu and Scanlan, 1996). The scale factor of 10.16 was chosen so that a whole number of modules and the 2 end plates should fit exactly the 1.24 m width of wind tunnel experiment room. In order to clarify the effect of shape upon aerodynamic stability of the Column, a model of square section, with same length as the EC model, but with a width equal to the average width of the pyramidal module was used as a witness model for comparing the results (Fig. 2(b)). Dimensions of the model of 124.0 cm × 4.43 cm × 8.86 cm (height × small base × big base) were obtained, but the mass of the model become very high, $m_{model} = 12$ kg. Therefore, in order to clarify the influence of mass upon stability to wind, models of lower masses were also tested. In total, six models of various weights and two different sections were used: three models of the "Endless Column" with Scruton numbers of 29.3, 47.4 and 71.1, which were abbreviated as EC_{29}, EC_{47} and EC_{71}, respectively, and three square cylinder models with same *Sc* numbers of 29.3, 47.4 and 71.1, which were noted as SQ_{29}, SQ_{47} and SQ_{71}. *Sc* numbers used herewith had defining expression as per Scruton (1963). Structural characteristics and geometric details of all the tested models are detailed in Table 1. Characteristics listed under $EC_{sculpture}$ notation denote the full dimensions of the monument "Endless Column" existent in Tg. Jiu, Romania. As expected the high structural damping and weight of the full scale structure "Endless Column" led to a very high *Sc* number of 721 for the sculpture. The parameter, μ, defining the ratio between the models' mass and the mass of the fluid displaced by the models (Blevins, 1990) was find to be very high as well: 740.6, 1185, 1777.5 and 1831.34 for EC_{29}/SQ_{29}, EC_{47}/SQ_{47}, EC_{71}/SQ_{71} models and for the full scale structure $EC_{sculpture}$, respectively.

Both types of models were successively mounted on eight springs and were allowed to oscillate in across-wind direction, while the torsion degree of freedom was blocked by piano wires. Tests were performed in smooth flow, for angles of attack of $\alpha = 0^\circ$, 10°, 45° and for *Re* numbers in the range of 4000–46,000, corresponding to a wind speed of $U_{WT} = 0.9$–12.0 m/s, respectively, to a reduced wind speed of $U_r = 6.5$–100. During experiments, logarithmic decrement of damping of $\delta = 0.002$ has been

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