

Flow conditions for aerolastic stability of modular slender structures

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ABSTRACT: While the wind flow around conventional shapes was well studied, and its aerodynamic mechanisms were well established, for structures as buildings and bridges with geometric shapes of particular modulations, a distinctive investigation is required. In terms of wind flow-structure interaction and the aerodynamic stability, among all the studied structural shapes, one has distinguished as exceptionally stable for high wind speeds. The structure itself is a post-modernist sculpture entitled “Endless Column”, created by C. Brancusi in 1916. The sculpture, which falls under the UNESCO patronage, was the object of several wind tunnel studies, which acknowledged the stability of the Column and the lack of galloping vibrations. However, considering the limitations of the experimental facilities, a clear explanation for these phenomena was difficult to provide. The current research completes the experimental series performed on the Column, through analytical means of CFD (Computational Fluid Dynamics), and provides a better understanding of the flow-structure interaction for this particular modular shape. For wind velocity of 5.45 m/s and, angles of attack of 0° and 10° were found to have certain influence on the formation of three-dimensional vortices on the rear side of the Column; the most stable case with a regular flow pattern behind the Column was identified for 45° angle of attack, where a vertical motion along each module was detected.

KEYWORDS: Endless Column, Wind-structure interaction, Flow pattern, CFD simulation.

1 INTRODUCTION

Constructed in 1916 as a commemorative monument for the victims fallen in the First World War, The Endless Column is situated in the central part of Romania, in the city of Tg. Jiu. Its creator, the famous post-modernist sculpture C. Brancusi has envisioned a slender shape for his masterpiece, composed by a repetition of 15 pyramidal modules of dimensions 45 x 90 x 45 cm, plus two halves-modules at the extremities. The cast iron modules have inside a rectangular steel shaft, which spans the entire height of the column of 30 m (Fig. 1 a). For a structure of such dimensions, taller than most of the surrounding buildings and slenderer than a chimney, the stability to wind would be a main concern; however, the Column has intrigued the aerodynamicists of our times through its stability. Some researchers considered the interaction between wind flow and the Column's modular shape as an explanation for this stability, and they characterized the Column as “aerolastic indifferent” (Safta et al, 2003, Sofronie et al, 2001, Gabbai et al, 2007). In 2000 when the Column was dismantled for rehabilitation, Column's structural characteristics, such as natural periods, distributed mass and damping were determined through in-situ measurements (Lungu et al, 2001), and consequently wind tunnel experiments were performed, for a fixed scaled segment of 4 modules of the Column, under laminar flow conditions (Solari et al, 2002). In 2005 a complete series of wind tunnel experiments were carried out for a scaled segment of 6 modules and for a complete three-dimensional Column model (Fig. 1 b), which preserved the geometric and dynamic properties from its original prototype through aerodynamic scaling (Yamada et al, 2005, Dragomirescu et al, 2009). Tests on a conventional square shape column were also performed for comparison. Both wind tunnel experiments have shown that the Endless Column model is very stable for high wind speeds, where the square model will encounter already galloping vibrations. However, for the lower wind speeds, the resonant phenomenon of lock-in was encountered with similar magnitudes of vibrations for both models, the square and the Endless Column.



Figure 1: Endless Column, Tg. Jiu, Romania (a) Site location (Dragomirescu et al, 2009), (b) Wind Tunnel Experiment (Yamada et al, 2005)

Several countermeasures in the form of dimples, helical spires, etc., exist already for overcoming the resonant lock-in phenomenon for slender structures; for galloping wind induced vibrations however, more complicated measures or control devices, such as dampers, must be considered. Unexpectedly, the “aerolastic indifference” of the Endless Column, manifested through stability for high wind speeds, might be considered as a geometric countermeasure against galloping. Nevertheless, none of the performed wind tunnel experiments have included a three-dimensional visualization of the wind flow around the Endless Column, and a clear explanation of the flow-structure interaction could not be expressed, hence the usage of its modular shape as a countermeasure for galloping could not be attested. Therefore, the current research employs an extensive 3D Computational Fluid Dynamics (CFD) simulation for elucidating the flow formation at different levels of the Endless Column and the induced aerodynamic forces.

2 SIMULATION ALGORITHM

The flow around The Endless Column was simulated in a rectangular domain; the dimensions of the Column were considered as per the aerolastic model described in Yamada et al, 2005 and Dragomirescu et al, 2009, namely 1,467 cm height, 4.5 cm module’s big base and 2.25 cm module’s small base which corresponds to a scale of 1:20 from the prototype. The grid system had the major axis of $5H$, the minor axis and the thickness were $1.33 H$, where $H = 1.4675$ m, is the height of the Column, as schematically represented in Figure 2 a. The Cartesian referential system x , y and z axes were chosen for along stream-wise direction, transverse to the stream-wise direction and the column-span direction respectively. A total number of 1.5 million tetrahedral cells and 250,000 nodes were employed. The non-slip boundary condition was specified on the surfaces of the Column, and the in-flow boundary condition was set to $u_x = 5.45$ m/s $u_y = u_z = 0$.

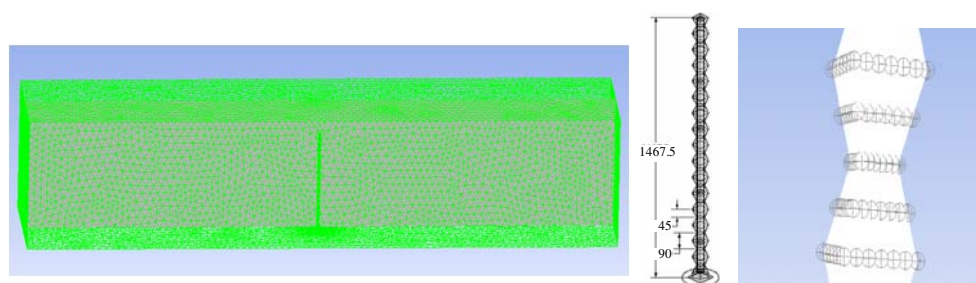


Figure 2: CFD Simulation details (a) Mesh Characteristics, dimensions in mm, (b) Monitored points

Pressure was monitored along an entire pyramidal module by sampling data from 5 rings (Fig. 2 b). This arrangement will help identify the influence of the geometric shape upon the wind induced pressure and the disturbance of the wind flow created by one module. The previous experimental investigations (Yamada et al, 2005) have shown a better response of the column for 45° and a slight vibration for 0° and 10°, starting at a wind speed of 5.45 m/s. Hence, three wind directions were investigated herewith, for angle of attack of $\alpha = 0^\circ, 10^\circ$ and 45° .

The large eddy simulation (LES) with the Smagorinsky subgrid-scale model was employed for the CFD simulation. The three dimensional incompressible Navier-Stokes equation and the equation of continuity in non-dimensional form are:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + 2 \frac{\partial}{\partial x_i} \left(\frac{1}{Re} + \nu_{sgs} \right) D_{ij} \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

where u_i is the velocity component of grid-scale, and P is the sum of the grid-scale pressure and the residual stress. D_{ij} in Eq. (1) is the strain-rate tensor on the grid-scale velocity components:

$$D_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3)$$

The subgrid-scale eddy-viscosity, ν_{sgs} , in Eq. (1) is expressed as:

$$\nu_{sgs} = (C_s \Delta)^2 \sqrt{2 D_{ij} D_{ij}} \quad (4)$$

where Δ is the filter width and was given as the cubic-root of grid volume and the C_s , Smagorinsky constant, was set to 0.1 in this study. The inviscid flux vector was determined by a standard upwind, flux-difference splitting through the low-diffusion Roe approach. For estimation of the secondary diffusion terms and velocity derivatives, the least square cell based spatial discretization was used and Third-Order MUSCL equation was considered for the flow density-based solver. The time step was chosen as $t = 0.003$ s; pressures along the entire surface of the model was integrated, and lift and drag aerodynamic forces were determined. More convenient, drag and lift coefficients C_D, C_L , were extracted from the definition formulas below (Simiu and Scanlan, 1996):

$$F_D = \frac{1}{2} \rho U^2 B C_D \quad \text{and} \quad F_L = \frac{1}{2} \rho U^2 B C_L \quad (5)$$

Where F_D, F_L are the drag and lift aerodynamic forces, ρ is density of air, U is wind speed upstream from the model deck and B is the nominal diameter of the Column's model.

3 TWO-DIMENSIONAL FLOW-STRUCTURE INTERACTION

In order to determine the effect of the pyramidal module upon the aerodynamic stability of the Column, localized velocity field distribution were recorded at different heights along the module for $0^\circ, 10^\circ$ and 45° (Figs. 4 a to f).

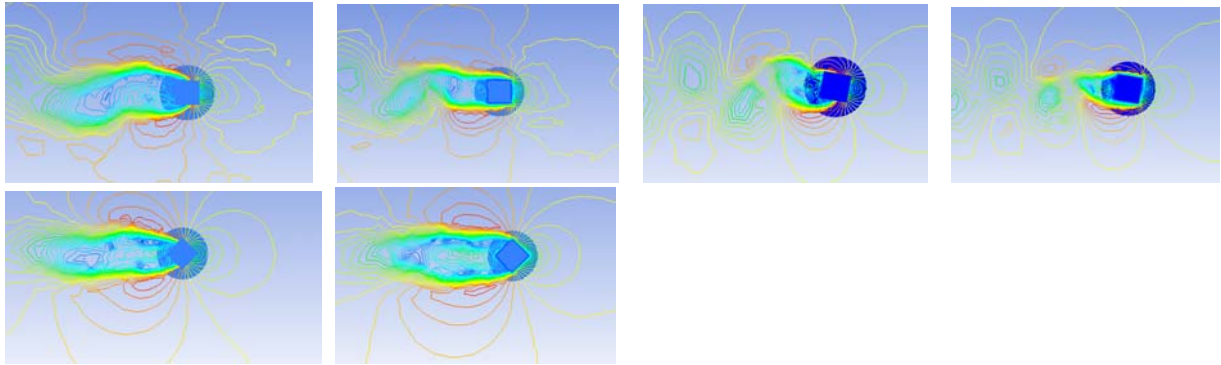


Figure 3. Two-dimensional instantaneous velocity isolines for (a) Small base, $\alpha = 0^\circ$, (b) Large base, $\alpha = 0^\circ$, (c) Small base, $\alpha = 10^\circ$, (d) Large base, $\alpha = 10^\circ$, (e) Small base, $\alpha = 45^\circ$ and (f) Large base, $\alpha = 45^\circ$.

For 0° , around the small base of the module (Fig.3 a), alternation of shear layers is noticed from both edges of the Column which, however, will not interfere with each other downstream the flow. For the large base of the same module (Fig.3 b), the streamlines of the velocity field have a similar evolution; however downstream the Column these shear layers tend to connect generating turbulent flows. Shedding of several vortices downstream the Column was noticed for 10° , generated by the shear layers which detach from the edges of the Column, around both small and large base of the module (Figs. 3 c and d) while for 45° a slight turbulence can be noticed within the shear layers which envelop one major vortex, which varies in intensity and shape with the position along the Column, e.g. smaller vortex behind the small base of the module (Fig. 3 e) and bigger vortex formation behind the larger base of the module (Fig. 3 f).

Pressure monitored around the module at the small and large base location showed that after a dominant positive pressure at the incoming flow, the Column was dominated by suction especially on its rear side. For $\alpha = 0^\circ$, pressure varied between 19 Pa, on the front side of the column, where the incoming flow directly hits the structure, and a suction of up to - 17 Pa downstream the Column was noticed, for the crest of the module where surface exposed to wind is higher (Fig. 4 a). On the small base of the module, an earlier flow detachment is noticed. Also behind the Column after the shear layers detach from the edges, a constant region of negative pressure is noticed, indicating that no vortex formation appeared in the vicinity of the Column surface. For 10° angle of attack, after the sudden drop in pressure from 10 Pa to -20 Pa, indicating the shear layer detachment from both edges of the Column, a variation in the suction monitored on the rear side was noticed, of the as it can be seen in Figure 4 b; this might be due to the alternate vortex formations, which might be a possible cause of unbalanced lift force and appearance of incipient vibrations described during the experiments (Dragomirescu et al, 2009). The maximum induce pressure, was in the same range of 19 Pa, however the suction created on the rear side of the Column and through the vortex formation, was - 27 Pa, much lower than for 0° and 45° . A gradual transition from the strong pressure induced by the incoming flow, towards the negative pressure registered on the rear of the Column could be noticed for 45° , caused by the triangular exposed shape (Fig. 4 d). A constant suction on the rear side of the Column indicated that no vortex or turbulent flow formations will reattach to the module in this area. No significant difference was noticed between the flow acting on the small base and on the large base of the module.

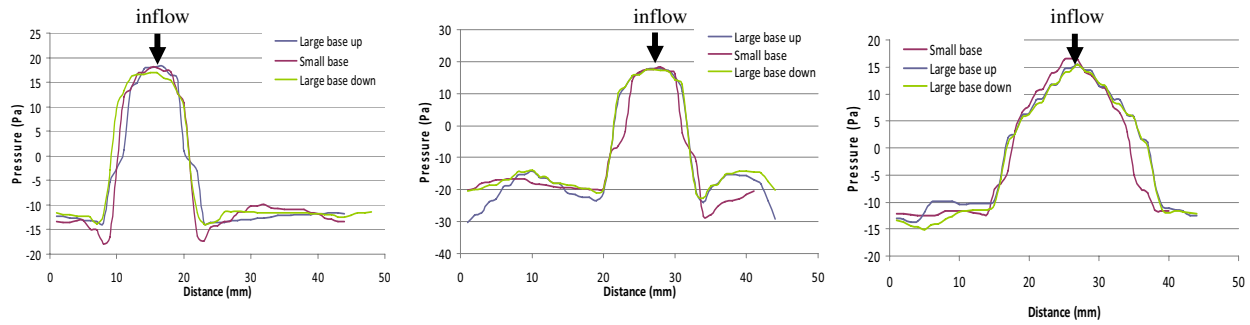


Figure 4. Average pressure on the surface of the Column, for different heights along the module for (a) $\alpha = 0^\circ$, (b) $\alpha = 10^\circ$, and (c) $\alpha = 45^\circ$.

The coefficients C_D and C_L , represented by hollow triangles in Figures 5 a and b, were found to be in good agreement with the experiments performed by Solari et al, 2000, represented by hollow dots, and with those performed by Dragomirescu et al, 2009, represented by full dots in the same figure. The highest lift force is registered for 10° , as also indicated by the previous experiments, while the drag force would be dominant for 45° ; when the wind speed is perpendicular to the front face of the Column, ($\alpha = 0^\circ$) both aerodynamic forces were within moderate limits. In spite of the averaged values of the aerodynamic forces, the experiments (Yamada et al, 2005, Dragomirescu et al, 2009) have shown that if the Column is allowed to vibrate in smooth flow, the highest across-wind vibrations for 5.45 m/s are registered for $\alpha = 10^\circ$ followed by $\alpha = 45^\circ$. It should be mentioned that the same experiments have revealed that a square column tested under the same conditions would have four times higher vibration amplitude.

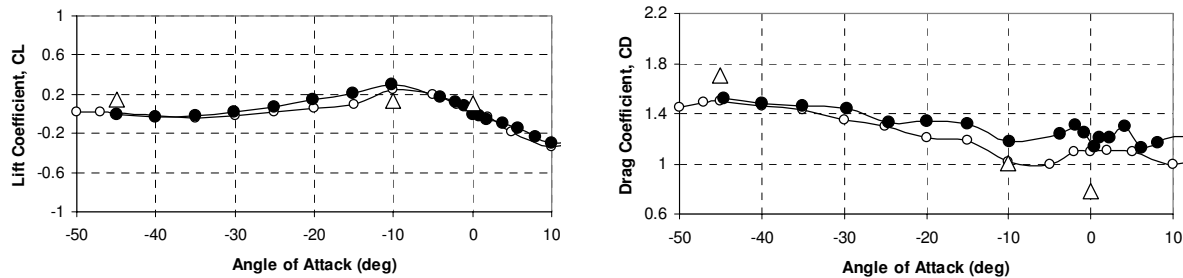


Figure 5. Variation of aerodynamic coefficients with the angle of attack: (a) Lift Coefficient, C_L , (b) Drag Coefficient, C_D

4 THREE-DIMENSIONAL FLOW-STRUCTURE INTERACTION

The particular shape of the Endless Column was considered to provide certain stability against galloping vibrations at high wind speeds and this was certified by several wind tunnel tests (Solari et al, 2000, Yamada et al, 2005). Most of the aerodynamic theories consider the cross section as a reference nominal area; however a two-dimensional cross section in this case would be reduced to a basic square shape, for which aerodynamic characteristics are much below the structural capacities of the Endless Column. Hence a three-dimensional interpretation of the wind flow structure interaction is required for better understanding the aerodynamic stability of this particular structure.

The flow visualization was conducted by sampling instantaneous velocity streamlines, simulation very similar to smoke visualisation practiced in the experiments. The velocity stream-

lines indicated a vertical motion along the Column, initiated by the free-end effect, in spite of the horizontal direction of the incoming wind flow, and sometimes rotational flow formations appeared between the modules behind the Column. At $\alpha = 0^\circ$, when the entire front side of the modules is facing the incoming wind flow of initial velocity 5.45 m/s, the impact with the Column will determine a change in direction of the velocity streamlines, otherwise horizontal, and will produce vertical downwards flow movements, periodically re-attaching to the Column in the module's crest region (Fig. 6 a). For the case of 10° , the modules will accelerate slightly the lateral streamlines of velocity up to 6.0 m/s. Also, due to the trough between the modules and the inclination of the wind direction, the wind velocity was redirected downwards along the Column, which changed their linear pattern into a more irregular one (Fig. 6 b). When the corner of the Column is directly exposed to the wind ($\alpha = 45^\circ$), acting as a wind breaker (Fig. 6 c), the regular velocity streamlines were partially maintained even after encountering the structure, a slight disturbance being observed only downstream the Column, at a distance of 0.2 m.

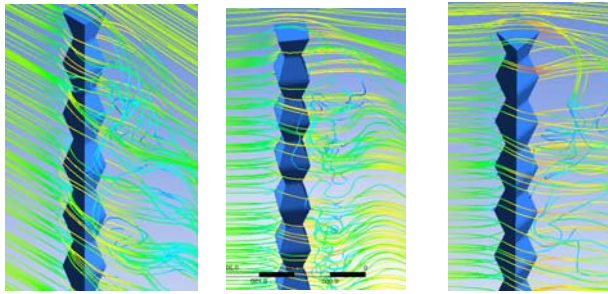


Figure 6. Three-dimensional flow pattern streamlines for (a) $\alpha = 0^\circ$, (b) $\alpha = 10^\circ$ and (c) $\alpha = 45^\circ$,

Whenever the vectors of the velocity curl are extracted, indicating the rotation axis and the sense given by the right-hand rule for each rotational formation appearing around the structure, was noticed that, for all the investigated cases, $\alpha = 0^\circ$, 10° and 45° , often on the edges of the Column, where wind detaches after the impact, the vectors will have opposite senses, hence cancelling out the motion along each of the modules, as represented in Figures 7 a to c. The rotational activity on the vertical direction is not entirely absent, but appears on the rear side of the Column, having very small intensity, of 1.36 s^{-1} and which is more concentrated in the troughs for the case of 0° . For 10° , the velocity curl reaches higher values of $1.04 \times 10^3 \text{ s}^{-1}$, and is unevenly distributed along the rear side of the Column and along the edges; dominant direction of the flow will remain the along-wind direction. For 45° , lower intensity of the rotational activity was recorded, and opposite vectors appear clearly on the right side and left side along the edges, where detachment is encountered and more organized patterns and dominant along-wind flow vectors were noticed surrounding the Column.

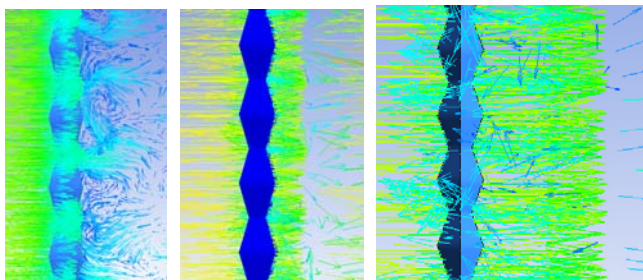


Figure 7: Velocity curl vectors for 5.45 m/s for the Endless Column at (a) $\alpha = 0^\circ$, (b) $\alpha = 10^\circ$ and (c) $\alpha = 45^\circ$,

In Figures 8 three-dimensional flow formation around the entire Column are depicted. For $\alpha = 0^\circ$, well defined three-dimensional turbulent formations are shed from both edges of the structure, and form a series of vertical flow patterns, which travel until 0.4 m downstream the Column. The measurements showed suction on the edges of the Column, of about -20 Pa, in the trough region, while on the crest of the modules, positive pressure of up to 19 Pa is recorded. The three-dimensional turbulent formation is also present downstream the Column at $\alpha = 45^\circ$ (Fig. 8 c) however it seems to be only one single vertical vortex behind the Column instead of several shed vortices as for 10° , and the distance spanned by it is much lower, of 0.52 m. the most critical case of $\alpha = 10^\circ$ showed a complex flow formation behind the Column, with several vertical vortices which travel in their consistent shape on higher distances of up to 0.8 m downstream the Column (Fig. 8 b). The color code indicates suctions of up to -40 Pa were achieved at the detachment surfaces.

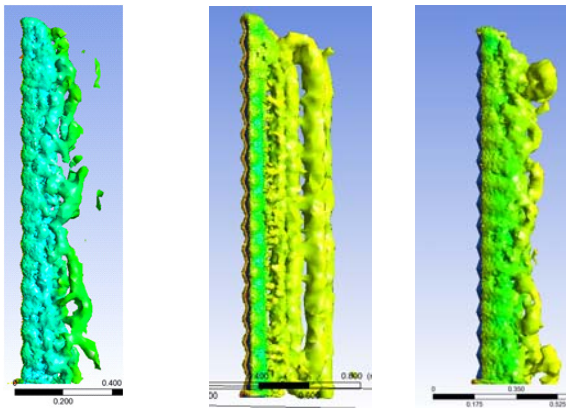


Figure 8: Three-dimensional flow formation around the Endless Column for (a) $\alpha = 0^\circ$, (b) $\alpha = 10^\circ$ and (c) $\alpha = 45^\circ$.

A section through the three-dimensional flow formations revealed the vertical pressure distribution for angles of attack 0° , 10° and 45° (Figs. 9). Clear shedding of turbulent flow can be noticed initiated from the large base of each module towards downstream and local pressures of -10 Pa to -20 Pa alternate for the regions between two consecutive crests for 0° (Fig. 9 a). Several rows of vortices were confirmed along the height of the Column, of different intensities and induced pressures.

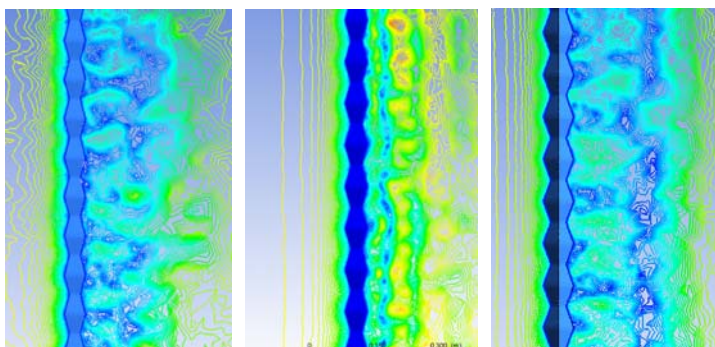


Figure 9: Pressure distribution around the Endless Column for (a) $\alpha = 0^\circ$, (b) $\alpha = 10^\circ$ and (c) $\alpha = 45^\circ$.

The pressure measured on the exterior three-dimensional vortices shed downstream the Column was of 27 Pa; the interior of the vortices however, will exhibit a strong suction of -25 Pa, in the immediate vicinity of the Column and -12 Pa, when departed from it, for the $\alpha = 10^\circ$ (Fig. 9 b). The vertical pressure distribution for 45° clearly showed the main vertical vortex formed on the rear side of the Column had a local pressure of -10 Pa and only localized spots of -20 Pa, which dissolved quickly in the flow (Fig. 9. c).

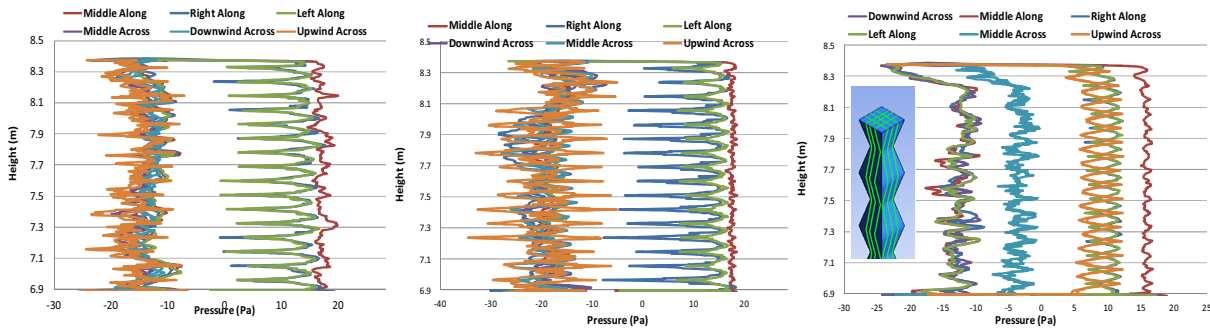


Figure 10. Instantaneous pressure on the height of the Endless Column, for (a) $\alpha = 0^\circ$, (b) $\alpha = 10^\circ$, and (c) $\alpha = 45^\circ$.

Figures 10 a, b and c show the pressure distribution at the surface of the Column for the incoming wind direction considered as the middle position and at 0.1 m left and right from the middle position. Also on the across-wind direction the middle line was monitored and the two lines at 0.1 m towards the incoming flow (upstream) and towards the downstream of the Column, as it can be seen in the detail of Figure 10 c.

For the $\alpha = 0^\circ$, mainly suction (-15 Pa to -20 Pa) was registered on the middle line in the across-wind direction indicating the shear layer detachments showed also in Figures 3 a and b, while the middle line in the along-wind direction, as expected high pressure of almost 20 Pa was registered on one side and suctions of -10 Pa were registered on the other side of the structure. Little fluctuation was noticed for both middle lines. For the other two lines in the along-wind direction (left and right) however, high fluctuations were noticed at the incoming flow along the modules, reaching 19 Pa at the large bases and almost 0 Pa at the small base of the modules, while limited fluctuation is shown on the rear side of the Column the right along- and left along-wind lines. For the across-wind direction, the upwind line showed the highest pressure fluctuations of -10 Pa to -20 Pa, which indicates that turbulent flow around the Column is already formed before the shear layers detach from it. The pressure on the downwind across-wind line had similar values and variations as for the middle across-wind line.

Consistent positive pressures of around 19 Pa were registered for the incoming wind surface of the Column on the middle line for $\alpha = 10^\circ$, as it can be seen in Figure 10 b, while the left and right lines for the same along-wind direction had similar pressure patterns as for the $\alpha = 0^\circ$. On the across-wind direction the upwind line had extreme variations along the modules spanning from -10 Pa to -30 Pa which is consistent with the pressure distribution and the vertical vortices formations reported in Figures 8 b and 9 b. The downwind line will also register fluctuations along the module's height however the pressures are not very high, being in the region immediate after detachment.

The case of $\alpha = 45^\circ$, was the most stable in terms of pressure distribution on the across- and along-wind directions as follows (Fig. 10 c): the middle line for the along-wind direction registered smaller pressures of around 16 Pa due to the minimum nominal area exposed to wind and had a very limited fluctuation along the modules. The across-wind middle line registered the smaller suction of -5 Pa which confirms the absence of any turbulent or vortex formation down-

stream, in the immediate vicinity of the Column. The left and right lines on the along-wind direction will have similar patterns as for the 0° and 10° , however the values of the recorded pressure are much lower of around 5 Pa to 10 Pa on the incoming wind face and -10 Pa to -15 Pa for the rear side of the Column. The main difference for the $\alpha = 45^\circ$ is that the upwind across-wind line will yield only positive pressures which indicates a flow attached to the outside edges of the Column, which does not appear in any of the above figures. The downwind across line will register only negative pressures as for the other two cases of 0° and 10° .

5 CONCLUSIONS

The three-dimensional flow visualization was conducted through CFD simulations for the Endless Column, in order to clarify the effect of the modular shape upon the stability to galloping vibrations and to determine the detailed flow-structure interaction. The dimensions of the model, the wind speed and angle of attack were chosen so that it followed the wind tunnel experiments reported by Dragomirescu et al, 2009.

The effect of the geometric shape of one pyramidal module was investigated and was determined that the crest regions of the module would have less influence upon the aerodynamic activity, while the crest regions would establish a continuous accumulation of suction on the rear side of the Column, which indicates the existence of a vortex formation. The velocity streamlines, pressure contours and vertical flow formations re-attested the fact that the Column facing the wind at an attack angle of 10° would be the most inconvenient arrangement; these wind directions would produce an earlier detachment of the incoming wind flow, after the impact with the structure, and would determine the creation of several three-dimensional vertical vortices of high suction behind the Column, in its immediate vicinity and up to 0.8 m downstream. The negative pressure will determine an unbalanced lift force which might explain the incipient vibrations reported by the wind tunnel experiments (Yamada et al, 2005, Dragomirescu et al, 2009).

The angle of attack of 45° , when the corners of the aligned pyramidal modules are facing the incoming flow acting as a wind breaker, would ensure a smoother flow detachment, hence the vertical vortices behind the Column will register a weaker suction on the rear side which would confer a higher aerodynamic stability for the entire Column. Also was noticed that the vertical fluid motion was cancelled for trough regions along the modules, indicated by the opposite sense of the curl vectors. However, for completely understanding the lack of galloping for the “Endless Column” and the effect of its particular shape composed of a repetition of pyramidal modules, numerical CFD simulations should be conducted for a broader range of wind speeds, of up to 15 m/s, where the experiments were stopped due to limitations of the instrumentation.

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