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MIRCEA MIHAILESCU

CALIN MIRCEA

RESPONSE OF THE "ENDLESS COLUMN" UNDER WIND ACTION

H. Yamada
Yokohama National University, Tokiwadai 79 – 7, Yokohama, 240 – 8501, Japan
yamada@cvg.ynu.ac.jp

ABSTRACT
Endless Column is one of the most beautiful and intriguing sculptures of modern art movement. Constructed in 1938 by an engineers team leaded by Georgescu and under direct supervision and design of its author, C. Brancusi, the column stays in Tg. Jiu, Romania, as a commemorative monument for the victims of the First World War.
Its amazing stability against wind challenged many researchers to conduct a detailed study and to express technical opinions which could explain the exact cause of Endless Column's "aerolastic **indifference**"[1]. Complete tests were carried out in October 2004, in the Wind Tunnel Laboratory of Yokohama National University, including sectional two dimensional and aerolastic semi rigid tests in smooth and turbulent flow for various angles of attack and wind speeds.

Keywords: Endless column, wind tunnel experiment, aerodynamic characteristics.

1. INTRODUCTION

After 1940, C. Brancusi was recognized as one of the pioneers of the modern sculpture. Among his world famous works is the sculpture entitled "Endless Column". The Column is located in Tg. Jiu, Romania, on an opened platform arranged as a public park, without trees and other tall vegetations, which makes the area susceptible to a ZONE II roughness category, without significant turbulent air currents. The medium annual velocity was registered as 3.6 m/s in NW direction and 2.1 m/s in SE direction, while the maximum annual wind velocity reaches 34 m/s on SW direction [2].
It's height, original shape and slenderness tries to defy and disobey the simple rules of nature and physics and in the same time is raising intriguing discussions among researchers regarding its stability and fatigue.

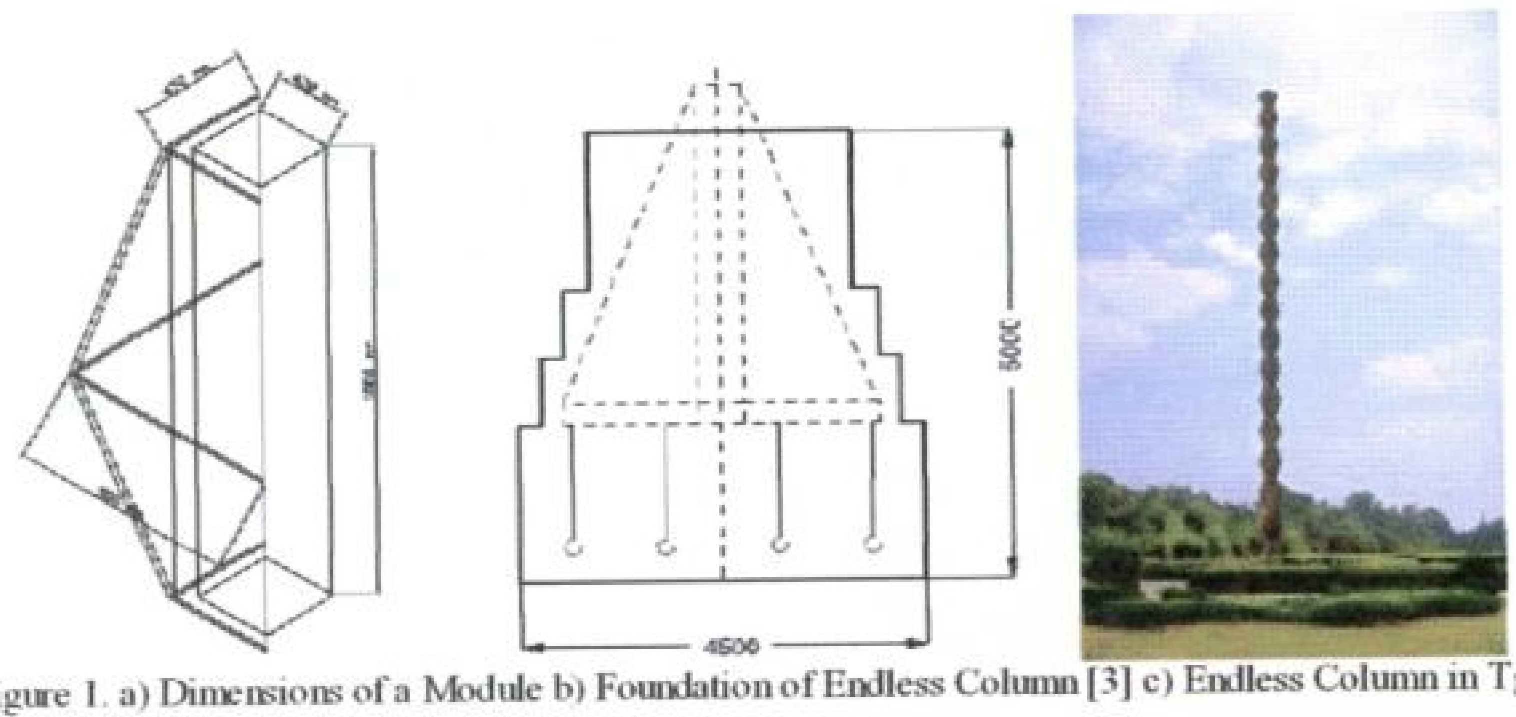


Figure 1. a) Dimensions of a Module b) Foundation of Endless Column [3] c) Endless Column in Tg. Jiu[4]

The column is made by 3 main components: foundation, consisting in two concrete blocks of dimensions 4.50 x 4.50 x 2.00 m and 3.50 x 3.50 x 5.00 m respectively, and an anchorage of metallic profiles shaped as a pyramid and inserted in the concrete block where was fixed with 3 m long bolts. A second component is the internal spine made of carbon steel with a square section of 420 x 420 mm and 28.9 m long; on this shaft are mounted a succession of 15 double pyramidal modules, sectioned at the top part (Fig.1.a) plus two halves at the top and bottom ends, which would be the third component of the column. Dimensions of each module are 0.18 m height, 0.45 m small base and 0.9 m large base [5,8]. The weight of the inner spine is 14,947 kg while the weight of the outer modules is 16,148 kg, which makes the total weight of the column of approximate 30 tones. The height of the column rises till 29.35 m and considering its total weight, than its distributed mass becomes around 1 tonne per metre, which means that the Endless Column of Tg Jiu, is not only very slender but also considerably heavy. Therefore remains to be decided which is the influence of the module's shape and which is the influence of its weight on the aerodynamic stability, which will become the aim of this research.

Endless Column underwent a restoration process between 1996 and 2000 under financial support of World Bank and expertise commission of UNESCO and, for the first time, in situ measurements were performed and natural periods of the column were revealed for the first mode as $T_k = 1.949$ sec for x and y axes for the column covered with modules and $T_k = 1.205$ sec for column after modules were removed [6]. Damping ratio ξ_k was measured as around 0.0082 for the column without modules and $\xi_k = 0.02$ for the column with all modules remounted. Also wind tunnel test were carried out in the Boundary Layer Wind Tunnel in Prato, Florence on sectional model for different wind speeds and numerous angles of attack. For Stroulial numbers of $St = 0.13 - 0.17$, aerodynamic force and moment coefficients were experimentally determined: C_D was always smaller than 1.6, C_L was not higher than 0.35 while C_M was almost negligible [7].

2. WIND TUNNEL TESTS

Wind tunnel tests were carried out in Yokohama National University Laboratory, Japan, in a closed circuit wind tunnel which was built in 1993. The test section is 1.8 m wide x 1.8 m height and its total length is 17 m, while the distance from the fan to the measurement point of 2D section models is around 15 m. The maximum wind speed is 34 m/s (Fig.2.a).

In a first stage wind tunnel tests were performed on a segment of the column consisting in 6 modules plus two halves at the ends, modules whose dimensions are reduced from the dimensions of the Endless Column by a scale of 1:10.16. This scale factor was chose so that, an exact number of modules could fit the length of 1.24 m, which is the width of the wind tunnel section wherein measurements can be recorded, without the influence of boundary layer. The model was mounted on a system of four springs at each end of the model. Piano wires were used to keep the model straight, so that it should face the wind direction and prevent torsions, but allow vibration on a vertical axis only. Experiments were conducted in smooth flow for different angles of attack: 0, 5 and 10 degrees. The approaching wind speed was varied from 0 to 15 m/s in wind tunnel. Given the special repetitive form of the column, experiments were also conducted on a square cylinder, in order to have a reference shape with which a comparison can be made. In the figures bellow and later in this article, Endless Column will be referred to as EC while Square Cylinder will be referred to as SC, for readers' convenience.

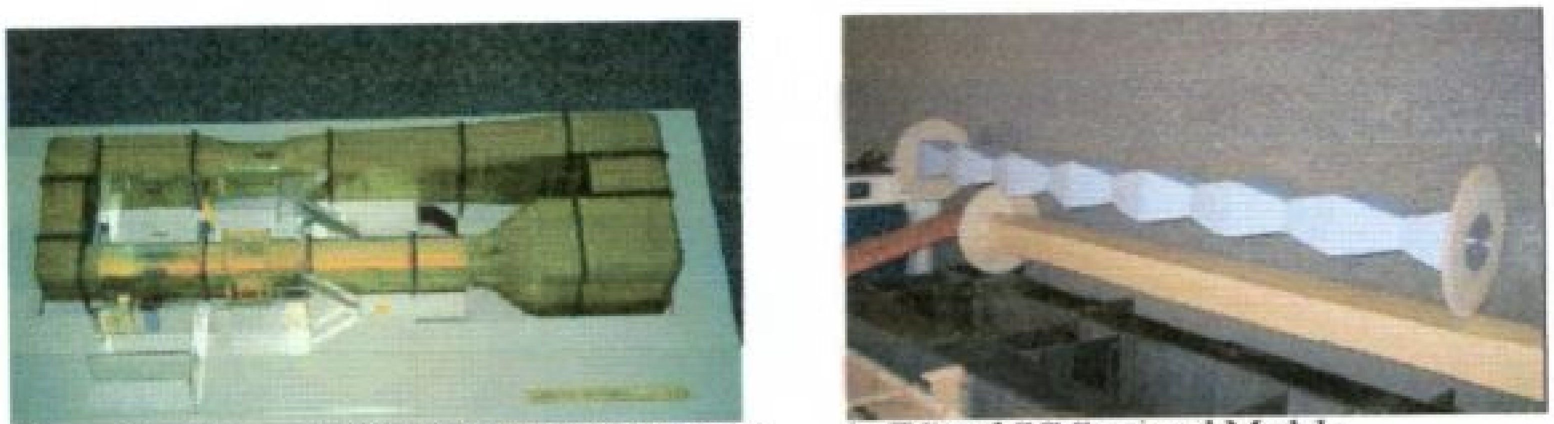


Figure 2. a) Image of YNU Closed Wind Tunnel b) EC and SC Sectional Models

As it will be explained in detail in the following section, the column presented a good aerodynamic stability against wind, compared with the square cylinder. In order to clarify the influence of the shape and the effect of the Scruton number (implicitly, of the weight of the column) upon aerodynamic stability, a comparing study was carried out for different Sc numbers: 279, 447, 670 and 837, corresponding to different weights of the model: 5 kg, 8 kg, 12 kg and 15 kg.

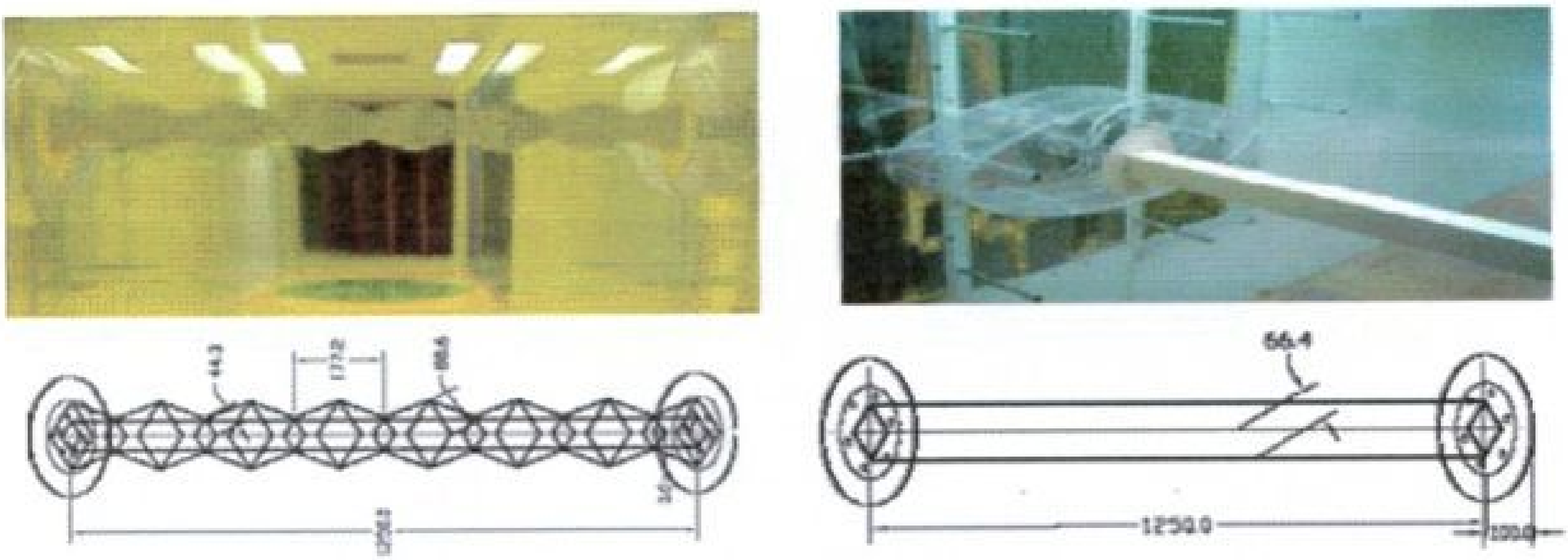
Table 1. Structural Properties of Experimental Models

	Parameter	Model 5 kg	Model 8 kg	Model 12 kg	Model 15 kg	Endless Column
Endless Column	Mass Ratio	13950	22350	33500	41900	33500
	Natural Frequency	2.35 Hz	1.93 Hz	1.94 Hz	1.74 Hz	0.513 Hz
	Log. Decrement (δ)	0.02	0.02	0.02	0.02	0.1
	Scruton No.	279	447	670	838	3500
Square Cylinder	Mass Ratio	14500	23200	34800	4350	
	Natural Frequency	2.35 Hz	1.93 Hz	1.93 Hz	1.74 Hz	
	Log. Decrement	0.02	0.02	0.02	0.02	
	Scruton No.	290	464	696	870	

In a second stage experiments were carried out on an aerolastic semi rigid model of 1.67 m height, considering a scale of 1:20. The experiment was carried out for different angles of attack (0, 5, 10, 15, 30 and 45 degrees) and for smooth and turbulent flow. Turbulent flow was created by simulating terrain irregularity through roughness elements arranged on the floor of the wind tunnel and by installing of 3 spires of 1.8 m height at around 15 m upstream of observation point. Considering the fact that the structure is situated in the Municipal Park of Tg. Jiu, the roughness terrain category II, which corresponds to Open Surface Terrain. In order to avoid the influence of the boundary layer induced by the ceiling of the wind tunnel, amplitude of vibration was not taken exactly at the top point of the structure; therefore determination of first mode shape and its equation were also carried out. The final displacement and amplitude of vibration were corrected in regard with the mode shape equation.

3. SECTIONAL 2D TESTS

As mentioned above, tests were carried out on two models, a reduced model of a segment of Endless Column formed by 6 modules plus two halves at the ends, fixed on two round end plates. The other is a square cylinder used as reference model for the Endless Column; dimensions of square cylinder were chosen as an average of EC dimensions. Vibrations on structure's vertical axis only were allowed, torsional degrees of freedom were fixed by the aid of piano wires. Structural damping ratio used in experiments, $\delta = 0.02$ was quite low in comparison with real structure (Table 1). There were 3 cases performed for each model: endless column and square cylinder, for 3 different Scruton numbers: 279, 447, 670 for EC and 290, 464 and 696 for SC, each of the Sc numbers corresponding to different masses: 5kg, 8kg respectively 12 kg, as already mentioned in Table 1. Only for certain wind speeds, experiments were conducted for Sc = 837 for EC and Sc = 870 for SC, both equivalent with a 15 kg model. Mechanical properties for all the models are summarized in Table 1. Verification of models stability and structure's response were done for two main types of wind excited dynamic instabilities: formation of Karman vortices induced vibrations in the wake of the model and appearance of divergent vibration at high wind speeds.



Figgure 3. a) EC Model Mounted on Springs b) SC Model Mounted on Springs

One of the first obvious observations is the fact that, the same model has a different response if its Sc number and angle of attack are different; for 0 deg, the model of $Sc_{EC} = 279$ has an amplitude of vibration much higher than the same model but of $Sc_{EC} = 447$ respectively $Sc_{EC} = 670$. For square cylinder, for 0 deg angle of attack, the peaks of amplitude of vibrations for vortex induced phenomenon appears to be more pregnant and appear for all the Sc numbers: $Sc_{SC} = 290$, 464 and 696, compared with EC model where vortex induced oscillations appear for all the cases, but the magnitude vibration amplitude is much lower. Also for square cylinder the vortex shedding will develop a little faster: for a reduced wind speed of $U_r = 8$, already vortex shedding is developed, for $U_r = 8.5$ a tendency of stabilizing the vortex is noticed, but at around $U_r = 9$, amplitude of vibration is increasing. Finally the phenomenon will stabilize from Ur = 9.8 – 10 (Fig.5). The magnitude of response is higher for smaller Sc number models, gradually decreasing for models with higher Sc. The RMS response is in accord with maximum amplitude response, only the magnitude differing, which is normal. Meanwhile, for the EC Model, at 0 deg, at about $U_r = 8.2$, vortex shedding starts to be developed, at $U_r = 8.7$ a maximum of vibration amplitude is registered and from $U_r = 9$, 9.2 and 9.8 the $Sc_{EC} = 670$ model, 447 model respectively 279 model will stabilize (Fig.4 and Fig.5).

If we make reference to the existent research of experiments performed on square cylinders [Fig.5.b], we can notice that vortex induced oscillations will appear at reduced wind speeds of around $U_r = 8$ for all the Sc numbers, fact which coincides with the results obtained from the experiments performed in the Wind Tunnel from Yokohama National University. Therefore it can be confirmed upon the correctness and accuracy of the experiments. In the same time, if we pay attention to the same results obtained for Endless Column Model, we can notice that vortex induced oscillations will appear (for all Sc numbers) almost at the same reduced wind speed ($U_r = 8.2$) as the SC. For both models, SC and EC, the phenomenon tends to stabilize earlier for high Sc numbers and later for smaller Sc numbers. Still it should be mentioned that, presently research exist for square cylinder with Sc = 0 – 90 , while the research described in this paper deals with much higher Sc numbers for both SC and EC: Sc = 290 – 870.

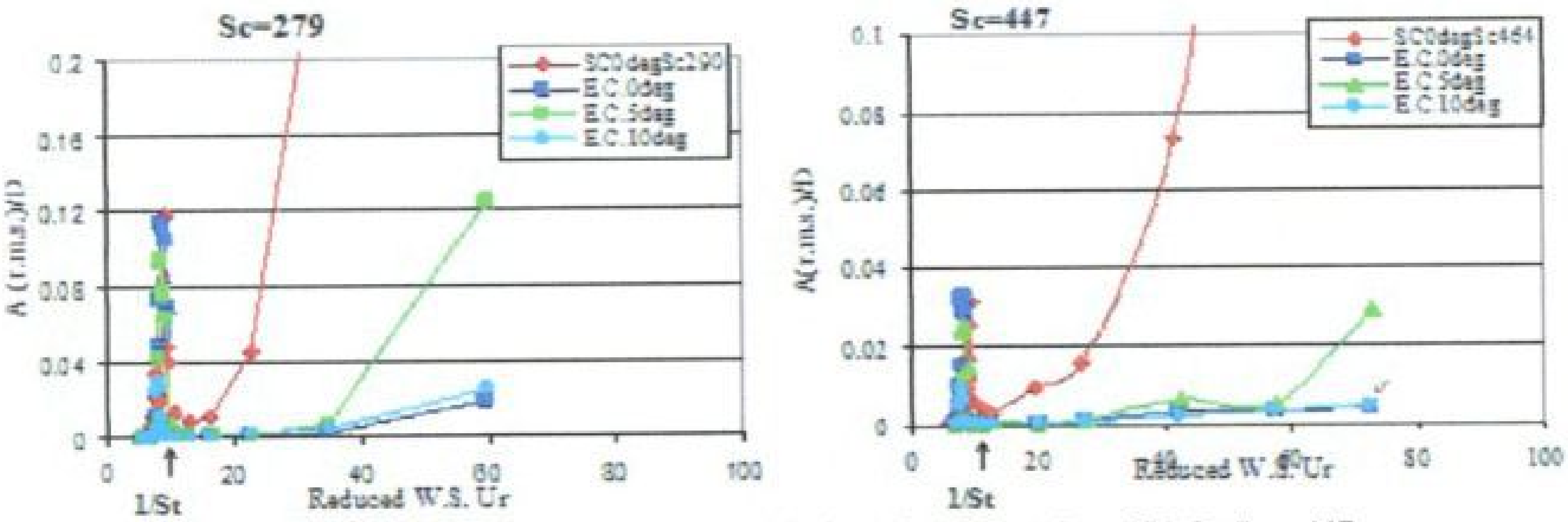


Figure 4. Amplitudes of Vibrations for EC and SC Models for 0 degrees: a) Sc = 279, b) Sc = 447

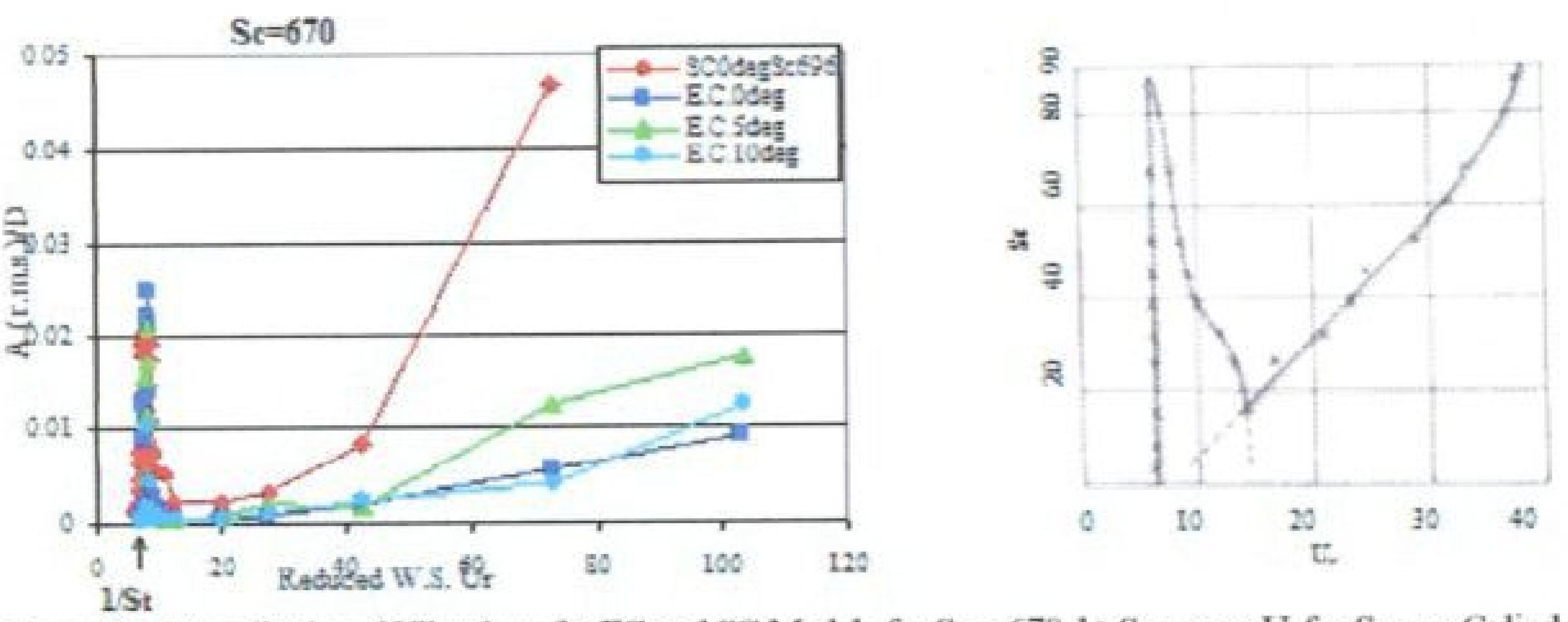


Figure 5. a) Amplitudes of Vibrations for EC and SC Models for Sc = 670, b) Sc versus U_r for Square Cylinder [9]

The amplitude of vortex induced vibration is almost the same for EC and Square Cylinder Models. Divergent vibrations appear clearly for Square Cylinder at around reduced wind speeds of around Ur = 26 for Sc = 670 and Ur = 18 for Sc = 447.

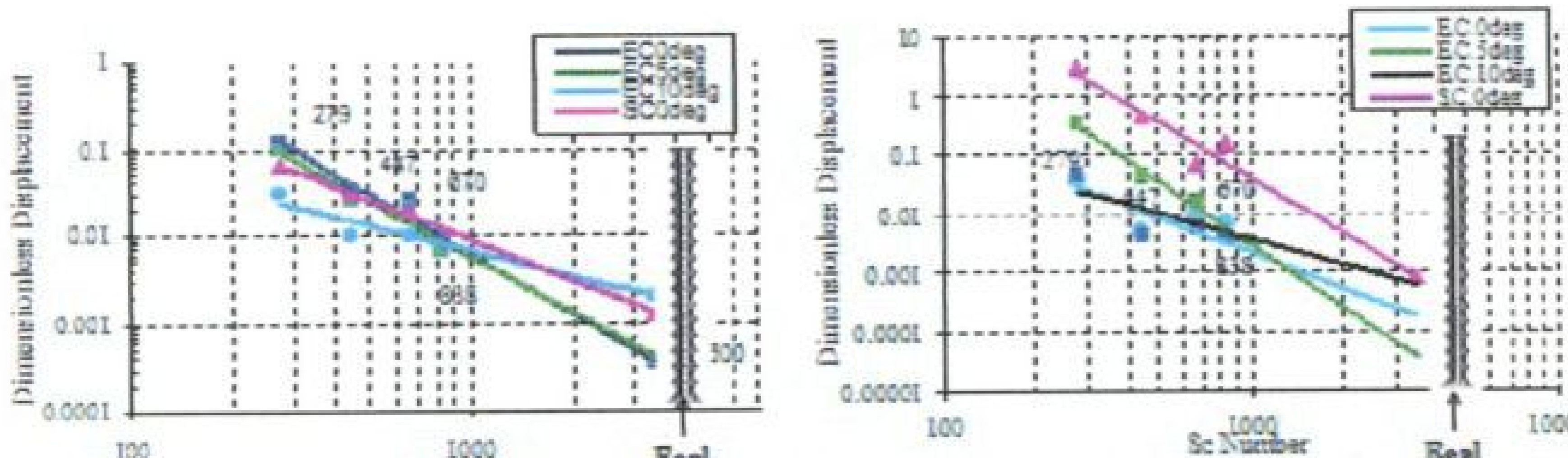


Figure 6. Evolution of dimensionless displacement A/D versus Sc Number for reduced WS of a) $U_r = 8.5$ b) $U_r = 80$

When Sc number of 3500 was determined for the Sculpture Endless Column, the average of dimensions (450mm and 900 mm) was considered. For sectional model of Endless Column, the same principle was applied and Sc numbers were obtained as shown in Table 1 and Fig 6. Following the experiments, the dimensionless amplitude for the peak of vortex induced vibration was plotted versus Sc numbers of 279, 447, 670 and 838 corresponding to different weights of the model: 5, 8, 12 respectively 15 kg. Dimensionless amplitude was considered as the

ratio between the registered vibration amplitude and the sectional dimension of the model (0.664 m for SC and 0.6645 m for EC). Therefore the response of the real structure can be predicted as being insignificantly small, as shown in Fig.6. For EC at 0 and 5 deg the amplitude of vortex induced vibration decreases drastically with the increase of Sc number. For 10 degrees, the amplitude will not have such a sudden decrease and will approach more to the behaviour of square cylinder but at 0 degrees. Even for the lowest Sc number the amplitude of vibration is considerably small; therefore the model would not create any worries regarding induced vibrations from Karman vortex phenomenon. Still this phenomenon appears almost at the same wind speed having almost the same magnitude as in the case of a square cylinder model, which means that the original shape does not have any decisive influence upon this kind of aerolastic instability.
For higher wind speeds though (Fig. 6.b), where for square cylinder the divergent vibrations appear very strong and clearly determined, the EC will develop small instabilities, much smaller than the SC model, phenomenon which was indeed described previously as "aerolastic indifference" [1].

4. SEMIRIGID AEROLASTIC TESTS

For determining a more accurate structural response which will take account of the mode shape also a 3 dimensional semi rigid model was tested in turbulent and smooth flow. Damping ratio was stetted as 0.007 while the natural frequency of the model was measured as 3.9 Hz.

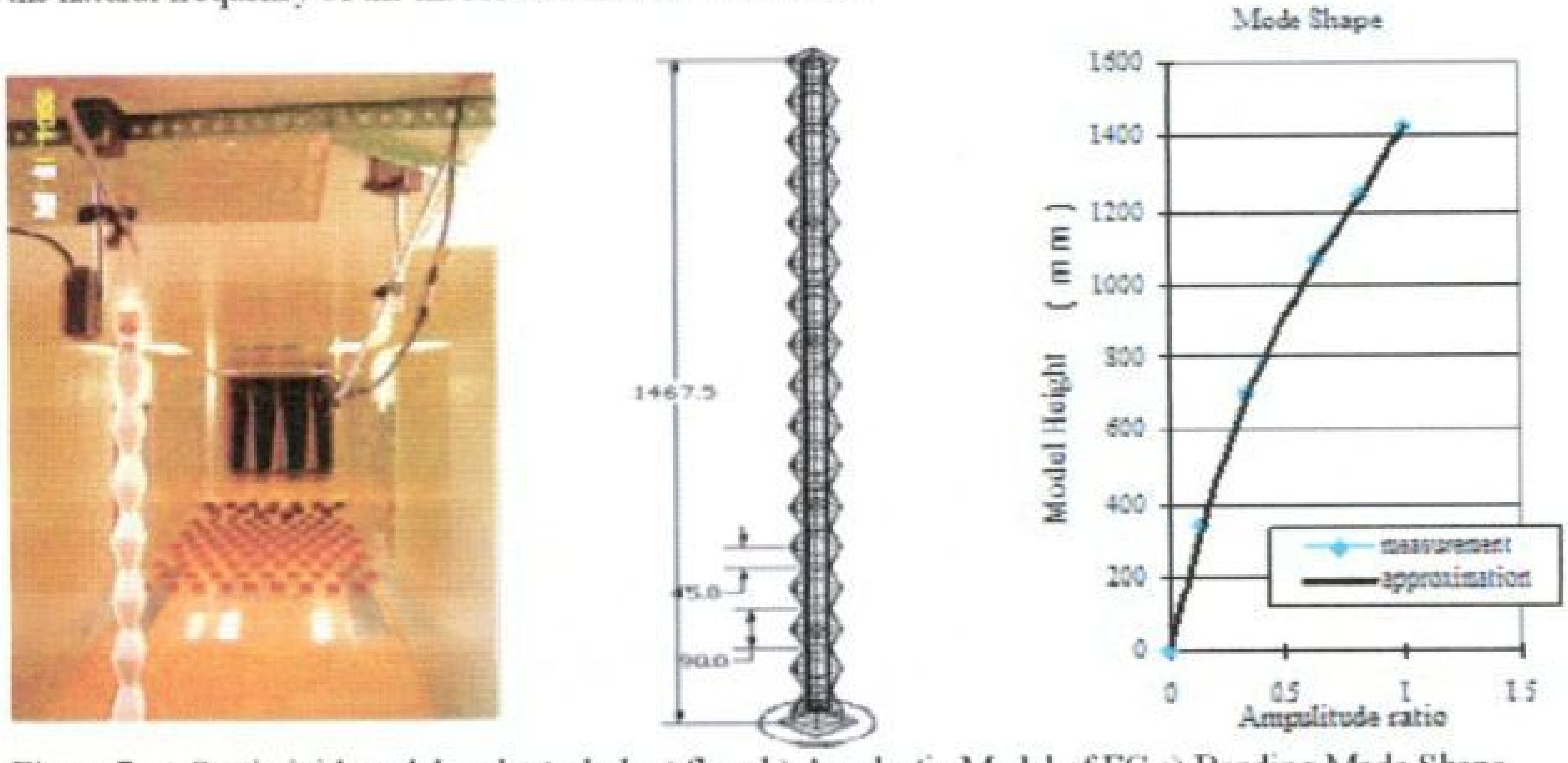


Figure 7. a) Semi-rigid model under turbulent flow b) Aerolastic Model of EC c) Bending Mode Shape

As displacements were not measured exactly at the top of the column, separate measurements were taken in order to establish the equation governing the first (bending) mode shape (Fig. 7.c.). Therefore, along and across wind responses of the column were converted to responses of the top by mode shape equation (Eq.1.)

$$f(x) = -8\times10^{-12}x^3 + 3\times10^{-7}x^2 + 2.8\times10^{-3}x \qquad (1)$$

Tests were carried out in turbulent and smooth flow. Target intensities of turbulence were decided as per Eq. 2.

$$I_u = \frac{\sqrt{\overline{u}^2}}{\overline{U}} \qquad I_w = \frac{\sqrt{\overline{w}^2}}{\overline{U}} \qquad I_v = \frac{\sqrt{\overline{v}^2}}{\overline{U}} \qquad (2)$$

Where: I_u, I_w and I_v are turbulence intensities on along wind, across wind respectively vertical wind directions. $\overline{u}, \overline{w}, \overline{v}$ are the components of fluctuating wind speed in the main flow, horizontal and vertical directions, and $\overline{U}$ is the height of the model.

Table 2. Turbulence Intensities

	I_u (%)	I_w (%)	I_v (%)
Top	16	8	14
Middle	18	9	16

In the wind tunnel, turbulence intensities were simulated by the aid of 1.8 m spires and roughness elements arranged on the floor of the wind tunnel as shown in Fig. 7.a.The turbulence intensities used in the experiment for top and middle height of the model are presented in Table 2. The wind profile obtained from measurements and the target wind profile are illustrated in Fig. 8.

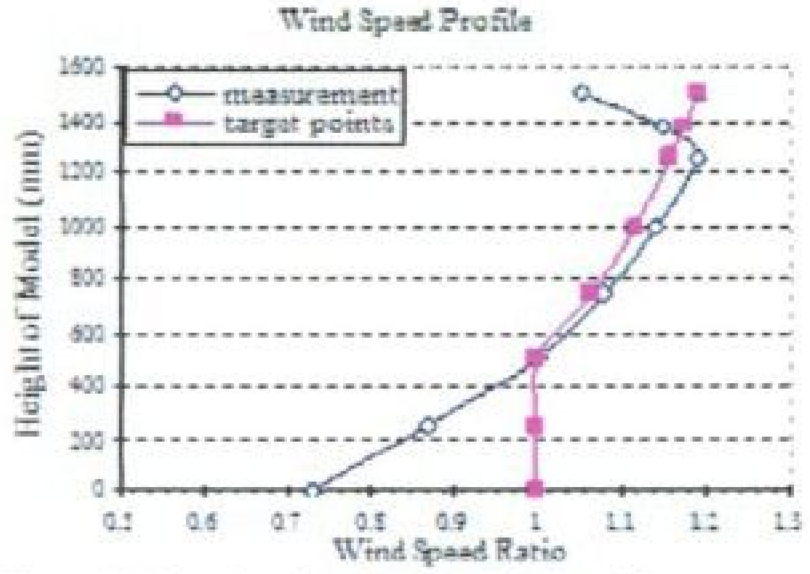


Figure 8. Simulated and target wind profiles

In fig. 9 and fig.10, displacements at the top of the model are plotted, after being corrected by mode shape equation, Eq.1 as explained above. Responses were recorded for x and y structural axes. In smooth flow, as expected the response on X axis is always lower than the vibrations on Y axis. Only for 45 degrees the responses become symmetric on both axes. Karman vortex induced vibration appears at around 3 m /s for 0, 5, 10 and 15 degrees, while for 30 and 45 degrees limited vibrations appeared at 2.7 and 2.8 m/s. The highest response was registered for 0, 5 and 10 degrees on Y axis, while from 15, 30 45 degrees vortex induced vibration registered a much lower magnitude (Fig. 10 a and b). For higher wind speeds (25 – 30 m / s), divergent vibrations are registered the highest response on X axis being for 30, 45, 15 degrees, while for Y axis, the response under wind angle of attack of 45, 30, 15 but also 0 degrees registered high values.

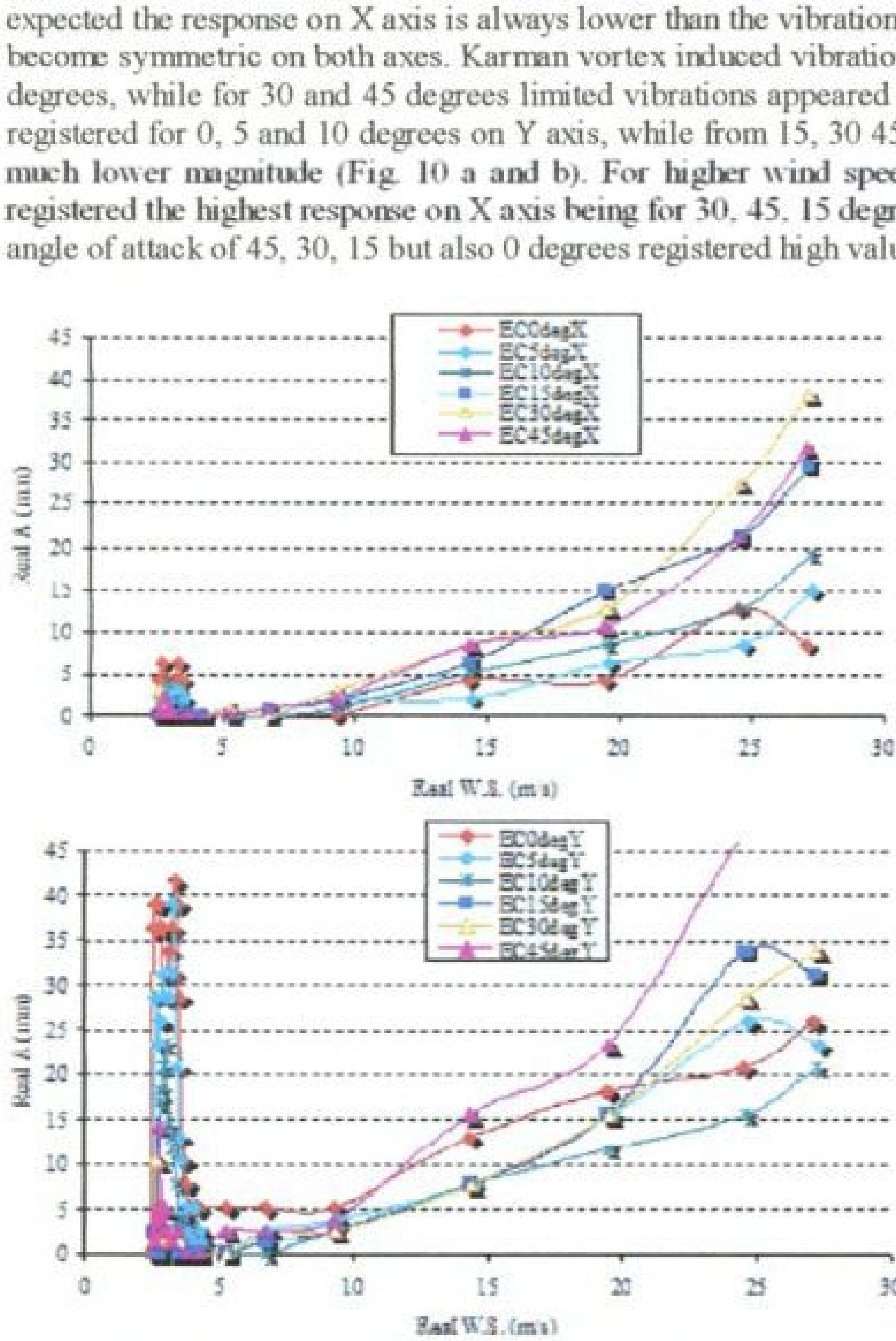


Figure 9. Response of EC in smooth flow, on a) X structural axis b) Y structural axis

For turbulent flow, the vortex induced vibrations appeared from 3 m/s for 0, 5, 10 degrees while for 15, 30 and 45 degrees appeared a little earlier, from 2.7 m/s, behaviour which is similar with the one under smooth flow. Divergent vibration appear faster then in the case of smooth flow, from around 15 – 20 m/s. The response on X axis is similar, having almost same magnitude, but for Y axis o, 15 and 5 degrees can be considered as having stronger response than the other cases.

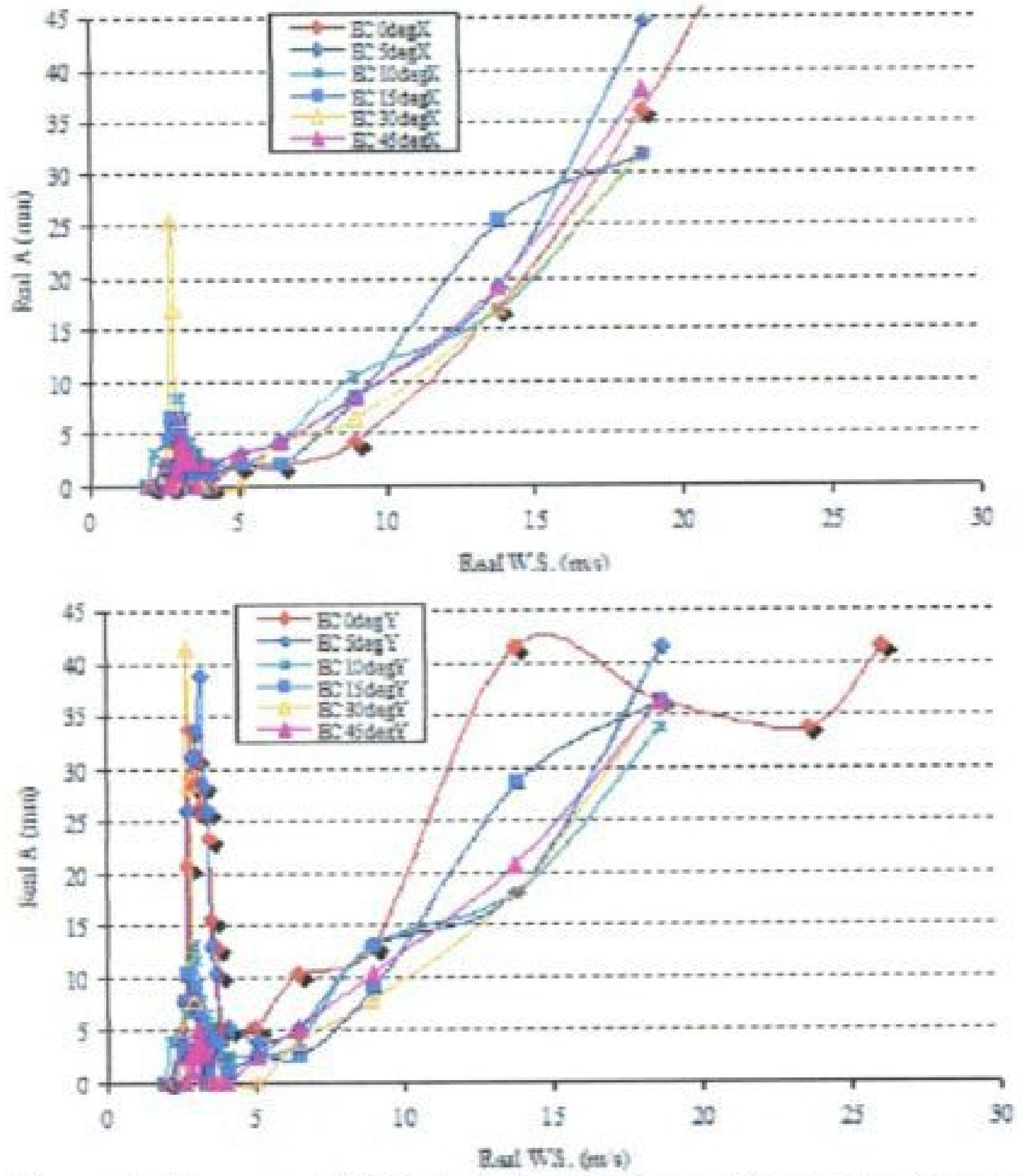


Figure 10. Response of EC in turbulent flow, on a) X structural axis b) Y structural axis

As response on X axis did not raise any special problems, only responses for Y axis in smooth and turbulent flow were compared in Fig. 11. Divergent vibration were higher under turbulent flow (Fig. 11.a), but Karman vortex induced vibrations were bigger under smooth flow, in the case of 0, 10 and 45 degrees (Fig. 11.b).

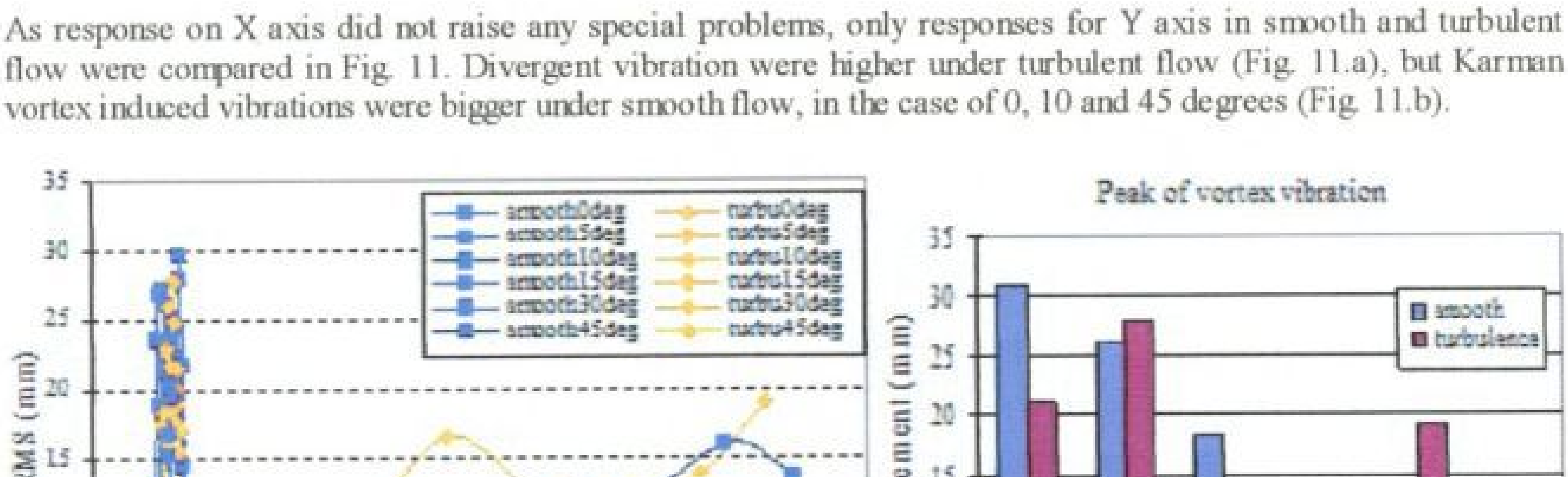


Figure 11. a) Response under smooth and turbulent flow b) Displacements for various angles of attack

5. CONCLUSIONS

The aerolastic three dimensional experiments reconfirmed the stability of the Endless Column of Tg. Jiu, in smooth as well as in turbulent flow. As illustrated in Fig. 9 and 10 Karman vortex induced vibrations do appear (at wind speeds of 2.7 – 3 m/s) but, if we consider the similarity conditions between model used in wind tunnel and the real structure of Endless Column, we can conclude that the magnitude of those vibrations is just a few millimetres, even for the highest response. Therefore, once again we can prove the phenomenon of "aerolastic indifference" of the Column under the action of wind, mentioned by Safta [1].

In some cases the turbulent flow acts in the sense of stabilizing the Karman vortex induced vibrations (0, 10 and 45 degrees), in same cases the response is almost the same, but a little higher for turbulent flow (5, 15 degrees) and only for 30 degrees angle if attack, turbulent flow induced a much higher amplitude of vortex induced vibrations.

In this article, aerodynamic properties of the Enless Column were investigated using 2D sectional model and 3D elastic model. Conclusions are summarized as follows'

1. Special shape configuration of the Endless Column shows very effective performance to suppress the divergent response in higher wind speed range, compared with of the square cylinder. On the other hand, this contribution was not recognized at the critical wind speed ($U_{cr}=1/St$) in lower wind speed range.

2. Scruton number of the Endless Column is very large. It is found that a high Sc is very effective to make its aerodynamic response negligible. Order of amplitude of the response of the real structure will be 0.1mm at the top.

3. Magnitude of the response at the U_{cr} depends on azimuth of the wind. Its maximum response is obtained at 5 degree from the normal direction.

4. At some azimuth of the wind, larger response was found in the turbulent flow than in the smooth flow.

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