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AN EXPERIMENTAL INVESTIGATION OF THE WIND FORCES ON TREES

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ABSTRACT

The paper illustrates the experimental techniques and the experimental results obtained at the Wall of Wind (WoW) of Florida International University (FIU), in Miami, concerning some tests on trees under wind loading. The motivation of the scientific work comes from unresolved questions that the designers of high rise buildings in Milano had to deal with in the design of the flower box containing trees up to 6-7 m high. The question was: can the tree fall down the terrace by turning inside the box or by breaking the trunk of the tree? How can be evaluated the forces due to wind? Thanks to the Real Estate Investment promoter, HINES Italia, an experimental program has been organized and implemented at a wind tunnel facility (WoW at FIU) which could allow for testing full scale trees.

Key words: Wind Action On Trees; Dynamic Analysis; Tunnel Wind Tests.

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The' Bosco Verticale' Buildings

The' Bosco Verticale' (Figure 1) residential buildings are designed by Arch. S. Boeri for the urban requalification of the so called' Isola' area, as a part of the more general urban requalification project named' Porta Nuova', downtown Milan. The height of the two buildings are about 80m and 110m, and they are characterized by significant surface balconies where the architectural design has positioned concrete flower box containing trees up to 6-7m height. Several full scale wind tunnel tests at the Wall of Wind (WoW) of the Florida International University (FIU) are conducted in order to understand the behaviour of the trees under the wind actions and to ensure the functioning of the trees bracing and safety systems.

FIG 1. Balconies and construction stages.

Wall of Wind

The WoW facility has dimensions 30.5 x 24.4 x 10.7 m comprising of twelve electric fan-motor units controlled by two variable frequency drives (VFDs) (Figure 2). They can generate sustained wind speed up to 70 m/s (157 mph) (the highest classification in the Saffir–Simpson Hurricane Scale, Category 5, is reserved for storms with winds exceeding 69 mph (155 m/s)). A dynamically controllable 4.9 m (16 ft) diameter turntable is located 2.7 m (9 ft) downstream of the WoW. Test samples are placed on the turntable to simulate the wind directionality effects. Moreover, considering the significant outer area in front of the building, the WoW forms a large open testing system. This kind of wind tunnel is very useful to tests full scale models and to lead destructive tests.

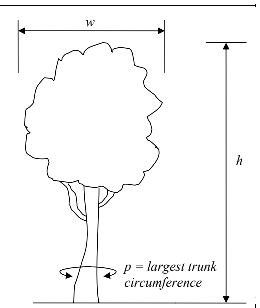
Tests Programme

The aim of the tests at WoW is to control the system of the concrete box and the inserted steel cage under the design wind action. The program is subdivided in two phases. Phase 1 is dealing with full tests on trees at different velocity levels, measuring the forces (shear and moment) at the base by the load cells system. Phase 2 is concerning with full scale tests on the complete system' tree + concrete box+ steel cage' using different wind velocities; displacements of the trees, tensile force of the safety steel cable are evaluated quantitatively, while the global behaviour of the brace system and the ground are estimated only qualitatively by vision inspection. The kind of trees, indicated by the botanic expert in Milano are Quercus Virginiana (QV) Tipuana Tipu (TT). Unfortunately, they were not available immediately in the local nurseries, so CIS-E decided to use other kind of trees geometrically very similar to QV and TT but having a lower wind resistance behaviour. Prof. M. Ross, Associate Professor of the Dept. of Earth and Environment Research Centre, FIU, suggested to use Gumbo Limbo (GL), Bay Rum (BR), Green Buttonwood (GB) and Pigeon Plum (PP).

FIG 2. 12-fan WoW and WoW inner area.

Table 1. Trees.

	GL	BR	GB	PP	QV	TT
h	4.20 m	3.40 m	3.35 m	3.45 m	3.50 m	4.50 m
w	1.80 m	1.30 m	1.37 m	1.42 m	1.20 ÷ 1.50 m	2.20 m
p	0.40 m (base)	0.40 m (base)	0.25 m	0.21 m	0.35 ÷ 0.42 m	0.38 ÷ 0.44 m



Phase 1: Evaluation of Wind Forces on Tree

Shear and bending moment at the base and tension force in the cable are measured by no.5 load cells (no.4 at the base of the steel cage and no.1 at the steel cable). The 'steel frame' , designed in order to fix the tree to the turntable, is represented in Figure 3. Following Table 2 gives loading data of the performed tests in Phase 1.

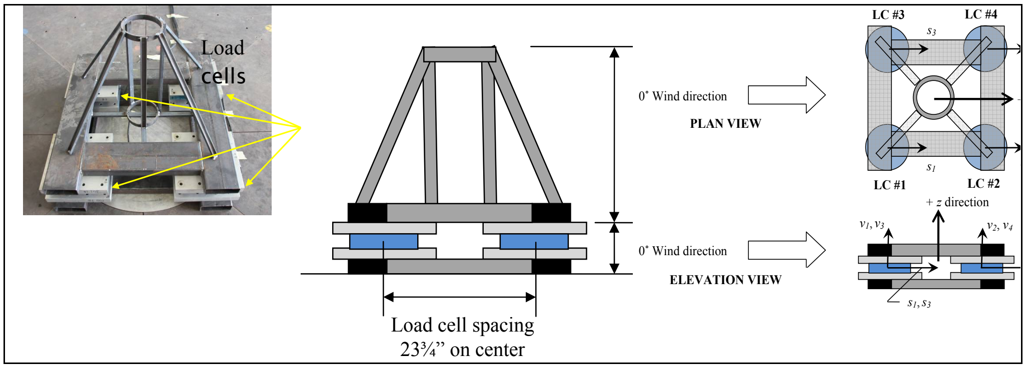


FIG 3. Steel frames and load cells of phase 1.

Table 2. Loading steps of Phase 1 (v1=13.4 m/s;v2=26.8 m/s;v3=40.2m/s;v4=54.9 m/s).

Test	Velocity	Time	Cable	Tree
A	v1 - v2- v3	3’- 3’-3’	no	GL
B	v1 - v2- v3	3’- 3’-3’	yes	GL
C	v1 - v2- v3	3’- 3’-1’	yes	BT
A’	v1 - v2- v3	3’- 3’-3’	no	BR
B’	v1 - v2- v3 – v4	3’- 3’-3’-10’	no	PP
C’	v1 - v2- v3 – v4	3’- 3’-3’-10’	yes	PP

Loads on the trees (Figure 4) are self-weight Fz; wind load Fx and base reactions measured by the load cells S1, T and S2, C. The shear aerodynamic force is evaluated at each time step by summation of the horizontal loads measured by the load cells. The aerodynamic moment My is evaluated at each time step as My=T L/2+c L/2.

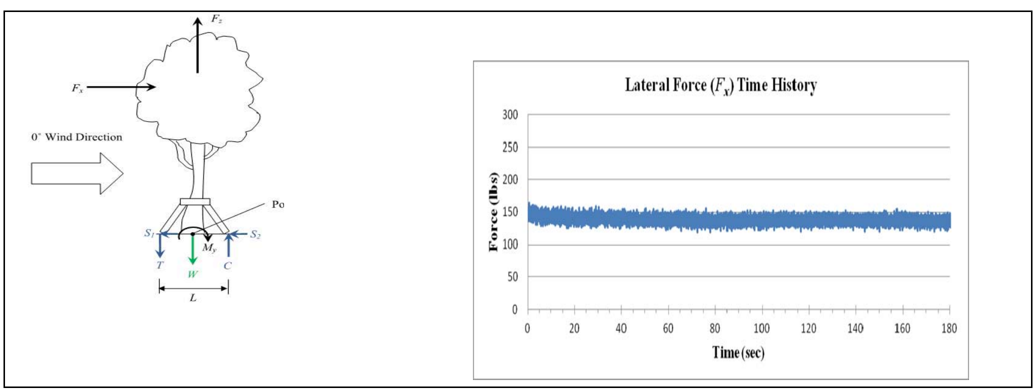


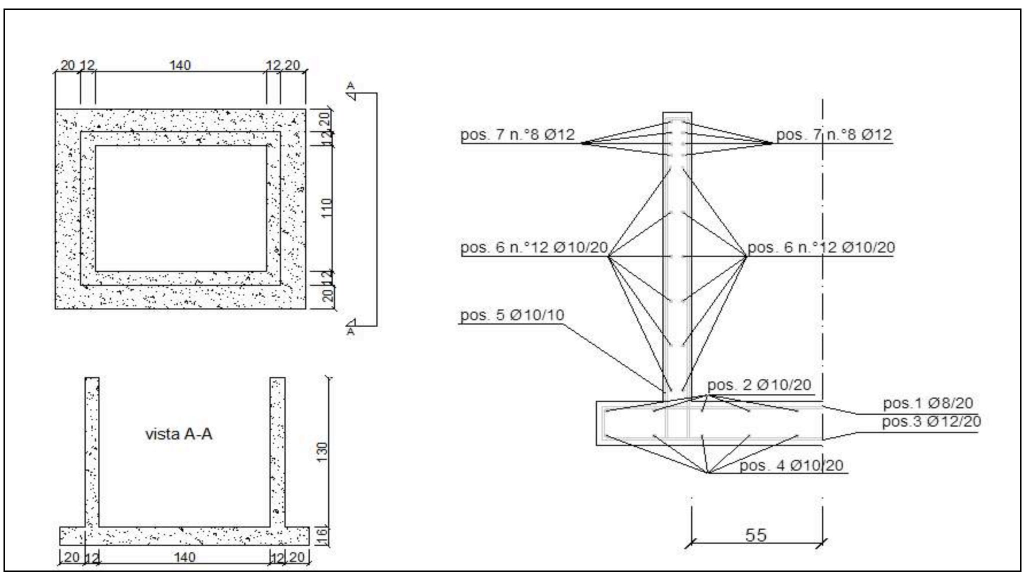
FIG 4. Loads on the tress and time history of Fx .

Results (Figure 5): GL has shown a significant loosing of leaves at the end of the test, while BM has maintained a crown very similar to that of the initial condition. It is interesting to underline that, in any case, the surfaces of the leaves are damaged and consumed during the tests so that the tree crown is increasingly less dense.

FIG 5. BM phase 1 and trees after the test (GL and BM).

Phase 2: Actual Behaviour of Tree Inside Concrete Box

Phase 2 is subdivided in two steps. Step 1 of the phase 2 is dealing with the entire system (concrete box + steel cage + tree), tested for different wind velocities and two wind directions. The instrumentation consists of no.1 load cell placed on the safety cable. The concrete box and the steel cage have been constructed in Miami, following the drawings developed for the actual structure to be erected in Milano. Step 2 of the Phase 2 is intended to test the system without the two upper square tubing of the steel cage (see Figure 6). Following Table 3 gives data and results concerning tests of Step 1 – Phase 2.



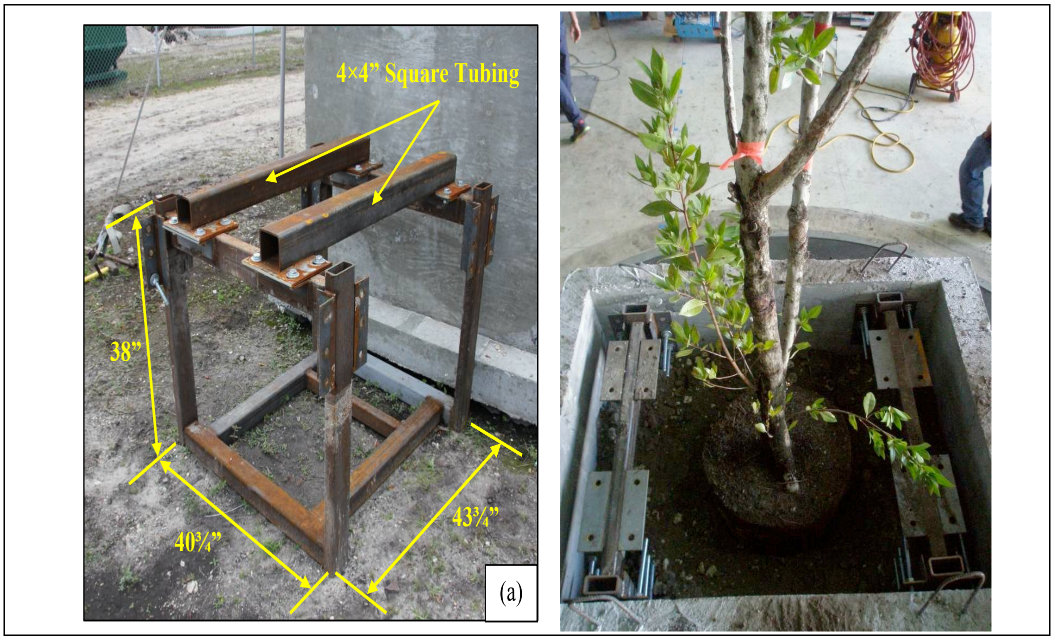


FIG 6. Concrete box scheme, steel cage, and their assembling with tree.

Table 3: Data concerning tests of Step 1 - Phase 2.

Test Designation	Speed	Time	Cable	Wind Direction	Nmed [Kg]	Note
A	v1 -v2 -v3	3'-3'-3'	yes	0°-0°-0°	≅ 5-20-55	Tree residual inclination, trunk close the upper profiles.
B	v1 -v2 -v3	3'-3'-3'	yes	90°-90°-90°	≅ 3-10-40	Residual inclination
C	v1 -v2 -v3	3'-3'-3'	no	90°-90°-90°	---	Slight residual inclination.
D	v1 -v2 -v3	3'-3'-3'	no	0°-0°-0°	---	Slight residual inclination
E	v4	30''	yes	0°	≅ 85	Speed greater than vd
F	v4	30''	no	0°	---	Speed greater than vd

GB has shown only a slight residual inclination at the end of the Step 2 (Figure 7), so that the behaviour of the tree was very similar to the behaviour observed in Step 1 – Phase 2 (without the upper square profiles).

FIG 7. Phase 2 (PB, before and after the test).

Numerical Analysis

A numerical analysis is carried out using a FEM of the trees where the trunk is represented by beam elements. The Drag force on the trunk (Ft) is evaluated by Ft = (1/2)ρv2CDtAt , under the hypothesis that the trunk is a cylinder. The CDt curve is showed in the following Figure 8 and At is the surface of the cylinder invested by the wind (At = 2R·Hcylinder).

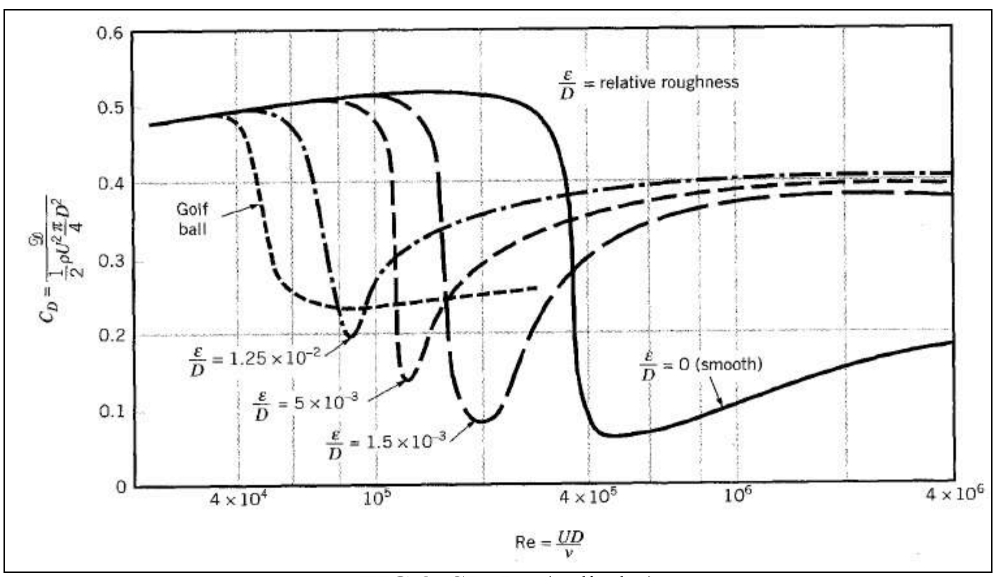


FIG 8. CD–Re (cylinder).

The relation Fc = Fx – Ft is used to evaluate the force on the crown (Fc), where Fx is the total Drag force measured at WoW. Fc has been considered as a concentrated force at a distance from the tree base, in the FEM model, such that the numerical and experimental moments are the same.

Maximum horizontal displacement of the trunk, calculated by the FEM under Ft and Fc (at level 2/3·htrunk), is very close to the displacement recorded at the WoW (Δx-FEM = 61 cm, Δx-WoW= 55 cm). It's important to estimate correctly the drag coefficient peak value CD, which takes into account the permeability of the crown's surface, to evaluate, in design phase, the force at the base of the tree. By recalling that Fx = CD·pc·Ac, where Fx has been evaluated at WOW, pc = (1/2)·ρ·v2 and Ac , elliptical surface of the crown, is given, the CD curves (for PP and GL) may be computed (Figure 9).

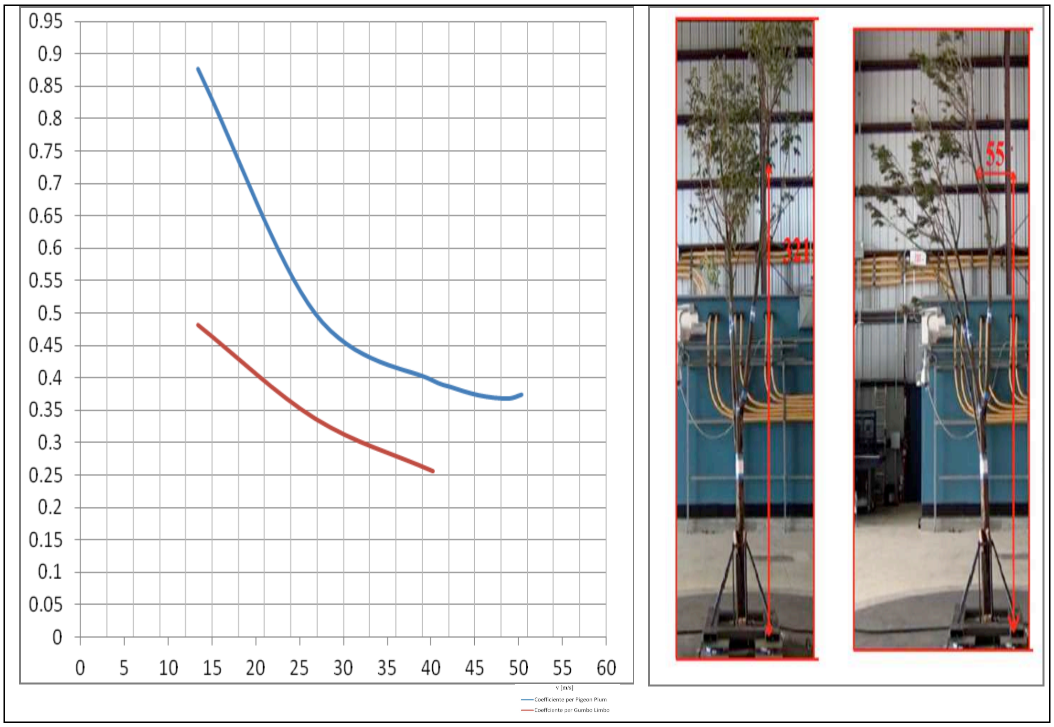


FIG 9. CD curves for PP and Gl trees; displacement control at WoW.

<u>Numerical Construction Stage Analysis</u>

A construction stage analysis using a' concrete box + soil + tree' FEM, with solid elements, has been carried out. Two phases have been considered: Phase 1: tree + soil + box subjected to self-weight loading; Phase 2: wind loads have been applied to the tree + soil + box, with soil elements subjected to an initial stress state coming from Phase 1. The soil is a backfill (no cohesive) and it has a low fiction angle (15-20°). The concrete box is schematized by suitable boundary conditions. The FEM results are qualitatively in accordance to the behaviour of the soil experienced at the WoW (Figure 10).

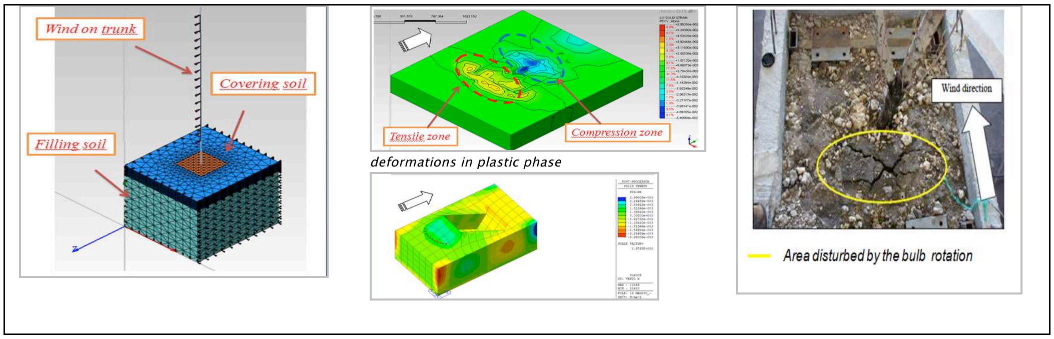


FIG 10. Construction stage Analysis and results comparison to the WoW test.

Conclusion

Present paper analyses wind action on the trees with the aim to evaluate the performance of possible trees bracing structures and the relative safety system. The paper presents experimental results obtained at WoW of Florida International University (FIU) in Miami. Two types of models have been tested: a first type of tests for the evaluation of the maximum forces at the tree base under different loading speed, and a second type of tests where the entire structural system (concrete box + soil + tree) has been tested in order to evaluate the possibility of collapse-failure of the tree. Experimental results have shown forces lower than the assumed design values, and no collapse or failure has occurred. Numerical analysis have shown promising results in order to control maximum displacements of the tree under wind loading.

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