

Digital and physical models for the validation of sustainable design strategies

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1. Introduction

The project was inspired by the general idea that globalisation's impact on the built environment is manifested in the explosive growth of cities around the world. In this regard, through the 2010/31/EU Directive [1], the Countries of the European Community are committed to reducing current levels of emissions and energy consumption by 20% and increasing the use of renewable energy in new building construction by 20%, by the year 2020.

In this sense, the concept of the project was developed by applying active and passive bioclimatic strategies, in compliance with the new European Standards. This includes everything from optimum shape selection, architectural language, and technology choices, to the structural design. The objectives were to maximise the energy gains by using renewable resources and reducing fuel consumption and emissions into the atmosphere.

The detailed design of renewable energy-based buildings took advantage of physical modelling that, if properly developed, might be a

powerful tool to integrate and correct traditional analytical approaches. In the contemporary age, in which generative tools and computer modelling afford opportunities to create complex shapes, the aid of physical modelling represents one of the ways through which designers can materialise their mental concepts [2]. Regarding the geometry, it is important to underline that the skyscraper, by its nature, has always been intended as a static building, lacking in dynamism. In recent design approaches, however, more attention has turned to the movement of volumes, using different manipulation strategies such as rotations, translations, or twisting, made possible by recent digital modelling software, which are strongly related to rapid prototyping techniques [3–7].

As a design representational medium, the advantage of the model-making process is that it can lead to new forms beyond the original concept. In fact, theoretical models are separately applicable to a single performance, and while they are technically valid in some respects, they were woefully inadequate for the purposes of this paper. This evidence resulted in the need to identify a method that would allow for the control of their effective integration. The coexistence of opposing performance knots created a need to test the building as a system, including the relations with the environment. For these reasons, it was decided to exploit traditional wind tunnel tests, in order to check with a holistic approach the structural loadings, renewable energy production, and the wind comfort at different levels. The model-making process was also useful for the communication between designers and technical staff in order to describe the complexity of the architectural concepts and to

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develop the construction of the final model [8]. The models generally serve as intermediaries between design and construction. This technique is hundreds of years old; many great architects, like Michelangelo [9] and Palladio [10], have already used physical models to explain construction techniques, building structures, and inner space ambience to clients and workers.

2. Theoretical framework

The creative and artistic process is characterised by different kinds of representation: architects, for example, explore many design possibilities through design sketching, hard-line drawings, and physical models, manufacturing artefacts for the exploration of diverse ideas [11]. Currently, the development of advance technologies, such as generative modelling tools with parametric transformations and CAD scripting, provides an opportunity for architects to control the building's development at the first stages of the design process by calculating the optimised shape and the best organisation of the inner space in order to reduce the total amount of energy demand and to achieve the standards of energy efficiency. However, nowadays, it is a common practice for designers to use the CAD–CAM technologies only in the concluding stages of the design process.

This paper presents the key aspects of the methodological framework to build physical models at various scales using different materials and techniques as part of the entire creative design process from the beginning to the end. RP is used as a design methodology in support of a paperless design and construction process.

RP is one half of a bigger field identified as digital fabrication (DF), a field that spans the application of RP for design and CAD–CAM for construction [12]. RP has been used mainly by product and industrial designers to demonstrate design concepts to clients through physical models. There are three principal types of RP techniques. First, 2D cutting devices such as vinyl and laser cutters are most frequently used by designers and architects to produce models of various scales and materials. Second, subtractive devices in the form of milling machines for desktop design carve from foam or other softer materials. Finally, additive manufacturing devices build solid models from loose powders or liquefied plastics. All three manufacturing types are generically known as CNC devices, and they are intended to translate from RP devices to real-world construction.

One of the main features of digital fabrication is the high quality of its output. It is possible to reach high levels of accuracy with both 3D models and laser cutting technologies, especially for complex designs. The creative process for producing variations of a single model or different models at various stages of design is supported by the RP technique. The potential applications of the RP modelling technique not only are useful in the design and construction process, but they also have certain didactic advantages that support the acquisition of knowledge and design procedural structures [13], such as those presented in this paper.

This paper describes three areas of research and design practice using RP. The first is the exploitation of RP in the early stage of design and the creation of designs as 3D shapes putting attention on the verification of architectural concepts and spaces. The second area is an emerging interest in the functional building model as a prototype for structure validation through test campaigns in wind tunnels. The action of the incident wind on a structure and its response to this environmental action are difficult to assess, but are of fundamental importance in the design of buildings and other civil facilities. The pattern of flow around a building and the corresponding pressure field is a very complex phenomenon; despite the available computing potential, both analytical and numerical approaches may lead to unsatisfactory approximations, in particular if applied to complex building shapes. This is because refined numerical models cannot disregard a proper calibration procedure based on experimental data and should be hence validated with regard to direct measurements [14].

The third and final area of research is the production of a 1/250 scale model, completely produced by RP technique, for the validation of building functionality and architectural concept as well for the aesthetic and communication skills of the model presented in the Culture Nature exhibition, a collateral event of the 12th International Architecture Exhibition Biennale of Venice (Fig. 1b).

The work presented here attempts to synthesize the conceptual stage materialisation through RP and construction information modelling. We demonstrate that the process of design is situated between conceptual design and building product modelling as a construction information model.

3. Design concept of the sustainable tower

The project area is located between the historical city of Roman origin, characterised by orthogonal street distribution, and the rest of the city of Turin, successively developed with a freer grid. This area was part of a wider refurbishment programme proposed to compensate for the almost total absence of green parks in the urban area, by creating an urban boulevard with trees and connecting the two parts of the city originally divided by the railway (Fig. 2).

The proposed skyscraper and the nearby railway station of Porta Susa constitute a place in the middle of change. This concept is embodied by the lines that move from the beginning of the lot (from the side toward the old passenger building of Porta Susa) enhancing their dynamism to totally break the historical rigid scheme. Everything flows in a vortex of sinuous lines, culminating in the tower that is the epicentre of the whole movement that continues up to its top, finally vanishing in the air. It is a building born from the earth and returned to it through a natural cycle: this was the generating concept of the project.

To minimize the environmental impact on the existing context, more attention was paid to the shape and orientation of the building, service location, finishing materials able to guarantee protection from solar radiation, integration of energy plants at different building levels, and natural ventilation.

The peculiarities of the project that made it necessary to conduct an experimental check and process various physical models were many and closely integrated. With reference to the envelope, the building façades were oriented according to different functional purposes: for the residences, a maximum south/southeast exposure facing the urban park, with the integration of a greenhouse system able to collect free energy contributions during colder seasons; for the hotel rooms, characterised by a lower residence time, a northeast fenestration with an urban skyline view was chosen; and finally, for the common spaces, an east–west orientation was designed in order to guarantee panoramic views of the city, the Alps, and the Mole Antonelliana.

The spatial solution included two buildings: the first, with an elliptical shape, for hotels and offices, and the second, curved and parallel to the perimeter, for residences. The two substructures were spaced so as to generate a central common area – aligned in an east/west direction – properly shaped in order to accelerate the incoming wind flow, improving natural ventilation and wind energy capture. The air passing through the inner living spaces contributes to the energy efficiency by producing natural air conditioning, which maintains the health of public spaces and is able to generate a level of environmental comfort consistent with the needs of the inhabitants. This, together with a maximisation of south exposure, was one of the energetic strategies considered in the development of the project, in order to achieve the integration of all renewable energy sources (Fig. 3).

The project provides a vertical succession of villages, each of which is characterised by the presence of a covered public square equipped with shops and hotel lobbies, overlooked by five more storeys of residences, hotels, and offices. The plan grows vertically with a complex volume, surrounded by an external diagrid structure modelled with a waisted silhouette which recalls the typical shape of a female bust and offers, at the same time, larger commercial areas at the base and the top of

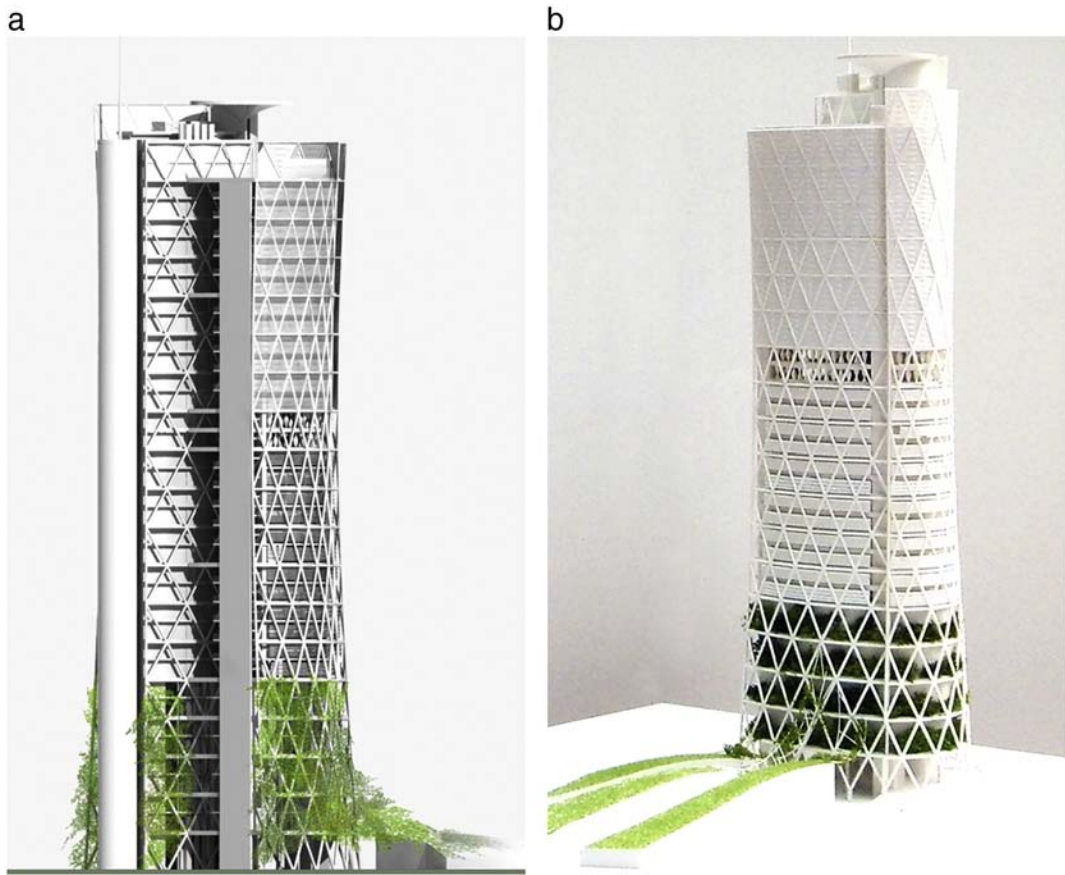


Fig. 1. a, b (from left to right) Digital rendering and 1/250 scale architectural model. The architectural model was produced with rapid prototyping techniques (ABS and starch powders) at the end of the experimental testing phase.

the building and a profile suitable for guaranteeing adequate stiffness toward the wind (Fig. 1). As a matter of fact, the building structural system consisted of steel columns, reinforced concrete cores, and a spatial diagrid [15] structure made of steel tubes, resistant against vertical and horizontal actions (Fig. 4).

From an eco-friendly stand point, the exploitation of wind energy associated with solar power creates the need to calibrate wind speed along walkways to satisfy two conflicting requirements: on one hand, the maximisation of natural wind ventilation and energy production, with its need for rather strong and constant air speed facilitated by



Fig. 2. Environmental section and master plan of the proposed tower.

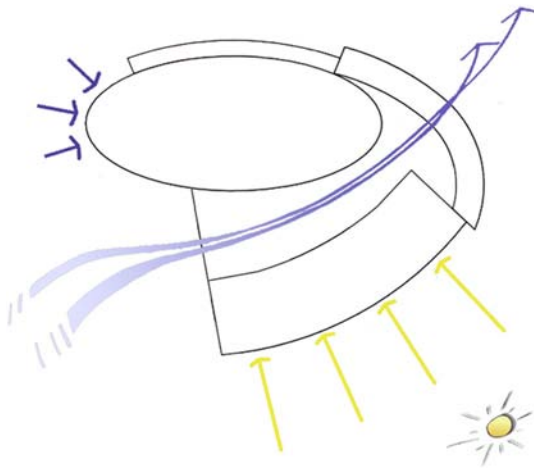


Fig. 3. Bioclimatic strategies: maximum southern exposure and natural ventilation activated by wind flowing inside the village canyon.

the village narrowing; on the other, the environmental comfort, with the need to reduce the wind speed perceived by walkway users.

The three solutions proposed for the façade, due to the use of different finishing materials, were the result of passive and active strategies toward weather conditions, but, while the vertical succession was dictated by technical and environmental aspects, technological solutions were the answer to architectonic influences of the city of Turin. These solutions provide multiple effects of colour that varies according to the seasons. When the sun rays, characterised by different angles, hit the different materials, they create different plays of light and colours that make the tower never equal to itself.

This effect was emphasised by the green façade (Fig. 5) designed for the bottom of the tower, whose choice was supported by the low values of wind speed and pressures. During the summer, deciduous plants freely grow on the steel structure, screening the interior spaces exposed to the south; during the winter, the lack of foliage prevents overheating and glare and allows sunlight to penetrate inside, providing free solar gains. The change in colour of the foliage is also an expression of empathy between the tower and the existing context, a feature that reduces the visual impact of the tower volume.

For the intermediate levels of the building, since the wind pressure increases up to medium intensity values, building-integrated photovoltaics (BiPV) were provided. These systems are characterised by a

variable inclination according to the incidence angle of the sun. Plain metal louvres were designed for the shaded areas in order to mitigate the wind disturbance and still ensure panoramic views over the city (Fig. 6).

Two storeys in the middle of the tower are devoted to the installation of technological services and vertical axis wind turbines, effectively working under every wind direction.

Finally, on the upper part of the tower, where the pressures of the wind are rather high, the façade was made of a plastic and transparent finishing material realised with overlapping layers of ethylene tetrafluoroethylene (ETFE), resulting in transparent, translucent, screen-printed membranes characterised by blue-toned colours getting lost into the sky and hence contributing to the minimal visual impact of the entire tower [16] (Fig. 7).

The design of this technological façade came from the clear intention to finish the building with a lightweight and transparent material, but with high mechanical and physical properties, that resists the action of horizontal loads of wind and other weather. The result is a series of inflatable cushions that close the building envelope: each floor is divided by three air cushions; the top one can open to allow natural ventilation and air changes. The “pillow” system also has a large inner flexibility: depending on weather conditions, temperature and solar radiation, the sole membranes are able to assume different configurations by adjusting the pressure inside the air cushions moving internal screen-printed films to get the best possible comfort.

Because of the technological complexity, the digital and physical modelling were also useful during the executive design phase, avoiding severe interferences between the proposed façades and the structural scheme and allowing a better understanding of the visual impact of the selected solutions.

4. Research strategy and methods

4.1. Physical and digital models

The design hypotheses selected in the preliminary phase were experimentally and numerically validated by means of physical and digital models. Due to the technological and morphological complexities, it was necessary to prepare several physical models at different scales and with specific purposes (Figs. 1b, 8c, d, 9, and 10). The techniques used were many, and advanced RP systems have been accompanied by more traditional ones.

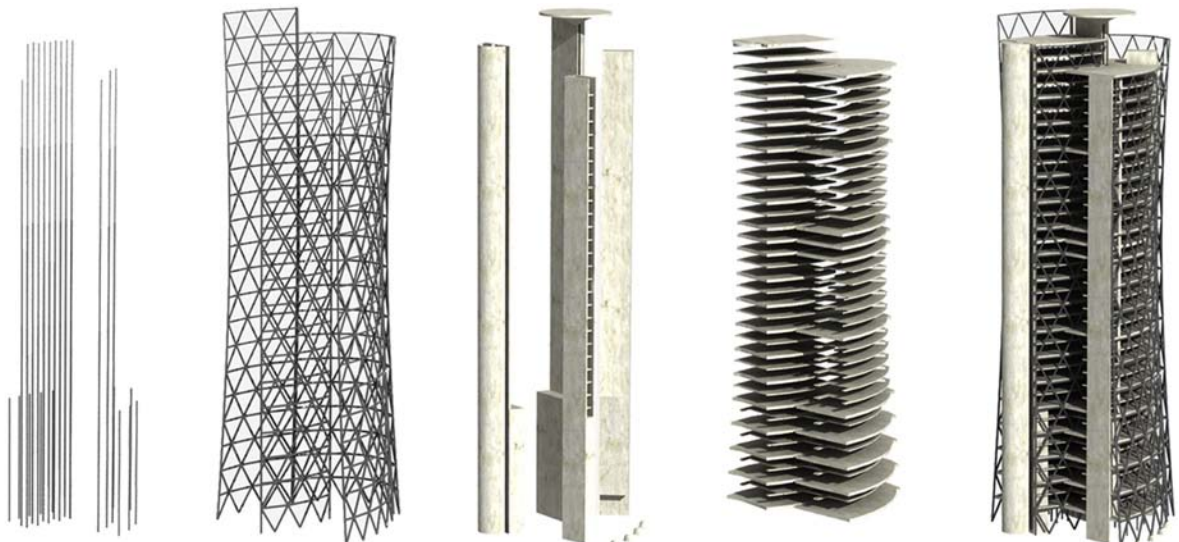


Fig. 4. Structural scheme of the proposed tower: steel columns, steel diagrid structure, concrete shear walls, and steel/concrete floors.

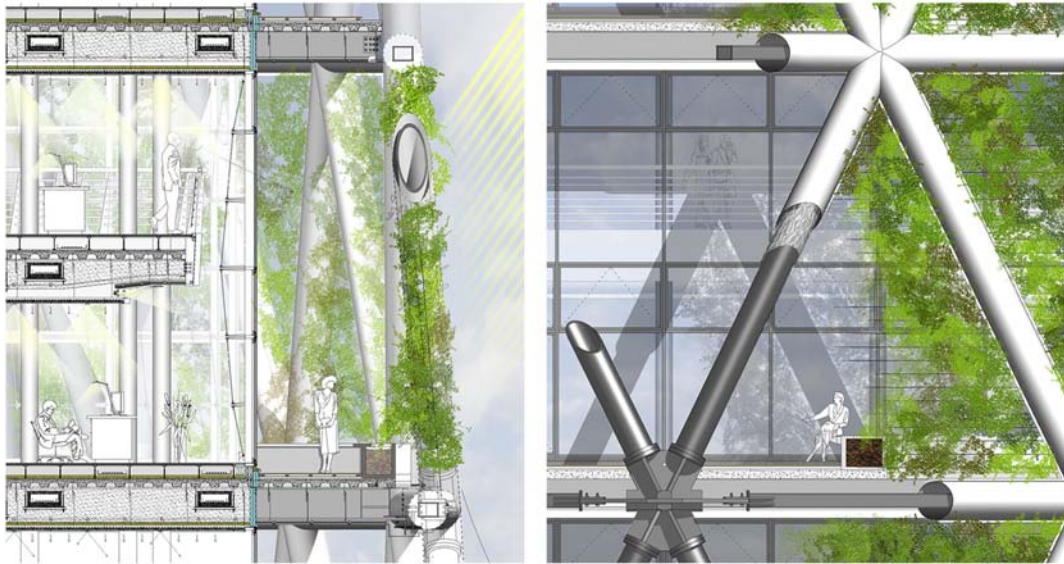


Fig. 5. First-level vegetal façade.

Since digital models (Fig. 8a and b) seemed to be insufficient for the comprehension of building complexity, preliminary RP scale models were produced to improve the effectiveness of the interaction among engineers with different skills, the design team, and the wind tunnel staff. For this purpose, a 1/100 scale starch powder replica of the diagrid structure (Fig. 8c) and a 1/250 scale mock-up of the actual shape (Fig. 8d) were printed by means of 3D rapid prototyping methods. The production of these models involved remarkably low work times, if compared to those related to manual techniques, but required a precise development of 3D drawing files and an advanced knowledge and mastery of the machine software. In this environment, a remarkable task was the transformation of project drawings into production machine interface files: this simplification process can only be developed on the basis of a good scientific background of drawing and modelling techniques [17].

After the simplification of the building geometry and the comprehension of the technical aspects related to the preparation and instrumentation of rigid aerodynamic models, as suggested by the wind

tunnel team, a 1/100 scale wood model of the village was prepared (Fig. 9).

Accessibility of the inner parts of the mock-up was checked, and a proper instrumentation was prefigured, confirming the strategies to be followed for the production of a final model suitable for wind tunnel testing.

The use of a 1/100 scale was required by the test methods and finally involved the preparation of a large model (height larger than 1.60 m), with certain strength characteristics (Fig. 10).

Moreover, it became apparent the need to vertically open the model in order to place a number of cables, sensors, and transducers (Fig. 11) for the transposition and reading of the experimental data. The simplest solution to cut the whole shape was discarded and, to ensure the horizontal and vertical continuity of the elliptical surface, a vertical slice of the northeast façade was chosen (Fig. 9a).

For the transposition of the digital model into a material one, different techniques were chosen, taking into consideration containment of production costs of a model exclusively designed for experimental

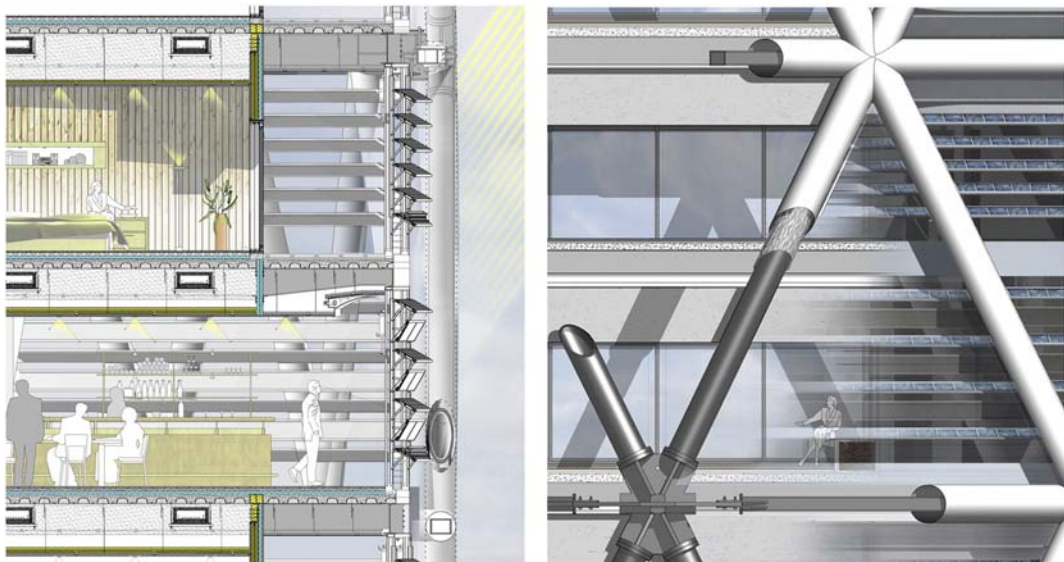


Fig. 6. Mid-level façade, characterised by wind louvres equipped with photovoltaic cells in correspondence with the southern elevation.

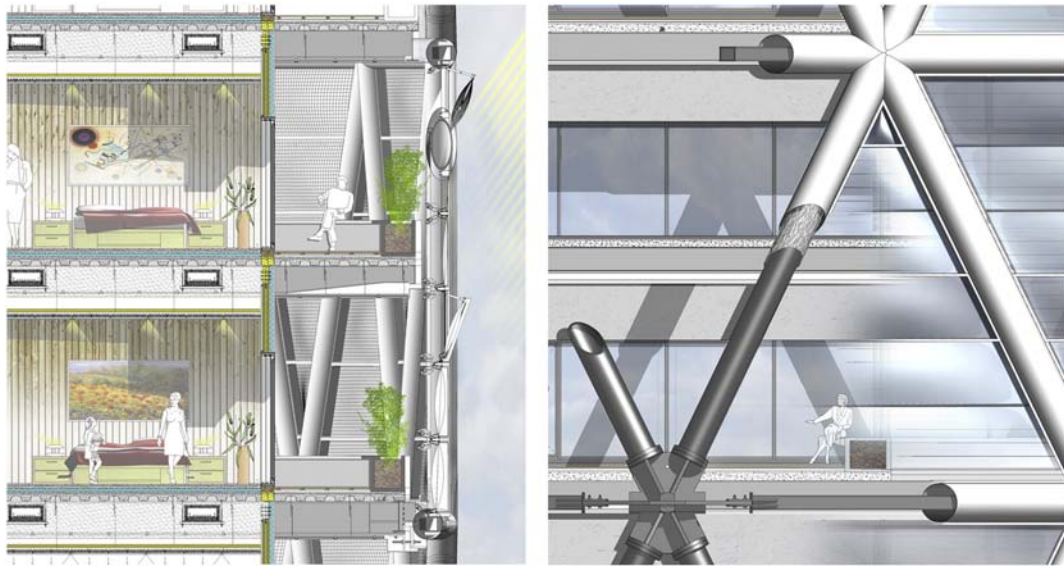


Fig. 7. Upper-level façade, characterised by ETFE cushions.

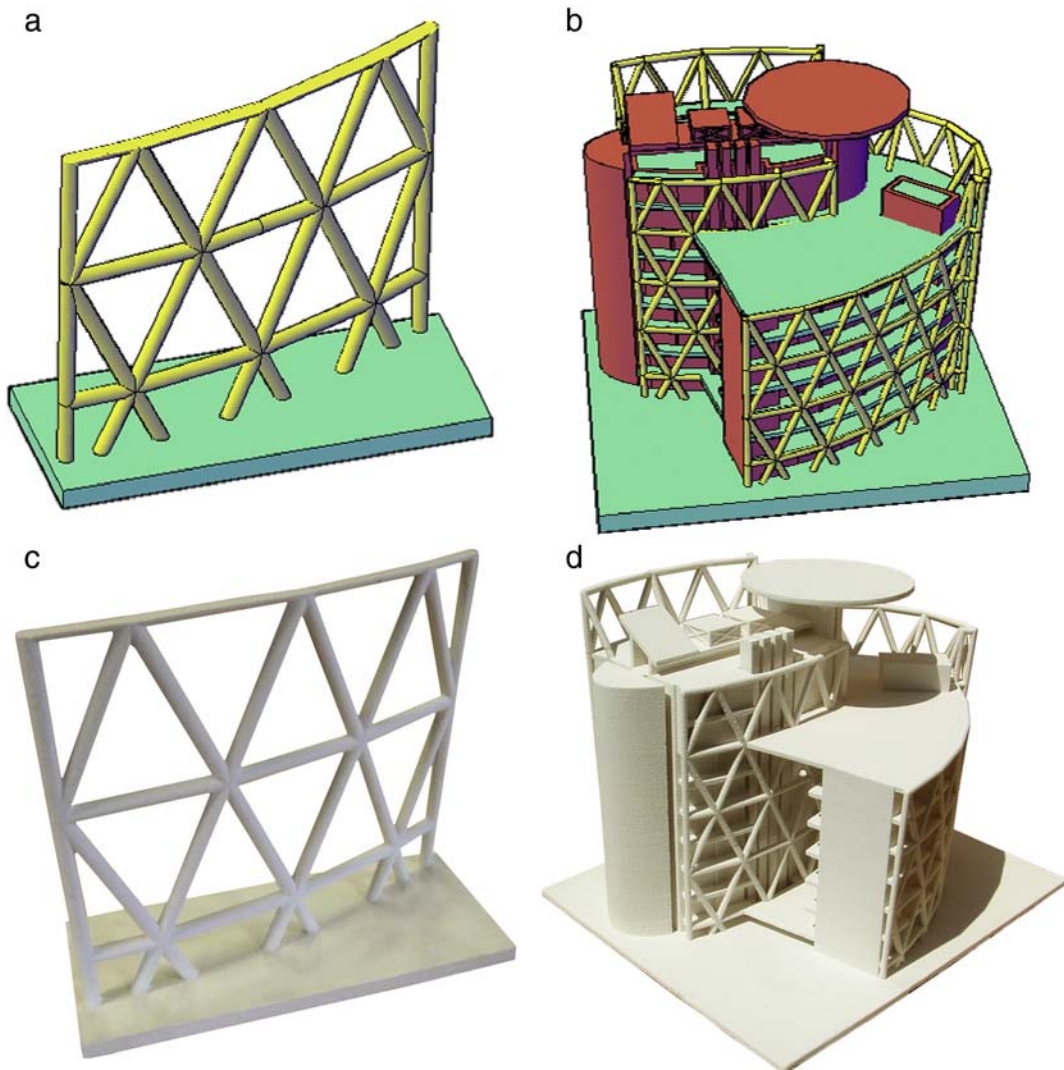


Fig. 8. a, b, c, and d (from left to right) Preliminary CAD and rapid prototyped models: diagrid structure (1/100 scale) and top of the tower (1/250 scale).



Fig. 9. 1/100 scale preliminary wood models, used for discussion with the wind tunnel team and to verify the proper instruments for the final model testing.

testing and therefore potentially exposed to damage. Starting from the digital design, a complete redefinition of the new physical model was hence carried out with regard to the choice of materials, which were evaluated with reference to different characteristics such as workability, permeability, surface finishing, and mechanical strength. The RP technique was used for the diagrid because of its complexity and the need to

precisely simulate the permeability of wind shields fixed on the tubular structure (Figs. 10c and 12).

It was instead decided to prepare the remaining parts with traditional wood-cutting techniques (Fig. 13), as the size of the set of significant buildings to be made and the low degree of precision required did not justify the use of numerically controlled (CNC) machines, which are



Fig. 10. a, b, and c (from left to right) 1/100 scale rigid aerodynamic model for wind tunnel testing.

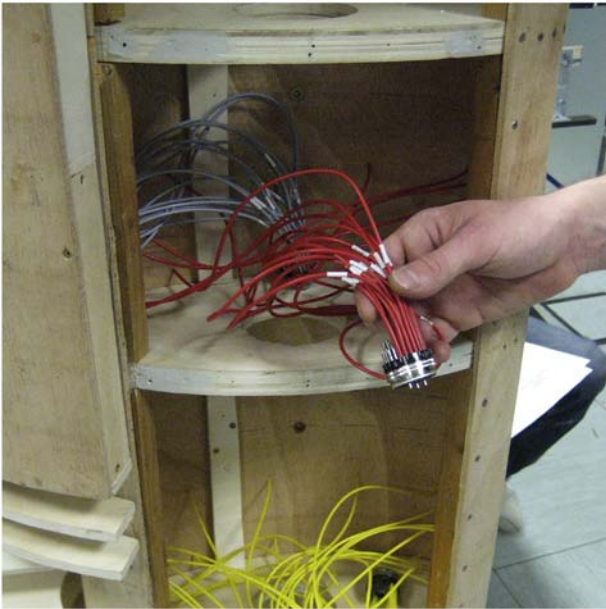


Fig. 11. Pressure transducers and cables.



Fig. 13. 1/100 scale floors prepared by means of traditional wood-cutting techniques.

very expensive and not available in the Politecnico di Milano Prototypes Lab.

Despite this obstacle, the whole 1/100 scale rigid aerodynamic model was first developed in a CAD digital environment, which was instrumental for the interference evaluation and the production of precise manufacturing drawings. The last phase of the physical model preparation was conducted to simulate the specific context. As a matter of fact, for test purposes, it was important to check the effect that surrounding buildings could have on the skyscraper, in terms of friction, vortex development, and increase of wind suction; this required the use of physical elements able to represent a reference urbanised area (Fig. 14).

Alongside the development of physical models, numerical models were prepared and used for a rough estimation of qualities of engineering interest, instrumental for the preliminary design. The development of the Finite Element models gave prominence to the three-dimensional

CAD digital models built in earlier design stages; as a matter of fact, the spatial distribution of beam, truss, and shell elements was directly derived from the digital architectural model.

For the purposes of structural analysis, the structural scheme was analysed and designed by using a numerical technique of proven validity, known as the Finite Element Method (FEM) [18]. From a practical point of view, the structure was initially divided into a finite number of interconnected domains called elements. The connection points between the elements are called nodes, while the set of nodes and elements is called mesh. At the finite element level, the relations between the nodal variables (displacements, forces, velocity) are determined by the laws of classic mechanics. From the mathematical point of view, the finite element structural analysis has as its objective the determination of a distribution of displacements (and consequently of stresses and strains) under predetermined conditions of load and constraint.

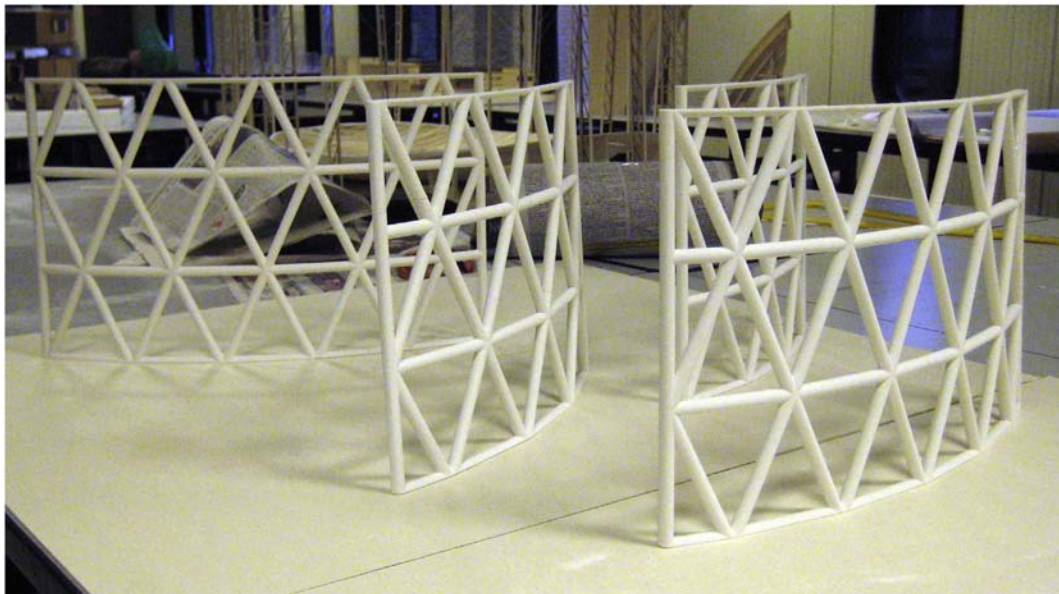


Fig. 12. Rapid prototyped diagrid structures produced for the 1/100 scale rigid aerodynamic model.



Fig. 14. Wind tunnel experimental testing.

The function that represents this distribution is respectful of the physical laws and meets the conditions imposed on the boundary of the domain. This function is defined in discrete form and is expressed in terms of nodal values. This approach represents the real-world problem by means of a system of algebraic equations (linear or nonlinear) of the nodal values of the chosen variable and hence seeks to identify a numerical approximation of the exact solution.

During the structural analysis it was necessary to apply the FEM, in order to optimise the structural choices made in the preliminary design. In this regard, the complex structural organisation of the tower was broken down into subsystems consisting of a tubular structural element (diagrid), a system of seven reinforced concrete shear walls, a set of tubular steel columns, and a series of composite steel/concrete slabs. The development of the Finite Element models (Fig. 15) gave prominence to the three-dimensional digital model built in earlier design stages; as a matter of fact, the spatial distribution of beam, truss, and shell elements was directly derived from the digital architectural model. The use of numerical sub-models allowed us to determine with rather good

precision the effect of parasitic actions, generally neglected in basic analytical approaches. Numerical models were also prepared in order to investigate the structural behaviour of orthotropic floors (composite steel floor deck), i.e., characterised by different flexural stiffness in plane directions.

As previously stated, at the end of the numerical and experimental verification process, a 1/250 scale architectural model (Fig. 1b) was produced; the main shape was realised by means of Zcorp machines based on starch powders (Fig. 16), while the more delicate structural and technological meshes consisted of harder ABS materials printed with Dimension machines.

4.2. Experimental tests

On the 1/100 scale rigid model of the tower, several aerodynamic tests aimed at evaluating the building behaviour under local winds were carried out. In particular, the tests focused on the following:

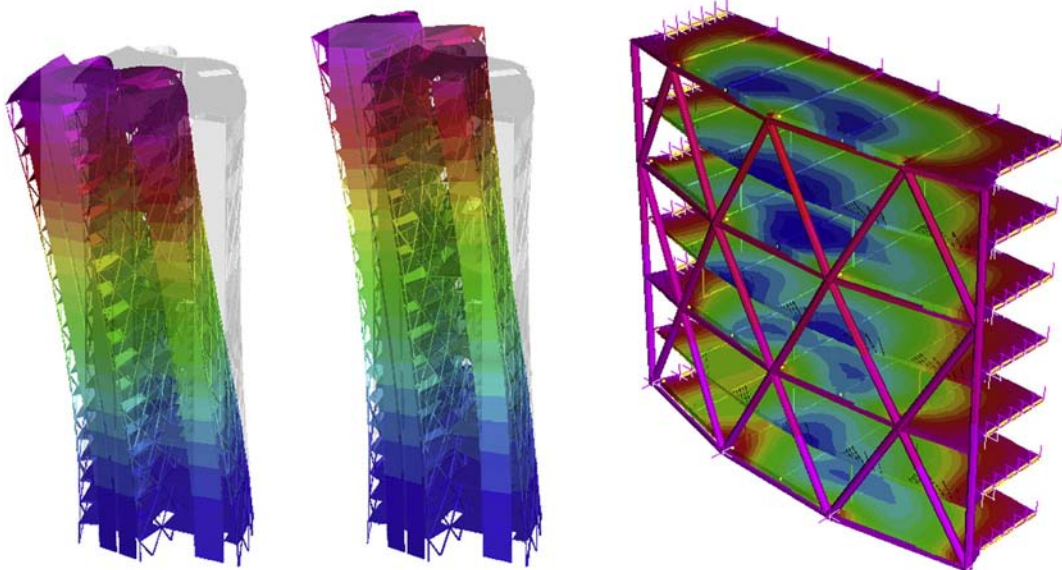


Fig. 15. FEM analyses: translational mode shapes for the structural dynamic analyses and displacement map on a static sub-model.



Fig. 16. Zcorp starch powder-based machine.

- environmental testing, i.e., calculation of wind speed in the outdoor spaces of the tower at different levels to assess pedestrian comfort;
- estimation of wind speed at technical storeys to confirm wind turbines' minimum activation speed;
- experimental test on a rigid model in order to estimate wind pressure coefficients on the building shell; and
- qualitative evaluation of wind flows.

The reliability of wind tunnel predictions has been widely demonstrated over the years by comparing experimental data to full-scale measurements [19]. The Politecnico di Milano Wind Tunnel facility consists of a closed circuit in which two test chambers are vertically arranged. The aircraft test chamber, delimited by a convergent upstream and a divergent downstream, is characterised by a low turbulence level, and the inside air can reach speeds of up to 55 m/s. Its section, 4×4 m in size, is located at the lower level. On the other hand, the upper test chamber (the boundary layer test section) has a section of 14×4 m, making it particularly suitable for civil, environmental, and orographic testing (also because of the maximum accessible speed, which is approximately equal to 16 m/s [20]).

The tests were carried out in turbulent flow conditions, achieved by the inclusion of upstream passive turbulence generators able to recreate the ultimate limit state of wind speed distribution, as proposed by the Eurocode [21]. The permeability of the louvre façade systems was reproduced by using two wire meshes characterised by different void ratios so as to properly simulate the air flow through envelopes designed with diverse technologies (Fig. 17).

At these levels, four Irwin probes [22] were placed and connected to the data acquisition system so as to measure the actual speed of the air flowing through the building. The differential pressure measurement provided by the probe was then correlated to the wind speed by

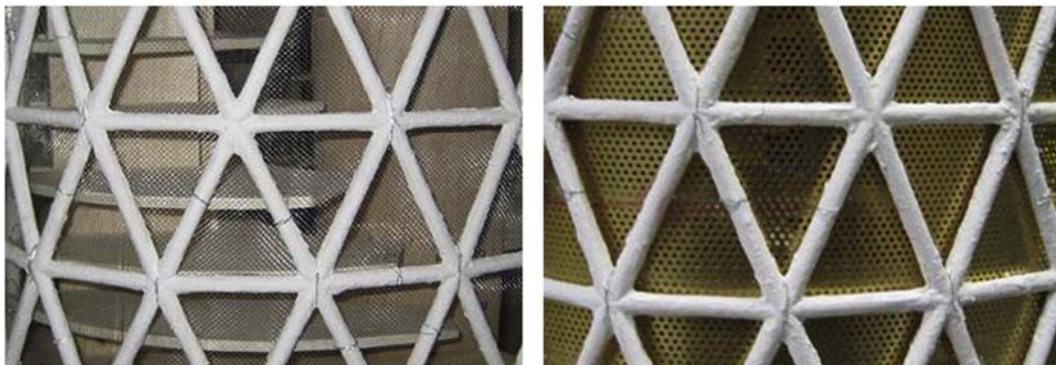


Fig. 17. Metal wires and rapid prototyped diagrid structure properly treated in order to ensure an adequate mechanical resistance.

Table 1

Experimental evaluation of average wind velocities in public squares.

Sensor	Height [m]	Undisturbed average speed [m/s]	Wind amplification factor [-]	Design speed [m/s]
A	46.5	3.5	0.67	2.35
B	46.5	3.5	1.15	4.03
C	69.5	3.9	0.42	1.64
D	125	4.4	0.05	0.22

means of experimentally calibrated parameters; by dividing the wind speed at the Irwin probe by the one measured at the same height in the undisturbed domain, a multiplier called speed-up or wind amplification factor [23] was finally estimated. This factor is of fundamental importance since it can be either applied to serviceability limit state wind speeds, allowing the estimation of average design data suitable for pedestrian comfort control. For this purpose, preliminary data of interest were acquired from official documents reporting the average wind speed in the city of Turin (made available by the European Wind Chart and the Italian Wind Atlas), while in the last phase of the project the weather data collected at the local airport were used, considering the average values of wind speed, as reported in Table 1.

4.3. Generalizability and reliability of the proposed procedure

It is important to emphasise that the proposed procedure is extensible to any type of building. In fact, regardless of the geometry and the use classification, accurate physical models can be produced with the support of the RP technology. As widely shown in the literature, experimental tests on scale models still represent an effective method for the validation of architectural projects. In contrast to analytical methods, which generally require a gradual simplification of the engineering problem with unavoidable loss of accuracy, the experimental approach can provide accurate results [19].

In general terms, the accuracy of the experimental results is conditional upon the degree of precision of the model (including a proper choice of materials), the design of the testing procedures and the processing of the collected data. All these aspects have been extensively studied over the years, leading to a level of knowledge that, if properly transferred, can significantly improve the traditional design practice. Unfortunately, a critical aspect might be related to the production and processing costs of the physical models that to date, excluding research projects, has resulted in an application only on buildings of strategic interest, characterised by high levels of complexity.

5. Results

As previously stated, the tests conducted in the wind tunnel were devoted to the evaluation of wind-induced structural and environmental effects by measuring experimental values on two village modules

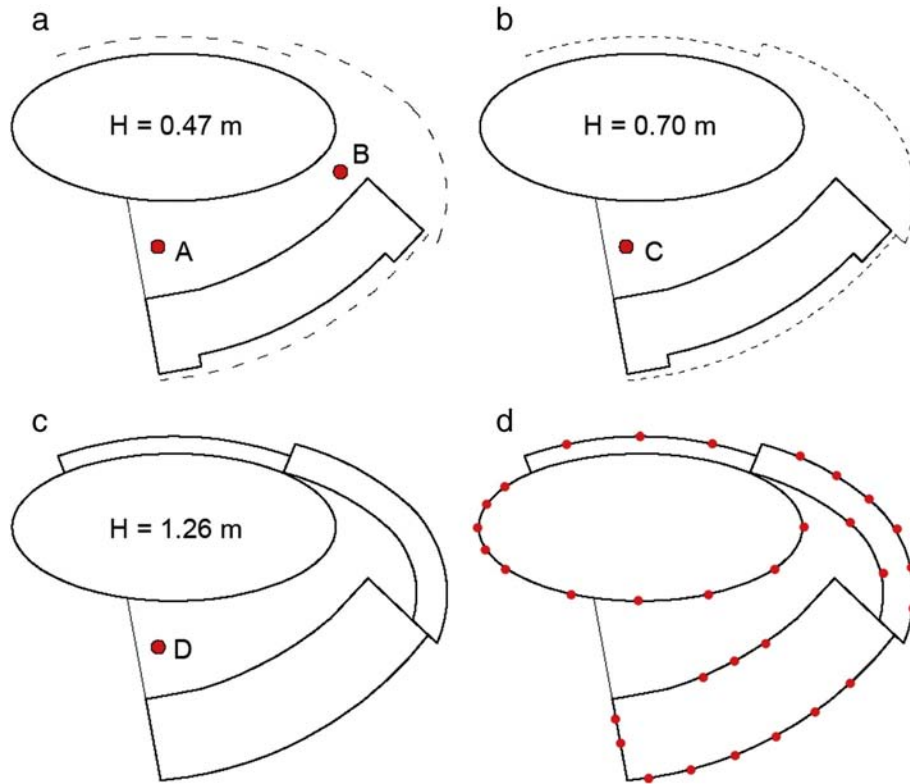


Fig. 18. a, b, c, and d (from left to right) Position of sensors A, B, C, and D for the experimental evaluation of wind speed and pressure sensor distribution around the tower perimeter.

placed in the central part of the tower just below and above the double floor that housed the technical facilities. Fig. 18 shows the position of sensors, with respect to the floor height, as measured on the scale model.

Following the procedure introduced above, we confirmed the acceptability of the inflow speeds (also in the narrowing regions subjected to the Venturi effect) as well as the compatibility of the velocity field with the housed functions. Thanks to the experimental measurements, average speeds lower than 5 m/s were estimated (see Table 1); as shown in the literature [23,24], this value is related to acceptable levels of comfort in cases of long-term sitting, long-term standing, and walking activities.

During the experiment, the effect of wind speed amplification due to a narrowing of the passage section was also examined. In the building system design, it was suggested that we exploit this effect in order to

maximise the amount of energy produced by vertical axis wind turbines installed on the technical floors. Those wind turbines are generally characterised by an activation wind speed of 1–3 m/s and it was hence proved that, since the narrowing provided an amplification of about 15% of the average natural wind (point B of Table 1.), a mean speed of 4 m/s is provided, allowing the selected system to produce energy throughout the year.

In Fig. 19 it should be noted that, for A and B probes, the wind amplification factors were higher than the ones read by probes C and D although the latter were placed at a higher level, characterised by the presence of an ETFE façade (Fig. 17). This behaviour confirmed the usefulness of the three façade technologies and gave information regarding the permeability coefficient modulation that had to be adopted, according to the height. In fact, knowing the permeability of the model, we can trace the void ratio back to the real situation by applying a first approximation reduction factor of about 15%.

The third step in this experiment aimed at determining the maximum values of pressure coefficients acting on the building façades (Fig. 20). These data are of fundamental importance in the structural calculation phase since they allow us to determine the ultimate loads and avoid problems of detachment or damage to the façade as a result of high depression peaks that could be achieved under particular wind directions. With further details, the peak pressure coefficients on the ETFE façade represented on the right-hand side of Fig. 19b, could reach a value of -2.1 (suction), 40% higher than the values suggested by the Codes for cylindrical shapes, i.e., -1.5 . As a matter of fact, in the case of the building proposed in this publication, the skyscraper did not have a configuration similar to any regular geometric shape, and the only possible analytical approximation, therefore, consisted of inscribing the building in a regular solid that best approximated it: a circular cylinder with height equal to the height of the real building, i.e., 150 m. A qualitative representation of the deformed shape of the circumscribing geometry subjected to the Code-suggested pressures is presented in Fig. 21. Although the approximation was very crude, this approach allowed us to determine, with a first level of approximation,

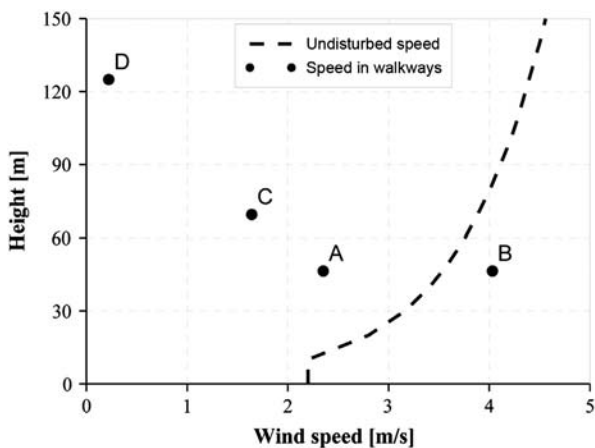


Fig. 19. Comparison between average undisturbed wind velocities and experimental walkway velocities.

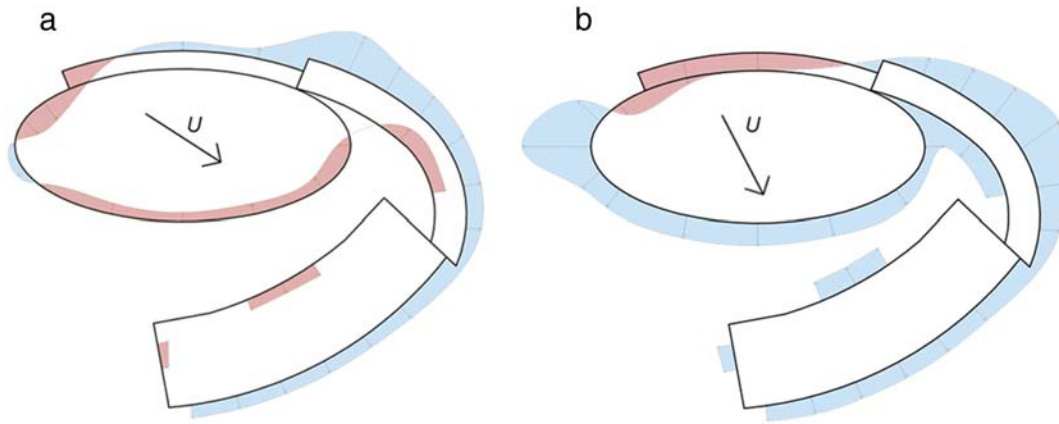


Fig. 20. a and b (from left to right) Qualitative pressure coefficient distribution under two selected wind directions (u). The darker hatch stands for positive pressure, while the lighter one represents suction.

the integral forces acting on each floor (derived from wind pressures) that could be useful in the early stages of structural calculation but that revealed, thanks to the experimental campaign, the limits of the analytical approaches in the case of complex architectures.

Since wind tunnel testing on scale models is still of fundamental importance in the verification phase of preliminary designs, significant efforts were made in the last decades in order to increase the amount of experimental data derivable from traditional test campaigns. As a matter of fact, the visualisation and measurement of wind flows may also be performed through image-based path lines tracking techniques that make use of tiny soap bubbles filled with helium [25], lit by a concentrated beam of artificial light.

Fig. 22 shows two video frames inherent with the experimental visualisation of wind flows on the 1/100-scale rigid model, instrumental for the identification of leading stagnation points, laminar flow regions, separation zones, and vortices. The direction of the prevailing flow was taken equal to the one shown in Fig. 20a, confirming the fact that, according to the Bernoulli Principle, stagnation points are characterised by positive pressure, while on lateral surfaces high negative pressures typically arise. This evidence was also borne out in the case of Fig. 20b, where the highest C_p absolute values were read by sensors placed orthogonally to the undisturbed fluid vein.

6. Conclusions

As shown, the application of rapid prototyping methods to physical building models at different stages of the design process and different levels of detail allowed the development of laboratory tests with results that led to the evaluation of building behaviour, which favoured appropriate architectural, technological, and structural choices. The outcome of the preliminary design was a complex architectural solution based on the application of innovative technologies and a flexible modulation of energy needs that, for the variety of innovative content, were not well covered by the traditional analytical verification approaches.

The use of small-scale models still represents the most affordable way to predict quantities of interest as wind velocities and pressure coefficients on complex shapes. This procedure of idealisation, digitalisation, and conversion into a physical object can be easily generalized to any kind of building and must be seen in the context of decision support by means of computer-aided engineering. As a matter of fact, craft procedures, like the ones used in the past for the preparation of technical drawings, have been gradually but increasingly radically modified by the diffusion of digital drawing methods that led to a profound revolution of project development procedures. Among these, the connection between digital design and CNC machines for the mechanical

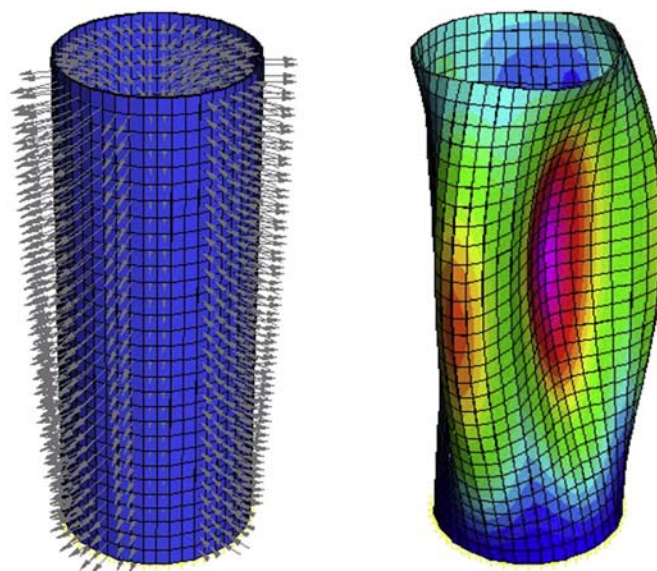


Fig. 21. Wind pressure distribution on a cylindrical approximation of the tower and qualitative deformed shape.

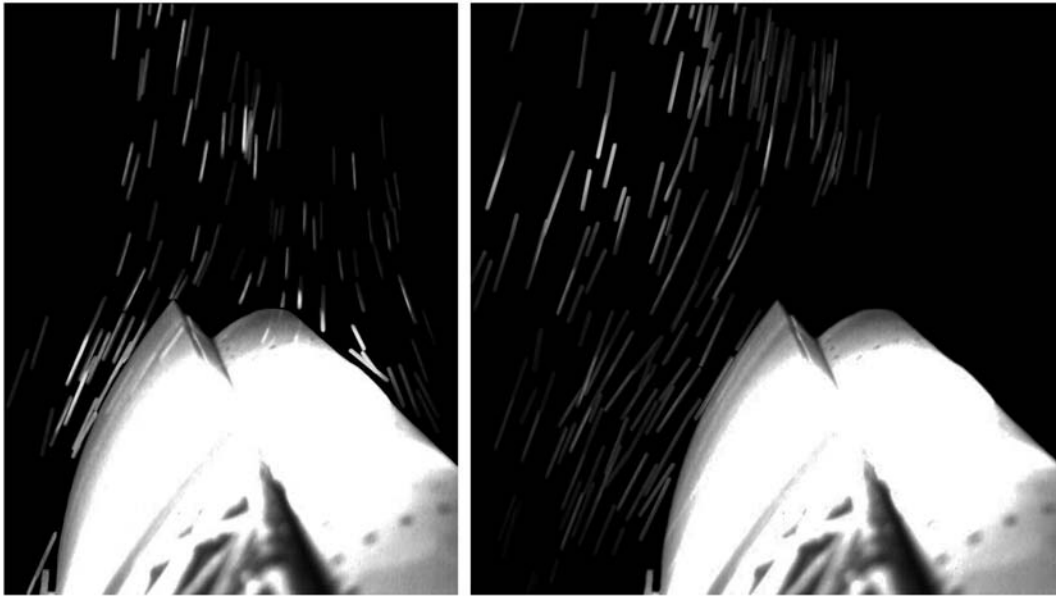


Fig. 22. Image-based path lines tracking technique.

production of prototypes at various project scales is substantial and useful. Techniques typical of industrial production might be hence effectively transferred to the building design process, revealing their substantive utility in decision-making phases. It turns out that the ease of use of physical models in previously not practised areas as in this case is a fundamental support to guide technological choices of innovative architectures.

From an eco-friendly stand point, the utilisation of wind energy associated with solar power required calibration of wind speed on the walkways to satisfy two conflicting requirements: on one hand, the maximisation of natural wind ventilation and energy production, with its need for rather strong and constant air speed facilitated by the vortex morphology of the village canyon; on the other, environmental comfort, with the need to reduce the wind speed perceived by walkway users. The experimental data obtained were hence instrumental in defining the levels of environmental comfort, volumes better suited to withstand the dynamic action of the wind, and even the possibility to provide green areas at high altitude. The results coming from the experimental evidence allow us to design façades with an integrated approach and to choose the most suitable permeability, with respect to their installation height, properly calibrated to ensure required performances.

As experimentally proven, when the incident flux interacts with the structure, it develops positive and negative pressure areas that may vary in space, time, and exposure. The geometry of the building was a key factor in the distribution of wind pressures and forces, as the turbulences were mostly generated by the building itself. The mathematical formulations proposed by the Codes for the determination of pressure coefficients acting on the buildings seemed to be applicable only on simplified shapes because of the complexity of the fluid dynamic phenomenon.

Through such considerations, it was pointed out how the function of the physical model as a tool to assist and validate the design choices has been weakly considered so far in the construction sector, which frequently recognizes its validity only for the final project presentation to an audience or a purchaser, identifying it as a communication technique of choices previously developed and tested in other disciplines despite a significant application potential in the field of experimental testing.

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