3D-PRINTING HIGH PRECISION COMPONENTS OF BUILDING SCALE-MODELS FOR WIND TUNNEL TESTING

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The article explores the transformative role of 3D-printing in architectural and engineering research, with a specific focus on its application in producing scaled models for wind tunnel testing of photovoltaic (PV) systems. The study highlights how 3D-printing enables the creation of prototypes which can be essential for the investigation and optimisation of structural designs. A case study explores the use of advanced 3D-printing technologies in the fabrication of extremely accurate and intricate items, such as instrumented PV modules incorporating hollow channels for pressure measurements, gear, racks, and sliding components. The integration of PolyJet and SLS technologies combined with tailored materials and meticulous post-processing treatments (such as sandblasting, spray polymer coating, alkaline solution dip, etc.) ensured high precision, functionality, and adaptability. This approach significantly reduced production time and costs while enhancing the reliability of experimental results. The findings underscore the potential of 3D-printing to revolutionise experimental methodologies, facilitating rapid design iterations and fostering innovation in sustainable and resilient building design.

INTRODUCTION

3D-printing has emerged as a transformative technology across numerous industries, including architecture and engineering, by enabling the creation of accurate, intricate, and highly customisable prototypes. Among its most fascinating applications is the development of scaled models for laboratory testing, such as wind tunnel experiments [1]. These models are instrumental in studying the aerodynamic behaviour of structures, identifying potential issues related to wind resistance, vibrations, and structural stability, and ultimately refining design solutions.

Wind tunnel testing is a cornerstone of modern engineering and architecture, providing critical insights into the interaction between buildings and environmental forces [2,3]. Whereas even minor deviations in geometry can significantly influence test results and the accuracy and reliability of these tests depend heavily on the quality of the prototypes used, although 3D-printed model can nowadays ensure great reliability as conventional models [4,5]. In this context, 3D-printing offers unparalleled advantages, allowing for an accurate yet quick and cost-effective the reproduction of complex geometric features and intricate details that are often essential to replicate real-world conditions [6].

Moreover, 3D-printing supports a wide range of techniques and materials [7], including resins, polymers, and composites, which can be tailored to meet specific project requirements. This flexibility ensures that prototypes not only mimic the geometric characteristics of the structures they represent but also possess the necessary mechanical properties to withstand testing conditions, such as aerodynamic loads and high-speed airflow.

One of the most significant benefits of 3D-printing is the efficiency it brings to the prototyping process. Traditional methods, often involving manual craftsmanship, were time-consuming and expensive, requiring specialised skills to produce even basic models. In contrast, modern 3D-printing technologies enable the rapid translation of digital designs into physical models, often within a few days or just hours. This accelerated timeline empowers engineers and architects to iterate more effectively, incorporating feedback and optimising designs with minimal delays.

In wind tunnel experiments, 3D-printed models are required to be provided with an ultra-high precision as they are generally equipped with sensors and other instrumentation to measure aerodynamic forces and pressures with high precision. These measurements yield valuable data that guide the design of safer, more efficient, and better-optimised structures. The ability to produce high-precision models through advanced 3D-printing techniques [8] represents a significant leap forward in experimental methodologies, offering both enhanced accuracy and reduced costs.

CASE STUDY

Nowadays, the integration of photovoltaic (PV) systems on buildings to enhance energy efficiency has become an increasingly relevant topic, especially in the context of large roofs. These surfaces, if properly designed and utilised, can ensure significant energy productivity, contributing substantially to sustainable energy solutions. To maximise the energy output of such systems, it is essential to install solar arrays with an optimal orientation and tilt angle designed for the specific latitude of the site. This precision ensures that PV modules capture the maximum possible solar radiation throughout the year.

However, in practical applications, PV modules are often installed coplanar to the roof slope, since higher tilt angles, though more efficient for energy capture, are associated with increased wind-induced loads transferred to the support structure of the PV modules and since the reference regulations [9] do not always provide exact specifications for such conditions. While this approach simplifies installation and reduces structural stress, it also typically leads to a compromise in energy productivity.

To provide designers with more information about the wind loads on rooftop PV modules, wind tunnel tests were carried out [1] on a 1:10 scale model of a representative building featuring a quadrangular footprint and a flat roof situated at a height of 10 meters (Figure 1). The model incorporated standard PV modules arranged in parallel 8 strings (each is ~20 meters long in real scale), tilted with angles varying between 5° and 30°, assumed to be parallel to the slope direction and/or the building edges. The design of the model required to feature specific adjustments to allow for the investigation of the influence of several geometric parameters, i.e. the tilt angle of the strings (5° to 30°), the spacing between rows (0.6 to 1.15 m), the wind direction (all-round), and the clearance between the panel's bottom edge and the roof plane (15 to 30 cm), as shown in Figure 2.

Therefore, the strings length had to be enough to avoid the affection of pressure coefficients by corner vortexes. According with the previous studies, a 12 photovoltaic modules string (1920 mm long) was considered adequate.

Moreover, increasing the side spacing between adjacent modules has proved having minimal effect on the force coefficients, while the wind load coefficients increase as the rows spacing is increased. For this reason, the model strings were designed without providing any gap between modules.

Furthermore, for roof-mounted arrays the wind load coefficients appeared to decrease with increasing perimeter gap from the building edge. It was then conservatively chosen one standard distance of 1.5 m from the edge, which can be considered the minimum to allow the integration of a perimetral gutter and a maintenance walkway.

Each PV string needed to be equipped with a total of 56 pressure taps in correspondence of 28 positions distributed along both the upward and downward sides of the modules (Figure 3), to be connected to pressure sensors via tubes embedded in the module thickness, enabling accurate measurements of wind-induced pressures. For symmetry, half of each string featured instrumented modules, while the other half comprised solid components (Figure 1).

Given the complexity of the adjustable components and the precise instrumentation required for the PV modules, the small scale of the model posed significant manufacturing challenges. Traditional production methods would have struggled to achieve the necessary level of detail, precision, and adaptability within a reasonable timeframe and budget. In this context, 3D-printing proved to be a transformative solution, offering unmatched accuracy and flexibility. This advanced manufacturing technology not only enabled the creation of intricate parts with fine tolerances but also facilitated rapid prototyping and adjustments, ensuring that each component met the stringent requirements of the experimental setup.

Moreover, 3D-printing allowed the integration of complex features, such as internal channels for pressure taps, directly into the module design, which would have been nearly impossible with conventional techniques. By reducing production time and costs while maintaining exceptional precision, 3D-printing played a pivotal role in the success of the wind tunnel tests, enabling a faithful and reliable

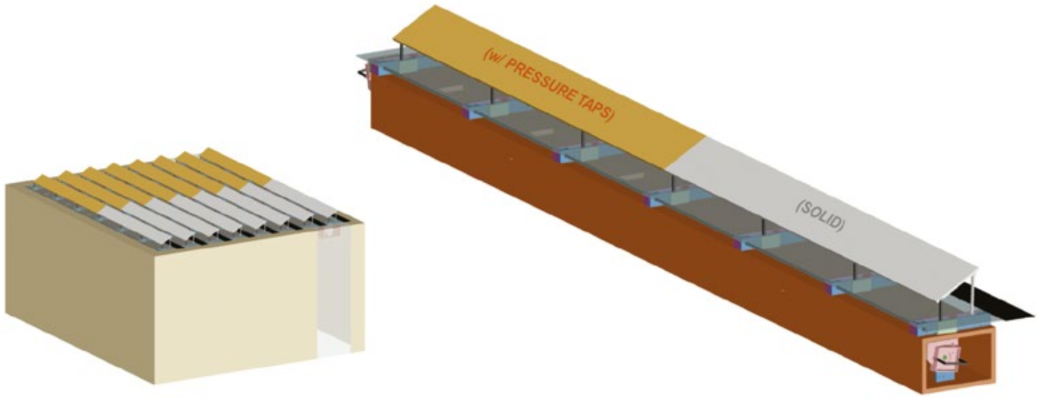

Figure 1: Representative building 1:10 scale model.

Figure 2: Typical geometric parameters for flat-roof mounted PV strings.

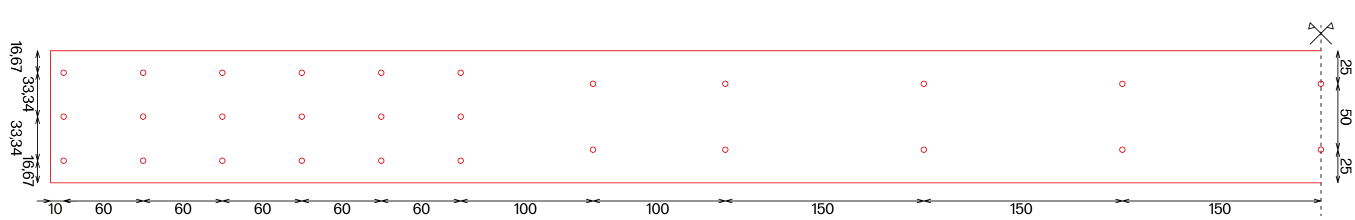

Figure 3: Pressure taps position on the half string.

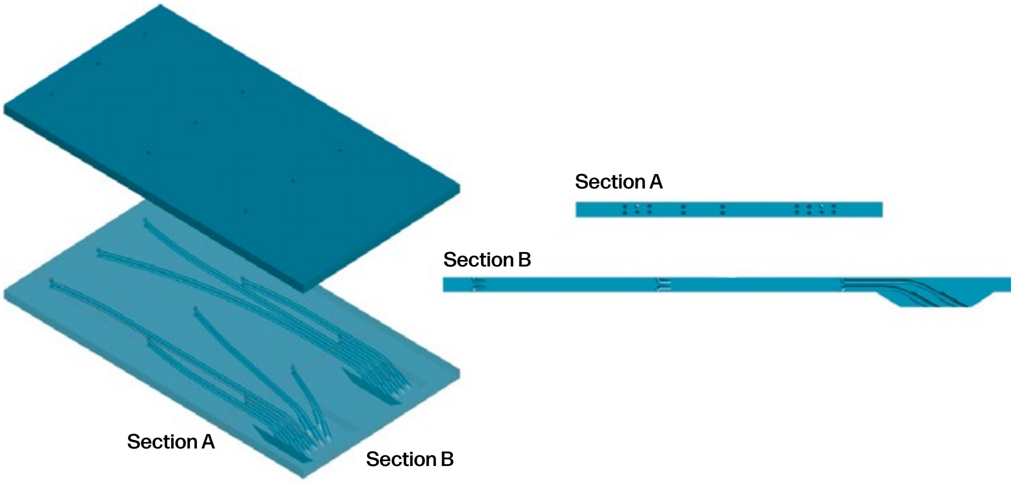

Figure 4: Virtual model of 1:10 instrumented solar panel provided with pressure taps and connection tubes. Panel cross-sectional thickess is 5.0 mm; tubes diameter and minimum wall thickness are 1.0 mm; minimum curve radius is ~10.0 mm.

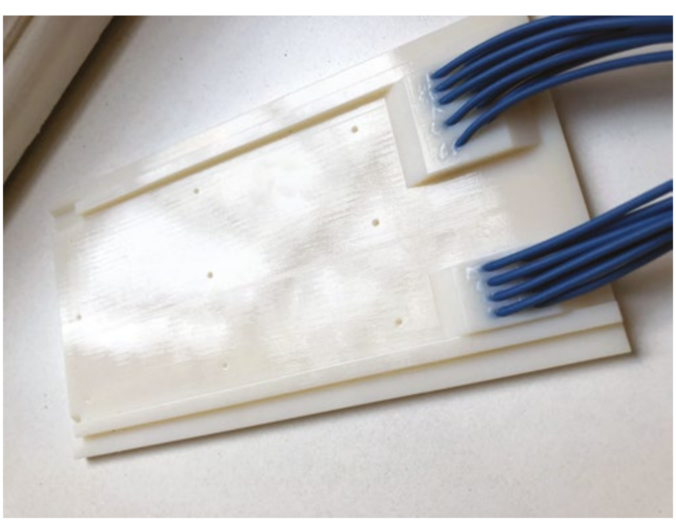

Figure 5: 3D-printed instrumented solar panel, fully assembled.

Figure 6: PolyJet 3D-printing of instrumented solar modules with embedded pressure tubes.

simulation of real-world conditions. Its application in this context highlights its potential as a game-changing technology for the development and optimisation of advanced experimental models in engineering research.

The model's components were manufactured using a variety of advanced printing technologies, each chosen based on the specific requirements of the individual parts.

The most complex items were the instrumented solar modules, which presented a significant challenge due to their intricate design, which needed to accommodate high-precision features within a very limited thickness of just 5 mm. Within this thin profile, two rows of hollow tubes were integrated, each with a diameter of 1 mm and a wall of 1 mm (Figure 4). These tubes served the critical function of connecting pressure taps (holes), strategically positioned on both main surfaces of the panel, to an end collector. The collector itself was meticulously designed to allow the insertion of silicon tubes, which were subsequently fixed in place and sealed using an adhesive and then connected to pressure sensors, forming a complete system for pressure monitoring (Figure 5).

The primary technical challenge in creating these modules lays in achieving hollow geometries with an extremely high precision. The tubes had to maintain a constant cross-section along their entire length and be completely airtight to prevent any errors in the pressure readings. Any deviation from these stringent requirements could compromise the functionality of the pressure system.

In order to meet such requirements, the modules were fabricated using a Stratasys Objet260 Connex3 3D-printer, a machine equipped with advanced multi-material jetting photopolymer technology, commonly referred to as PolyJet. Such technology operates by jetting ultra-thin layers (down to an impressive 16 μm) of a liquid photopolymer onto the build platform. These layers are then progressively cured using UV light and bonded together (Figure 6), resulting in parts with outstanding precision and extremely fine and precise wall thickness. The printing material used for the modules was a simulated polypropylene, known as "digital" polypropylene, obtained by combining VeroWhitePlus and Agilus30. This combination provided the printed components with good mechanical properties and a smooth surface finish that met the design specifications.

To create hollow geometries, SUP706 support material was utilised. This material, intended to be soluble in alkaline cleaning solutions, filled the internal cavities during the printing process, ensuring structural integrity and accurate dimensional control. However, removing the support material proved to be a particularly labour-intensive process. Each printed item required multiple cycles of cleaning to ensure the internal cavities were completely free of residual material. This process involved soaking the parts for 5 minutes in a heated and agitated cleaning station containing a solution of 2% sodium hydroxide and 1% sodium metasilicate. Following the soaking, a fine nylon monofilament, with a diameter of 0.5 or 0.7 mm, was repeatedly inserted into each tube to mechanically dislodge any remaining material, and then the ends of the tubes were rinsed using a high-pressure water jet to ensure complete removal of the support material. Concerning the whole cavities cleaning process, 3D-printing proved to be the best approach since it allowed initially a quick and easy optimisation of tubes geometry in terms of section diameter, wall thickness, and curve radius in order to comply with the strict quality and precision requirements. Eventually, each printed model was dipped for 30 seconds in a 15% glycerol solution for strengthening.

In contrast, other components of the model, such as the dummy solar modules and parts of the adjustment mechanisms with simpler geometries, were fabricated using an alternative production method better suited to their functional and design requirements. These components were produced with an EOS Formiga P110 selective laser sintering (SLS) 3D printer (Figure 7). This method employed PA12 nylon powder as the base material, chosen for its excellent mechanical properties, including robustness and resistance to wear, making it an ideal choice for structural components expected to endure prolonged use.

Once the printing process was completed, the components underwent an accurate post-production sandblasting process. This step was essential for removing residual powder from the items' surface, ensuring a clean, smooth and uniform surface appearance, crucial for the functionality of the parts, and preparing the components for subsequent treatments.

Certain components with specific performance requirements, such as gears, racks, and other sliding elements belonging to the adjustment mechanisms required additional treatments to enhance their operational efficiency. These parts were treated with a spray-applied polymer coating, which smoothed the surface further, significantly reducing roughness due to the printing process, and sealed the material, making it non-absorbent to preventing the ingress of contaminants. The latter treatment was intended to prepare the surface for the application of a PTFE lubricant, which was crucial for minimising friction in areas where low resistance was essential. The combination of the smooth, sealed surface and the PTFE lubricant significantly improved the performance of the sliding components, ensuring reliable and consistent operation.

This enhanced functionality was critical for enabling smooth transitions between different string configurations. Each configuration adjusted the tilt angle and bottom clearance of the solar modules through an operation driven on each string by a system of 2+1 NEMA17 stepper motors (Figure 8) controlled by an Arduino shield which provided accurate control and synchronisation across the system, ensuring accurate positioning.

Eventually, 3D-printed parts were integrated with other components (i.e. envelope panels and strings support frames produced by CNC milling wooden panels, and strings top covering panels made by laser cutting PMMA slabs) to create the whole model (Figure 9).

The careful integration of materials, fabrication methods, and post-processing treatments ensured that all model's components met the stringent requirements for functionality and precision of this advanced prototype.

CONCLUSIONS

In conclusion, the integration of 3D-printing into architectural and engineering research has proven to be a groundbreaking development, particularly in the production of scaled models for laboratory testing. This technology has revolutionized the approach to experimental studies, offering unprecedented precision, adaptability, quickness and cost-effectiveness. The ability to create complex geometries, replicate intricate details, and incorporate functional features directly into the prototypes is unmatched by traditional manufacturing methods.

The application of 3D-printing in the wind tunnel testing of photovoltaic systems demonstrates its transformative potential. The intricate instrumented PV modules required for these tests, featuring hollow channels, pressure taps, and thin-walled structures, were made possible only through advanced 3D-printing techniques such as PolyJet technology. The exceptional precision of this method ensured airtight tubes and geometries that met the strict requirements for accurate pressure measurements. Simultaneously, the flexibility to produce robust yet simplified components, like adjustment mechanisms and dummy solar modules, using SLS technology highlighted the versatility of 3D-printing in handling diverse manufacturing challenges.

Furthermore, the use of tailored materials, such as digital polypropylene and PA12 nylon, allowed for the optimisation of mechanical properties while meeting the specific demands of different components. The post-production treatments, including cleaning, surface finishing, and lubrication, further exemplified the adaptability of 3D-printing to achieve high-performance standards in demanding applications.

The success of this project underscores the pivotal role of 3D-printing in advancing experimental methodologies. By significantly reducing production time and costs, while maintaining the highest levels of accuracy and functionality, this technology has proved to enable engineers and researchers to rapidly iterate design refinements in order to eventually gather reliable data for real-world applications. By bridging the gap between digital design and physical prototyping, this technology is reshaping the possibilities of sustainable, efficient, and resilient building design.

Looking ahead, 3D-printing is bound to become an even more crucial part of engineering workflows. Such technology, as demonstrated by its great contribution in the creation of high precision components for experimental testing, is not only a manufacturing method, but also a catalyst for innovation, enabling the creation of safer, more efficient, and better-optimised structures.

REFERENCES

[1] G. Scrinzi, *Experimental testing methods for the performance control of standing seam roofing systems for large-roof applications and photovoltaic systems integration*, PhD Thesis, Politecnico di Milano, 2023.

[2] American Society of Civil Engineers, "Wind tunnel studies of buildings and structures", *ASCE Manuals and Reports on Engineering Practice No. 67*, 1999.

[3] A. P. Jeary, "The use of wind tunnel measurements in building design", IntechOpen, 2011.

[4] S. K. S. Boelens, R. A. W. M. H. J. Smits, D. H. Van Campen, "Models for wind tunnel tests based on additive manufacturing technologies: A review", *Aerospace Science and Technology*, 2018.

[5] H. I. Shahidin, M. R. Abdul Rahman, A. Che Idris, M. R. Saad, "3D printed models vs conventional models: Comparison of aerodynamic performance for wind tunnel experiments", *Jurnal Kejuruteraan*, 2021.

[6] E. Kroll, D. Artzi, "Enhancing aerospace engineering students' learning with 3D printing wind-tunnel models", *Rapid Prototyping Journal*, 2011.

[7] S. F. Iftekar et al., "Advancements and Limitations in 3D Printing Materials and Technologies: A Critical Review", *Polymers*, 2023.

[8] E. Kluska et al., "The Accuracy and the Printing Resolution Comparison of Different 3D Printing Technologies", *Transactions on Aerospace Research*, vol. 2018, pp. 69-86, 2018.

[9] European Committee for Standardization "Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions (EN 1991-1-4:2005)", 2005.

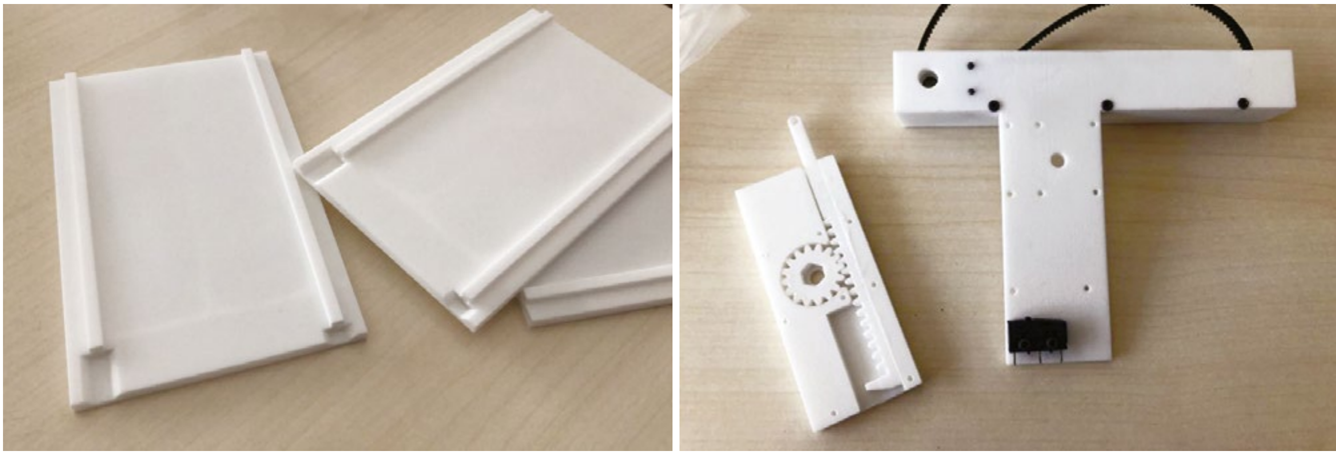

Figure 7: SLS 3D-printed solid PV modules and example of adjustment system components.

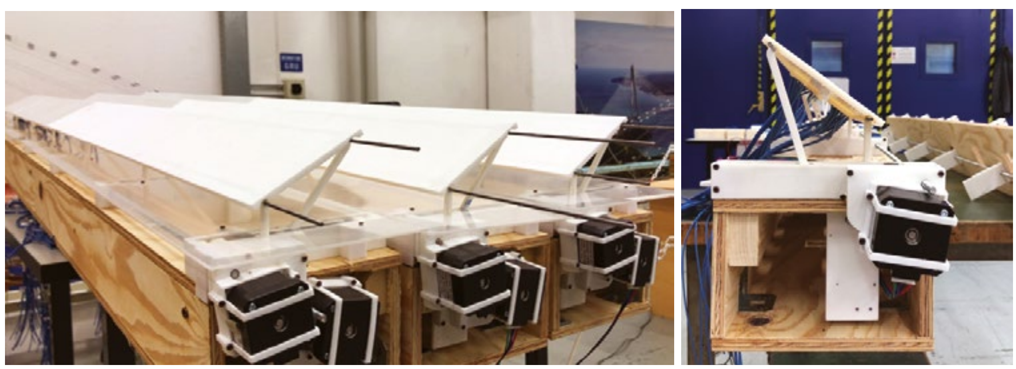

Figure 8: Scale model strings assembled and equipped with stepper motors for adjustment capability.

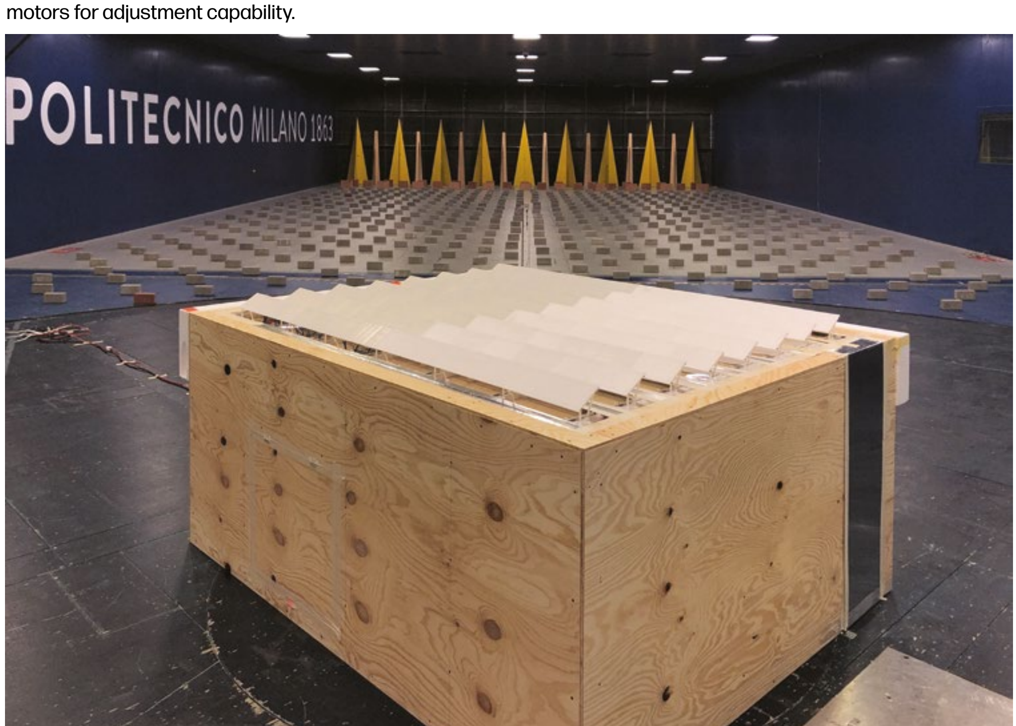

Figure 9: Scale model fully assembled inside PoliMi boundary layer wind tunnel.