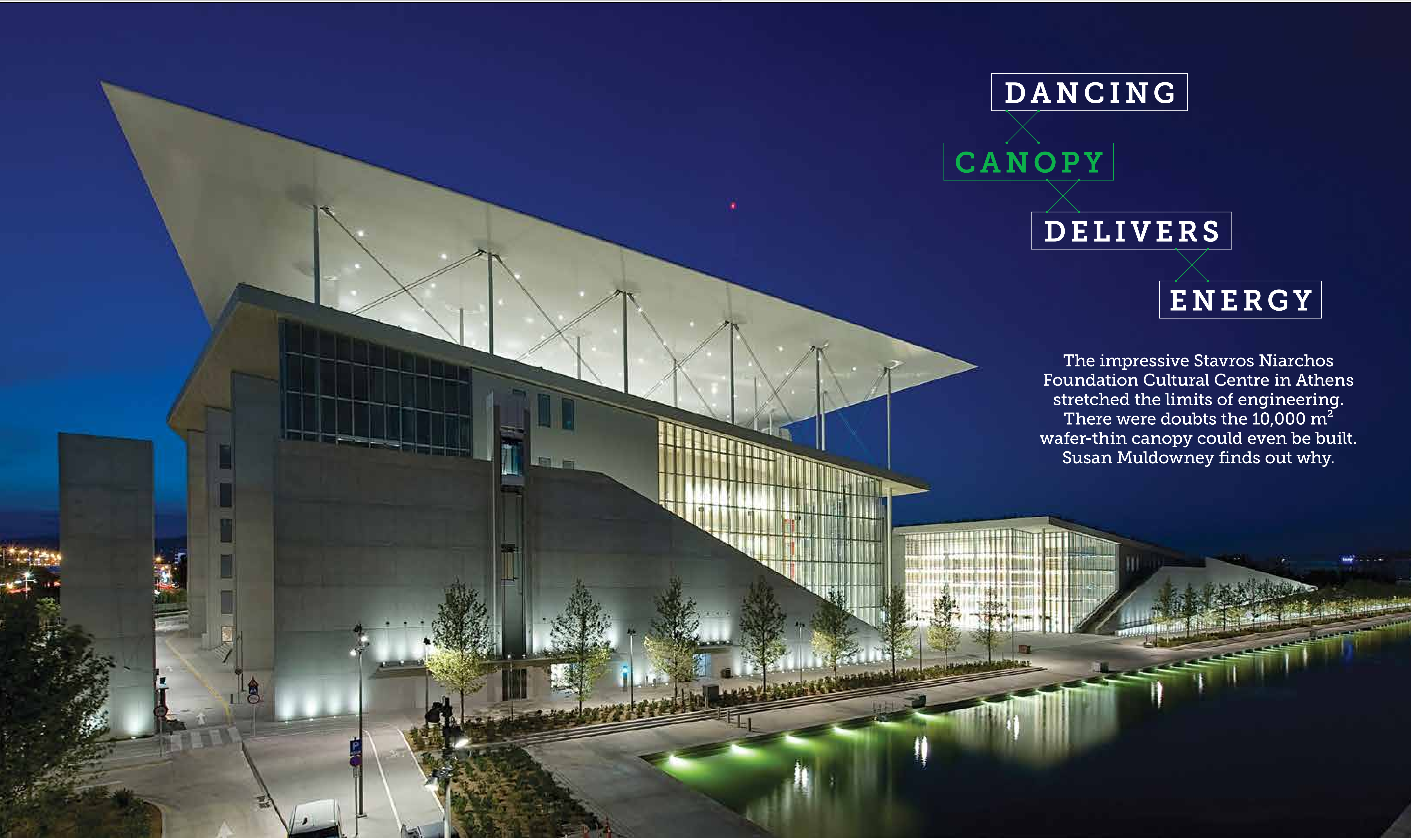

DANCING CANOPY DELIVERS ENERGY

The impressive Stavros Niarchos Foundation Cultural Centre in Athens stretched the limits of engineering. There were doubts the 10,000 m^2 wafer-thin canopy could even be built. Susan Muldowney finds out why.

In the bay of Phaliron in Athens, the Stavros Niarchos Foundation Cultural Centre (SNFCC) rises out of the ground like a dislodged piece of the earth's crust. The complex is home to the new National Library of Greece, a National Opera House and a 210,000 m^2 landscaped park that gives a much-needed injection of greenery to one of the city's most densely populated neighbourhoods, Kallithea.

It was designed by Renzo Piano, who, along with Richard Rogers, left the architecture establishment aghast in the 1970s with an inside-out design of the Pompidou Centre in Paris. While Piano's design of the SNFCC lacks the visual shock value of his earlier architectural icon, it certainly kept the engineers on their toes.

Set on the site of a former car park established for the 2004 Olympic Games, the 566 million euro (A$836 million) project was funded by the Stavros Niarchos Foundation, a private charitable organisation formed by the late Greek shipping magnate. Leading Greek and international construction companies were invited to submit bids and were given 10 months to prepare a detailed technical proposal. The contract was awarded to Italy's Salini Impregilo, which led a joint venture with Greece's TERNA, and construction commenced in 2012.

The SNFCC was designed to look like a dislodged piece of the earth's crust.

Give me shelter

Piano envisaged the SNFCC emerging from the landscape like "a dislodged piece of the earth's crust", as he has described it. The grass-covered slope of the structure's roof rises from ground level to its highpoint of more than 35 m.

The opera house, which includes a 28,000 m^2 auditorium, and library are topped by a glass-enclosed terrace, called the Lighthouse, and a 10,000 m^2 wafer-thin canopy made of ferro-cement appears to hover above it.

The canopy proved the greatest sticking point throughout the tender process. "Very large construction companies from Europe officially wrote to the owner and said that the canopy should be excluded from the tender because they were not sure that it could be built," says Dr Gregory Penelis, civil engineer and owner of Penelis Consulting Engineers SA, which worked with Salini Impregilo as structural and earthquake engineering consultants on the project.

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"We had the same concerns about whether it was [possible] or not. The joint venture spent a lot of resources, both time and costs, during the tender to evolve the technology to allow it to be built and we did a lot of mock-ups of the canopy during the tender."

The main challenge, as Penelis explains, was the canopy's slender form. It is comprised of 720 panels that span almost 7 m x 3.5 m with sections as narrow as 3 cm. Each panel is made from ferro-cement – a low-tech material more commonly used in rowboats than buildings and which has never been used in a structure of this size.

"Given that there is no code for ferro-cement design and only recommendations, everything had to be verified by testing," says Penelis. "From the beginning, there was an extensive program of testing, which started in small sections and ended up with full-scale panels."

Ferro-cement has strict geometrical tolerances when used as a structural system. Penelis says that for every 3 m, there was a tolerance in the order of around 5 mm.

"This cannot be done by hand, so we decided that it had to be pre-constructed using steel moulds that would allow us to achieve this geometrical tolerance. Otherwise, there would be the risk of second-order effect buckling."

Salini Impregilo set up a 4000 m^2 factory on site with two production lines and around 300 people to fabricate each ferro-cement panel. It was a six-month process that Gianni Botteon, project manager with Salini Impregilo, has described as recalling "those workshops of the Renaissance".

Such a humble description belies the engineering innovation required to build not only the individual panels but the canopy as a whole. The panels join to form the upper and lower shells of the canopy, which are connected by a maze of diagonal steel tubes that resemble a space truss. Each panel has its own unique geographic coordinates to ensure that it slots perfectly into place with a margin of error no more than 2 mm.

Below: The SNFCC canopy is crowned by a 40 m glass fiber polymer mast. Above: Interior.

Dancing in the wind

The canopy is supported by 30 steel columns, each a mere 30 cm in diameter, and column-head mechanisms, which allow the canopy to hang from the columns rather than rest upon them. "There are structures controlled by springs for lateral movement, but for a structure of this scale it's the first time that it's been done," explains Penelis.

While the canopy is 4.5 m high in the centre, its perimeter dips to 2.5 m and this is where the columns are placed. "We had to find springs that could fit in there," says Penelis.

"Mechanical springs were calculated but were in the order of 2 to 2.5 m, meaning that we would have to change the shape of the canopy. As you know, the role of a structural engineer is not to modify the architectural shape but to find ways to make the shape work."

A solution was found in the Belgian railways system, which uses silicon-based springs as shock absorbers between train carriages. A 30-year-old spring was tested to see how it operated after three decades of operation and was found to be at 95 per cent of its original design specs.

"This meant that this technology, which could fit within our structure, was safe," says Penelis. "The loading and unloading cycles of a train were much more than what we needed. We only needed about a quarter of that."

Each column is supported by four column heads comprised of four springs and two dampers. This allows the canopy to move accommodating vertical loads and the springs also protect the canopy from collapsing in an earthquake.

Penelis describes the canopy's movement as like a gentle waltz. "It's not 'Gangnam Style'," he says. "The dampers help it move smoothly and we control the damping to avoid resonance. After the wind stops, the canopy moves two more cycles then stops, so that when the next gust of wind comes, it's not still moving from the previous wind."

Environmental innovation

The canopy also contributes significantly to the SNFCC's environmental credentials. While Piano was insistent that no joins be visible on the lower shell (when he gazed up at the canopy from the rooftop terrace his desire was to see a seamless white surface that shone above him like the bonnet of a Cadillac), the upper shell serves a more practical purpose.

MAST THAT BENDS IN THE BREEZE

The SNFCC canopy is crowned by a 40 m glass fiber polymer mast designed to sway in the breeze or bend in a squall without snapping.

"There was a similar attempt made [with a mast] at the Canary Wharf in London but it didn't wobble," explains Dr Gregory Penelis. "The mast we designed is the first in the world that wobbles as foreseen."

Wind loads were calculated using a fluid dynamics model developed at the Polytechnic University of Milan and the design was based on a second-order nonlinear analysis and a raindrop algorithm.

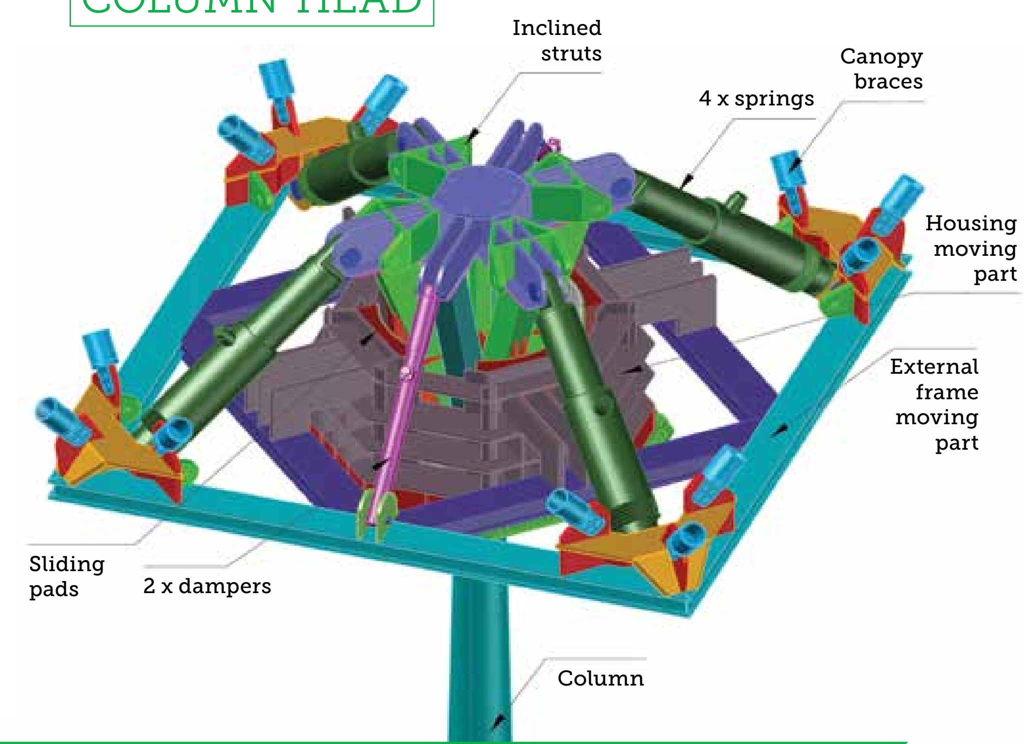
"The problem was that when the mast is vertical there is almost zero deflection and when the wind gusts, in the initial stages, you have the full area of the mast being subjected to the wind," he says.

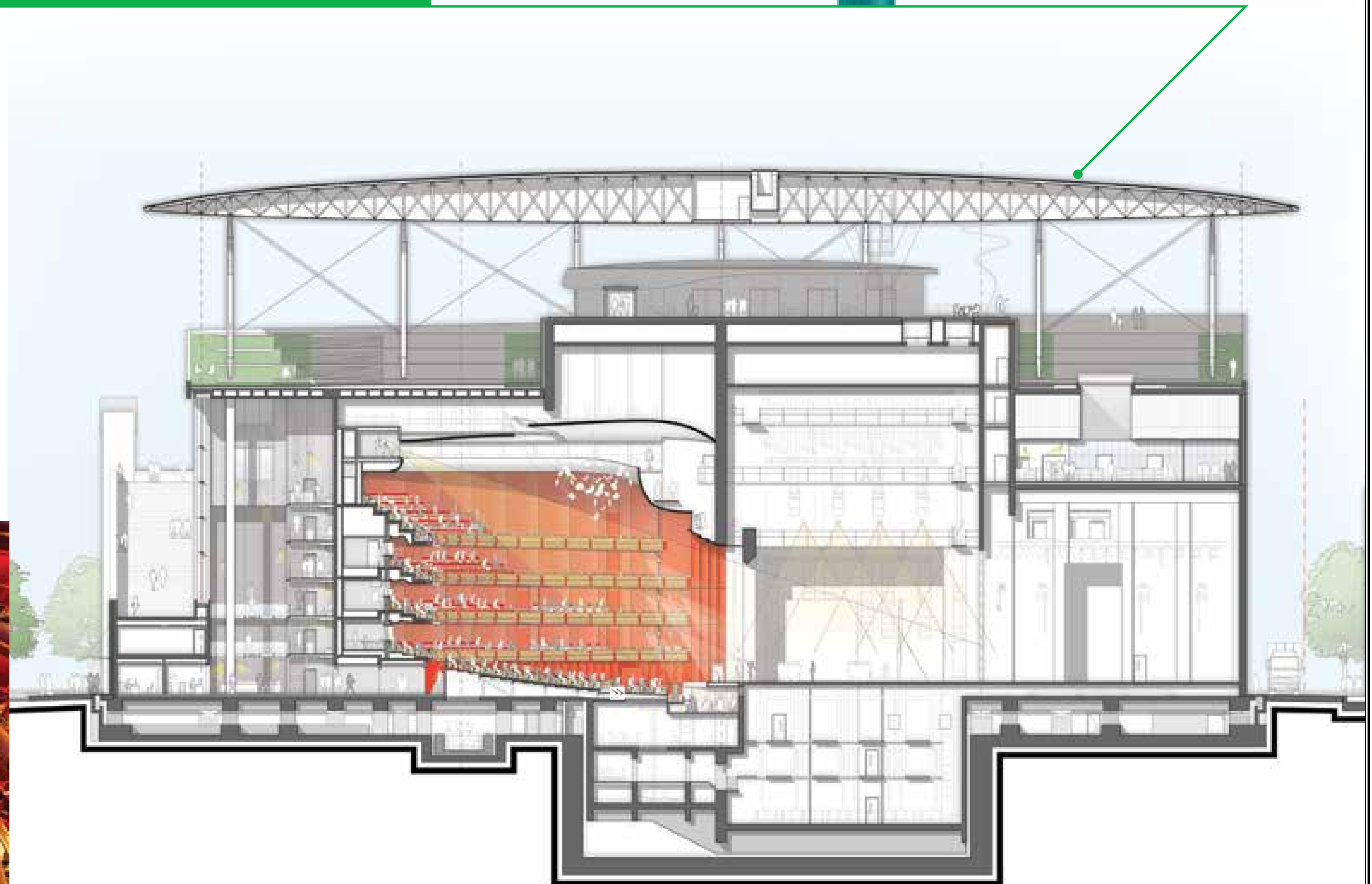
The mast is designed to deflect 5 m at its tip in gusts of 10 m per second. "As the wind increases, the area that is under the wind load actually decreases because the mast bends," explains Penelis.

Penelis and his team also had to test how the mast would behave over time and calculated that each section is resilient for 50 years. When construction of the mast was complete, Penelis and personnel from Salini Impregilo joined Renzo Piano at the Port of Genoa for final testing in high wind. "Before it was shipped to Athens, we wanted to see how it behaved and to verify that our calculations were correct," he says.

"It's a different thing to have it in Genoa where nobody knows what it is and if it fails for whatever reason than to have that happen in site. We had it controlled by wires so it wouldn't fail completely if there was a problem. Then we got the go ahead to bring it to Athens."

COLUMN HEAD





From left: the canopy's shell has no visible seams from below; the opera house; and a section through the opera house.

It is designed to catch maximum rays via 5560 photovoltaic panels that can generate 2280 kWh of electricity each year and help fulfill the energy requirements of both the opera house and library beneath it.

The canopy also acts as shades to reduce solar gain while the grassland that rises over the library improves thermal insulation. Rain falling on the canopy is captured in an invisible gutter along the perimeter. It then flows down pipes inside the canopy's steel columns and is carried to gravel trenches buried throughout the park.

The SNFCC has received a Platinum level LEED (Leadership in Energy and Environmental Design) certification due to principles of sustainable construction and environmentally-innovative practices.

When the earth moves

Engineering ingenuity was further challenged by the fact that Greece is one of the most seismically active countries in the world.

The SNFCC's opera and library are mounted on inverted pendulum seismic isolators that are also among the world's largest – some in the order of 2.5 m x 2.5 m.

"Imagine that the building is sitting on a skateboard – the skateboard moves but the building remains stable," says Penelis, explaining that lateral acceleration would be around five per cent due to friction of the isolators.

Seismic isolation of some of the columns in the opera and library have an axial force of around 7000 t, however the opera stage pit presented an obstacle due to its huge, column-free span. "This results in very high axial loads being transferred to the ground at specific locations around the stage," says Penelis.

WHAT IS FERRO-CEMENT?

The material used to craft the SNFCC's majestic canopy was invented in the 1840s as the stuff of humble flowerpots. French gardener Joseph Monier was dissatisfied with the fragility of clay pots and began experimenting with a reinforced concrete that would provide greater durability at a lower cost.

At the same time, fellow Frenchman Joseph-Louis Lambot was investigating a similar material to build a rowboat. He exhibited the boat at the 1855 World's Fair in Paris and patented the vessel and its water-resistant, malleable material, which was created by applying cement mortar over wire mesh and thin steel bars.

Ferro-cement was surpassed by reinforced concrete but was resurrected almost a century after its first applications when Italian structural engineer and architect Pier Luigi Nervi began using the material in the design of boats during WWII.

Nervi refined ferro-cement by redistributing the steel rods in the mortar to increase the contact area between the two materials to increase its malleability and reduce the chance of cracking. He became the first to use the material in building construction, notably the celebrated Turin Exhibition Hall, which features ferro-cement elements in its roof system that spans 94 m.

"Renzo Piano's choice of ferro-cement for the SNFF canopy is thought to be a nod to Nervi (both had also built their own yachts from the material) and is the first ferro-cement structure of this scale in the world."

As seismic isolators could not go inside the 3000 t opera stage pit, it is hung upside-down from the adjacent structure and surrounded by diaphragm walls.

The challenge in creating new innovations for the SNFCC is that they were developed on the run during the timeframe construction. Seismic isolators were scaled down by 20 per cent and tested in a San Diego Caltrans laboratory.

"The whole project was completed in 38 months and all these things needed to be solved within the first 20 months," says Penelis. ●

The SNCC is the vision of architect Renzo Piano.