Raising the bar

The challenges of designing a new university campus that spans above a subway station

Authors Hironori Hisaki, Junichiro Ito, Mitsuhiro Kanada

Nagoya Zokei University is a renowned art and design university in Japan's fourth most populous city. When it chose to move its entire campus from the outskirts of the city into the bustling urban centre, severe physical limitations on the new site and potential exposure to earthquakes were the catalysts for a highly innovative and inventive building design.

Arup provided structural engineering, seismic design, and mechanical, electrical and plumbing (MEP) services for the 20,917m² project, which has a subway station and line running below the site. To avoid putting additional load on the upper part of the station, the decision was made to elevate the building using a bridge-like design straddling the subway, with a 40m-wide steel truss spanning between concrete cores. The design creates a central 'art street' that passes through the building, offering a semi-outdoor space to the local community which encourages social interaction through art. The truss supports a massive flexible studio on the fourth floor that features only a few standing walls and just one type of thin diagonal bracing.

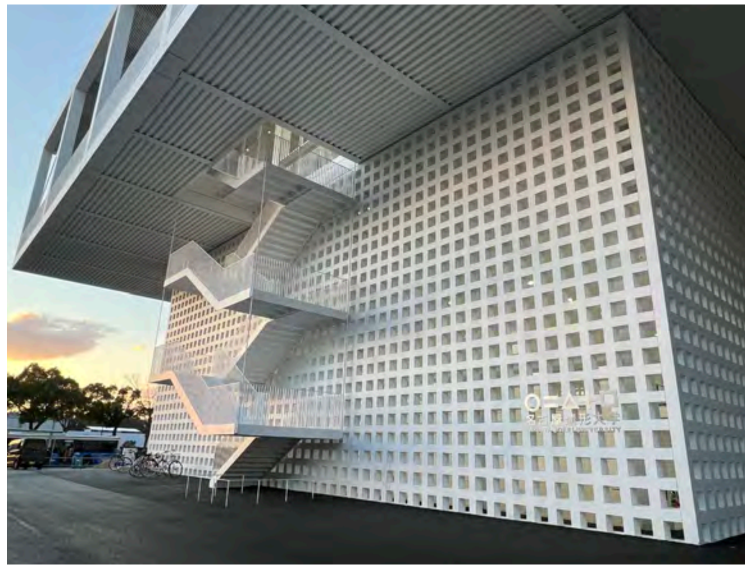
Aichi Prefecture, where the university is situated, is in an active earthquake zone where solid seismic walls are a necessity. To ensure the seismic performance, Arup adopted highly transparent, earthquake-resistant, precast hybrid concrete and steel lattice walls to connect the foundation and the fourth floor. The walls wrap around the university, combining elegant architectural design with precise

1.

1: A key design feature of the new Nagoya Zokei University is a central 'art street' that passes through the building

2: The structure features transparent, earthquake-resistant, precast hybrid concrete and steel lattice walls that connect the foundation and the fourth floor

2.

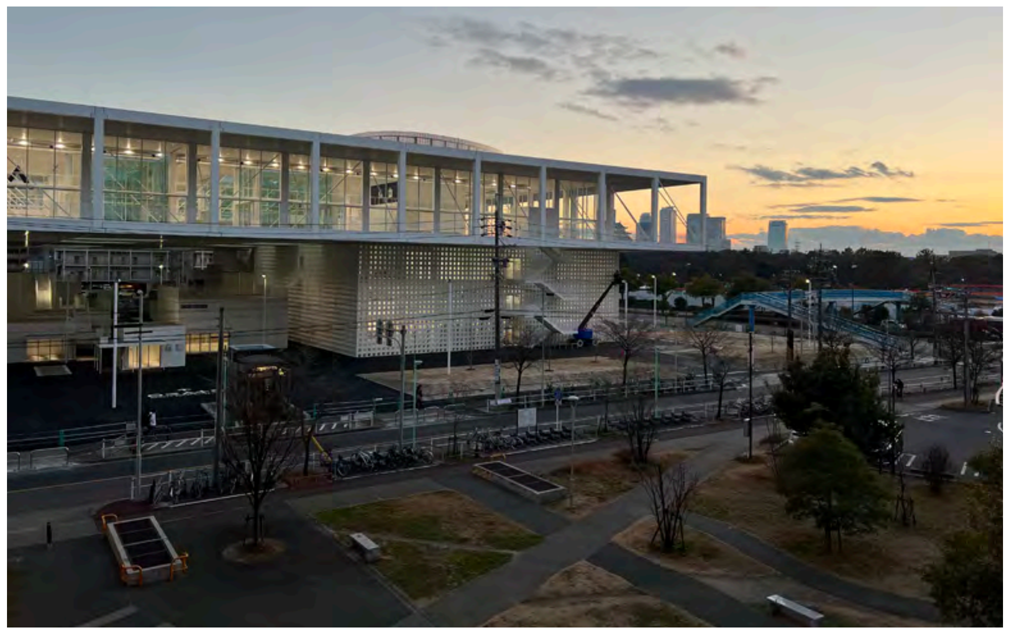


3.

3: The innovative use of lattice walls minimises material use and increases seismic resilience

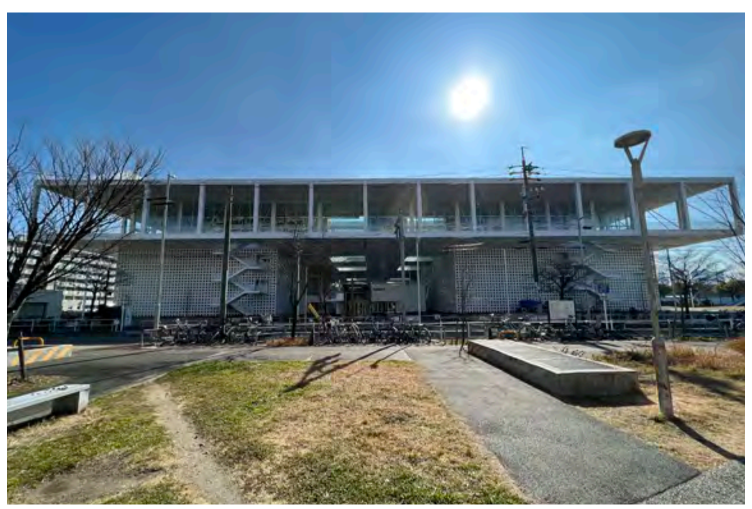
4: Nagoya Zokei University is a renowned art and design university in Japan's fourth most populous city

5 & 6: The fourth floor includes an external terrace which can be used as an open studio



4.

5.



6.

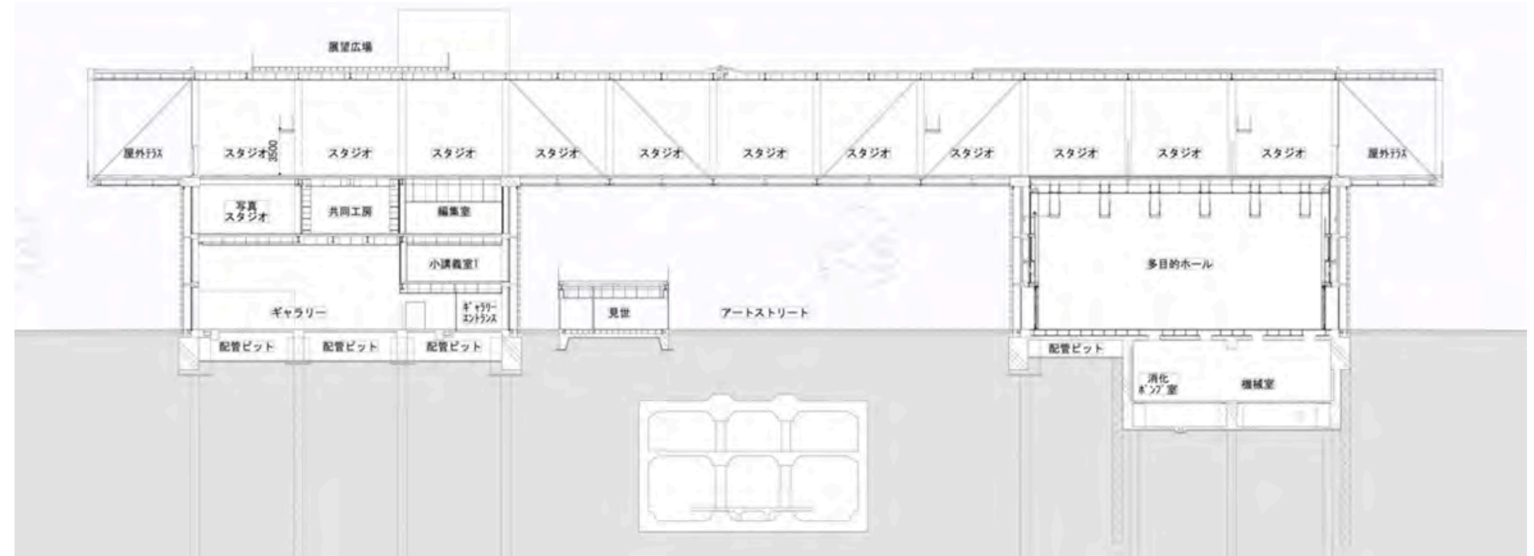
seismic engineering at very fine scale. This structural scheme using lattice walls is an innovative strategy that minimises material use and improves the bearing capacity, leading to increased seismic resilience. All of the structure is exposed and integrated with the architectural design. This eliminates short lifespan finishes and contributes to the whole-life sustainability of the project.

Furthermore, a focus on low-carbon design inspired the development of a floor cooling and heating radiation system for the studio, lowering overall energy consumption and improving indoor thermal comfort. A sophisticated building energy management system gives the building's facilities management team granular control over systems in different areas and rooms and provides live monitoring data on energy consumption to help optimise performance.

The architectural vision

The plan to relocate the university from a relatively remote location on the outskirts to the city centre began to take shape in 2018. The 4.5-acre site is conveniently located on the eastern side of Meijo Koen Park, a major public park, and close to one of Japan's landmark castles, Nagoya Castle, built in 1612. An existing university laboratory building is located to the south and a development of small houses to the east.

The new building has four 3-storey high concrete blocks (containing a library, lecture halls, a cafeteria, a gym, a gallery and workshop facilities) positioned at each corner, and a basement. The 104m x 104m studio on the fourth floor houses open-plan facilities for students and staff, and an external terrace (which can be used as an open studio).



7.

Architect Riken Yamamoto is known for projects that physically connect people with their surroundings. Interior spaces often allow users to engage with the outside world, either visually or audibly, and key building functions are pushed to the edges to create space for circulation to draw people in. His 1977 project Yamakawa Villa encapsulated this philosophy, its internal veranda connecting functional spaces on the periphery of the house arranged as a cluster of architectural masses containing bedrooms, bathrooms and a living area.

The same architectural language infuses the design for Nagoya Zokei University, most notably in the semi-open-air art street at ground level. This is accessible by local residents and subway users and incorporates a series of smaller, house-like structures used variously as study areas, exhibition spaces and shops.

Meijo Koen station on the Nagoya Municipal Subway bisects the site from north to south, and stringent safety protocols limited the load-bearing capacity of the station structure to just 10 kN/m^2, making only 1- or 2-storey structures viable. This informed the decision to split the building into two halves, creating the full-length art street above the station, with the truss structure spanning the 40m gap between the four reinforced concrete cores. The truss acts as a roof for the street and releases the open-plan studio space on the fourth floor. The open-plan design was conceived to enhance spaces for art creation and exhibitions, minimising the number of enclosed lecture halls.

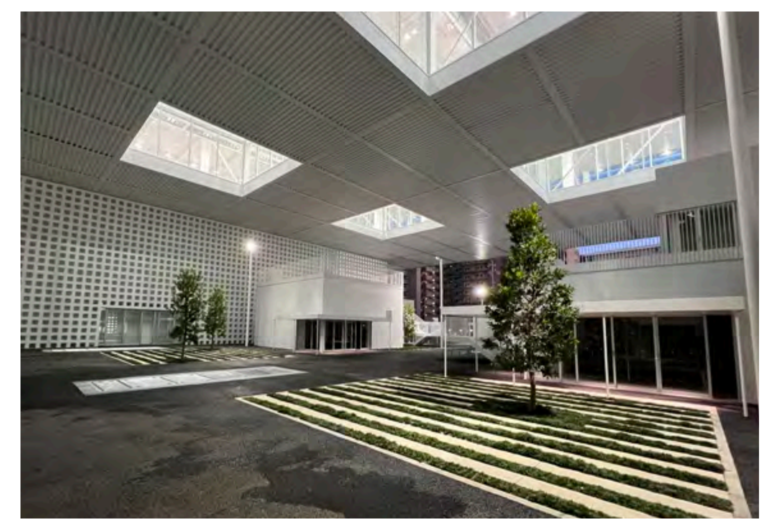
Lattice façade

The architectural ambition to create visual connections between interior and exterior spaces included the design of the perforated ventilated façade enclosing the four cores. Rather than install the lattice as a secondary, non-structural façade element, Arup designed for it to function as a primary, earthquake-resistant structural façade. This is a first for Japan, where seismic walls are typically made of solid reinforced concrete to resist high seismic loads. The lattice façade also reduces the amount of direct sunlight in the interior and allows for natural ventilation, alleviating the load of the building's cooling system and improving environmental performance.

The Arup team initially felt that the lattice elements would be difficult

7: To avoid loading the upper part of the subway station below, a bridge-like design using a 40m-wide steel truss spans between concrete cores

8: This design creates the central 'art street', offering a semi-outdoor space to the local community which encourages social interaction through art



8.

9.

10.

to realise structurally, as the precast lattice devised for Fussa City Hall, a previous project by the same architect, featured larger cross-sectional sizes more appropriate for structural materials. However, through an extensive 18-month design process, Arup developed a workable solution.

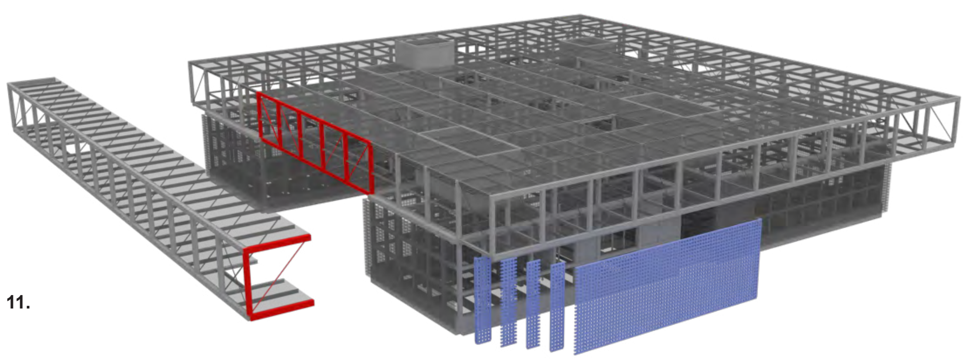
The firm developed the lattice into a hybrid steel/concrete outframe that connects the piled foundations to the base of the long-span truss. Set out on a 500mm grid, the 200mm x 200mm precast columns and beams, with 16-22mm steel plates attached to the rear, work in combination with the building's reinforced concrete frame. The lattice does not support vertical forces but resists horizontal forces and maintains uniform rigidity, while the frame ensures overall strength.

The first-of-its-kind design required intensive analysis to verify rigidity, strength and the potential for concrete cracking. The lattice also needed sufficient axial force to prevent the steel plates from buckling. An international effort saw structural engineering teams in Arup's Japan and London offices collaborate, using digital tools including LS-DYNA and Midas iGen to create and analyse the lattice wall model.

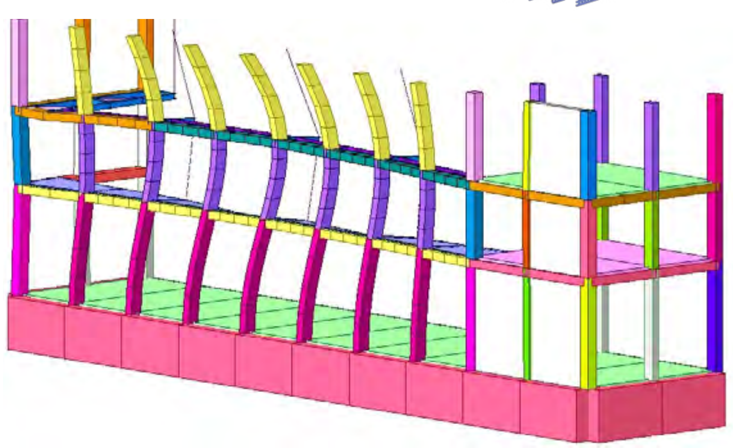
Efforts to refine the design ultimately paid off; real-life stress tests by Obayashi Technical Research Institute confirmed that the precast panels sufficiently stiffened and prevented buckling in the steel plate, and design strength and stiffness verified the calculations.

Seismic loads are not the only forces the lattice walls have to resist; they must also absorb horizontal forces generated by the truss above. Special joints and bolts were developed to transmit the large shear forces from the truss into the columns, but not the axial forces generated by the downward weight of the truss.

Bolts and joints on the column heads posed a problem for the structural design. Repeated earthquakes form gaps between round bolts and holes that would prevent seismic forces from being properly transmitted into the lattice wall. To overcome this issue, specially machined square bolts were developed to connect into custom bearing plates on the column heads. This arrangement improves the bearing surface, boosts overall shear strength and, in an earthquake, allows the lattice walls to shift and then return to their original position.



11.



12.

9: The hybrid steel/concrete outframe is set out on a 500mm grid

10: The outframe features 200mm x 200mm precast columns and beams

11 & 12: Digital tools including LS-DYNA and Midas iGen were used to create and analyse the lattice wall model

13.

13: Strain gauges were attached to the steel plates and demonstrated that stresses caused by concrete shrinkage would not affect the bearing capacity

14: Testing in the Obayashi Technical Research Institute confirmed the design strength and stiffness of the precast panels

15. A total of 300 factory-made lattice wall panels were fixed together on site

Fabrication of the lattice wall panels raised further issues due to concerns that shrinkage as the concrete dried would put stress on the steel plates, causing tolerance issues. Analysis revealed that tolerance could be reduced to within 5mm by adopting low drying shrinkage concrete and installing special supports after the steel plates were formed. Strain gauges were subsequently attached to the steel plates and demonstrated that stresses caused by concrete shrinkage would not affect the bearing capacity.

Moving into construction, the precast lattice panels were welded together at various points, including along the steel plates and connecting reinforcement bars. Very little expansion or contraction in the panels was predicted once the reinforced concrete frame was completed, yet there were concerns about whether the welding might shrink the walls and cause cracks in the concrete.

Some 0.1mm cracks did appear on the surface of panels when work began on welding the reinforcement. Collaborating with the contractor, welding jigs were used to apply compressive force to the rebar in advance of welding, which proved successful in overcoming this issue. In all, a total of 300 factory-made lattice wall panels were fixed together on site using approximately 6,300 joints.

Reinforced concrete frame

The design team refined the size and weight of the structure further through the reinforced concrete frame. The designed columns have a thin cross-section, of just 400mm x 600mm, which prohibits any form of bending if the structural design is to function effectively.

Large-span reinforced concrete beams with steel pin joints at the ends were developed to transmit shear forces in the structure. The pin-jointed beams helped minimise bending moments, allowing the columns to support the massive axial forces of the truss more efficiently. Finite element method (FEM) analysis verified the performance of the joints, but difficulties were experienced in production because the steel end plates, into which headed stud bolts are attached, warped under the heat of welding. The plates have to withstand complex stresses in situ, so the patience and diligence of the steel fabricators was key to refining the approach and getting it right.

Flexible spaces

The building design included a new curricular system and academic structure for the university's faculties. The old system of a single art and

14.

15.

design department with nine different disciplines was transmuted into five separate 'domains' – Art Expression, Visual Literature, Community Area Design, Design of Community Sense, and Representation – each one defined by the architectural configuration.

Learning spaces and studios are spread across the fourth floor, where flexible layouts allow functions to be shifted around to accommodate different teaching styles and learning methodologies. A common area in the centre of the floorplate, known as the Art Plaza, is where students and professors meet to discuss and exchange ideas, and where people from different studios and domains can see what is going on in other studios.

The need for flexibility and seamless spaces, coupled with the drive towards architectural elegance, saw Arup work to minimise the cross-layer truss structure as much as possible and virtually eliminate the need for diagonal bracing and standing walls – a particularly tough target for a building in an active earthquake zone. Developing a constructable solution was a complex process, as several different constraints had to be factored into the final truss design. The approach, at concept stage, was to create a fully precast concrete building, partly because of the architectural preference for the texture and appearance of concrete over steel. The structure included only an intermediate storey truss over the internal street.

The scheme evolved, during detailed design, into an inter-storey precast concrete truss. However, this structure was found to be prohibitively heavy, required thick diagonal bracing, and involved substantial costs related to heavy machinery on site. Instead, Arup proposed a full inter-storey steel truss constructed on top of a 3-storey high reinforced concrete frame. This design reduced costs, required only one type of slender diagonal bracing element spanning the studio space, and reduced the size of cranes needed for installation.

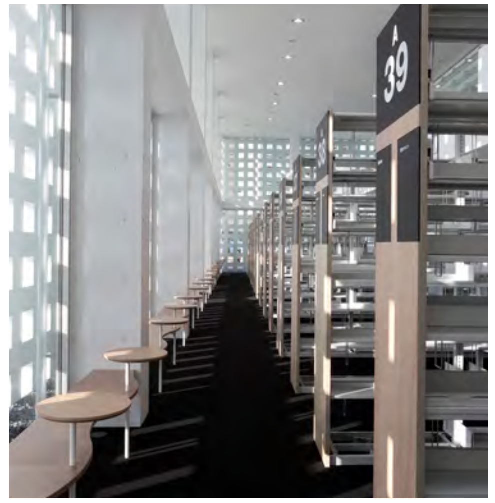
Steel truss

Switching to a steel frame for the truss still posed challenges, though. There were concerns over potential floor vibration in the studios caused by trains travelling through the subway station below. Thick steel bracing sections are normally used in Japan to resist earthquakes, prevent deformation and reduce vibration. The Arup team calculated that, by using a reinforced concrete floor slab for the fourth floor, the extra mass would dampen vibration and make it possible to reduce the cross-sectional size of the inter-storey truss diagonals. Nevertheless, the slender 11m-long diagonals were still predicted to experience considerable deformation, potentially by as much as 100mm.

Arup therefore turned to the onsite welding process to minimise deformation by increasing the amount of tension in the bracing. The steel portal frame for the truss was erected first, then the diagonal bracing was installed and welded at each end to fixed joints. The 7.25mm gap between the portal frame and the bracing naturally contracts by 1-2mm when welding is carried out, creating tension in the diagonals and compression in the framing, and resulting in a much stiffer structure to withstand loads.

This novel approach required detailed examination and testing before it could be implemented on site. The construction sequence was reviewed by a structural engineering team in Arup's Hong Kong office and a full-scale mock-up of a truss joint was built. The welding itself was highly challenging due to the thickness of the members, the difficult angles of joint connections and the behaviour of welding wire under heat.

Ultimately, by using a combination of two different weld positions, changing the type of welding wire according to weld difficulty, and altering the temperature of the weld area between passes, it was possible to maintain workability, achieve the necessary tensile strength and pass the Charpy impact test (a standardised high strain rate test which determines the amount of energy a material absorbs during fracture). The expertise of Japanese construction company Tomoe Corporation was critical to achieving this result.



17.

16.

16: All of the structure is exposed and integrated with the architectural design

17: The lattice façade reduces the amount of direct sunlight in the interior and allows for natural ventilation

18: The lattice design is a first for Japan, where seismic walls are typically made of solid reinforced concrete to resist high seismic loads

Energy management

Efforts to manage temperatures of a very different kind came into play when Arup was developing the scheme for the building's MEP systems. The open-plan 6,000m² studio features a large, 2-storey atrium, and relying only on a conventional air flow HVAC system to maintain thermal comfort was considered inefficient. The Arup team opted instead to combine it with an underfloor radiation cooling and heating system, cast with the concrete slab, which controls floor surface and room temperature, lowering overall energy consumption and improving indoor thermal comfort.

Furthermore, the limited number of walls on the fourth floor made it necessary to also install power outlets and local area networks within the floor. An innovative 'MEP-Trough' cable route was installed in the slab before radiation pipe installation and concrete casting to prevent electrical cables and floor radiation pipes interfering with each other. This trough also contributes to preventing concrete cracking due to thermal expansion.

In another bid to drive down operational energy usage, as well as enable more effective facilities management, Arup devised a new process for building energy management and equipment monitoring. The cutting-edge building energy management system can operate electrical systems separately in different floors and areas of the building, including separate rooms in each department. It can also individually monitor the performance of equipment such as lighting, HVAC, ventilation, hot water and power outlets. This is predicted to reduce the building's overall energy use by 10%.

New connections

In successfully providing structural and MEP services for Nagoya Zokei University, Arup has played a key role in delivering an iconic, resilient and sustainable building that is a prominent new base for education and cultural development in central Japan.

The transparent and open design is already helping forge new connections between students and the local community. The public access to the library, cafeteria, shops and the art street all help to root the university within its vibrant new urban context.

Authors

Hironori Hisaki worked on the building services design. He is a mechanical and electrical engineer in the Tokyo office.

Junichiro Ito was the Project Manager of the structural team. He is an Associate in the Tokyo office.

Mitsuhiro Kanada was the Project Director. He is a Director in the Tokyo office.

Project credits

Client Doho Gakuen
Architect Riken Yamamoto
Main contractor OBAYASHI CORPORATION
Steel frame contractor Tomoe Corporation
Facilities management, mechanical and electrical engineering, seismic design, structural engineer Arup: Kazuma Goto, Hironori Hisaki, Genki Ikeda, Junichiro Ito, Shintaro Ito, Mitsuhiro Kanada, Masahiro Kawabata, Seolmi Kim, Shintaro Kobayashi, Hirotaka Ogihara, Tsubasa Takeuchi.

Image credits

1, 3-16: Arup
2: Riken Yamamoto & Field Shop
17, 18: Shigeru Ohno

18.