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Parramatta Light Rail, Sydney, Australia
Daniel Weiss/Arup

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Leading the charge

An innovative design approach to a cutting-edge battery testing facility

Authors Todd Stonebraker, Josh Yacknowitz

1: The $77 million state-of-the-art GSL has set new benchmarks in battery testing

American innovation depends on a reliable and resilient power grid. However, traditional electrical infrastructure faces enormous stress from dynamic changes in industrial loads and consumer demand. Flexible resources like grid-scale energy storage can help overcome the challenges but will require the development of new advanced technologies. This fast-advancing field demands a new breed of state-of-the-art testing facilities, kitted out with the latest laboratory equipment and safety systems that protect against potential battery system failure during experiments.

The $77 million state-of-the-art Grid Storage Launchpad (GSL) has set new benchmarks in this field, establishing norms in managing hazards and lab design. Located on the Pacific Northwest National Laboratory's (PNNL) campus in Richland, Washington, GSL brings all phases of the battery development and deployment cycle under one roof, from fundamental materials and device prototyping to testing and validation. The facility, designed and constructed using a design-build development model, aims to boost storage adoption to make the nation's power grid more resilient, secure and flexible.

Arup worked in close collaboration with design builder Harvey Cleary and Kirksey Architecture on the project, which opened in August 2024. The firm played a critical part in the development of this innovative facility, delivering mechanical, electrical and plumbing building services design, and control infrastructure to ensure safe operations in the testing and validation cells. Arup also provided consulting services related to fire/chemical process hazards, bringing fresh approaches to lab safety and setup.

As part of its remit to accelerate next-generation grid-level energy storage technologies, GSL, which was funded by the US Department of Energy, evaluates the performance of electricity grid and transportation storage technologies through testing and validation. It develops new grid performance standards and requirements spanning the entire battery development cycle, from basic materials synthesis to advanced prototyping.

Grid batteries face challenging requirements. They must charge and discharge quickly, operate continuously for long periods and endure constant cycling, all while holding sufficient energy to make an impact at a large enough scale for the electric grid distribution system. Validating these properties is crucial when developing new storage technologies. PNNL is a leader in the field with the capability to test 5–10kW batteries, equivalent to a mid-tier electric vehicle (EV) charger or the average power draw from a few typical homes.

The new 93,000ft^2 (8,640m^2) GSL building dramatically enhances PNNL's capabilities, incorporating six test cell rooms where batteries with capacities of up to 100kW – enough to power several homes for weeks – can be put through their paces in realistic grid operating conditions. An additional 6,000ft^2 (557m^2) open-plan lab provides space for smaller scale 10kW battery testing where researchers can run multiple concurrent tests.

The facility also features 30 laboratories, including labs for electron microscope research, wet labs and a low-relative-humidity lab. A key aspect of Arup's design work was to ensure that the different spaces and testing scenarios could mitigate potential risks, helping to enable research to be carried out safely and effectively.

New benchmark for test cell design

The testing and validation cells – bunker-type concrete enclosures where arrays of batteries are tested for performance while connected to the electrical grid – were considered a


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particular risk. Separated from the rest of the building to protect against structural damage in the event of a fire or a battery system failure, each cell contains a separate test-monitoring area where scientists can observe battery performance remotely without being in close proximity to an experiment.

While the testing at GSL does not intentionally promote failure, the test cells need to be able withstand certain failure scenarios that may happen. With no existing code for the design of battery testing cells, Arup and the project team worked from first principles to evaluate the hazards and risk of testing the various battery types and develop a system design from the bottom up. The team drew on elements of National Fire Protection Association (NFPA) code 855, a standard governing the installation of stationary batteries, as well as codes tackling the threat of flammable gas in other types of facilities, such as pharmaceutical manufacturing plants. A battery testing expert with extensive experience developing and running a test lab was also appointed to the team to advise on protection strategies and processes, address areas not covered by existing codes and provide guidance on the behaviour of different arrays of batteries. When batteries are overcharged, overheat or suffer physical damage, they can release flammable gas in a process known as 'off-gassing', which can lead to thermal runaway or fire. Arup's fire process chemical experts identified the highest hazard off-gas compounds, calculated how fast gas is generated in a thermal runaway event, and at what point the test cell environment reaches its lower critical limit. Arup's UK-based team provided support on the SIL-2 instrumentation and on controls design.

Preventing catastrophic failure

Arup's analysis considered a broad range of off-gassing scenarios from different battery types. It determined that the worst-case scenario would be hydrogen off-gassing.

If a sufficient concentration of hydrogen filled the test cell space and ignited, it would be impossible to vent the blast through the use of vent panels and would result in the destruction of the test cell. The original concept design for the testing cells relied on structural hardening and venting to mitigate this risk.

Arup proposed enhancing the prevention strategy. This involved adding a third layer of mitigation using specialised instrumentation and process exhaust to keep gaseous pollutant concentrations below a critical limit.

2, 3: In addition to providing mechanical, electrical and plumbing building services design, Arup also provided consulting services related to fire and chemical process hazards

4: An interstitial utility corridor enables safe maintenance access to critical lab utility services without interrupting lab operations

5: This fast-advancing field demands a new breed of state-of-the-art testing facilities, kitted out with the latest laboratory equipment and safety systems


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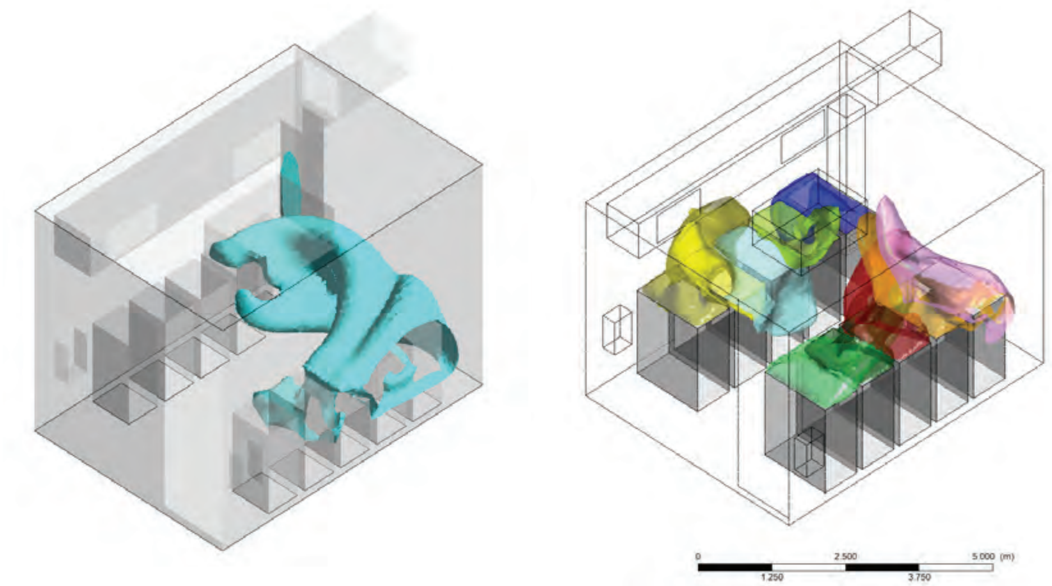
6, 7: Arup's design remit included delivering mechanical, electrical and plumbing building services

8: CFD analysis was used to demonstrate how to prevent the build-up of small pockets of hydrogen-rich air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The iterative design process required extensive client and stakeholder engagement and several months of modelling. To demonstrate the effectiveness of its approach, Arup carried out computational fluid dynamics (CFD) modelling of the testing cells, simulating the effectiveness of mechanical ventilation to offset real time off-gassing for different battery types. This considered multiple scenarios, such as where the battery might be located in the room and different configurations of room air extraction.

Beyond purging the entire space in an emergency, CFD also had to demonstrate how to prevent the build-up of small pockets of hydrogen-rich air, which could also prove dangerous. Arup's CFD modelling has allowed PNNL to validate the efficacy of the emergency purge system, and the models will support ongoing operations by verifying the safety of future experiment setups as battery technologies evolve.

Arup also leveraged the expertise of colleagues based in the UK on its functional safety team to help certify the safety instrument system, forming a key component of the design. The system had to comply with new safety integrity level requirements under code NFPA 69 intended to ensure a minimum level of fault tolerance during operation. The focus was therefore on simple, reliable operation. As an example, motor controller drives on fans require electronics and internal programming, but in this case the drives operate with a motor starter that provides a simple, less fault-prone solution to ensure the system works without issue when it is required.

The installed system features three extraction fans per test cell. The smaller fan provides continuous ventilation during normal operations and, in an emergency, a large fan kicks into purge mode, flushing out and replacing all the air in the room twice every minute, with a third fan providing redundancy. Extracted air is pumped through ventilation ducts and out through large metal exhaust stacks positioned to one side of the facility.

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9: Arup's previous work on the Energy Sciences Center (left) has facilitated the recapture and reuse of heat from an adjacent data centre in the GSL building

10: Located on the PNNL campus, GSL brings all phases of the battery development and deployment cycle under one roof

A template for chemistry labs

Rapid advances in battery research and development mean that PNNL needs flexibility for spaces to efficiently adapt to changing research equipment requirements.

In a bid to accommodate the need for flexibility across the various laboratory types at GSL, the project team developed and implemented a 'template' services infrastructure for the general chemistry labs. These are based on standard repeatable modules that are easily adapted to incorporate new equipment setups and bench arrangements. Most of the exposed infrastructure above the ceilings, including ventilation, power, communications and laboratory gases, has a standard arrangement and routing methodology, and that repeatability helped optimise fabrication and installation by the contractor.

Distribution manifolds act as hubs with multiple connectors, making it possible to quickly plug in or remove extraction hoods or other bench equipment, capping off anything that is not required. The templated approach is coupled with an interstitial utility corridor, which enables safe maintenance access to critical lab utility services without interrupting lab operations.

Reusing data centre heat

The building is configured to recapture and reuse heat from an adjacent data centre via a connection to the existing Heat Transfer Building (HTB) created as part of Arup's previous work on PNNL's Energy Sciences Center, which opened in 2021.

The HTB's utilities system features a cooling tower and pump house, which draws waste heat from the data centre then distributes it to the GSL and other campus buildings via a network of distribution piping for direct heating coil or heat recovery chiller use. This results in lower heat generation demand in the facilities. The system takes heat from the data centre that would otherwise be released into the atmosphere and channels it to provide different functions through the heating, ventilation and air conditioning (HVAC) system, helping to condition spaces more sustainably and with less reliance on fossil fuel-based systems.

At present, the data centre is not running at full capacity, resulting in limited heat to share across the campus, but in the future, it should enable a fully electrified HVAC system in the GSL. The heat pump-ready solution allows PNNL to start dialling back the need for fossil fuel burning boilers and hot water heaters in the future.

Arup's focus on resilient and future-proofed design will help ensure GSL can advance scientific frontiers for many years to come, accelerating the development of next-generation storage technologies.

Innovative prototyping and production

Promising materials for batteries are often first tested in an easy-to-manufacture coin cell, similar to those found in watches, followed by a larger pouch cell, like those in power tools or some electric vehicles. GSL adds more lab space for coin and pouch cell production and testing, allowing the simultaneous testing of more prototype batteries.

A major new capability is a production line for prismatic cells, larger units that enable EV and grid battery configurations capable of packing a bigger power punch with fewer cells. This facility is unique among national laboratories in the US.

GSL is also home to PNNL's Material Innovation through Robotics & AI Lab (MIRAL), where robotics and AI are harnessed to accelerate the pace of materials discovery. Once an experiment is designed and tested, MIRAL can autonomously run it 24/7, with far greater consistency and precision than a human.

Alongside pioneering research and development, GSL will function as a hub for collaboration where PNNL and other Department of Energy national laboratories will work alongside research institutions and industry partners to address a range of energy storage challenges. The building will also be used to train the next generation of battery researchers.

Authors

Todd Stonebraker was the Project Manager. He is an Associate Principal in the Houston office.

Josh Yacknowitz was the Project Director. He is a Principal in the Seattle office.

Project credits

Owner/end client Pacific Northwest National Laboratory
Operator Battelle Memorial Institute for the US Department of Energy
Design builder Harvey Cleary
Architect Kirksey Architecture
Structural engineer Pinnacle Structural Engineers
Civil engineer J-U-B Engineers Inc
Energy modelling, fire and life safety consulting, mechanical, electrical and plumbing engineering
Arup: Daniel Bakun, Emma Blouin, Chris Chan, Judy Coleman-Graves, Jon Eisenberg, Virchus Ferguson, Alexej Goehring, Akshay Gore, Victoria Grimes, Michael Hanson, Smrithi Pranatharthi Haran, Brent Johnson, Takumi Kammerzell, Noah Kenner, Mark Knowles, Mike Lepisto, Josh Lyons, Payton Masoner, Michal Milewski, Nicole Moes, Brandon Owston, Justin Prince, Erin Richmond, Chloe Robinson, Natalia Sanabria, Daniel Spencer, Todd Stonebraker, Chanpreya Thou, Cress Wakefield, Tracy White, Dave Whitham, Sarah Wolfe, Josh Yacknowitz.

Image credits

1-7, 10: Kirksey Architecture
8: Arup
9: Aker Imaging

10.

Connecting Sydney's future

A transformative infrastructure project reshaping Western Sydney

Authors Ryan Andriessen, Adrian Callus, Brian Hetherington, Louise Millward, Ciaran Murphy

The Parramatta Light Rail (PLR) is a landmark infrastructure project designed to reshape Western Sydney's urban landscape by improving connectivity, supporting population growth and unlocking economic potential. Parramatta, one of Australia's earliest European settlements, has historically played a central role in Greater Sydney, yet has long been underinvested compared with the city's eastern harbour suburbs. As Sydney's population expands westward, the PLR offers a vital opportunity to bridge that historic divide – linking communities, stimulating local business and delivering lasting value to a rapidly growing region.

With the Parramatta central business district (CBD) emerging as a key commercial and residential hub, and its population expected to grow by nearly a third over the next 20 years, the PLR forms a core part of the New South Wales (NSW) Government's broader urban renewal and placemaking strategy.

The first stage of the light rail features 16 stops along a high-frequency, two-way track, connecting key destinations including Westmead Health Precinct, CommBank Stadium, Rosehill Gardens Racecourse and three Western Sydney University campuses. The line opened in December 2024.

Arup, as Infrastructure Technical Advisor for Transport for NSW (TfNSW), played an important role in supporting the delivery of the Stage 1 project, providing multidisciplinary expertise across planning, approvals, engineering and public realm design. The 12km route includes 1.3km of sustainable green track and extends through areas like Camellia-Rosehill, where the light rail supports major town centre renewal. By blending transport infrastructure with thoughtful urban design, Arup helped position the project as a catalyst for Sydney's '30-minute city' vision – enabling people to access work, education and lifestyle opportunities within half an hour of where they live.

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1: The project prioritised public spaces, helping to create vibrant, activated streetscapes

2: PLR will be pivotal to enhancing Parramatta's status as a thriving and connected metropolitan hub

Arup's contributions to the PLR include detailed geotechnical engineering assessments and structural evaluations for bridge designs, significant contamination remediation strategies at complex sites, such as the stabling yard for the light rail vehicles, and creative roadway modifications to optimise public spaces and minimise property impacts. The firm also provided expert guidance on blending the rail infrastructure with broader urban renewal initiatives, such as supporting the revitalisation of Camellia-Rosehill's town centre, ensuring the transport system deliberately contributes to community connectivity and placemaking objectives.

Designed as an integral part of a broader multimodal transport network, PLR enhances connectivity between precincts while providing easier connections to major centres. Strategic transport interchanges at Westmead, Parramatta and Carlingford help facilitate efficient transfers across the wider network. The core light rail spine between Westmead and Camellia complements existing rail, bus, ferry and active transport options, ensuring clear and accessible routes through the heart of Parramatta.

Beginning in June 2016, Arup served as the Infrastructure Technical Advisor for the PLR project. In this role, the team supported TfNSW in evaluating credible options, facilitating stakeholder negotiations and ensuring the project delivered best value-for-money outcomes.

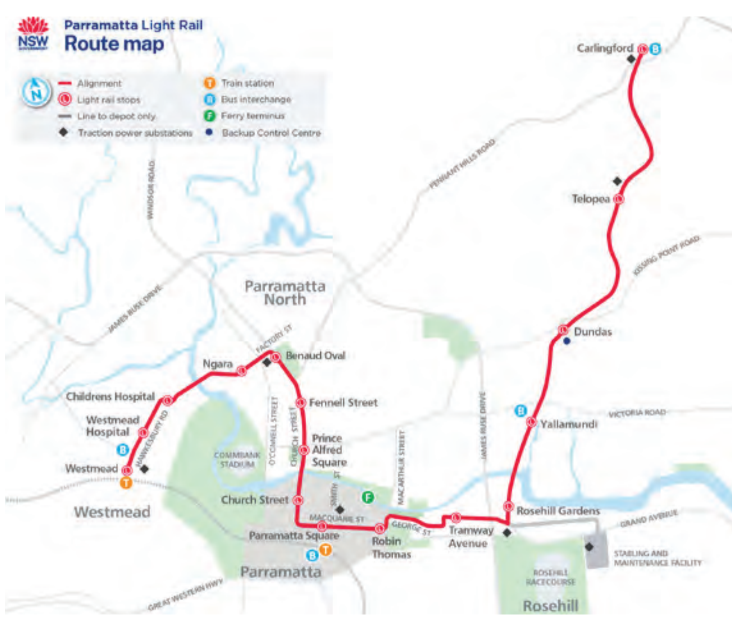
Following this, the firm played a critical role in conducting a multi-criteria analysis to assist TfNSW in shortlisting preferred routes and project alignments. This work continued through the optioneering phase, refining the alignments and culminating in the pre-concept design submission in January 2017. Arup worked with TfNSW and the project stakeholders to define the project requirements, shape the final business case and inform the Environmental Impact Assessment. Arup undertook detailed design for the enabling works packages and carried out reviews of the design and construct packages on behalf of TfNSW. The firm continued to provide strategic guidance, drawing on global and local best practices developed through its extensive transport infrastructure experience. The team proactively identified and mitigated project risks, ensuring the successful delivery of a resilient and future-ready light rail network for Greater Parramatta.

Stage 1 route

Stage 1 of the Parramatta Light Rail connects Westmead to Carlingford via the Parramatta CBD and Camellia with a 12km two-way track and 16 light rail stops.

It connects the Parramatta CBD to:

- **Westmead Health Precinct.**
- **CommBank Stadium.**
- **Powerhouse Parramatta (the Arup-designed museum, currently under construction, will be the largest in NSW).**
- **Parramatta Square.**
- **Rosehill Gardens Racecourse.**
- **Three Western Sydney University campuses at Westmead, Parramatta and Rydalmere.**



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3: The first stage of the PLR connects key social, cultural and commercial destinations

Connecting communities

A key objective of the PLR is its role in strengthening communities through strategic placemaking. In Camellia-Rosehill, the project supports the NSW Government's town centre renewal plans by enhancing accessibility and fostering a pedestrian-friendly environment. The transport link is designed to catalyse investment and urban revitalisation, making the precinct more attractive for businesses, residents and visitors.

By prioritising public spaces along the corridor, the light rail contributes to the creation of vibrant, activated streetscapes. The team's involvement in landscape and public realm design ensured that the project went beyond transit infrastructure to deliver high-quality places that encourage social interaction and economic activity. Through increased canopy cover, improved walkability and carefully designed stop precincts, the light rail fits into the urban fabric, supporting the NSW Government's broader placemaking initiatives.

The firm's services included civil, bridge, rail, electrical, environmental, fire, geotechnical, hydrological, mechanical, project management, risk and safety engineering, sustainability, systems engineering, landscape architecture, urban design, urban planning and digital engineering services.

Collaborative culture

One of the standout aspects of the PLR project was the cooperative working environment. The client, consultants, engineers, planners and designers were co-located in a single project office, an approach that encouraged open communication, streamlined decision-making and led to innovative problem-solving. This investment in culture, where all team members were valued regardless of their employer, resulted in a diversity of thought that improved project outcomes.

Arup was regarded as an extension of the client team, enabling a level of trust and shared ownership that accelerated progress and enhanced efficiency. This close collaboration facilitated a seamless integration of expertise, ensuring that engineering solutions aligned with broader urban renewal goals and community expectations.

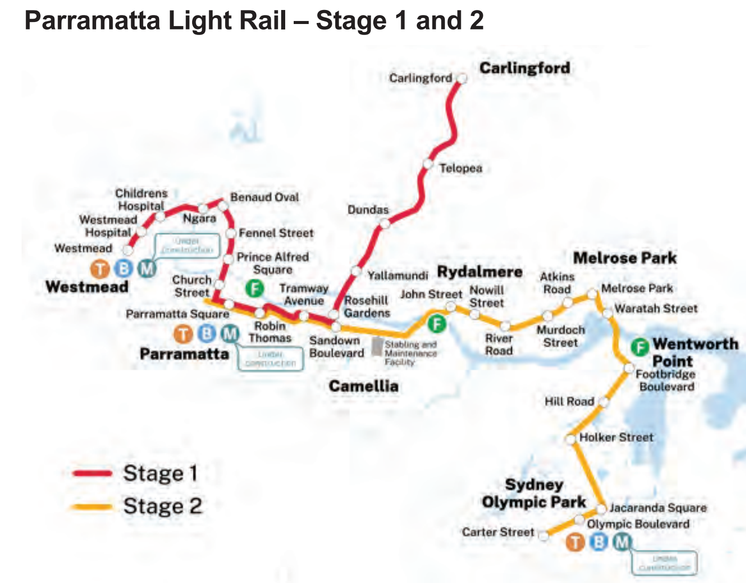
One of the key lessons learned from the PLR was the need to understand the project inputs needed from each of the consultants and their relevant timings. Arup played a crucial role in driving the project development, and helped identify critical tasks, as well as identifying achievable timelines. The firm helped TfNSW reach agreements with key stakeholders, including City of Parramatta, Urban Growth, Health Infrastructure, and the Department of Planning and Environment. Establishing these agreements early helped manage project risk and uncertainty in the later stages.

Guiding flood resilience

Arup played a central role in guiding the NSW Government through the complex planning process for the PLR, particularly regarding flood resilience and climate adaptation. From the outset, Arup engaged closely with the approving authorities, demonstrating how the flooding model was developed, and carefully walking stakeholders through various scenarios to ensure comprehensive preparedness for possible future flood events.

4: Stage 2 of the PLR will comprise 10km of two-way tracks with 14 stops

5: By 2026, roughly 130,000 people will be living within walking distance of a Stage 1 stop



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The firm's multidisciplinary team developed integrated solutions for stormwater management, civil design and operational strategies to create safe human-centred public spaces. Crucially, the planning process involved extensive consideration of long-term operational sustainability, explicitly including climate change projections to secure the project's viability over the next 25 years and beyond.

From the outset, Arup tackled one of the most critical challenges: understanding and addressing the significant flood risks along the proposed route. Given Parramatta's location within a flood-prone river system and the rapid, unpredictable nature of local flooding – where even relatively minor weather events can impact parts of the CBD – flood resilience was central to shaping the alignment and design.

The light rail infrastructure had very limited tolerance for flood levels, requiring careful planning to ensure its viability. Arup took a proactive approach, rapidly assessing flooding risks along the entire 12km corridor. The firm played an important role in supporting TfNSW by rapidly developing robust analysis to guide design decisions and support the planning approval process. This early, strategic work laid the foundation for a flood-resilient transport system and

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6: The light rail is supporting population growth and unlocking the economic potential of Western Sydney

7: Residents now have alternative transport options to access Greater Sydney

8: The green track is helping to bring down local air temperatures and reduce flooding by absorbing heat and stormwater

enabled the project to move forward with confidence.

Inclusive active transport link

Beyond light rail infrastructure, the project strongly emphasised active transport, reinforcing Parramatta's status as a walkable, bike-friendly city. Arup collaborated with the project team and external stakeholders, including the council, to contribute to the design of a dedicated active transport link between Carlingford and Parramatta, which connects to existing shared walking and cycling paths. This corridor was met with widespread approval from the cycling community, who commended its safety, accessibility and contribution to sustainable travel choices.

As part of the PLR, the project incorporated a new shared pedestrian and cycling path – the active transport link – for the Greater Parramatta region. Designed for inclusive accessibility, the path accommodates pedestrians, cyclists, mobility scooters, motorised wheelchairs, scooters, skateboarders and people with prams, while providing resting points along the way.

Running approximately parallel to the light rail corridor between Camellia and Carlingford, the link enhances safety and convenience for local travel, providing easy access to nearby shops, parks, community facilities and public transport hubs. Complementing the light rail, this active transport link encourages commuters to reduce car usage. The 5.7km route connects with the Parramatta Valley Cycleway at Rydalmere, supporting the city's broader ambitions for a pedestrian and cycling network. By prioritising pedestrian and cyclist infrastructure, the light rail project promotes healthier, greener mobility options, reducing dependency on private vehicles and easing congestion on road networks. Well-lit pathways, safe crossings and high-quality public realm improvements make the corridor a valuable asset for the community.

Australia's longest green track

A defining feature of the PLR is its green track – 1.3km in total over three sections. It is the longest of its kind in Australia and the first in New South Wales. Green tracks, which incorporate vegetation within and around light rail tracks instead of traditional asphalt or ballast, provide numerous environmental and aesthetic benefits. The design uses drought-resistant plant species, including native grass and vegetation, and innovative soil technology to create a living infrastructure. These features can help to filter stormwater, reduce flooding, encourage biodiversity and increase visual appeal.

The heat island effect is of major concern in Western Sydney. It is a phenomenon where urban areas become significantly warmer than surrounding rural regions due to dense buildings, concrete surfaces and limited vegetation absorbing and retaining heat. In Sydney, it is predicted that it causes temperature increases of up to 8-10°C. Green tracks can absorb heat, reducing temperatures in the area. The green foliage further reduces glare and noise. Through the incorporation of increased canopy cover, green tracks and permeable surfaces, the project actively reduced local temperatures, improved stormwater management and enhanced the area's urban resilience.

This initiative represents a significant step forward in sustainable transport design. The green track helps mitigate the heat island effect, an issue of

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increasing concern as climate change intensifies. By embedding vegetation into transport infrastructure, the project demonstrates how green engineering can be integrated into urban environments to deliver tangible benefits.

Decarbonisation, circular economy and biodiversity

Sustainability was at the heart of Arup's approach to the PLR. The firm supported TfNSW by developing project specifications that mandated sustainable outcomes. Sustainable materials and resource-efficient construction methods were prioritised to minimise waste and lower the project's overall carbon footprint. The project implemented decarbonisation and circular economy principles through the selection of lower-carbon rail systems and the re-use of existing materials. The infrastructure works were completed by Parramatta Connect, a 50:50 joint venture between CPB Contractors and Downer on behalf of Transport for NSW.

The PLR incorporated a range of initiatives to reduce waste, lower emissions and support biodiversity. Significant materials were reused, including over half of the existing heavy rail, ballast and sleepers, helping to cut carbon emissions by thousands of tonnes. Environmental enhancements were also prioritised, such as a major increase in native nectar-bearing trees and shrubs to support local wildlife, including the threatened flying fox bat and swift parrot.

Nest boxes were installed to replace lost tree hollows, while thousands of square metres of existing asphalt were resurfaced rather than replaced. The use of recycled materials, like glass in asphalt and fibre-reinforced concrete in place of steel, further reduced the project's carbon footprint and embodied emissions.

As a result, PLR Stage 1 received a record-breaking score of 104.35 points out of 110 for the 'As Built' phase under the Infrastructure Sustainability Council rating scheme due to its positive economic, social and environmental outcomes. The project achieved a cumulative total carbon dioxide output reduction of over 76,000tCO_2e. This demonstrates TfNSW's commitment to sustainable outcomes.

Arup supported a design that prioritised stop visibility, accessibility and integration within the streetscape, while enhancing connectivity and public space quality in line with Parramatta's vision. A distinct design approach responded to the area's built form and landscape, creating a cohesive and legible light rail corridor.

Collaboration across the project team maximised opportunities for green infrastructure, incorporating urban planting to increase canopy cover and permeable surfaces. These measures help mitigate the urban heat island effect while supporting water treatment, collection and reuse, contributing to a more sustainable and resilient urban environment.

Innovative geotechnics

Arup successfully led on several significant geotechnical aspects of the PLR project. Firstly, extensive investigation was required to assess the structural capacity of the Lennox Bridge – a heritage-listed structure that

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PLR Stage 1 in numbers

- **12km, two-way track.**
- **16 light rail stops.**
- **5.7km walking and bike riding path.**
- **12 new or refurbished bridges.**
- **1.3km of green track.**

9: There is a total of 1.3km of green track across three sections

10: Arup assessed the structural capacity of the heritage-listed Lennox Bridge

11: Strategic transport interchanges at Westmead, Carlingford and Parramatta (pictured) facilitate efficient transfers across the wider transport network

the PLR crosses. Through detailed analysis and comprehensive load testing, Arup confirmed the bridge's capability to support the additional loading from the light rail safely.

Secondly, within the constrained alignment in the Westmead area, the route faced spatial limitations requiring the road alignment to encroach onto property owned by Westmead Hospital. This necessitated a partial property acquisition that considered the hospital's future development plans. To address this challenge, Arup engineered a suspended roadway design, allowing future excavation or undermining beneath the roadway without disrupting the rail operations. The solution involved constructing an embedded retaining wall along one boundary, with the single lane road deck cantilevered from it. Where dual lane road deck is required, it is supported by both the embedded retaining wall and king posts designed to be exposed easily, facilitating future excavation beneath the structure as needed by the hospital.

Arup also undertook substantial work to support the remediation of the contaminated site of the future stabling and maintenance facility. In addition to initial remediation planning, the firm developed the early concept and provided detailed assessments and reviews of designs and documentation, including installing a hydraulic cut-off wall to prevent contaminated groundwater migration.

A resilient, connected future

The new PLR significantly improves connectivity, opening up different community areas and providing residents with alternative public transport options into Greater Sydney. Alongside the rail corridor, the adjacent active transport link further enhances accessibility by offering pedestrians and cyclists safe, convenient crossings and improved regional connections.

The PLR represents a critical investment in the city's transformation. By enhancing connectivity and unlocking urban renewal, it will support sustainable growth and create attractive, accessible places for people to live,

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work and play. It will play a pivotal role in shaping Parramatta's future as a thriving, well-linked metropolitan hub.

By 2026, around 22,000 commuters are expected to travel on the Parramatta Light Rail daily, with an estimated 130,000 people living within walking distance of one of the 16 stops.

Parramatta Light Rail Stage 2

Throughout 2016 to 2018 and 2022 to 2024 Arup was also technical advisor, responsible for the concept and definition design for PLR Stage 2. It advised on the active transport connections in and around the light rail alignment. The firm undertook extensive research, planning and technical assessments for Stage 2 of the PLR, laying the groundwork for a 10km two-way track with 14 stops.

This stage is designed to fit in with PLR Stage 1, Sydney Metro West, and heavy rail services at Parramatta and Sydney Olympic Park, while also connecting passengers to ferry networks at Rydalmere and Sydney Olympic Park. The comprehensive study by Arup ensures efficient, multimodal connectivity for Sydney's rapidly growing western suburbs.

Authors

Ryan Andriessen was the Project Director. He is a Principal in the Sydney office.

Adrian Callus was the geotechnical lead. He is an Associate in the Sydney office.

Brian Hetherington was the Project Manager. He is an Associate in the Sydney office.

Louise Millward led the civil engineering design. She is an Associate Principal in the Sydney office.

Ciaran Murphy led the stormwater and flooding design. He is an Associate in the Sydney office.

Project credits

Client Transport for NSW
Contractor CPB Contractors, Downer
Civil, bridge, rail, electrical, environmental, fire, geotechnical, hydrological, mechanical, project management, risk and safety engineering, sustainability, systems engineering, landscape architecture, urban design, urban planning and digital engineering technical advisory Arup: Mick Agius, Amelia Agnew, Rihab Ahmed, Shahrzad Akbarzadeh Pooladi, Ghazaleh Akhzary, Anas Alwahwah, Nicoletta Andreou, Ryan Andriessen, Allen Ang, Josh Atkinson, Ron Au, Sam Balian, Nigel Barefoot, Richard Bartholomew, Hailey Blackburn, Edward Bond, Art Bonifacio, Laith Booth, Niall Brady, Ian Brocklehurst, Russell Bunn, Sam Burge, Michael Burgess, Peter Burnton, Filippo Caccamo, Zini Cai, Adrian Callus, Daniel Carnovale, Mathew Carter, Maria Caruda Martinez de Castilla, Martin Catolico, Raphael Chagellis, Nathan Cheah, Alvin Chen, Jessica Chen, Jonathan Cheng, Aneeq Choudhry, Ethan Clarke, Tessa Colclough, Natasha Connolly, Mike Cook, Tim Cook, Ben Cooper-Woolley, Luca Costa, David Dalton, Ian Darlington, Donny Darmawan, Oliver Davey, Tom David, Emma Davies, Kelvin Davis, Daniel De Cataldo, Ellie Dean, Sam Diamond, Jarred Dickson, Gajendra Dimo, Anna Dombrowski, Martin Donohoe, Chris Downs, Evie Dryden, Alan Dulnuan, Thomas Dunlop, Josh Eaton, Sian Elliott, Alex Falvey, Martin Fong, Aaron Fretwell, Chris Garven, Tom Gasson, Jack Gelabert, Alison Goddard, Guillermo Gomez, Anushka Govalupillay, Jack Green, Phillip Gregory, Karli Grumley, Arthur Ha, Penny Hall, Sham Handalage Don, Liam Hanrahan, Darren Hansen, Kurt Harris, Peta Hay, Jason He, Brian Hetherington, Craig Hodder, Daniel Holdsworth, Damian Hong, Ashley Horton, Leah Howell, Jiayu Hu, Emma Huang, Troy Hunt, Phil James, Tom Jenkins, Lorraine Jiang, Steven Jones, Evan Kaillis, Aashel Karan, Jen Kemp, Gelareh Khakbaz, Zuhdi Khraim, Vanessa Khuu, Elizabeth Kraska, Shivam Lall, Jonathan Lambxin, Hannah Lazenby, Ian Leach, Emeline Lemoto, Carter Leung, Dan Li, Eric Li, Jenny Li, Colin Little, Chang Liu, Oliver Lock, Ryan Loe, Ben Loftus, Raymond Lowe, Codee Ludbey, Ronan Lyons, Fiona Ma, Chris Macpherson, Chris Madigan, Jesse Mainey, Hatem Makkar, Anthony Marquez, Macarena Martinez Medina, Brad Massey, Anacel Maybituin, Dara McDonnell, Claire McGregor, Ronan McParland, Simon Meares, Lawrence Meire, Dave Metcalf, Regan Miles, Louise Millward, Radney Minerva, Sharon Moller, Lachlan More, Andrew Mullins, Ciaran Murphy, Simon Murray, Malaeka Nadeem, Stephanie Nguyen, Shane Norton, Jorke Odolphi, Brendan O'Halloran, Karen Oj, Sam Oswald, Adam Owen, Parisa Pakzad, Hillary Pan, Mahaveer Pareek, Dhany Parker, Justin Peachey, Ryan Phillips, Kevin Pinkerton, Aidan Potter, Robert Potts, Jacek Przysiezny, Sophie Quang, Habib Rasouli, Ed Rowe, Paula Saad Antonio, Opinderjit Samra, Pausali Sanyal Ghosh, Sudipta Sarkar, Antony Schofield, Orla Sherwin, Mathew Simon, Garima Singh, Sam Singleton, Linda Slechta, Anna Squire, David Stuart-Smith, Mary Sung, Daniel Tadic, Trent Tam, Sarah Tasic, Ben Taylor, Nicole Thompson, Stephen Thompson, Tatiana Torjinski, Joseph Tormes, James Turner, Filipe Valadares, Ivan Varga Sampedro, Georgia Vitale, Nihal Vitharana, Jo Walton-Hespe, Jack Wang, Michelle Watson, James Webber, Amelia Welsh, Stanley Weng, Laura Wheat, Glenn Wheatley, Tracy White, Danny Wilcox, Alex Williams, Oliver Williams, Derek Wong, Andy Wood, Michael Xia, Dhyan Yahampath, Richard Yalda, Oliver Yan, Samantha Yealland, Sophie Zachulski, Amir Zalnezhad, Angel Zhang.

Image credits

1, 2, 5-10: Daniel Weiss/Arup
3, 4: Transport for NSW
11: Brett Boardman Photography

1.

A record-breaking bridge

The Fengyi Bridge, which supports economic growth and functions as a public space, is the world's widest full-floating multi-tower cable-stayed bridge

Authors Luca Stabile, Hui-Zhen Wen, Ngai Yeung

The Fengyi Bridge in Xi'an, China, is a landmark for the Shaanxi Province – a literal and metaphorical bridge between the ancient city of Xi'an, which was once the eastern terminus of the Silk Road, and its high-tech future.

The 526m-long structure, which opened in May 2024, facilitates travel into and out of the city's High-Tech Industries Development Zone, a rapidly expanding tech district across the Feng River on the western side of the city. At 57m in width, it can comfortably accommodate two five-lane carriageways and a separate outer path for pedestrians and cyclists, complete with viewing platforms.

Arup was instrumental in delivering both the human-centric architectural design and the innovative wide-spanned deck system. Throughout the scheme design process, the firm provided multidisciplinary services, including planning, landscape and lighting design, as well as architecture and structural engineering. During the detailed design stage, Arup continued to act in a consultant role to help control critical design elements for the client, Xi'An High-tech Zone CITY CORE Development and Construction Co., Ltd. Arup brought together a multidisciplinary team from around the globe for the project, with architects and designers from Shenzhen, Shanghai, Milan and Copenhagen working in collaboration with bridge engineers based in Hong Kong, London, Shenzhen, Guangzhou and Macau.

2.

1: The bridge facilitates travel into and out of Xi'an's High-Tech Industries Development Zone

2: Xi'an is home to the Qin-era Terracotta Army, making the city one of China's most popular tourist destinations

A growing tech hub

Xi’an is the administrative centre of Shaanxi Province in central China, and served as the capital of several ancient dynasties, including the Qin and Tang. Its historic importance, as home to the Qin-era Terracotta Army and the last stop on the Silk Road, has made it one of the most visited tourist destinations in China.

More recently, it has also become a major focus of scientific and technological development, particularly in software, advanced equipment manufacturing and the biopharmaceutical industry. Since it was established in the 1990s, the high-tech zone has grown to host 60,000 companies, including multinationals such as GE, IBM, Samsung and Siemens, and prominent Chinese companies such as BYD and Huawei. It is eventually intended to cover more than 150km^2.

To support this growth, a major road bridge was needed to connect the zone to the Xihan Expressway and other major routes on the western side of the Feng River. But the client wanted to bring more than a new road. Xi’an lies on a flood plain, criss-crossed by eight rivers and surrounded by wetlands rich in wildlife. A plan emerged to build two bridges across the Feng River, connecting these green spaces with a circular route of footpaths and cycleways. The bridges would act as public spaces, with scenic viewing platforms set apart from the traffic, where people could stop and take in the views of the river, lakes and the Qin mountains beyond.

3: The Xihan Expressway and other major routes feed the bridge on the western side of the Feng River

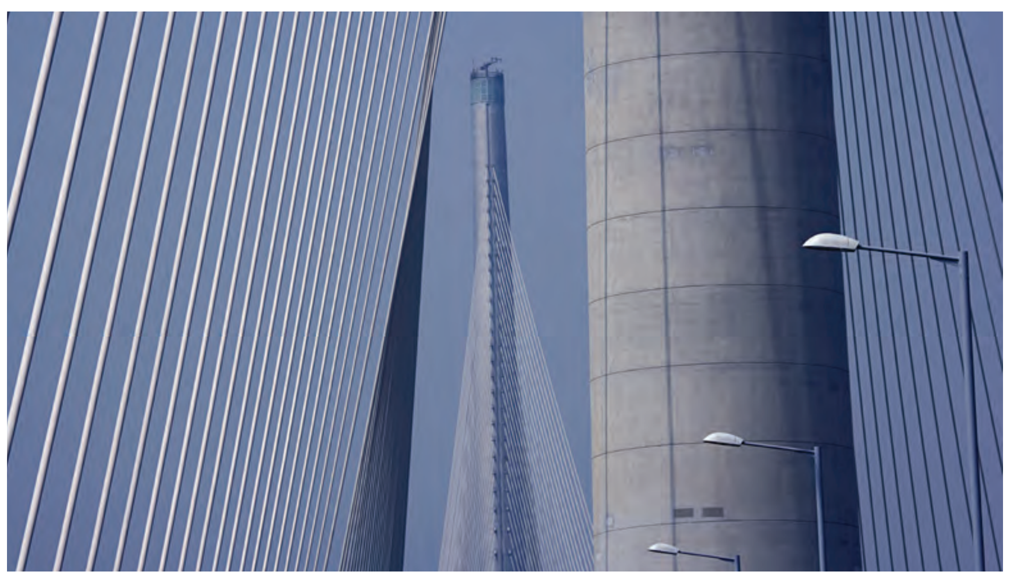
4: The Arup team was able to draw on previous experience working on the design of the 1.6km-long Stonecutters Bridge in Hong Kong

3.

Inspired by history

In 2019, a competition was launched with Arup winning the landscape bridge schematical design project, including the Fengyi Bridge. The firm did two rounds of design research and created eight design options, which were presented to the client and local government officials. During the second round of proposals, Arup created designs that included a suspension bridge with a single tower and a unique arched structure that looped twice over the length of the deck like a loosened running stitch used in embroidery.

The selected option originated from the architectural team in Arup’s Milan office (see box, right) and was supported by a range of disciplines from different Arup offices, the result of truly integrated total design. The proposal was for a graceful structure of three slightly tapering pole-like towers, 95m high and 176m apart. From the top of the towers, tensioned cables fanned out to the outer edges of the deck. As well as providing the main support for the bridge, the triangulated pattern of cables echoes the peaks of the adjacent Qin mountain range. The cables also evoke strands of silk, drawing on the city’s most famous legacy. At this stage of the process, a 10m-wide elevated walkway was included in the design, above the main deck.



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Structural solution

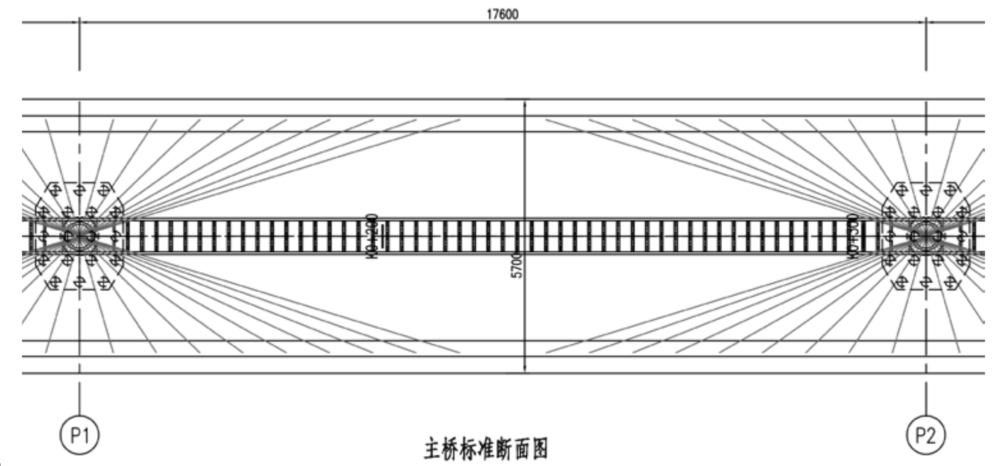
The Arup architectural team from Italy collaborated closely with a structural team in the Hong Kong and London offices, and landscape and lighting teams in Shenzhen and Shanghai, some of whom had previously worked on the design of the 1.6km-long Stonecutters Bridge in Hong Kong. The latter has a main span of 1,018m and is one of four cable-stayed bridges in the world with a span in excess of 1km.

For the Fengyi Bridge, close attention was paid to the deck design. With a width of 57m, it essentially behaves like a bridge in both longitudinal and transverse directions. Extensive computational analysis was conducted to understand the flexural behaviour of the deck under different loads, including

5: Each strand in the cable stays is 15.2mm in diameter

6: The deck comprises two five-lane carriageways and an outer path for pedestrians and cyclists

7: The initial design for the bridge included a walkway that rose above the lower deck, bending in an S-shape between the towers



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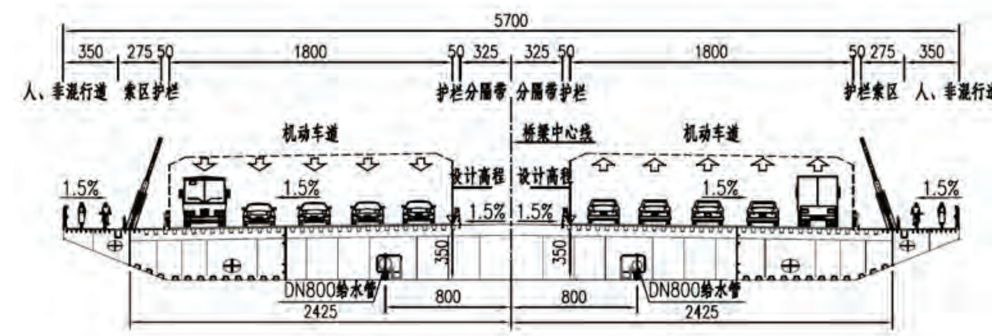

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The Italian connection

So how did a team of architects in northern Italy end up designing a bridge 7,600km away in China? It began in 2018, when a conference was held in Milan to discuss Italian involvement in various initiatives around the Silk Road. A delegation from Xi’an was interested in Italy’s historic tradition of creating bridges that also function as public spaces. The city, which is criss-crossed with rivers and wetlands, wanted to develop up to 50 new bridges as part of Xi’an’s economic growth plan.

Following this initial contact, Luca Stabile, a director from Arup’s Milan office, contacted his colleagues in Shenzhen to discuss opportunities in working on some of the bridge projects. His colleagues in China were already working up concept designs for the Fengyi crossing, and were happy to collaborate on a cross-continental proposal.

Knowing that Xi’an was keen to embrace new approaches to public space, the Milan team developed a two-deck solution, with an elevated walkway bending in an S-shape between three cable piers. The cables for the two decks would form an intricate pattern, in an allusion to the city’s silk heritage.

In order to make sure this unique deck system was viable structurally, the architects worked closely with Arup’s Hong Kong office, whose expertise in cable-stayed bridges included the city’s Stonecutters Bridge (2009) – still the fourth-longest structure of this type in the world.

The design selected was one of eight options created by the integrated design team, composed of different offices and professional teams, but winning the commission required the architectural team to deliver a two-stage formal presentation to the client and city officials. With two 3m-long maquettes of the bridge as hand luggage, they flew to Xi’an. The climax of the presentation was a virtual reality demonstration, allowing the selection panel to enjoy the experience of walking along the bridge as it meandered over the lower deck.

the compression in the deck to balance the cable tension, and using different structural configurations.

The chosen design consists of twin orthotropic steel box girders, with an overall width of 57m and depth of 3.5m, connected by 3.5m x 0.6m cross-girders spaced 3m apart. These are made of structural steel, which was preferred to prestressed concrete in order to minimise the weight and reduce the number of supporting cables required. The thickness of the deck plate ranges between 8mm and 50mm, and is typically 16mm under the inner fast lanes and 28mm under the slow lanes, which have to cope with the additional stress of heavy vehicles.

A 6.5m-wide void runs the length of the bridge between the two box girders. This performs both a structural and aesthetic role, stabilising the deck under fluctuating wind load on the structure and breaking up the uniform expanse of the road surface. The three towers rise up through this central void from 70m to 73m-deep piles driven into the riverbed, providing a bridge with four continuous spans – two 176m main spans and two 87m back spans. The circular form of the towers tapers slightly from a 8.1m diameter at the base to 6m at deck level and 5m at the top. The base section is built from reinforced concrete, with an upper section of circular steel skins with steel anchor boxes inside for anchoring the stay cables. There are 108 stay cables in total, with 18 pairs at each tower. The stay cables are multi-strand, with 1,860 MPa strength in HDPE pipes, each comprising 34 or 43 strands depending on the cable forces at different locations. Each strand is 15.2mm in diameter.

The main deck is equipped with transverse-movement-limiting cables at all three towers and the two abutments, totalling 16 numbers. These cables are carbon fibre, made of 7mm diameter wires with yield strength of 2,800 MPa and elastic modulus of 175 GPa. These cables ensure the safe operation of the bridge under normal operation and

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8: The outer pathways are separated from the two carriageways, creating public spaces from which people can view the natural surroundings

9: The triangulated pattern of cables echoes the peaks of the adjacent Qin mountain range

accidental seismic effects. The carbon fibre cables have the benefit of corrosion resistance and low elastic relaxation, and have four times stronger fatigue strength and only 20% of the weight compared with high strength steel cables for the same conditions.

A floating deck

An innovative aspect of the structure is the use of a fully floating deck. The longitudinal structure is completely welded along the main span. No bearings are required to restrain the longitudinal movement even under seismic effects, while the spring supports have been deployed for energy dissipation in the longitudinal direction. This makes the Fengyi Bridge the first full-floating cable-stayed bridge in the world equipped with spring supports.

This unusual articulation system allows the deck to move freely under the restraining forces of the stay cables, with the spring support limiting the longitudinal movement of the deck under temperature and traffic actions for safe operation and to dissipate seismic energy during an earthquake. The bridge has the world's widest multi-tower cable-stayed deck with a full-floating articulation system.

An additional challenge arose later in the design process, when the cycle and walkways needed to be moved to the outer 3.5m of each road deck. This required substantial vehicle-induced vibration analysis and section model wind tunnel testing to verify the aerodynamic stability of the bridge. A particular area of concern was the potential for vortex shedding – a phenomenon that could cause oscillations in the bridge deck under cross winds, leading to potential discomfort for pedestrians walking across a vibrating surface. The testing indicated that only minimal adjustments to the design of the steel deck was required.

A fully floating solution offers another important advantage in bridge design. With no bearings within the main part of the structure, the need for costly and potentially carbon-intensive maintenance and replacement programmes is reduced. Durability was a key consideration on the Fengyi Bridge. Part of the client's sustainability strategy was to give it a 120-year design life, through the use of robust materials and connections, and a structural health monitoring system for long-term and periodic monitoring and analysis of the spatial positions, mechanical properties, and changes in key parts of the bridge. The accumulated data is used to monitor and evaluate the bridge’s load-bearing capacity, operational status and durability during its service period. This ensures the safety of the bridge’s users and extends its lifespan.

Construction and opening

Detailed structural design was carried out by a local design institute in China, in accordance with national regulations, but Arup remained in an advisory role throughout the delivery process. Construction began in May 2022, following the end of a citywide covid lockdown. The decks were prefabricated in an assembly yard in half-width sub-panels, before being welded together into 18m-long sections. These were then delivered to site, where the towers had already been erected, with the concrete lower sections cast in situ using climbing formwork. The deck segments were hoisted onto temporary supports and launched into position using a trolley system. Finally, the cables were connected and tensioned, with each cable, weighing up to 6,700kg, providing an anchoring force of up to 330 tonnes for the completed bridge under dead loads. The Fengyi Bridge opened to traffic in May 2024.

Arup’s services have allowed for the creation of this innovative structure, which supports the growth of the high-tech zone through literal connection. Whilst the structure itself is modern, the design choices pay homage to the rich history that surrounds it.

Authors

Luca Stabile was the architectural design director. He is a Director in the Milan office.

Hui-Zhen Wen was the Project Manager. She is an Associate in the Shenzhen office.

Ngai Yeung led the structural design. He is an Associate Director in the Hong Kong office.

Project credits

Client Xi’An High-tech Zone CITY CORE Development & Construction Co., Ltd: XinYi Zhang, Dong Yang, JunTao Die, YiFan Wu, NiNi Song, Ying Zheng, HaiLi Ji, Fei Zhang, Ming Yang, ZengQiang Pan

Schematical design consultant Arup: Chris Cao, Bi-Tong Chen, Zhi-Xin Chen, Qi Cheng, Cindy Choi, Matteo Codignola, Bing-Jie Cui, Anna Dombrowski, Martina Dozio, Xiao-Jie Du, James Finestone, Jia He, David Hirsch, Li-Yuan Ke, Henry Law, Yingyan Li, Fion Mai, Aurora Migliarini, Filippo Minora, Francesca Pedroni, Luca Stabile, Michele Vettorello, Hui-Zhen Wen, Kristian Winther, Lake Yang, Ngai Yeung, Hong-An Yin

Detailed design consultant CSCEC AECOM Consultants Co., Ltd: SiRun Ren, YanFei Liu, Fan Gao, CongXin Liu, YaLin Luo

Main contractor China Railway Third Bureau Group Co., Ltd: YongTao Zhang, XingShuang Xu, ZhiWen Luo

Image credits

1, 8-10: Xi’an High-tech Zone CITY CORE Development and Construction Co., Ltd

2: Rasmus Gundorff Saederup/Unsplash

3, 5-7: Arup

4: John Nye

10.

10: The 108 stay cables reference strands of silk in a nod to the city’s past

1.

A new integrated transport hub for Northern Ireland

The largest ever investment in public transport in Northern Ireland has delivered Belfast’s new transport hub

Authors Laura Brady, Chris Caves, Reuben Lucas, Michael Mitchell

1: Belfast Grand Central Station acts as a gateway for visitors arriving in the city

The Belfast Grand Central Station, which opened in September 2024, is a new landmark for the city, providing a gateway for arriving visitors. The £340m project brings rail and bus services together in the city under one roof for the first time, and is the largest integrated transport facility on the island of Ireland.

In addition to streamlining journeys around the city and the wider region, the new station is supporting economic growth, encouraging visitors, cutting carbon emissions and improving air quality. The station has integrated seamlessly into Belfast’s existing transport network and is a catalyst for a wider regeneration of this area in the south-west of the city centre. The development also houses bus maintenance services, including fuelling, washing and servicing areas, along with administration facilities and amenities for users of other transport modes (including taxis, cyclists, private car users and pedestrians).

Arup’s technical specialists led the station’s design process from 2014, collaborating with Translink – the public transport provider for Northern Ireland – and lead architect John McAslan + Partners, to ensure the best

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2: With passenger demand growing, both the Europa Buscentre (pictured) and Great Victoria Street railway station had reached their capacity

3: The new station has integrated seamlessly into Belfast's existing transport network

4: The station is the first step in the regeneration of the new Weavers Cross quarter in Belfast

possible passenger experience. Arup brought together a host of the firm's industry experts across engineering, urban planning, landscaping, environmental consultancy, project management and a wide variety of specialist services. Arup's expertise has been crucial in masterplanning the station and its surrounding area, which will provide new mixed-use commercial and residential space, and in making sure the station meets modern standards for efficiency, accessibility and sustainability.

The challenge: modal shift

Over a decade ago, Translink recognised that Belfast's Europa Buscentre and Great Victoria Street railway station were under considerable strain. Passenger demand was growing, but both of the constrained station sites had reached their capacity. With buses and trains departing from different stations, it was one of the reasons many people were choosing car travel over public transport.

Translink's vision for Belfast Grand Central Station was to create an integrated, purpose-built transport hub, where passengers could change easily between frequent train and bus services, encouraging a modal shift from private cars to public transport and active travel.

Arup's multidisciplinary design approach, using a wide range of specialist disciplines, has turned that vision into reality. Drawing on the firm's experience in major transport projects, such as King's Cross St. Pancras Station in London, Arup worked in collaboration with lead architect John McAslan + Partners on the design of the station, its surroundings and the wider masterplan from the outset, guiding the project through to successful completion.

To enhance the bus and train networks and provide frequent, reliable services for passengers, Arup carefully examined the track requirements, considered how services might evolve and evaluated competing demands on the available space. The resulting station layout incorporates 26 bus stands and eight railway platforms within an 8-hectare city centre site – a significant increase from the previous 18 bus stands and four platforms.

4.

The durable Busway Bridge

A crucial part of the project was the design and construction of the Busway Bridge, which passes over the new railway track alignment at the south end of the site, providing a quick route for bus services operating to and from the station.

The overbridge is a key section of the new bus lane that provides a direct route for passengers using bus and coach services operating between the M1/ Broadway Roundabout and the bus stands. The bridge opened in August 2023, initially providing access to the Europa Buscentre; it now connects to the completed Belfast Grand Central Station.

The bridge's design constraints included the need to keep the busway route alignment as low as possible to minimise the height and gradient of the approach ramps, while at the same time, satisfying the vertical clearance requirements for future electrification of the railway lines below. With four railway lines splaying below the bridge, the design also needed to facilitate the transition from four to eight lines on the approach to the new station platforms.

Taking these considerations into account, Arup designed the bridge using a single-span, half-through steel-concrete composite deck, thereby minimising the structural depth. Spanning 51m and 14.75m in width, the 480-tonne Busway Bridge was constructed using weathering steel, which prevents corrosion, achieving a design life of 120 years and reducing maintenance requirements.

The bridge was inspired by Arup's previous work utilising the benefits of weathering steel for similar structures, including the Bridge Street overbridge located at Newport Station in Wales. Giving the bridge a distinct rust-like appearance, this specific steel structure is the first of its kind on Northern Ireland's public transport network and has set a new benchmark in sustainable infrastructure development.

The bridge consists of two longitudinal 150-tonne steel plate girders ranging in depth from 3.45m to 3.85m, with closely spaced transverse steel box girders. Precast reinforced concrete L-shaped units were used to form the bridge parapets and part of the deck slab. The units were stitched together with cast-in-situ reinforced concrete that also formed the remainder of the 675mm-deep deck slab. The design has a minimum vertical clearance of 6.005m above the railway to account for the required space below the bridge soffit for any future overhead electrical equipment.

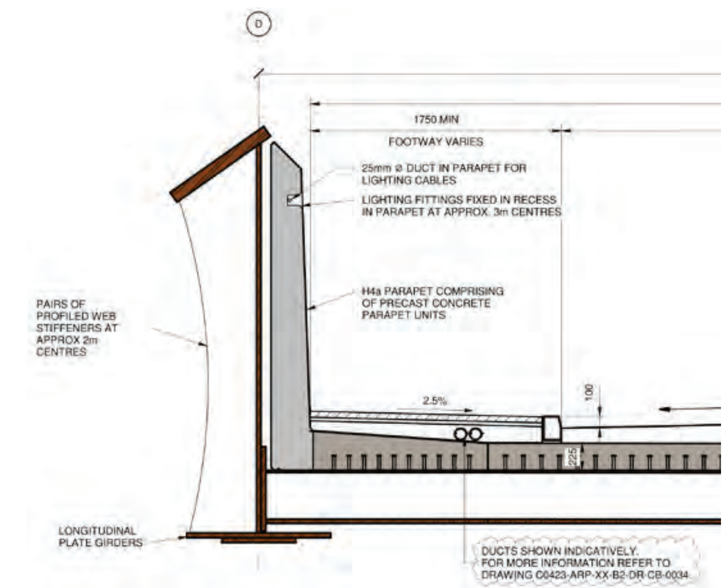
The Busway Bridge project was separated from the main element of the construction

5.

5: The Busway Bridge is a key section of the new bus lane that provides a direct route for passengers using bus and coach services operating between the M1/Broadway Roundabout and the station

6:Precast reinforced concrete L-shaped units were used to form the bridge parapets and part of the deck slab

7: The bridge has been future-proofed, with a minimum vertical clearance of more than 6m above the railway to facilitate any rail electrification



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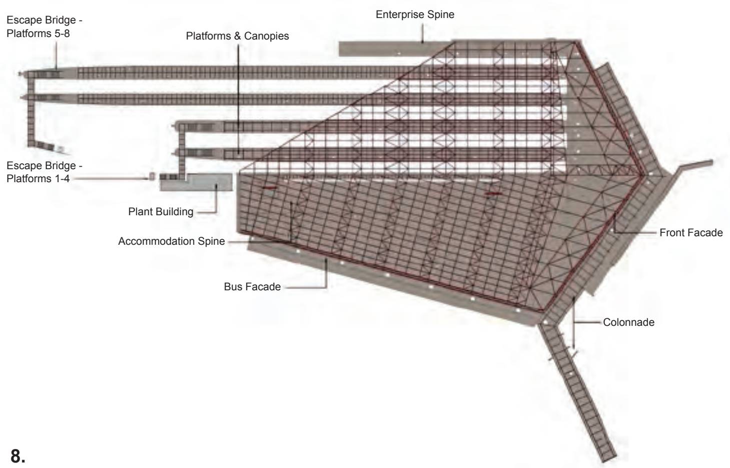

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8: The roof consists of a series of steel trusses, which form a sawtooth arrangement

9: The platform canopies consist of cantilever steel columns at 11m centres with steel outriggers and a lightweight roof

10: The platform canopy support columns are founded on piles and designed for future electrification

11: The roof includes a section with a 65m span truss over the rail platforms

10.

11.

works, with Arup coming on board not just as the designer, but as the project manager, working in collaboration with Translink and the wider contractor team. The bridge was constructed by GRAHAM, which also carried out a significant enabling works package on the site.

Station design

The station building consists of a large double height space with the concourse and train platforms under a single roof. Due to the challenging ground conditions, with the site underlain by estuarine alluvium (a soft organic silt or clay known locally as 'Belfast Sleech'), the building is founded on continuous-flight-auger concrete piles. The piles range from 450mm to 900mm in diameter and are up to 27m deep.

A culvert that ran under the footprint of the building was diverted as part of the enabling works contract. The Northern Ireland Water sewer tunnel running at depth beneath the southern portion of the site was maintained throughout the construction works, with an exclusion zone applied that restricted the proximity of piling to the tunnel.

The ground floor consists of a 300mm-deep reinforced concrete suspended flat slab supported on pile caps and individual piles at 6m to 7m centres. The building's predominantly single-storey steel frame has cross-bracing and concrete-shear walls, providing stability. Columns supporting the roof are spaced on a 22m x 12.875m grid. The roof consists of a series of steel trusses, which form a sawtooth arrangement, with spans ranging from 12.875m typically to 65m over the rail buffer zone. Between the trusses are 22m-span cellular beams.

The two storey back of house accommodation, which runs along the northern-west end of the building above the platforms, is also a steel frame, with a composite slab on metal decking, with typical bays of 5m x 12m. A two-storey accommodation block separates the public concourse and platform areas. It contains back-of-house areas as well as public areas containing retail units and an area for events.

12.

12: Belfast Grand Central Station is the largest integrated transport facility on the island of Ireland

Sustainability focus

From the outset, Arup focused on sustainability, accessibility and user experience. The firm led the planning and environmental work to achieve planning consent in 2018, working alongside Juno Planning. These elements included preparing the Environmental Statement, drainage and flood risk assessments. The team also convened an environmental liaison group with statutory consultees to engage in the design and assessment.

During construction, a waste compactor was used on site, reducing the number of trips needed for waste collection. Contractors delivering packaged or wrapped components took redundant packaging away on delivery vehicles. A target was set to recycle 80% of waste during the enabling works and 70% of construction waste during the main works. Arup provided a dedicated BREEAM and BREEAM Infrastructure assessor to work collaboratively with the client and contractor from feasibility through to completion, undertaking workshops to embed sustainability within work practices.

A construction strategy was formulated in collaboration with Translink for the contractor to develop and implement. The plan included logistics, diversions, phasing, health, safety and environmental management, demolition, deconstruction, ground works, structures, workforce, traffic management, public information, site security, emergency planning, waste management, construction compounds, operation of equipment, site layout and facilities, hoarding and working hours. The environmental management plan detailed control measures for ecology, water quality, air, noise, landscape, ground conditions, and heritage, as well as outlining monitoring and maintenance requirements.

The site drainage was designed with allowance for climate change by increasing the rainfall intensities of the design storm events. The finished floor levels are above the 1 in 100-year flood level, with an additional 600mm freeboard to mitigate impacts of climate change. Efficient water consumption measures include low flush toilets, passive infra-red taps, leak detection on water mains, solenoid valves on water supplies and meters to facilitate monitoring water usage and detection.

Carefully placed glazing and skylights help maximise daylight and reduce the need for electric lighting, saving energy. The roof architecture allows natural light to flood into the station concourse, with the roof designed to accommodate photovoltaic panels positioned to maximise their energy efficiency. Electric lighting design incorporates daylight-sensing lighting controls and absence detection controls. Toilets and other central spaces incorporate presence detection to minimise lighting energy, with energy efficient light-emitting diodes (LEDs) used throughout.

Modelling to enhance comfort

One of Translink's priorities was the air quality inside the station building. To analyse this, Arup used computational fluid dynamics to model airflow throughout the concourse area. The team factored in weather conditions, peak and off-peak passenger capacity, and upcoming changes to the rail locomotives. This analysis influenced the design of the roof, conceived by John McAslan + Partners architects to reference the city's industrial heritage and its 19th century linen mills. The sawtooth roof echoes the folds of linen used in the weaving industry that once occupied this Belfast city centre site. The internal arrangement and structure were adjusted and refined to ensure that air quality would surpass that of a typical railway station.

Passive design is used throughout the new concourse to keep operational energy use low, reducing direct solar gain and minimising the need for heating and cooling. The building is on track to receive BREEAM 'Excellent' and BREEAM Infrastructure 'Excellent' awards, recognising the project's exceptional environmental and social performance.

To ensure that all passengers experience the station as a welcoming, safe and accessible space, Arup undertook extensive pedestrian modelling. Using the firm's 3D MassMotion software, the team predicted the paths people would take to, from and through the station, examining dwell times and potential pinch points. This analysis informed the dimensions of platforms, the ideal number and location of ticket gates, and the most efficient evacuation strategy for the building. The models were also used to design the wayfinding strategy and elements of the surrounding public realm.

Keeping a major project on track is a huge challenge requiring meticulous planning. Advanced 3D modelling helped devise a phasing and implementation strategy for the project, including rerouting the complex web of services in the streets surrounding the site. Fully integrated with BIM Level 2, the project team could view information and collaborate in real time, supporting good communication across the team.

Weavers Cross regeneration

Arup's involvement extended to ensuring that the station integrates well with the surrounding urban environment, enhancing connectivity within Belfast and supporting economic growth. The local community will see the benefits of the station with the new public realm works, cycle priority and pedestrian routes into the new station that are currently under construction.

Arup played an important role in obtaining outline planning permission for the redevelopment of the station's surrounding area. The station is the first step in the regeneration of the new Weavers Cross quarter in Belfast. This will be a dynamic and imaginative mixed-use development, fit for all users and communities, aiding inward investment, and providing a significant regeneration opportunity for the city and Northern Ireland.

The public realm enhancements will provide recreation space for local residents and visitors, improving links between local communities and the city centre and improved transport access, employment and leisure opportunities. Landscaping and planting will include tree, shrub, flower and grass species in the detailed design planting schedule, benefitting wildlife. Pollinators will also benefit in line with the All-Ireland Pollinator Plan 2015-2020.

Arup was also instrumental in the development of the active travel proposals. The civic square in front of the station will allow access to the Belfast Bikes Network of urban cycleways, is adjacent to the existing Belfast Bikes public bicycle sharing scheme and will facilitate the provision of high-quality bike parking for up to 200 bicycles.

Drawing on Arup's experience of urban renewal projects like Coal Drops Yard in London, and the local team's in-depth knowledge of Belfast, the firm has worked to maximise the project's regeneration potential. This will help develop the surrounding area, including the Saltwater Public Square, currently under construction, and several future development sites.

Shaping Belfast's future

In September 2024, Belfast Grand Central Station welcomed its first passengers onto trains and bus services offering easier and faster connections. It provides seamless access to bus, coach, rail and active travel connections across the city and beyond, driving a modal shift towards more public transport and active travel. The station is ensuring people are better connected, while helping Northern Ireland achieve the carbon emission reduction targets set out in the Northern Ireland Climate Change Act.

The station has simplified travel across Northern Ireland and now hosts 15 daily train services between Belfast and Dublin. Around 400 bus services travel across the Busway Bridge on a daily basis, with passengers saving approximately 10 minutes on journey times when travelling to and from the new integrated station on services that use this direct bus lane and busway bridge.

Inside the station, passengers can wait for the new, seamless services in comfort and enjoy a range of seating areas, shops and cafes with passenger feedback at a 96% satisfaction rating. Translink announced that an additional three million passenger journeys were made in 2024/25 compared with the previous year and it anticipates that Grand Central Station will serve 20 million journeys per year by 2040, three times as many as its predecessors. This new transport hub, and the regeneration opportunity it has enabled, are the foundations for a more sustainable, better connected future for Belfast and stand as a visible symbol of investment in the city.

13.

13: Passengers now benefit from rail and bus services being under one roof for the first time in Belfast

14: By 2040, the station should serve 20 million journeys per year, which is three times as many as its predecessors

14.

Authors

Laura Brady was the design lead for the Busway Bridge element of the project. She is a senior engineer in the Belfast office.

Chris Caves was the Project Director. He is a Director in the Belfast office.

Reuben Lucas was the Project Manager and design lead for the station project. He is an Associate Director in the Belfast office.

Michael Mitchell was the Project Manager for the Busway Bridge element. He is an Associate Director in the Belfast office.

Project credits

Client Translink
Lead architect John McAslan + Partners
Planning consultant Juno Planning
NEC project manager for the station Arcadis
Main works contractor Farrans Sacyr JV
Main works contractor designers RPP Architects, Doran Consulting (civil & structural engineering), Tetra Tech (M&E designers), Dowds Group (M&E sub-contractor)
Busway Bridge and enabling works contractor GRAHAM
Busway Bridge and enabling works contractor designer Mott McDonald
Environmental consultancy, fire engineering, masterplanning, mechanical and electrical design, project management, public health engineering, rail infrastructure design, structural engineering, traffic Arup: Faysal Abukar, Thomas Adamson, Charlotte Adcock, David Algie, Katie Amos, Josh Archer, Hannah Beard, Tara Begley, Agnieszka Bianchi, Amy Black, Philip Bleakley, Christina Borland, Laura Brady, Pearce Braidan, Matthew Brown, Phil Brown, Richard Bunn, Kieran Butler, Martin Bywater, Will Campbell, Kieran Carlin, Patrizia Carpentieri, Paul Carr, Ken Carter, Patrick Casey, Chris Caves, Steph Chapman, Wayne Charles, Anqi Chen, Dennis Christie, Wojciech Chrząszcz, Stacy Clements, Kelsey Coey, Declan Coleman, Mark Cooper, Jack Copner, Anna Coppel, Philip Craig, Francesca Crossan, Lisa Curren, Artur Czarnecki, Nathan Dalzell, Ben Davies, Mark De Melo, Richard Denham, Brian Devlin, Patrick Devlin, Hassan Dia, Tammy Dodds, Seda Dogruel, Gary Donnelly, Mick Donnelly, Remant Doorgakant, Aaron Dougan, Grace Dowdall, Matthew Dowie, Kamil Drozd, Mike Dutton, Thomas Dysart, Karolina Dziag, Louise Edward, Mohammed Eleyan, Ciaran Elliott, Iolo Ellis, Sophie England, Thomas English, Gwyn Ephraim, Ioan Evans, Stephen Evans, Calum Ferreira, Meghan Fick, Paddy Finnegan, Dean Foster, Louise Foster, Andrew Foxon, Maxine Fraser, John Freeman, Jake Frew, Jonas Gauffin Dahlin, Nabihah Ghufoor, Sofia Gkino, Anthony Gleadhill, Michal Gorczynski, Simon Graham, Pete Gray, Kamil Grzebalski, Jake Hacker, Dan Hackett, Emma Haggan, Mark Hale, Adrian Hall, Llew Hancock, Ricky Hancock, Greg Harris, Matthew Harvey, Nathan Hattersley, Guneet Hawley, Nick Hawthorne, Paul Haywood, Karl Hegarty, Lukasz Hetmanski, Neil Howley, Lan Huang, James Hughes, Kevin Hughes, Alastair Hume, Val Ismaili, Michal Jajeåšnica, Venon Jalali, Lauren Jayes, Andrew Jenkins, Natalia Jesionowska, Paul Johnston, Piotr Kaczor, Menekse Kaya, Magdalena Klos, Eirini Kotrotsou, Weronika Kowal-Szabelska, Tomasz Kuchna, Arjuna Kulupana, Ray Lake, Andy Lambert, Robin Larcombe, Jasmine Lau, Gareth Lawlor, William Legg, Michal Legucki, Keith Lilly, Sophia Liu, Cian Long, Agnieszka Lopez-Parodi, Reuben Lucas, Ana Luisa Maldonado, Paul Lynch, Donncha Madden, Beata Mamel, Panagiotis Manis, Kinga Marecik, Daryl Marshall, Charlie Martin, Giulia Matteoni, Colm Maxwell, Jim Maynard, Joanne McAnulty, Laura McCann, Anthony McCauley, Pauric McCloskey, Suzanne McColgan, Daniel McCool, Phil McCullough, Emma McFarland, Bronagh McFarlane, Scott McGee, John McGill, Grace McGlen, Paul McGreevy, Christopher McGuinness, Shane McHugh, David McKenna, Calum McMillan, David McShane, Victoria Megraw, Dylan Melsom, Ciara Mitchel, Michael Mitchell, Conor Molloy, Agnes Monaghan, Chris Moore, Craig Moore, Megan Moore, Philip Morgan, Chirag Morjaria, Keith Morrison, Jonathan Morrison, Rachel Mullan, Lawrence Muller, Muiread Mulrooney, Matthew Munro, Charlotte Murphy, Christopher Murray, Ryan Murray, Anna-Lise Nanton, Matt Niblock, Chris Norman, Ben Oakman, Eithne O'Donnell, Rachel O'Kane, Agnieszka Okulowska, Laura O'Toole, Orest Owczarski, Thomas Parkes, Dobromila Pierzchala, Diarmuid Porter, Robert Powell, Brandon Price, Nuria Priego, Mario Querol, Cathal Quinn, Alfonso Ramirez Marchena, Aveen Ramlall, Sara Ramos, Aaron Regazzoli, Claudia Reinhard, Shannon Rice, Andrew Richardson, Peter Richardson, Aled Roberts, Ashley Robinson, Tariq Saeed, Eamon Scullion, John Scullion, Hasnaa Shaddad, Holly Shearer, Sam Shuttleworth, Chloe Sinclair, Matthew Skuse, Simon Sloan, Neil Smyth, Mariusz Spykra, John Stalder, Ben Staley, Michael Stevens, Darren Stewart, Lesley-Anne Stone, Tomasz Sularz, Urszula Suplicka, Aleksandra Synowiecka, Emilian Szarow, Matt Tanswell, Lukasz Tetiorka, Lucinda Thornton, Melanie Thrush, Klaudia Tokarz, Anil Toraman, Mark Townsley, Gary Turner, Craig Turp, Nick Upcott, Ben Urry, Pasan Walisundara, Jamie Wallace, Killian Walsh, Lisa West, Andrew Whinney, Napat Wiriyasubpachai, Kamil Wræblewski, Matt Wright, Greg Zabicki, Dominik Zolnowski, Lutalo Zuberi, Agata Zuchniewicz.

Image credits

1, 9, 12-14: Donal McCann Photography
2, 6, 8, 10, 11: Arup
3, 4: John McAslan + Partners
5, 7: Graham Construction/Translink

1.

Working collectively, alongside nature

An innovative vision for Wales that creates a pathway for society to work collectively and together with nature to build flood resilience

Authors Robin Campbell, Julien Clin, Malina Dabrowska, Lauren Davies, Rosemary Jenkinson, Nina Noreika

1: Welsh artist Prith Biant was commissioned to create an artwork supporting the vision

2: The artwork will be permanently displayed in the Transport for Wales headquarters, reinforcing the vision's long-term influence on policy and public engagement

Around the world, the risk of flooding is increasing because of climate change, ageing infrastructure, shifting demographics and changes in how people use land. Countries must increasingly respond to unprecedented events like major coastal or fluvial flooding. Building collective resilience within nations and harnessing creative ideas are essential to address these complex risks and how they impact communities.

In Wales, the National Infrastructure Commission for Wales (NICW) advises government on the country's long-term strategic infrastructure needs. In 2021, it was given a remit to assess how to minimise the nationwide likelihood of flooding of homes, businesses and other infrastructure by 2050, as part of the Welsh Government Co-operation Agreement. The Building Resilience to Flooding in Wales by 2050 project was launched to identify policy and practical actions for infrastructure that support the mitigation of flood risk, improve resilience and help better protect Wales. Using such a future-facing process has been part of the Welsh Government's approach since the introduction of the Well-being of Future Generations Act adopted in 2015 to ensure public bodies think more about the long term, working together to improve the well-being of Wales.

Arup initially carried out a scoping exercise for NICW to inform the process to be adopted on this project. The firm's work included a high-level literature review and consultation with a project advisory group made up of key stakeholders from across government, community, industry and academia. This work, carried out in collaboration with NICW, identified the need for a longer-term vision that would provide a common understanding for organisations and communities of the challenges ahead and foster shared goals. The ambition of the vision was to shift the narrative around flooding from one of fear to one of hope.

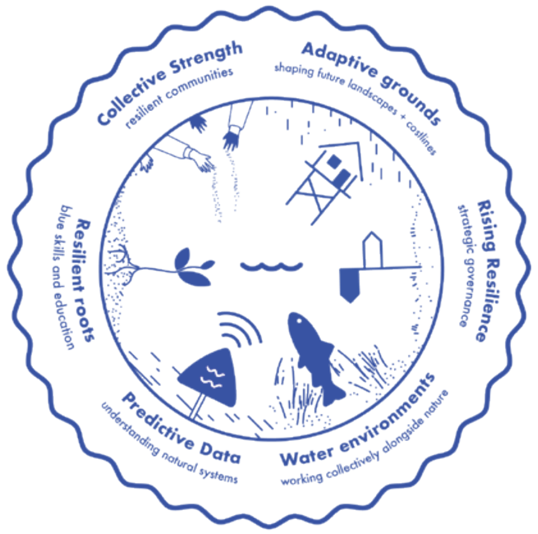
NICW commissioned Arup to develop a long-term vision of flood risk management for Wales. The aim was to address future flood risk challenges in a creative and innovative way that would engage the public and stakeholders, and produce a series of recommendations for improving resilience. This work was one of four NICW research workstreams on flood mitigation. The other workstreams were:

- Exploring the options for coordinated strategic and spatial responses to flood management.
- The funding and workforce resources needed.
- Quantifying and analysing the land use planning issues associated with flooding.

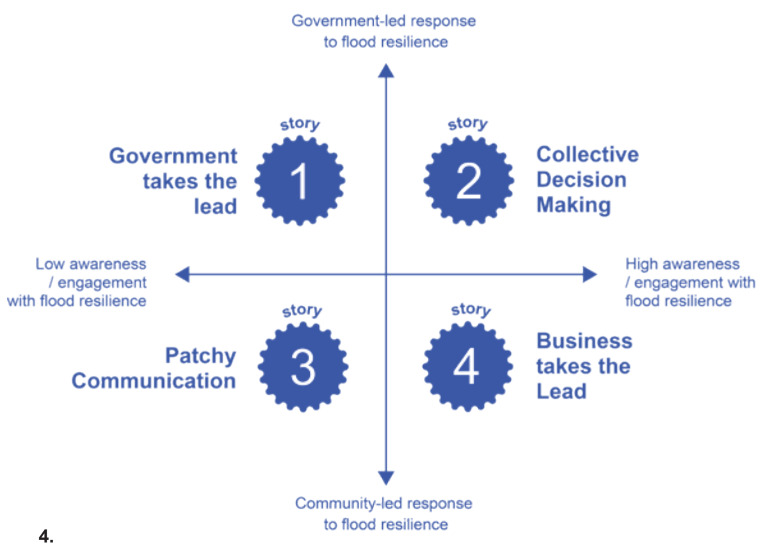
Vision painting

Welsh artist Prith Biant, who attended a community co-creation workshop to explore possible futures in Wales, was commissioned to create an artwork (left) supporting the vision. She drew inspiration from the workshop feedback and her own sense of what the vision for a flood resilient Wales could look like. Inspired by a river persona used in the workshop, she captured it as the essence of Welsh landscape – water and landscape in harmony with people. The artwork will be permanently displayed in the Transport for Wales HQ in Pontypridd (right) – a town badly impacted by flooding previously and the location of one of the project's workshops.

2.



3.



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3: The 2050 Vision highlighted six principles which bring different aspects of the resilient future Wales to life

4: Arup developed four possible future scenarios for use in the workshops

5: The personas included a politician, a student and a river

6: The use of the river persona was a first for Arup's Foresight team in using a 'more-than-human' persona

7, 8: Countries must increasingly respond to unprecedented events like major coastal flooding, such as the overtopping of Barmouth Promenade in January 2014 (7), and fluvial flooding, such as in Pontypridd in February 2020 (8)

Collectively shaping futures

Using Arup's deep technical knowledge of flood risk management and water infrastructure, combined with futures and design thinking, the firm explored how people across Wales can work together to develop future flood resilience. To create this vision, the team engaged with people living and working in Wales through participatory design methods, creating engaging and imagination-driven workshops exploring possible futures for Wales in 2050. Over 80 stakeholders took part in the vision-making exercises.

'Future stories' were key to helping participants imagine different future scenarios. They facilitated conversations on flooding risks today and future responsibilities of communities and the government, opening conversations about what desirable future flood resilient Wales could look like and what might need to change to support this transition.

Arup developed a series of transformative actions which can be taken today to set Wales on a pathway to a flood resilient future. These were included in the website and report published by NICW. This report, along with the reports from the three other workstreams, were presented to the Welsh Ministers in October 2024 to inform and shape how flood resilience can be achieved by 2050 and included a series of recommendations.

Setting the scene

At the beginning of the process, Arup worked closely with NICW to identify key areas for the project to focus on – governance, policy, funding and community resilience. This collaboration established the project's focus and ensured that it aligned with the needs of the Welsh Government, while using creative approaches to deliver on the radical recommendations NICW was seeking.

The Arup team initially identified the trends and key themes (flood resilience engagement and community/government-led response) that will influence the future trajectory of Wales regarding resilience to flooding and adaptation to climate change. These insights formed the basis of four future scenarios explored in the workshops (see box-out, right). They were compiled from a literature review of key legislation, case studies and research. A short video was created that set the scene, posing key questions to be considered by the workshop participants.

Worldbuilding workshops

Arup facilitated two in-person worldbuilding workshops, engaging with more than 80 participants to co-create and explore possible futures for Wales. They were hosted in two locations chosen for their relevance to flood resilience issues – Colwyn Bay in the north of Wales and Pontypridd in the south.

The community engagement consultancy Grasshopper helped bring together the stakeholders, who were individuals across different backgrounds, ages and

Future scenarios

The Foresight team developed four possible future scenarios, with Arup's water team helping to shape and ground these in the context of Wales, to ensure that the scenarios explored future policy, socio-economic context, nature and future generations.

i. **Government takes the lead: The government leads on the flood resilience efforts and provides strategies for communities and businesses to deal with floods, putting resources and efforts into a national campaign.**

ii. **Collective decision-making: Decision-making is marked by a transparent hierarchy with clear roles and responsibilities. This ensures that competing priorities do not obstruct collective action. This model favours a slower, reflective approach, allowing for a broader range of voices and perspectives to be heard and incorporated into policy and action.**

iii. **Patchy communication: The response to flooding in Wales is fragmented and reactive. There is no overarching strategy or joined-up thinking, and the current situation has continued with existing inequalities amplified. The discourse is around response, not prevention, and vulnerabilities are likely to increase.**

iv. **Business takes the lead: The commercial sector has taken the lead in flood resilience in Wales. With little regulation, the response has largely become a corporate responsibility. Businesses have formed enhanced relationships with local authorities and communities, leading to a shift towards a local community/business model. This has led to larger scales of community impact, but the affordability of such schemes has been a challenge.**

sectors. They included flood risk management professionals from local authorities and consultancies, political representatives, community groups and individuals, environmental organisations, academics, developers, emergency response groups and local residents.

The workshop participants explored the opportunities and trade-offs of the different future scenarios and who may or may not benefit. They were asked to imagine what the future could look like from a range of perspectives, based on eight future personas representing different individuals who might experience flooding in 2050 – a local resident, a farmer, a business owner, a politician, a student and a river – with the river being a first for Arup's Foresight team in using a 'more-than-human' persona. The participants were asked to embody these personas and consider, from their perspective, the impacts and needs in each scenario.

Although the future scenarios and personas were based on trends and drivers shaping flood resilience in 2050, the workshops were designed for a wide range of stakeholders to engage with complex systems and data through easy to follow and intuitive narratives of the stories. This approach allowed a technical subject to be tackled, set within a future specific to the Welsh context. Emerging principles and recommendations from these stories were used to develop the final 2050 Vision, ensuring all voices were included.

Achieving the collective vision

The vision imagines what a flood resilient Wales could look like in 2050, highlighting six principles which bring different aspects of the resilient future Wales to life.

1. Water Environments: working collectively, alongside nature
- Wales is a hub for flood resilience and adaptation, working alongside nature to enable resilience.
- Recommendations include: review how to consider nature as a stakeholder, considering opportunities to enshrine natural assets in law.

2. Predictive Data: understanding natural systems
- Emerging technology supports open and transparent access to data, which those in Wales understand and use to help steward landscapes.
- Recommendations include: consider opportunities to set up open data repositories that are inter-operable and accessible.

3. Adaptive Grounds: shaping future landscapes
- Our communities, infrastructure and landscapes are adaptable and water resilient.
- Recommendations include: set up a taskforce to explore how the uptake of nature-based solutions can be scaled and landscapes can be adapted to a future climate.

4. Rising Resilience: strategic governance
- Leadership and integrated responses support a flood resilient Wales.
- Recommendations include: explore and/or pilot collaborative catchment or coastal forums.

5. Resilient Roots: blue skills and education
- Action is empowered through education, training and skills.
- Recommendations include: review of the national curriculum to include or strengthen climate adaptation and resilience and consider a national education campaign to raise awareness across Wales.

6. Collective Strength: resilient communities
- Representation and collective decision-making support community action and resilience.
- Recommendations include: explore opportunities for forums which bring together broad disciplines supported by inclusive public representation to coordinate integrated catchment responses across the water environment.

Backcasting from the future vision to today, a series of impactful steps needed to set Wales on a pathway towards the 2050 Vision were identified through conversations and recommendations from the workshop participants. The project advisory group of experts from across 16 organisations – including Natural Resources Wales, the Met Office and Transport for Wales – helped shape the flood resilience insights, ensuring they were contextualised within future infrastructure needs.

The final recommendations from this project were considered by NICW, alongside the three other workstreams, and informed the development of a series of recommendations, presented to Welsh Ministers to inform and shape national action on flood resilience. Welsh Ministers responded to NICW's Review in April 2025 and at the time of publication NICW is considering the response.

The power of foresight

One common barrier to acting for a different future is how emotionally

9.

Vision 2050 – a message from the future

Twenty-five years ago, few people imagined that Wales would become a model for other countries and regions struggling to adapt systemically to a changing climate. Welsh infrastructure struggled to cope with increasingly likely flood events. Responses by the government and communities were fragmented and ineffective. It was time for a shift. The Welsh Government set out to create a flood resilient nation for thriving generations to come.

It drew on the country's dynamism, its strong communities and a hopeful future vision to steer by. This vision marked a shift from 'working in silos, often not in tune with nature' to 'working collectively, alongside nature'. Encouraging long-term perspectives and policies – particularly around equality, justice and the sustainable use of natural resources – helped to reframe how Wales can thrive. It enabled organisations and businesses to continue to flourish today, in 2050.

10.

11.

12.

13.

9: NICW commissioned Arup to develop a long-term vision of flood risk management for Wales

10: The workshop participants were asked to imagine what the future could look like from a range of perspectives

11: Eight future personas were used in the workshops representing different individuals who might experience flooding in 2050

12, 13: The workshop participants explored the opportunities and trade-offs of the different future scenarios

Foresight at Arup

Arup's Foresight team is a multidisciplinary team of futurists, designers and technical experts helping clients and partners to gain a long-term and insightful view of the future. They identify early signals of change, analysing the impact of major trends, and explore future operating contexts.

By using a broad range of strategic tools, as well as creative techniques, they engage diverse stakeholders in meaningful, structured conversations and research about the future. The aim is to obtain insights about the future and identify opportunities for organisational and technological innovation.

They use participatory world-building techniques and speculative design to help stakeholders articulate new futures. The methods used challenge assumptions, inspire and provoke change, and help clients make informed decisions to achieve ambitious and transformative outcomes.

Using an evidence-led approach, the Foresight team incorporates practical foresight into planning, design and engineering projects to help clients navigate disruption across increasingly uncertain and complex futures.

14.

14: Arup facilitated two in-person world-building workshops including one in Colwyn Bay

15: The vision report provides a coherent, long-term direction for Wales, inspiring a new way of thinking beyond the status quo

distant it can be. This project is a powerful testament to how foresight, art and design can make a variety of possible futures more tangible. Speculative fiction and participatory approaches to research can help stakeholders imagine other outcomes and help draw out a more desirable vision. By integrating flood risk management insights with design and foresight methodologies, complex flood risk data and future trends were translated into accessible narratives, ensuring all stakeholders – regardless of technical expertise – could meaningfully engage in shaping a resilient future.

The project was designed as a pilot for other parts of Wales and other nations to adapt and foster climate resilience in their own contexts. An open-access website hosts the workshop materials so that others can replicate the approach and continue conversations around resilience and adaptation.

The vision report demonstrates Arup's expertise in futures thinking and foresight, bringing together other disciplines to produce an innovative piece of work. It is a resource that will influence governmental decision-making on flood resilience, as well as help local communities bring about change. It provides a coherent, long-term direction for Wales, inspiring a new way of thinking beyond the status quo and acting now for future resilience.

15.

Authors

Robin Campbell was the Project Director. He is an Associate Director in the Cardiff office.

Julien Clin is an analyst with Arup's Foresight team and the narrative futures lead in the team. He is based in the London office.

Malina Dabrowska is a design lead with Arup's Foresight team. They are a senior designer in the London office.

Lauren Davies is a senior designer with Arup's Foresight team in the London office.

Rosemary Jenkinson was the Project Manager. She is a principal water consultant in the Bristol office.

Nina Noreika led the initial scoping work for this project. She is an engineer in the Bristol office.

Project credits

Client National Infrastructure Commission for Wales
Workshop engagement support Grasshopper Communications
Foresight and water engineering Arup: Robin Campbell, Julien Clin, Ann Cousins, Malina Dabrowska, Lauren Davies, Rosemary Jenkinson, Ness Lafoy, Maria Lawrence, Nina Noreika, Claudia Palcova, Tobias Revell, Dan Tram, Ros Vose.

Image credits

1: Prith Biant
2-6, 10-14: Arup
7: Mike Alexander
8, 15: Shutterstock
9: Andrew Hazard Photography

1.

The Real deal

Redesigning Real Madrid's iconic Santiago Bernabéu football stadium to welcome an ever-growing audience

Authors Matias García del Valle, Ignacio Fernandez

1: Each louvre in the stadium's stunning new stainless-steel facade has a unique geometry

Since it first opened its doors in 1947, the Santiago Bernabéu stadium has been home to Real Madrid football club and has hosted major football finals at club and international level, including four European Cup/UEFA Champions League finals and the 1982 FIFA World Cup final. Now, the iconic venue has undergone a transformational renovation. The redevelopment has created a modern, efficient stadium, enhancing the fan experience, and improving accessibility and comfort.

For this major refurbishment, Arup was appointed by Spanish building and infrastructure firm FCC Construcción to deliver architecture, facade engineering and acoustic and lighting design services – enabling the venue to become more versatile. The stadium capacity now stands at approximately 80,000, depending on the type of event, and the facilities have been adapted to accommodate an expanding and diverse audience for a variety of occasions, including sporting events and concerts.

Arup helped transform the exterior of the stadium through the engineering design of the stunning new wrap-around stainless-steel facade. The firm was also responsible for the architectural upgrade of the stadium bowl, working to a comprehensive set of specifications regarding capacity, VIP areas, accessibility, security and pitch views to future-proof the facility. The firm collaborated with gmp Architects, L35 Architects, and Ribas & Ribas Arquitectos, who were responsible for the architectural elements of the stadium's new envelope and roof. Arup used 3D models to design the stadium envelope and to define the position of the new seats, ensuring unobstructed views of the pitch.

The team also undertook performance modelling of the stadium for wind, glare, acoustic performance and comfort to enhance the spectator experience.

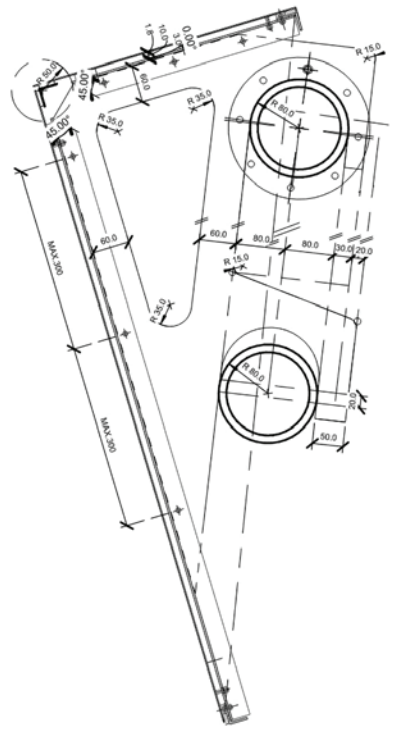
The football club's decision to retain the concrete structure of the existing stadium, rather than demolish and rebuild, significantly reduced the carbon footprint of the redevelopment. This did, however, add complexity to the new building envelope, which needed to work with the existing main structure that was not originally built to meet the typically required tight tolerances. An additional challenge for the project team was that the construction works needed to take place while keeping the stadium open for football.

The upgraded Santiago Bernabéu stadium now not only offers a memorable experience for fans and spectators, but also acts as a meeting point and leisure space for visitors, adding value at a local and national level. The venue now welcomes so many visitors as to be among the three most visited museums in Spain. The stadium will be one of the venues for the 2030 FIFA World Cup, which is being co-hosted by Morocco, Portugal and Spain.

Delivering the new building envelope

A unique stainless-steel facade is the most notable visible feature of the renovated stadium. Arup's building envelope specialists developed the detailed engineering design for the 60,000m^2 wrap-around facade. The team used Building Information Modelling (BIM) to develop a digital model of the facade, which ensured the elements were manufactured with the correct shape to create the stadium's outer skin in a cost effective and time efficient manner.

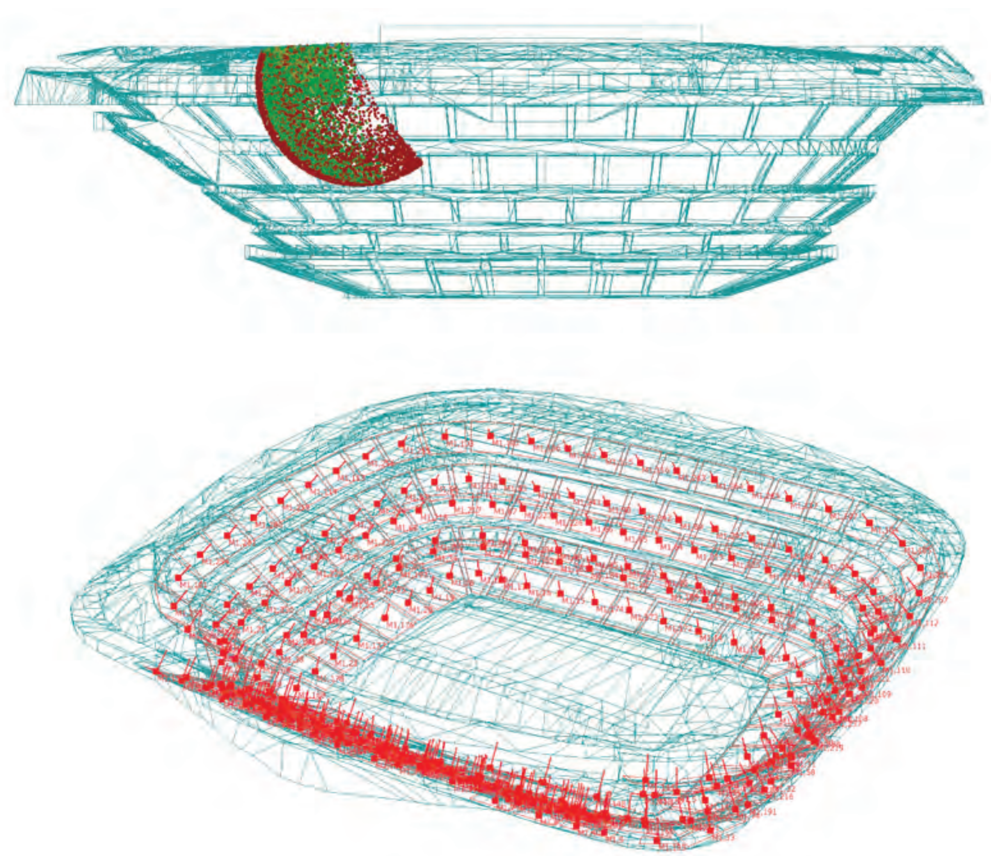
The facade is a double-curved enclosure formed by approximately 7,500 individual V-shaped stainless-steel louvres, each with a unique geometry, fixed to the large span substructure. The 7.5m-long louvres form the continuous enclosure to wrap around the stadium, while maintaining natural outdoor ventilation.



2.

From the outset, Arup had to design with a modular and safe construction mentality, reducing assembly operations, working in an open dialogue with the building envelope suppliers and contractors. The team defined a system that could work for all the louvres within the required construction tolerances. This was a significant challenge where the main structure (concrete walls and steel roof) was subject to large differential movements.

Each louvre's double curvature is formed by combining components with unique geometries. To design and manufacture the louvres on time, Arup needed to parametrically define each facade component, since defining each geometry by CAD drawings was not feasible due to time constraints. The geometry was automatically exported from the 3D model to the factory. This provided a smooth transition from the design to the fabrication drawings. The louvres were manufactured in Spain and, as part of the approvals process, an at-scale model (21.5m x 9.5m) was manufactured prior to construction on site.



3.

As the team had to ensure accuracy in their design without having the substructure in place, it required close collaboration with contractors to ensure the success of the project. Each louvre was equipped with a barcode for tracking its position in the stadium and was manufactured from the model rather than measurements from the structure. After assembly, the structure was scanned to ensure every point on its surface met the required tolerance of less than 3mm. This process allowed for precise manufacturing and installation, despite the challenges posed by the construction timeline.

Solar simulation

In addition to optimising the louvre geometry, Arup needed to minimise reflections from the sun off the metallic facade to prevent glare affecting passing pedestrians, cyclists and drivers, as well as nearby residents. The firm conducted analyses and adjusted the geometry and material of the louvres to meet the local authority's requirements and avoid disturbing people in the surrounding area. The team's lighting specialists carried out a sunlight reflection study. Using a parametric tool that simulated the sun's position throughout the day and right across the year, they generated the optimal geometry and louvre angle for each unit, changing the angle of reflection where required to ensure a suitable position to minimise the visual glare off the envelope.

Spectator point of view

Enhancing the spectator experience was a critical driver for the Santiago Bernabéu stadium redesign. Arup undertook the architectural design of the stadium bowl. The firm's specialists analysed the stadium's interior to ensure that each seat within the stands provided optimal comfort. The refurbishment included the design of the interior finishes throughout the bowl, including seat optimisation,

2: The facade is formed by V-shaped louvres, which support natural ventilation

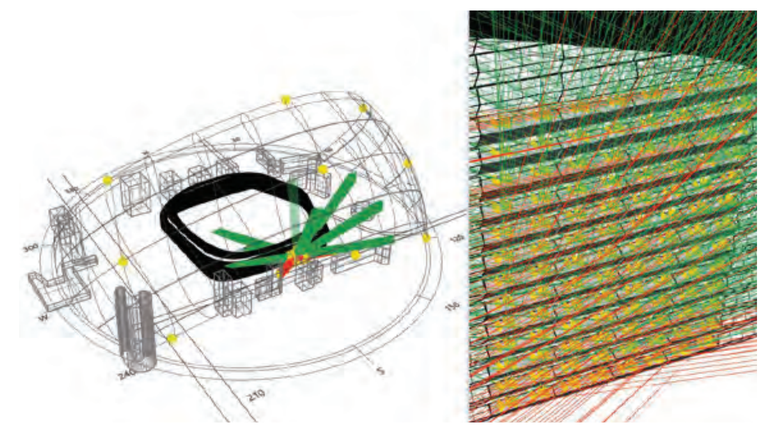
3: An acoustic study within the stadium informed the design, which balanced the needs of different events and sound intelligibility

4: Approximately 7,500 stainless-steel louvres were fixed to the substructure

5: Arup's lighting specialists studied how the sun would reflect off the facade

6, 7: The at-scale model was made to facilitate the design approval process

4.



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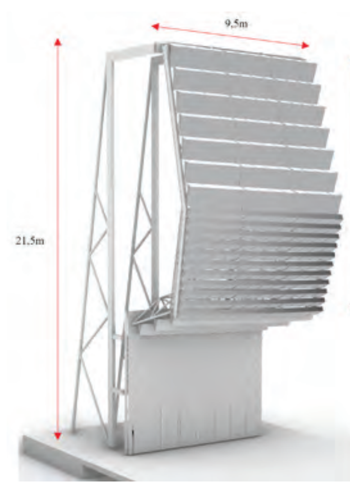

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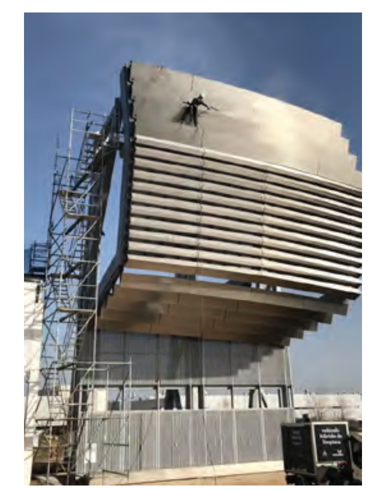


7.

glass handrails, air conditioning services and the access to the stands.

Arup used 3D models to define the updated seat positioning, ensuring unobstructed views of the pitch. The team also analysed wind, temperature and the sun path over the stadium as three key elements in providing better comfort for spectators. The seat arrangement and the location of stairs were redesigned to improve accessibility and safety, and to optimise the user experience.

The team designed a visually coherent and homogeneous grandstand, integrating box seats, new distribution walkways, end walls for the stands, and the envelopes for the upper areas of the Skywalk roof terrace, restaurant, and Skybar. Arup coordinated all the elements and installations located under the roof, as well as designing the canvases that cover the main structure, contributing to the functionality and coherence of the interior space. The firm created a 3D model to coordinate the substructure and catwalks for all the installations hung from the roof, including the videowall.

8.

8: Prior to this redesign, the stadium hosted four European Cup finals

9: The engineering design for the building envelope used 3D models for a smooth transition to fabrication

10: The redevelopment has created a modern, efficient stadium, with enhanced fan experience, comfort and accessibility

9.

Wind simulations

To help the football club manage the wind comfort for fans in the stadium, Arup's specialists developed computational fluid dynamics (CFD) modelling and wind simulations to analyse the wind loads on the facade and other integral parts of the stadium. The analysis was used to fine-tune wind loads applied in the design of the facade and roof, and to assess the indoor and outdoor comfort conditions. Predicting wind loads and wind flow through such a complex structure is only feasible using such tools. When employing CFD for analysing wind behaviour, the reliability of the simulation is paramount. Arup successfully calibrated the CFD model to correspond with previous wind tunnel test results. A comfort study was also carried out for the plaza adjacent to the stadium to minimise wind velocities through the surrounding area.

Lighting

The stadium facade was initially designed to project images through an LED lighting system on a 100m-long video wall on Paseo de la Castellana. This has later evolved into an array of more than 7,000 LED fixtures integrated into the stainless-steel louvres, currently under installation, creating the impression of an abstract lighting box with changing appearance. All this design, together with the work carried out on the below-roof covering membranes and coordination of the 360-degree video scoreboard, gives the Santiago Bernabéu the desired look of a 21st century stadium.

Acoustic studies

The redeveloped stadium is designed to serve more than just football but also other sporting events and concerts. Arup carried out a study on the intelligibility of sound within the interior acoustic environment. The firm focused on optimising materials and the design of envelope openings to enhance acoustic performance. The design aims to balance the atmosphere at a sporting event and the sound quality required for a concert, ensuring the stadium provides a good experience for both football matches and music events.

Enhanced fan experience

The redevelopment of the world-famous Santiago Bernabéu stadium has delivered an enhanced fan experience with Arup's breadth of expertise in stadium design and use of digital tools helping to produce stadium elements on schedule and to the highest quality. Over 100 staff across 22 different disciplines from seven Arup offices worked on the project. The firm's work is continuing at the stadium, developing elements to enhance the user experience in areas such as personal safety, acoustic improvements, and the architectural lighting of the exterior envelope. These efforts, building upon previous work, highlights the trust Arup has earned as a designer and engineering developer, from the initial phases through to the final implementation on site.

10.

Authors

Matias García del Valle was the Project Manager. He is an Associate Director in the Madrid office.

Ignacio Fernandez was the Project Director. He is a Director in the Madrid office.

Project credits

Client Real Madrid Club de Fútbol
Design and build (D&B) contractor FCC Construcción (also Arup client under D&B agreement)
Structural engineer FCC Construcción (stadium and roof) and Fhecor (facade substructure)
Design architect gmp Architects, L35 Architects and Ribas & Ribas Arquitectos
Executive architect Typsa
Building services FCC Industrial / ACIX
Project manager Bovis
Construction manager Ayesa
Acoustics, architecture (stadium bowl), building performance and energy analysis, facade and roof engineering, lighting advisory Arup: Jordi Alcaine, Diego Alcalde, Giulio Antonutto-Foi, Diego Cabellos, Archie Campbell, Marina Carretero Vallejo, Javier Caselles, Raul Ciria, Alberto Cubillo, Montse de la Maya, Victor De Lucas, Alborada Delgado, Alexander Diaz, Encarni Encinas, Santiago Estepa, Serena Fanetti, Doris Feijoo, Ignacio Fernandez, Jaime Fernandez, Sofia Galan, Fernando Garcia, Matias García del Valle, Alejandro Garcia, Alberto Hernandez, Jose Hernando, Simon Jackson, Mike Jaeger, Julia Landaburu, Marta Llamas, Jose Marquez Santoyo, Alejandro Martinez, Guillermo Martinez, Thomas Mays, Ruben Mediavilla, Jose Miguel Moreno, Mariana Perez, Catrin Powell, Benedetta Ravicchio, Adrian Roiz, Maria Sancho, Cristina Sanjuan, Ismael Sanz Gonzalez, Carolina Tello, Rick Titulaer, Julio Vara, Lina Youssef.

Image credits

1-7: Arup
8, 9: Luis García Zaqarbal
10: Zoser

1.

Preserving Brunel's iconic railway for future generations

An innovative and collaborative approach to designing a rockfall shelter that integrates with the natural surroundings

Authors Phil Harrison, David Morgan

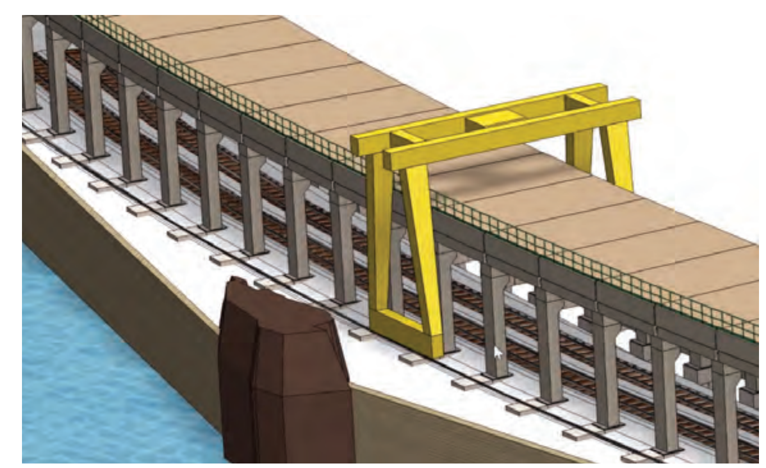
The Victorian-era railway in Devon and Cornwall, designed by renowned civil engineer Isambard Kingdom Brunel, is an essential transport link, providing a connection for 50 towns and cities in the south-west of England to the rest of the UK railway network. Like many railways, the section of the coastal route from Exeter to Newton Abbott has increasingly come under threat due to extreme weather heightened by climate change. A February 2014 storm, which closed the Great Western Mainline railway at Dawlish for eight weeks, led to a loss of £1bn to the economy.

Network Rail put in place the South West Rail Resilience Programme to identify and implement the best options to improve rail resilience on the coastal section of the line between Dawlish and Teignmouth. The improvement works included a new sea wall and upgraded promenade at Dawlish, and a rockfall shelter at Parson's Tunnel providing protection from the danger of cliff erosion to the north of the tunnel. Arup designed the new sea wall at Dawlish, which reduces wave overtopping onto the railway line and has improved protection for all promenade users from extreme weather events. Those works were completed in May 2023.

Further along the line south of Dawlish, rockfall threatened to disrupt rail operations. Network Rail needed a solution to improve the resilience and safety of this section of the line, while achieving wider sustainability, biodiversity and carbon reduction commitments. They appointed Morgan Sindall as principal

1: At peak production, 14 pre-cast units were delivered and erected in eight hours

2, 3: Arup and Morgan Sindall devised a construction methodology involving a travelling rail-mounted gantry crane on temporary, separate rails, spanning over the operational railway



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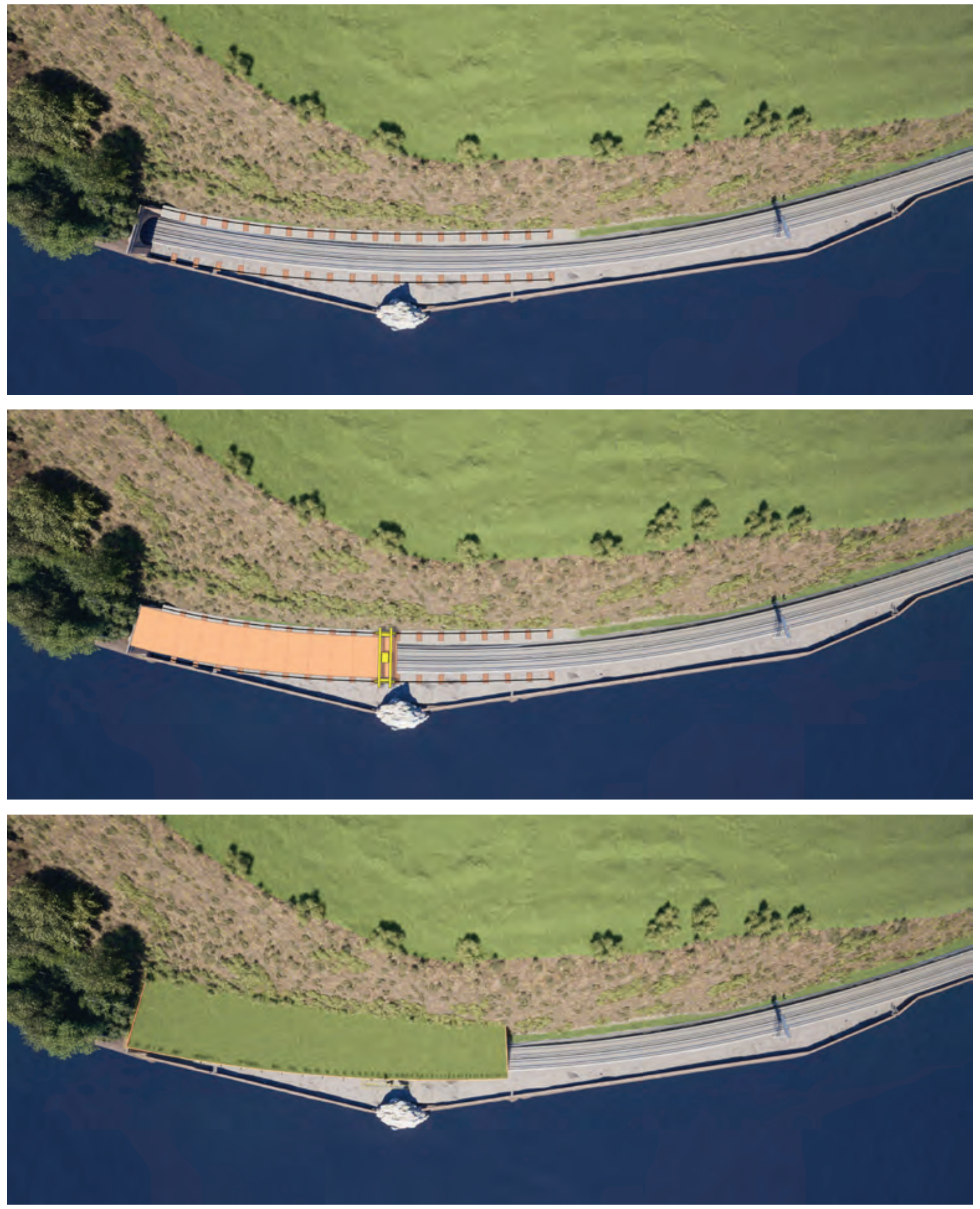

3.

contractor, with Arup working as their designer, providing multidisciplinary engineering services on the rockfall shelter at the Parson's Tunnel site for the design and build phase of the project.

The location is particularly challenging, being an isolated stretch of coastal railway between two existing tunnels, and sandwiched between the 30m-high cliff face and the English Channel. Capable of withstanding the impact of a five-tonne boulder falling from a height of 30m, the 104m-long shelter was designed using an innovative approach involving modern methods of construction (MMC). Composed of a series of identical portal concrete frames fabricated off site, the overall structure integrates with its natural surroundings to minimise its visual impact. Embedding sustainability at its core, the design approach enabled a 10% increase in biodiversity, while saving more than 100 tonnes of CO_2e.

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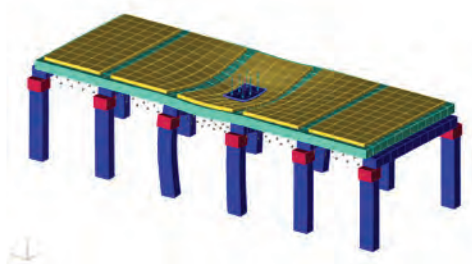

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The project is not only recognised for being the first rockfall shelter of its type in the UK, but also the first structure built using a crane moving along and over a live railway. Construction materials were carefully chosen to complement the existing landscape and the open portal design ensured that passengers could still enjoy stunning views of the Exe estuary.

Arup's geotechnical and civil structures expertise were employed on the project, along with support from rail systems specialists, in particular signalling. Fire and smoke modelling was also performed to ensure the structure met the stringent fire safety requirements.

Design journey

Due to the difficulty in accessing the site, a land-based construction methodology was initially not deemed possible. The reference design at tender stage was for an initial marine-based construction approach, with the shelter built using a jack-up barge located in the sea for the primary set-up and then using a mobile crawler crane placed on the partially built structure to complete the remaining works. The Arup and Morgan Sindall team reviewed this approach and assessed and discounted several marine and land-based methodologies before arriving at a new innovative methodology; a travelling rail-mounted gantry crane on temporary, separate rails, spanning over the operational railway with construction materials delivered by rail without the need for marine access.

This significantly de-risked the project by mitigating the impact of extreme weather, improving construction access and plant/materials logistics. It removed the higher risk construction activities of craning materials from the cliff top above the railway and of materials being delivered to the site by sea, while also avoiding impact on the seabed along the coast during any construction works. It maximised the use of available railway possessions (temporary rail closures used for construction) and avoided the need for costly marine-based access.

The original length of the shelter was 209m. However, through Arup's detailed geotechnical and rockfall analysis, which enabled a better understanding of the behaviour of the eroding cliffs and the inclusion of soil nails and netting in the design, the shelter was reduced in length to 104m, while still providing the required level of resilience. The cliff stabilisation system consisted of 1,400 soil nails and 7,000m^2 of netting. Nearly halving the length of the shelter achieved a significant carbon saving and reduced the safety risk. The shorter shelter also meant a reduced impact on the rail signalling system, bringing additional programme and commercial benefits.

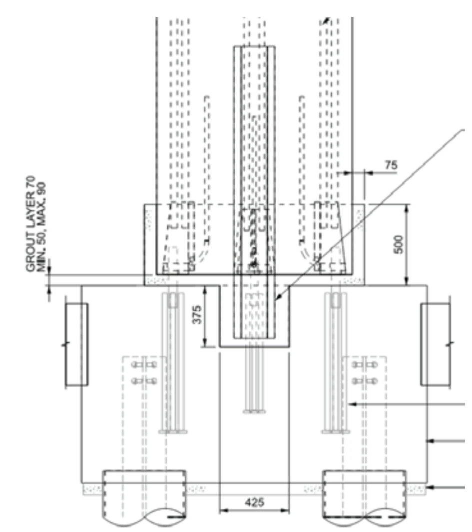
Rail engineering challenges

To ensure the project received approval from Network Rail, Arup's rail engineering specialists provided specific input and advice during the design process to help overcome design and construction challenges. As an example, the team worked together to develop a single integrated and BIM-enabled design model. This approach was essential to ensuring that all disciplines were coordinated, and that the shelter was compliant with clearances and interfaces, and met the requirements to enable future maintenance.

As fire poses a significant threat to such structures, Arup provided fire risk-assessment services to inform Network Rail about associated safety challenges. The firm undertook numerous assessments on the existing tunnel, the new structure and interface, using innovative computational fluid dynamics analysis. This tool allowed the team to understand the risk on the railway posed by a fire, predicting the performance of the shelter in multiple wind directions and wind speed scenarios.

Unlocking the potential of MMC

The use of MMC enabled the rock shelter installation on a site constrained by the sea, existing tunnels and a steep cliff. The shelter was conceived as a series of 19 identical portal frames at 6m centres. The construction method accelerated installation and improved quality through standardisation of precast elements manufactured in a controlled environment off site. The use of a travelling rail-mounted gantry crane enabled a controlled, consistent, safe



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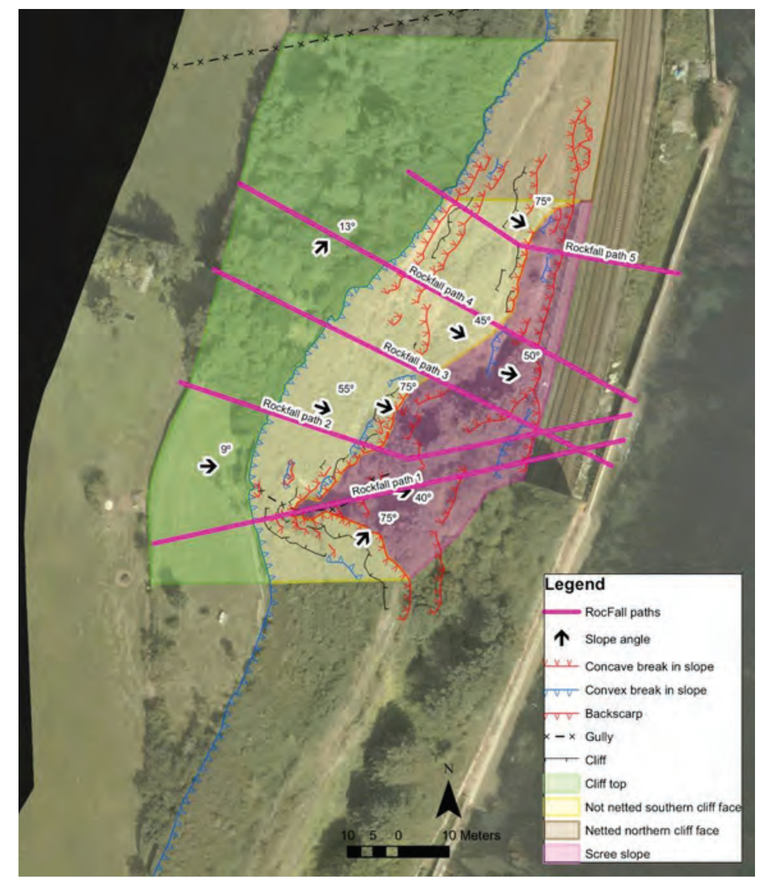


7.

4: The open portal design allows passengers to enjoy coastal views while passing through the shelter

5: The shelter is designed to withstand a five-tonne boulder falling from a height of 30m

6: The foundations included a cast-in-situ product to facilitate the connection of the 17.5 tonne columns

7: Detailed rockfall analysis gave a better understanding of the behaviour of the eroding cliffs and enabled the shelter length to be reduced by over 100m

8.

8: As part of the South West Rail Resilience Programme, Arup also worked on the design of the new seawall and promenade at Dawlish

9: The shelter is made up of 185 precast concrete units

and accurate installation, reducing the risk of rework on site and potential disruptions to train operations.

The delivery of materials by rail, instead of road, sea or from the top of the cliff, also enhanced the safety of workers while reducing traffic congestion on the rural roads of Devon. The precast units, some up to 22 tonnes in weight, were delivered to sidings at Newton Abbot by road and then delivered to the site along a 10km section of railway.

Ahead of construction on site, the installation method was tested using an offsite gantry crane trial, carrying out the test assembly of a precast portal frame. This had the benefit that the construction process could be safely verified and optimised prior to live implementation on site. The offsite testing also led to benefits of improved speed of installation, greater cost certainty and better certainty of railway possession requirements. It reduced set-up and hand-back time during rail possessions, which enabled better construction efficiency and productivity.

To maximise efficiency, the project team undertook a detailed time and motion study, and planned weekend operations minute by minute. Most of the structure, made up of 185 precast concrete units, was installed at night and during a series of eight-hour weekend rail possessions. This timeframe required the erection methodology to be lean and operated in a 'production line'-like manner. At peak production, 14 precast units were delivered and erected in a single Saturday night eight-hour possession. The railway was operational at all other times during construction and gantry crane operation, minimising the impact on rail services and passengers.

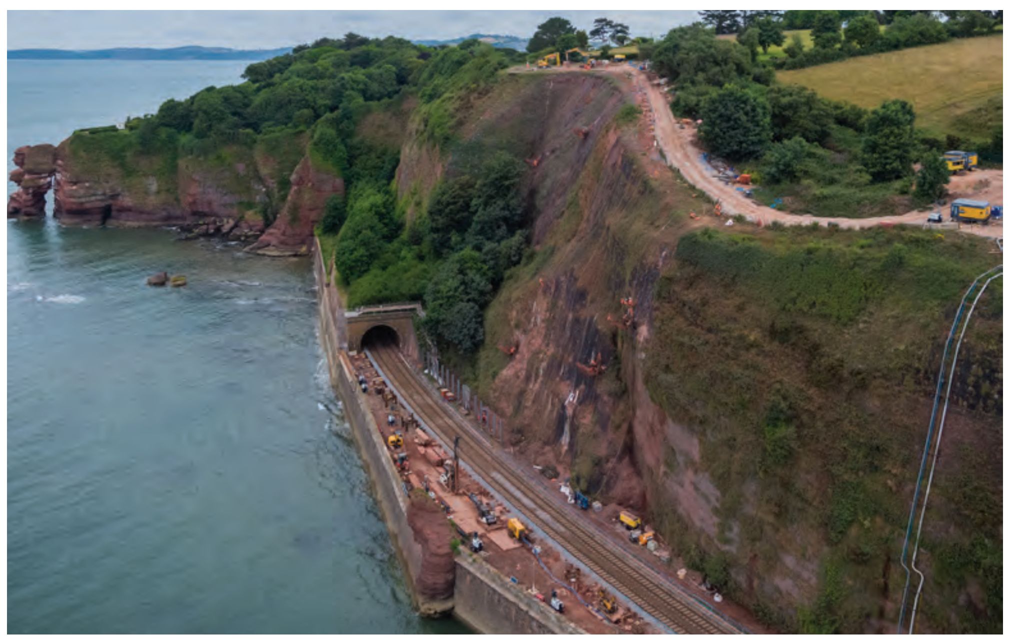
Designing with sustainability in mind

Although climate resilience was the main driver of the project, the design team's strategy unlocked additional environmental outcomes. Designing out precast units by shortening the shelter and altering the design of concrete members saved 1,686m^3 of precast concrete, which is the equivalent of 117.4 tonnes of CO_2e, reducing carbon dioxide equivalent emissions by 32%. Tackling biodiversity loss became essential to provide a longer-term positive impact. To reduce the risk of extinction of local species, the project recreated the local habitat and environment of the protected Cirl Bunting bird, and relocated and increased the amount of rare maritime fauna like sea lavender. In total, the project increased biodiversity by 10%, with over 200m of new hedgerows planted as part of the project.

The project team engaged the local community and made positive impacts on social and natural environments by using locally manufactured materials and minimising transportation movements on local connector roads by using rail for most material transportation movements and minimising disruption to local communities. The fabrication of all precast concrete elements was undertaken locally, delivering investment in local industries and businesses.

The visual impact of the structure was minimised by purposefully selecting the texture and colour of the concrete to sympathetically complement the red sandstone sea cliffs. The specialised pigmented concrete was tested at the offsite fabrication centre for quality and aesthetic. The use of prefabricated components manufactured in a controlled factory environment led to a significant reduction in energy consumption and resource use,

9.



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10: The site is located on an isolated stretch of coastal railway, and sandwiched between the high cliffs and the English Channel

11: Wall panels close off the structure on the cliff side

12: The shelter is 104m in length

11.

12.

13.

minimised waste and ensured optimal material utilisation and recycling. Low-carbon concrete was used in the soil nailing works, reducing carbon emissions for this element of the works by 35%.

Ensuring structural stability and resilience

Leveraging Arup's expertise in multidisciplinary design, the firm provided geotechnical services associated with the foundations to support the unique structure. Due to the challenging access to the site, existing geotechnical investigations that could be used to inform the design were very limited. To overcome this issue, Arup complemented these studies with additional data and observational information provided by Morgan Sindall. This data, together with experience gained from the construction of similar schemes in the Swiss Alps for snow and avalanche shelters, allowed Arup to design a buildable and robust foundation for the shelter.

With limited guidance on loading and performance requirements for such a railway shelter, a Swiss highway code for the design of avalanche protection structures was used to derive an equivalent static load based on boulder size, velocity and sand cushion parameters for the design of the shelter deck. The derived load of 2,500kN was distributed into a patch load that could be applied anywhere on the deck. In addition, train derailment forces were also considered in the design of the structure, while Arup led the design of the soil nailing system installed above and adjacent to the shelter.

Construction detail

Work started on site in autumn 2021. The foundations of the structure are made up of 450mm diameter bored piles and pad foundations, which are connected longitudinally at ground level by precast tie beams that help spread derailment loads. The 17.5 tonne precast columns were landed on these foundations, with the base connection a cast-in-situ product that allowed the columns to be landed on anchor bolts set into the foundations. This facilitated them being accurately levelled and adjusted before being fully grouted to achieve the required moment connection.

Bespoke precast 22-tonne U beams were placed on the columns spanning over the rail line and were stitched together before edge beams were placed to provide side formwork for the in-situ deck, which was cast on permanent formwork. The concrete for the deck was delivered from the cliff top running through a pipe system down the cliff face. On completion of the deck, precast L-shaped parapets were placed along the edges to retain a 1m-deep sand layer placed on the roof of the shelter. This 4,100-tonne sand blanket provides a cushioning layer to the structure and is seeded to recreate the local environment and habitat to support local plant species. The structure is closed off on the cliff side with wall panels (76 in total) and the space between the panels and the cliff face backfilled with foam concrete.

Enhancing resilience

The Parson's Tunnel Rockfall Shelter was completed in September 2023, ensuring Brunel's iconic rail link serving Devon and Cornwall is resilient to the effects of climate change long into the future. The project successfully extended the life of Victorian-era rail infrastructure by integrating modern materials and techniques to enhance safety and resilience. By enhancing the railway's resilience and mitigating the impact and effects of climate change, the project, as part of the overall South West Rail Resilience Programme, helps ensure the connectivity of the communities and protects the local economy. Each aspect was designed with sustainability, ecological impact, transportation, means of lifting, construction method, access constraints and future maintenance in mind, providing a solution that would deliver long-term resilience for this stretch of the railway.

Arup is exploring ways to apply this innovative methodology to benefit other rail and non-rail resilience projects across the UK. The firm is currently engaged with a highways client with the aim of implementing the MMC from this project for a potential rockfall shelter that will deliver resilience to a key two-mile-long highway link in a constrained and exposed site in the Scottish Highlands.

14.

13: The shelter was completed in 2023 and now protects the Victorian-era railway from rockfall

14: The texture and colour of the concrete rockfall shelter echo the red sandstone sea cliffs

Authors

Phil Harrison was the Project Director. He is the rail business leader for Arup's UKIMEA region and a Director in the Bristol office.

David Morgan was the Project Manager. He is an Associate in the Bristol office.

Project credits

Client Network Rail

Principal contractor Morgan Sindall

Civil, fire safety and ground engineering, hydrogeology, rail Arup: Fernando Aparicio Baneres, Raphaelle Barbier Saint Hilaire, Farah Binte Mohd Faudzi, Fermin Bazo, Andrew Bithell, Mike Burke, Ross Clayton, Abi Deas, Mike Deevy, Helen Dingle, Jono Dixon, Phil Harrison, Martin Howley, Simon Hurst, Sally John, Rafael Kamalov, Nick Maddock, Saeed Mojabi, David Morgan, Jake Oliver, David Parks, Aadil Patel, Richard Patten, Oras Scherf, Marcus Sheppard, Matt Smith, Lewis Triggs, Dan Wilcox, Hasan Yousaf.

Image credits

1, 9-13: Morgan Sindall

2-7: Arup

8: Andrew Hatfield

14: Geof Sheppard

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Tel: +44 (0)20 7636 1531

www.arup.com

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