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# CONCRETE

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## BUILDING AN HS2 BRIDGE

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for durability and resilience

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# DESIGN OF THE COLNE VALLEY VIADUCT FOR DURABILITY AND RESILIENCE



Set within one of the UK's most environmentally sensitive landscapes, HS2's 3.4km Colne Valley Viaduct demonstrates how durability, resilience and long-term maintainability can be embedded into major infrastructure. From innovative post-tensioning systems and extended-life bearings to structural health monitoring and climate change allowances, the project establishes new benchmarks for the design of high-speed rail structures. **Omar Nabeel, Juan Sevillano** and **Ioannis Koromilas** of **Rendel** report.

Once in operation, the Colne Valley Viaduct (CVV) will be the UK's longest railway viaduct. The 3.4km structure forms part of High Speed 2 (HS2) and lies within C1 package, a 21.6km section of the route north-west of London, that passes through parts of Greater London, Hertfordshire and Buckinghamshire. The contract also includes the 16km-long twin-bore Chiltern Tunnel, the longest tunnel along the HS2 route. The tunnel has 43 cross-passages between the two

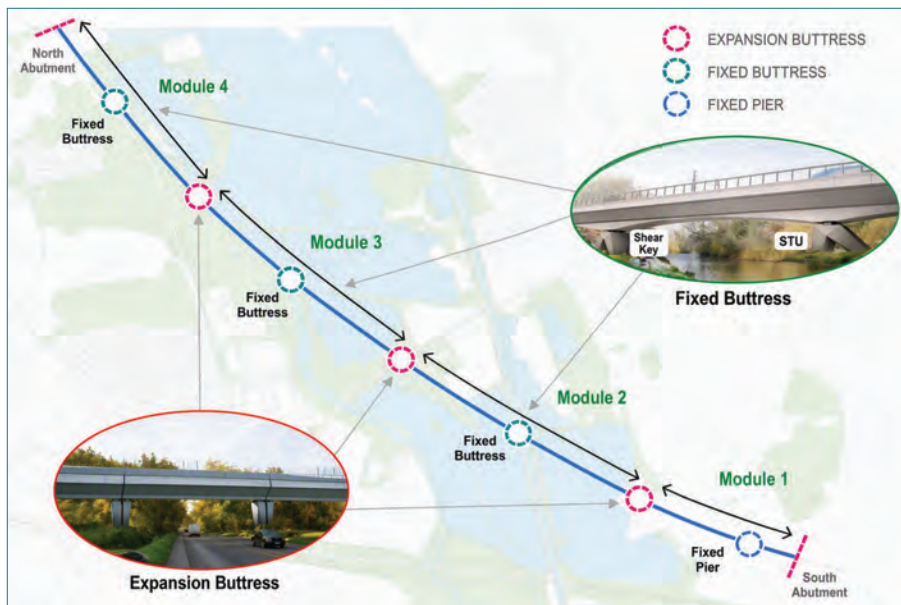
bores, five access and ventilation shafts with associated headhouses, and porous portals at either end. The C1 package is being delivered by Align, a design-build joint venture comprising Bouygues Travaux Publics, Sir Robert McAlpine and VolkerFitzpatrick. Align's designer is Align-D, a joint venture comprising Rendel, Ingerop and Jacobs, with Grimshaw as architect.

## STRUCTURAL ARRANGEMENT

The High Speed Rail Act 2017 identifies CVV as being the most



(Photo: HS2 Ltd)



#### MAIN IMAGE, FAR LEFT:

Figure 1 – Colne Valley Viaduct.

#### PREVIOUS PAGE, BOTTOM RIGHT:

Figure 2 – construction of the CVV.

#### LEFT:

Figure 3 – map showing the four modules and expansion buttresses of CVV.

#### BELOW LEFT:

Figure 4 – internal and external post-tensioning arrangement.

#### BELOW RIGHT:

Figure 5 – protection level 3 mock-up.

significant visible engineering feature of HS2 and, as such, its design is expected to reflect a structure of international significance.

The viaduct is situated in a high-value landscape with significant environmental sensitivities, including Sites of Special Scientific Interest, National Nature Reserves and Wildlife Sites. It crosses the Colne Valley Regional Park, dense woodland areas, several lakes and watercourses (including the Grand Union Canal and the River Colne), and two public roads, as well as passing near several rural settlements.

In responding sensitively to its setting, the 57-span viaduct is characterised by 'woodland' spans and 'water' spans. The former are typically 45–60m long and provide increased clearance beneath the viaduct and greater flexibility in pier location. Over water, span lengths are increased to 67–80m to preserve the open landscape views (see Figure 1). For a detailed scheme description, see *High Speed Architecture: HS2's Colne Valley Viaduct*<sup>(1)</sup>.

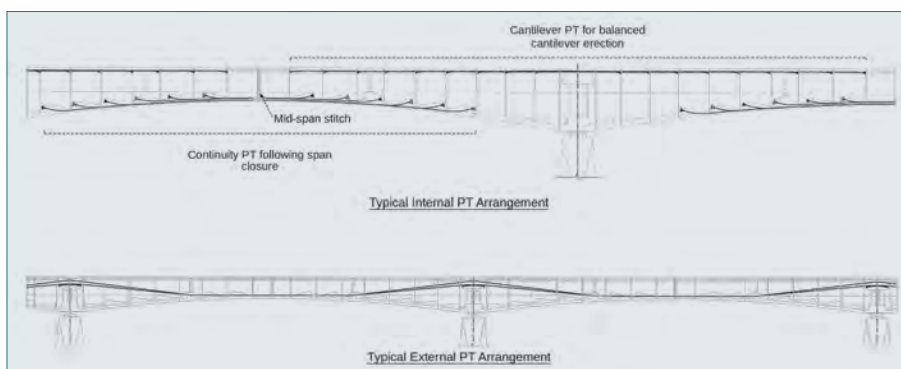
The viaduct's superstructure is a single-cell, precast segmental, post-

tensioned concrete box girder and is supported on stylised reinforced concrete piers founded on bored piles. The viaduct was erected using a launching gantry employing the balanced cantilever technique (Figure 2). This construction method reduced impact on local communities and enabled the structure to be built over rivers and roads with minimal disruption. A designated construction corridor, with site access roads, working and storage areas, a precast segment factory and four jetties, diverted the equivalent of approximately 4000 lorries from local roads.

During winter, a 3.4km-long structure could contract by up to 1.5m and, in summer, could expand by nearly a metre, exceeding the movement capacity of conventional trackwork expansion devices. Consequently, the viaduct is divided into four modules, with adjacent modules separated by an 'expansion buttress', a short independent 'inert' section of viaduct with negligible thermal movement (Figure 3). To minimise expansion/contraction movements, the point of longitudinal fixity is typically located mid-module, with the exception of the southern-most Module 1 as discussed below.

For Modules 2–4, the point of longitudinal fixity is provided through braced stability portals or 'fixed buttresses'. It was initially envisaged that this would be achieved by means of a portal formed by monolithic construction between superstructure and substructure at adjacent piers. However, such an arrangement is sensitive to ground conditions and is subject to large internal forces and stresses developing due to thermal effects and creep. Consequently, the designers decided instead to articulate the superstructure at these locations, with the deck supported on spherical bearings and with a steel shear key at one support and a shock transmission unit (STU) at the other. With this arrangement, there is only one permanent point of longitudinal fixity (at the shear key support), while the STU support allows longitudinal deck movement due to thermal and creep effects but engages under dynamic or impact loading (eg, from a braking train or a seismic event). This sharing of the longitudinal loads between the two supports reduces maximum foundation size.

For Module 1, which is approximately half the length of the others at 500m, longitudinal fixity is provided through a single fixed pier adjacent to the south abutment, removing the need for an additional rail expansion joint and limiting stresses in the continuously welded rail.





## HS2 SPECIFICATION FOR DURABILITY AND RESILIENCE

HS2's sustainability policy provides for building a high-speed network that is climate resilient for the long-term, minimises carbon footprint and delivers low-carbon, long-distance journeys that are supported by low-carbon energy. To this end, HS2 developed technical standards setting out requirements and guidance for construction materials and durability based on industry guidance and Standards, and also supplemented by durability planning and additional mandatory requirements specific to HS2.

Examples of specific requirements for the design of CVV include:

- HS2-defined additive safety elements: specifically, 5mm additional cover for climate change impact
- provisions for bearings to be installed with secondary top and bottom plates to facilitate removal and replacement
- protection level 3 (PL3) to *fib* Bulletin 33<sup>(2)</sup> for internal post-tensioning (PT) in segmental construction
- replaceable external/unbonded PT.

## POST-TENSIONING DESIGN

CVV uses both internal and external longitudinal PT (Figure 4). The internal PT comprises cantilever tendons running through the deck top slab to facilitate the chosen balanced cantilever construction method. Where two cantilevers meet and are joined with an in-situ stitch, internal continuity tendons are provided in the bottom slab.

Use of internal PT in segmental bridge construction in the UK has

### TOP LEFT:

Figure 6 – bearing assembly and construction above 1-in-100-year flood level.

### TOP RIGHT:

Figure 7 – noise barriers.

been subject to a moratorium since the 1990s due to concerns regarding the durability of the tendons. Thirty years later, this form of construction is being reintroduced through its adoption on CVV. This was conditional on being able to demonstrate that the prestressing system meets the strict durability requirements of PL3. This is the highest level of protection and requires complete encapsulation of the tendon within the duct to prevent ingress of corrosive agents. Importantly, the quality of encapsulation under PL3 must be measurable throughout the 120-year design life of the structure. The system adopted was developed by VSL, a global specialist in post-tensioning, and used polymer ducts with couplers at segment joints. The ducts are filled with grout and the anchorage caps fitted with electrical wires so that impedance can be monitored continuously to assess the integrity of the encapsulation. Mock-ups were undertaken on-site to validate the constructability and performance of the system (Figure 5). For more details about the design in this context, see Damage and Boiteux<sup>(3)</sup>.

The external PT takes a conventional draped form with deviators and is typically continuous over two spans. External PT is subject to protection level 2 (PL2), which requires encapsulation but not monitoring. HS2 requires external PT to be



(Photo: Grimshaw/Hufton+Crow)

replaceable – as such, the strands are individually sheathed within the outer ducts, which are grouted to allow replacement on a strand-by-strand basis. This is achieved by coupling a new strand to the existing one and pulling it through the sheath.

For additional robustness, the design incorporates provisions for increasing the PT across the structure by up to 20% in future using spare preinstalled external PT anchorages.

## BEARING DESIGN

As the viaduct has 58 supports and more than 100 bearings, the designers sought to minimise the requirements for replacement by specifying bearings with a 50-year design life rather than the 25 years required by HS2. This required adoption of innovative materials such as ultra-high molecular polyethylene, which is insensitive to chemical contamination and ageing, in place of conventional PTFE.

Design of the bearings was undertaken by Maurer, a specialist in bearing design and supply. To demonstrate and certify a 50-year design life, the 50km long-term approval test was conducted under extremely severe conditions. Even so, the sliding materials exhibited negligible wear and it is anticipated that a design life much longer than 50 years can be realised, subject to regular routine inspections and maintenance.

In accordance with HS2 requirements, to facilitate replacement, all bearings were installed with permanent top and bottom anchor plates: the bearings are bolted to these plates and are simply slid out when replacement is required.

For supports over water, all bearings were installed above the 1-in-100-year flood level, with an additional robustness allowance for climate change to improve resilience (see Figure 6).

## MATERIALS AND STRUCTURAL FORM

### NOISE BARRIERS

The noise barriers were one of the most important elements in the design of CVV and had to meet strict acoustic, environmental and architectural criteria (Figure 7). The functional requirements for the barriers were to:

- withstand the dynamic forces generated by HS2 trains travelling at over 320kph
- provide the level of environmental noise control needed in an Area of Outstanding Natural Beauty
- align with the architectural vision set out for the viaduct.

The 40-year panel design life specified by HS2 was extended to 60 years, thus removing one replacement cycle over the structure's 120-year design life. Design was undertaken by Littlewood Group, a specialist in the design, supply and installation of such barriers.

To verify acoustic performance, the UK's first full-scale insertion loss testing was undertaken with a 30m run of real-scale barriers. The performance exceeded that predicted by the computational models.

### UHPFRC

As a result of restricting deck width to minimise materials and associated embodied carbon, the space available outside the noise barriers for the parapets was limited. Adoption of ultra-high-performance fibre-reinforced concrete (UHPFRC) for the parapets enabled slender and geometrically stylised profiles to be developed, taking advantage of its superior material properties compared with conventional concrete, with compressive and tensile strengths of the order of three

to five times higher (Figure 8). The low porosity and strain-hardening behaviour of UHPFRC also results in exceptional durability performance.

### INCLINED FAÇADE PANELS

The superstructure depth along CVV varies between 3 and 6.7m. To reduce visual deck depth, the architects developed the concept of using inclined façade panels beneath the deck cantilevers. This key concept was introduced to project stakeholders early in the design and was subsequently developed to integrate the panels into the structural cross-section (Figure 9). This both removed the maintenance liability associated with upkeep of a separate façade and improved the transverse performance of the box girder, as the cantilever wing became a propped cantilever. Longitudinally, a 10mm gap was introduced at intervals so that the panels would not experience significant axial compression due to the deck PT. The solution achieves the desired aesthetic quality with an added structural function.

### STRUCTURAL HEALTH MONITORING

To ensure the long-term performance, safety and maintainability of the viaduct, a comprehensive structural health monitoring (SHM) system has been developed. The monitoring strategy is founded on the identification of failure mechanisms and their potential causes, and the anticipated deterioration processes affecting the structure throughout its service life. Based on this assessment, the critical physical parameters requiring monitoring have been defined and an integrated SHM architecture established. The system includes suitable instrumentation,

data management processes and predefined trigger and warning thresholds to enable condition assessment, early anomaly detection and timely maintenance intervention.

### CONCLUDING REMARKS

Once in operation, CVV will be the UK's longest railway viaduct. Since its inception, a collaborative design approach has fulfilled HS2's priorities: supporting new rail infrastructure while ensuring passenger comfort; achieving aesthetics that respect the local surroundings; delivering robustness and resilience alongside ease of maintenance; and providing an asset that was economical to build while minimising impact on the Colne Valley area. It is considered that a new benchmark has been set for UK infrastructure. **C**

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#### BELOW LEFT:

Figure 8 – UHPFRC parapets.

#### BELOW:

Figure 9 – inclined panels.

