Design of Electrified Railway Viaducts

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Abstract:
In recent years, throughout Victoria there has been a trend for grade separation projects to have the railway going over the road(s). Elevated viaducts are proving to be resilient, not only for typical engineering criteria such as strength, fatigue, and serviceability limit states, but are also improving the resilience of the communities below. Previously divided communities are now joined, with improved social resilience, which was essential during extended periods of pandemic restrictions.

The structural form of the railway viaducts included a combination of simply supported and continuous spans of precast concrete (prestressed and post-tensioned) and steel composite girders with earth retaining embankment approaches.

The main drivers for a successful design include constructability and safety within live electrified railway corridors, efficient and cost-effective structural solutions in brownfield environments, good urban design, rail systems (traction power, electrification, and signalling), sustainability and climate change considerations, and electrolysis and stray current mitigation.

Structural considerations including ground conditions, embodied energy, and material types; need to be evaluated in combination with these requirements. Close collaboration is required with a wide range of disciplines, stakeholders and end users of the railway including passengers, operators, maintainers, and trespassers.

This paper will discuss the design essentials for a sustainable railway viaduct in terms of different superstructure and sub-structure forms and material composition; provide guidance on the electrical hazards and the principles of track structure interaction; and finally introduce future trends for railway viaduct design amongst the practicing bridge engineers.

Keywords: electrified, elevated railway viaduct, structure.

Context
Population growth and increasing urbanisation has and will continue to drive demand for better transport infrastructure in cities around the world. Transport congestion occurs wherever railways and roads intersect. Hence there is a need for grade separations, to relieve congestion, improve safety and travel times. A further benefit of grade separation is a significant increase in pedestrian mobility and the creating of valuable land for social benefits, such as parklands. This also enables increased social cohesion and resilience in the communities in proximity to the railway.

Elevated railways are not uncommon and have been built for several decades. Many cities around the world have railway viaducts built over 100 years ago. In recent years in Melbourne, Australia, several existing railways have been converted from ground-level to elevated viaducts. New railways being proposed and designed are also being grade separated, either though tunnels or elevated viaducts.
Design Essentials

There are several essential design issues and factors to address for electrified railway viaducts in Australia, listed below, not in order of priority, as this would be governed by the railway authority requirements, site constraints and construction methodologies:

1. Train live loads – including axle loads such as 300LA or 245LA or 150LA (for light rail and tram), and various train related transient effects such as centrifugal forces, braking and traction forces, wind actions on trains, derailment and containment loads and nosing loads, noting that design loads for containment are greater for through-structure elements.

2. Structural clearance – between the kinematic envelope of the different types of rolling stock and all structural elements and associated infrastructure such as walkways, overhead wiring, and signal equipment.

3. Track form – ballasted or ballastless including embedded rail, rail on plinths, sleepers on top of concrete or embedded in concrete, monolithic in-situ, or precast concrete.

4. Super-structure form – structure beneath the track or through-girder or through-truss forms with partial structure above the track, noting that some railway authorities do not permit through-structures.

5. Sub-structure form – singular column piers or portals with multiple columns, or walls. The substructure and superstructure forms need to be complementary and in accordance with urban design requirements.

6. Rail, track, and structure interaction – this interaction is complex and elaborated below.

7. Passenger comfort – the vertical acceleration of the occupants inside the train needs to be below acceptable limits, in particular for train speeds greater than 100 km/hr.

8. Transition from the viaduct to the approach embankments – a smooth transition is required between the relatively rigid viaduct and the relatively flexible earth embankments at each end of the viaduct, for passenger comfort and for structural loads at the interfaces between structures. This is more than providing a 4 m long transition slab, and usually requires a graduated stiffness of embankment fill beneath a transition slab, over lengths in the order of 20 m to 40 m or longer.

9. Mitigation of electrical hazards, stray current, and electrolysis effects – an interdisciplinary approach is required mitigate damage and prevent deaths, due to direct current (DC) and alternating current (AC) high voltage, traction power systems for trains, and due to lightning strikes.

10. Common utility services – comprising high and low voltage power, signalling, communications data, water for fire safety, electrolysis mitigation and lighting.

11. Human factors for passengers, maintainers, and trespassers – during normal operation and emergencies. This includes the provision of maintenance access and detaining walkways with clearances to the kinematic envelope, handrails, emergency egress and maintenance access stairs.

12. Overhead wiring structures – preferred to be positioned directly on the sub-structure elements, however for viaducts with horizontal curvatures or with long spans, they may need to be positioned on the super-structure, subject to specific controls put in place and in accordance with railway authority requirements and the earthing and bonding strategy.

13. Signal structures – including maintenance requirements and space-proofing for walkways with balconies around the signal masts rotated into a supine position, suitable for maintenance. Signal masts are usually supported on the superstructure.

14. Noise and vibration issues – need to be mitigated with screens to reduce the impact of air-borne noise generated from the train wheels or motors, and structure-borne noise depending on the track form. Vibration issues need to be carefully analysed and addressed by the structural design, particularly at station platforms supported on the viaduct superstructure.

15. Privacy screens – are usually required for the full length of the viaduct if it is in proximity to residential properties. Privacy screens may also serve as acoustic screens and need to be designed to cater for structural loads such as wind, fire, and vandalism, and be suitable for the urban design.
16. Drainage of the deck – including pits at close intervals to capture the stormwater, and downpipes to ground level, in accordance with hydraulic, structural, and urban design requirements.

17. Fire and life safety – emergency egress stairs for the purpose of evacuation of passengers, are required at typically 500 m to 750 m spacings along the viaduct. A fire water main and fire hose cabinets at regular spacings are also required, at the deck walkway level. A facility needs to be provided for a track-mounted, emergency response vehicle that can be deployed in an emergency, from each end of the viaduct.

**Different super-structure and sub-structure forms and material composition.**

**Overview**

Generally, two main factors affect the choice of viaduct structure – the span lengths / number of spans and the types of obstacles (such as a river, road or rail crossing). Various structural alternatives can be considered for the same span length; however, various functional, economic and constructional factors could lead to the final configuration of the viaduct structure. The main structure types adopted for modern railway bridges include prestressed / post-tensioned concrete beams and box girders, concrete slab deck, steel plate girders and steel box girders, and concrete or steel through-girders. Railway underbridges have stringent deformation requirements, which require structures that are inherently stiff in flexure.

**Material Composition**

Guidance on construction materials for railway underbridge is provided in Australian standards, while additional requirements are provided by Rail Transport Operator (RTO) standards such as the Metro Trains Melbourne (MTM) Bridge Standard (1). Based on these, concrete and steel are commonly adopted construction materials for bridges. The selection of construction materials for the viaduct should be based on an understanding of the below factors:

- viaduct geometry and spans
- functional requirements of the project
- durability requirements and exposure classification
- economic implications of different materials, including material availability
- specific maintenance and access requirements
- design life requirements
- earthing and bonding requirements
- urban design requirements
- sustainability and circular economy considerations

**Super-Structure Types**

The primary engineering design objective is to adopt a super-structure configuration that maximises the structural stiffness while reducing the construction material and, thereby overall weight (and embodied energy) of the structure. The super-structure is that component of a bridge that supports the deck, and its primary purpose is to carry loads from the deck across the span and to the bridge supports. Loads may be transmitted through tension, compression, bending, or a combination of these three. The live load is transferred from their application point, the rails, to the support structure through rail sleepers and track form (ballasted or ballastless) to the bridge's deck.

The selection of the super-structure type is based on the below factors:

- material composition factors listed in the above section
- nature and type of obstacle to cross
- number of rail tracks
- overhead wire and signalling requirements
- space availability for construction and storage, for example in a narrow rail corridor, an in-line construction utilising a straddle carrier gantry may be more suitable, which leads to use of a post-tensioned segmental concrete box girder super-structure and longer span lengths. If there is sufficient width in the rail corridor then the use of prestressed precast Super-T girders will be suitable and cheaper.
- economic implications of at-grade or above-ground structures
- RTO standards and requirements when crossing roads or rail or creek or river
• railway authority requirements for structure form, such as whether through-structures (girders, trusses) are permitted and whether certain materials are permitted, such as steel
• loading requirements – vertical and horizontal train loadings, including derailment and containment, centrifugal forces, nosing loads and wind loads
• environmental considerations, including geotechnical requirements
• climate change considerations
• lifting and transportability of structural elements
• track alignment and vertical profile
• location of stations
• community and privacy considerations
• detraining, inspection and maintenance access requirements, including their live loads, if and when in combination with train live loads
• electromagnetic compatibility – earthing and bonding, lightning protection. For example, overhead wiring masts must be fixed to the sub-structure in accordance with the MTM standards, however, the masts can be fixed to the super-structure deck by obtaining a waiver from MTM, the rail authority.
• privacy screens and noise wall considerations. Material types are normally dictated by urban design requirements and material options such as precast concrete, acrylic, rotational moulded plastic should be considered.
• constructability and economies of scale of construction types
• track structure interactions for thermal effects and braking and traction forces

An appropriate super-structure type is adopted depending on the span requirement and placing of the support location. All the above factors must be considered in deciding upon a suitable super-structure configuration for the project.

**Sub-Structure Types**

The sub-structure of modern railway viaducts is commonly made of in-situ or precast concrete elements – abutments, piers, and foundations. The abutments typically have crossheads supported on piles behind retaining walls or embankments; or on continuous walls, which also behave as a soil retention system. Depending on the super-structure geometry, the piers consist of either a single or multiple columns arrangements. The foundation typically consists of deep structures in the form of precast or bored piles; shallow foundations are usually inadequate for railway viaducts. The primary function of these elements is to transmit the forces comprising dead load of the super-structure and substructure, live load effects of rail traffic, earthquake loads, collision loads, incidental loads and environmental effects such as temperature, creep, shrinkage, carbonation and chloride attack. Careful consideration is given to the geotechnical parameters when designing the foundation elements.

The stability of the overall structure is attributed to the substructure elements; careful consideration should be given in the design of the sub-structure and foundation of the rail underbridge. Below are the factors that need to be considered when selecting the appropriate substructure for the project:

• geometry and type of super-structure
• type of obstacles the viaduct is crossing
• specific geometric and loading requirements when crossing roads, railways, creeks or rivers
• RTO clearance requirements for road or rail tracks, beneath or beside the viaduct
• access and maintenance considerations
• positions of overhead wiring structures and signals
• geotechnical parameters and conditions
• urban design requirements
• environmental and heritage considerations
• climate change considerations
• integration with existing assets
• super-structure arrangements – span lengths, simply supported or continuous spans, bearing arrangements
• trespassing, graffiti and vandalism considerations
• electromagnetic compatibility – earthing
Electrical Hazards and Mitigation

There are generally:

- two main hazards, being electric shock to people and electrolysis damage to structures and equipment,
- three main causes, being stray current leakage from rails, fault currents from faulty overhead wiring equipment such as insulators and lightning strikes with extremely high voltages and currents, and
- two competing mitigation strategies, being electrical bonding of all metallic elements to each other, to the rails and to earth; and electrical isolation of metallic elements from the rails and earth.

Electrolysis damage to structures is real and can result in rapid section loss of steel reinforcement inside concrete members, not visible from the outside to the naked eye, leading to structural failure.

This subject is extensively dealt with in a technical paper presented at the Concrete Institute of Australia, 2021 Biennial Conference (2), which provides further details of the hazards, causes and mitigation strategies for reinforced concrete structures including viaducts, and foundations.

Track Structure Interaction

Overview

Interaction between the track structure and a bridge structure occurs because of the physical connection between them whether the rails are directly fixed or there is a ballast bed in-between the track and the viaduct. The interaction results in forces being applied to the track (rail, fastenings and ballast) and the viaduct (superstructure and substructure) as depicted in Figure 1 below. These forces are in addition to those which would be expected if the track and viaduct were analysed separately.

![Figure 1 - UIC 774 (3) Figure 9 Structural diagram for evaluation of track bridge interacting effects](image)

As a general principle, track engineers prefer to have viaduct which are designed to reduce the influence of the viaduct on the track to a minimum and to avoid use of rail expansion devices. Existing and proposed standards and codes set maximum limiting values of stress, forces and deformation on the rail. Rail expansion devices are expensive to install and to maintain, especially on high speed lines where impact forces arising from imperfect joints in the rail cause deterioration of the track and the supporting structure. On many urban railways there is a need to reduce the number of rail expansion devices to remove a source of noise.

The resolution of this apparent conflict between the interest of viaduct structureal designers and track designers should be based on an understanding of the economic implications of different solutions including relative construction and maintenance costs of, for example:

- installing rail expansion devices.
- modifying the viaduct design by increasing the stiffness.
- change to the overall configuration of viaduct structure (span lengths, expansion joint position, continuous span or simply supported spans).
- accepting higher operational stresses in the rails.
• releasing the clips at the high stress locations.

All the above factors were considered on projects, noting that rail expansion devices and higher operational stresses in the rails were not permitted by the rail authorities.

Loading

The load cases that can lead to interaction effects are those that cause relative displacement between the track and the deck including:

• rotation of the deck on its supports as a result of the deck bending under vertical train load.
• horizontal braking and traction forces according to the Australian standard AS5100.2-2017 (4) rational method, depend on the rolling stock parameters specified in rail authority standards.
• thermal expansion and contraction of the bridge only, in the case of continuously welded rail (CWR), or the bridge and the rail, whenever a rail expansion device is present,
• vertical temperature gradient and
• deformation of concrete structures due to creep and shrinkage.

Parameters Affecting The Phenomena

To analyse and manage the stresses and deformations within acceptable limits, there should be an understanding of parameters affecting the phenomena, which can be distinguished between viaduct parameters and track parameters.

Bridge Parameters

Expansion length: the distance between the thermal centre-point and the end of the continuous spans. It is recommended to limit the expansion length of a simple span carrying CWR on ballasted track to about 60 metres for steel structures and 90 metres for concrete structures. In the case of direct fixed track, a specific analysis should be carried out.

Span bending behaviour causes longitudinal displacement of the upper surface of the deck generating axial stress in the rail. Span length and bending stiffness of the superstructure affect the deck rotation and neutral axis position. The resistance of the deck to horizontal displacements greatly affects the interaction phenomena and is determined by the horizontal and vertical stiffness of the substructure.

Track Parameters

The resistance of the track is a function of the relative displacement of the rails to its supporting structure. The resistance increase rapidly while displacement remains low. The resistance is higher on loaded track than on unloaded track. The resistance is also dependent on whether the track is ballasted or not, the way track is laid and the standard in which track is maintained.

Track Form

The majority of the railway lines in Victoria and in Australia carrying passenger and freight trains (excluding light rail trains) are carried over conventional ballasted track systems. However, with the increasing demand for efficient high speed passenger rail services, an improved track structure system is required that provide better resilience. In Victoria, MTM mandates a slab track system for viaduct lengths more than 500 metres in their A1546 Bridge Design Standard (1).

Slab track is an engineered system, and the range of structural forms vary significantly more when compared with traditional ballasted tracks, with each form providing differing levels of performance and being associated with differing drivers and constraints. They are better suited for high-speed passenger trains with speeds between 140 km/h to 200 km/h. A technical paper on slab track considerations was presented at the 11th Austroads Bridge Conference in 2022 (5).

Future Trends and Challenges For Railway Viaducts

Sustainability

It is well known today that the production of cement from lime has a very large environmental cost and the production of concrete using that cement has a very high embodied carbon content. Concrete is a very favourable material for structures for numerous reasons and will continue to be used extensively worldwide, however the carbon footprint of concrete must be reduced. The production of steel also involves high amounts of energy which currently is almost entirely fossil fuel based. Various initiatives are underway in research and development and some solutions are emerging for reducing the carbon
footprints of steel and concrete; including substitutions for cement and using renewable energy such as green hydrogen, concentrated solar and wind, for steel production.

Opportunities to reduce the embodied energy of viaducts include the following:

- Designs to be efficient to minimise quantities of the most energy intensive elements: for example, this may require higher reinforcement ratios and less concrete, use of column piers in-lieu of wall piers and the use of higher strength concrete.
- Extend span lengths to reduce the number of piers and use spill-through abutments.
- Optimise girder depths with continuous spans, including for precast concrete girders with in-situ concrete stitches over the supports.
- Reduce cement content with use of supplementary cementitious materials, as described below. Research is also underway for the use of ordinary starch as a binder to produce a bio-composite concrete (6).

For ancillary structural elements on railway viaducts such as maintenance and emergency egress walkways, alternatives to steel are already available, such a glass reinforced plastic (GRP) flooring and composite fibre structural sections for handrails and posts. These materials have the added benefit of being lighter in weight and non-conductive to electricity.

There is a timber alternative to concrete and steel bridges, that may become viable under sustainability and circular economy criteria, in the not too distant future. Engineered timber bridges are technically feasible but will have challenges of span lengths, durability and cost, in comparison with concrete. However, they may become competitive for light-rail bridges, when the supply chain for engineered timber matures. Thousands of timber railway bridges existed in Australia till the early 1990s. It is conceivable that a return to timber bridges could occur in the future.

**Circular Economy Design**

The best ways to keep materials circulating is to keep using them for their original use or for a repurposed use, rather than sending them to waste landfills. There are many opportunities to extend the use of materials including the following:

- Design to last much longer than 100 years, such as 200 or 300 years or longer, example is the Gateway Bridge duplication in Brisbane.
- Design to last longer with or without maintenance of the major elements and specific components of the viaduct.
- Design for re-use of components at their highest value and for recycling.
- Design for disassembly and reconstruction.

Circularity rating metrics can be developed for all components of the viaduct, to allow circularity reporting during the feasibility, design, and construction phases.

**Ultra-High Performance Concrete (UHPC)**

The adoption of UHPC, as an innovation solution, offers significant possibility to address a variety of needs in bridge design, construction, rehabilitation, strengthening, durability and design life. Bridge engineering has mainly relied on conventional Portland cement concrete and steel reinforcement as the primary construction material. In last 20 years, there are hundreds of bridges around the world that have been designed and constructed using UHPC, ranging from minor structural elements to precast concrete segments to deck slab overlays. Today, UHPC is being widely used to design and construct bridges of different structural forms and spans, for example in Malaysia, there are over 185 UHPC bridges constructed since 2010 and in the design and construction of long span bridges in South Korea. In Australia, the bridge replacement over Shepherd’s Gully Creek in New South Wales is the first road bridge in the world that was constructed using Reactive Powder Concrete (RPC), which is another form of UHPC and was presented at the 5th Austroads Bridge Conference in 2004 (7).

UHPC is a relatively new generation of cementitious material with high strength, ductility and durability; strengthened with high strength steel fibre. UHPC has compressive strength greater than 120 MPa, with low permeability that enhances its’ durability and has adequate quantity of high strength steel fibre reinforcement to ensure ductile behaviour under tension. In some cases, it is also known as ultra-high performance fibre reinforced concrete (UHPFRC).

With the increasing demand for longer span railway viaducts while minimising the number of substructures, a robust superstructure is required that can provide better resilience and the use of UHPC
will afford this opportunity. This innovative solution can address a number of competing issues such as clearances (headroom and span), load carrying capacity, and longer longevity with lower maintenance and repair costs.

**Geopolymer and Alkali Activated Concrete**

Geopolymer concrete is made up of aluminosilicate by-products, alkali activators, aggregate and water, with no Portland cement. The by-products used are typically fly-ash and blast furnace slag and do not require excavation of virgin materials. Since no Portland cement is used, the process does not produce any CO₂. Hence there are two big environmental benefits. Using geopolymer and alkali-activated concrete mixes would reduce embodied emissions more than conventional concrete mix designs that retain some proportion of cement. According to Provis and van Deventer (8), alkali-activated concrete corresponds to concrete with binder systems derived by the reaction of an alkali metal source with a solid silicate powder (slag-based) and geopolymer concrete is a subset of alkali-activated concrete, specifically low-calcium alkali-activated systems based on aluminosilicates (e.g., fly-ash).

The efficiency of using these materials is location dependent. For example, fly ash based geopolymer concrete should be used in regions with abundant fly-ash available. Elsewhere, a slag based geopolymer may be more appropriate. Australia has a plentiful supply of slag and usable fly ash, and adopting geopolymer concrete and expanding its use in various applications (structural and non-structural) is a sustainable design approach.

**Recycled Concrete Aggregate (RCA)**

The use of recycled concrete aggregate (RCA) in concrete has been the subject of research for nearly 30 years and used in concrete for many years. However, its use has yet to translate to structural concrete mixes in the mainstream on larger projects. Part of the constraint has been the certainty of the supply chain both in terms of consistency of quality and sufficient quantity to service project demands. A dedicated batching plant is advantageous for recycled materials to prevent contamination with other aggregates for other uses and may be achieved on large projects with economies of scale.

The supply side has improved markedly over the past five years, with all major concrete producers accessing the product and using it in residential and commercial mixes. According to Cement Concrete, Aggregate Australia (9), approximately 5 million tons of recycled concrete and masonry are available in Australia, with 0.5 million tons being recycled concrete aggregate (RCA). It is noted that mixing RCA with small, crushed bricks and soil for pavement application is common. There is a significant potential for increasing the use of RCA in structural concrete on major projects.

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