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Design and construction of two irregular shaped bridge widenings

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Abstract

For transport infrastructure upgrade projects, bridge widening is typically a more economical and time effective solution compared to bridge replacement. The design and construction of bridge widenings is uniquely challenging. The design approach includes information collection, load rating, establishing design criteria, and structural analysis and design. At the start of the project, as much information as possible should be gathered from as-built drawings, past inspections, condition assessments and load ratings, site survey, etc. The load rating should assess the unaltered state, final widened state and temporary construction states. The load rating outcome informs the overall design solution. The design criteria are not so simple to establish because many existing bridges being widened were not designed for current design actions. In the structural analysis, particular matters that require careful attention include differential creep and shrinkage, differential settlement, construction staging, and load distribution between new and existing elements.

This paper presents some main considerations, challenges and solutions for the design and construction of short to medium span bridge widenings, with reference to two bridge widenings from the Warringah Freeway Upgrade (WFU) in Sydney. The WFU is an enabling works project for the current Western Harbour Tunnel project. WFU includes the widening of the Falcon Street and Mount Street overpasses, which are two steel I-girder bridges with concrete decks constructed in the 1960s. The widenings of these bridges, using composite steel I-girders, consists of two main girders placed parallel to the existing girders, and four splayed girders bolted to the new outer main girder. The connection of the new and existing decks, bridge articulation, steelwork details, and construction methods are discussed. Finally, recommendations drawn from the design and construction processes of these bridge widenings are presented, offering valuable insights for future projects.

Keywords: bridge widening, pier widening, bridge modification, steel girders, closure strip

1. Introduction

As traffic demands on roads and highways increase, existing transport infrastructure needs to be upgraded to cater for such demands. As part of these upgrades, the carriageways on existing bridges may be altered to introduce more traffic lanes or widen existing traffic lanes. Shoulder widths may also be increased to comply with the latest road safety regulations. To implement such changes, existing bridges are usually widened structurally. Bridge widening is typically a more economical and time effective solution compared to bridge replacement. During the construction of a bridge widening, a part of the existing bridge is usually required to remain open to traffic in order to minimise disruption to the road network during the upgrade project.

The design process for bridge widenings contains intricacies which are not relevant for new bridges. Information about the existing bridge, from dimensions to material properties, should be gathered. A load rating assessment considering the unaltered and widened states, as well as temporary construction states, is required. From a structural analysis perspective, the effects of differential creep, shrinkage and settlements between the new and existing bridge elements need to be considered. Besides, there are usually site and existing bridge interfacing constraints to be navigated in the design. Therefore, bridge widening design can be quite challenging.

The purpose of this paper is to provide readers with an overview of some of the considerations, challenges, and potential solutions when designing short to medium span bridge widenings. To provide examples, reference is made to the authors' experience of designing the Falcon Street and Mount Street Bridge widenings, which have irregular geometries, as part of the Warringah Freeway Upgrade (WFU) project. Section 2 introduces the Falcon Street and Mount Street Bridge widenings. Section 3 outlines the design approach for bridge widenings and highlights key considerations and challenges. Section 4 discusses bridge widening design and construction solutions, including examples from the Falcon Street and Mount Street Bridge widenings. Section 5 discusses the lessons learnt by the authors while working on the bridge widenings of the WFU project and offers recommendations for future bridge widening design. Finally, conclusions are drawn in Section 6.

2. Overview of Falcon Street and Mount Street Bridge Widenings

The WFU project in Sydney is an enabling works project run by Transport for New South Wales (TfNSW) for the current Western Harbour Tunnel project. The structural scope of the project includes the construction of several new road and pedestrian bridges, bridge widenings and modifications, cut and covers, retaining walls, noise walls, and gantries.

As members of the Jacobs Arcadis Joint Venture, engaged by CPB Contractors and Downer, the authors worked on the design of the Falcon Street Bridge widening and Mount Street Bridge widening as part of the Falcon Street and Mount Street interchange upgrades. Falcon Street Bridge and Mount Street Bridge span over the Warringah Freeway, the busiest road in Australia with over 240,000 vehicles per day. An interesting feature of both bridge widenings is their irregular geometry. These geometries accommodate bus lanes turning onto the Warringah Freeway heading southbound. The two bridges are described in further detail below.

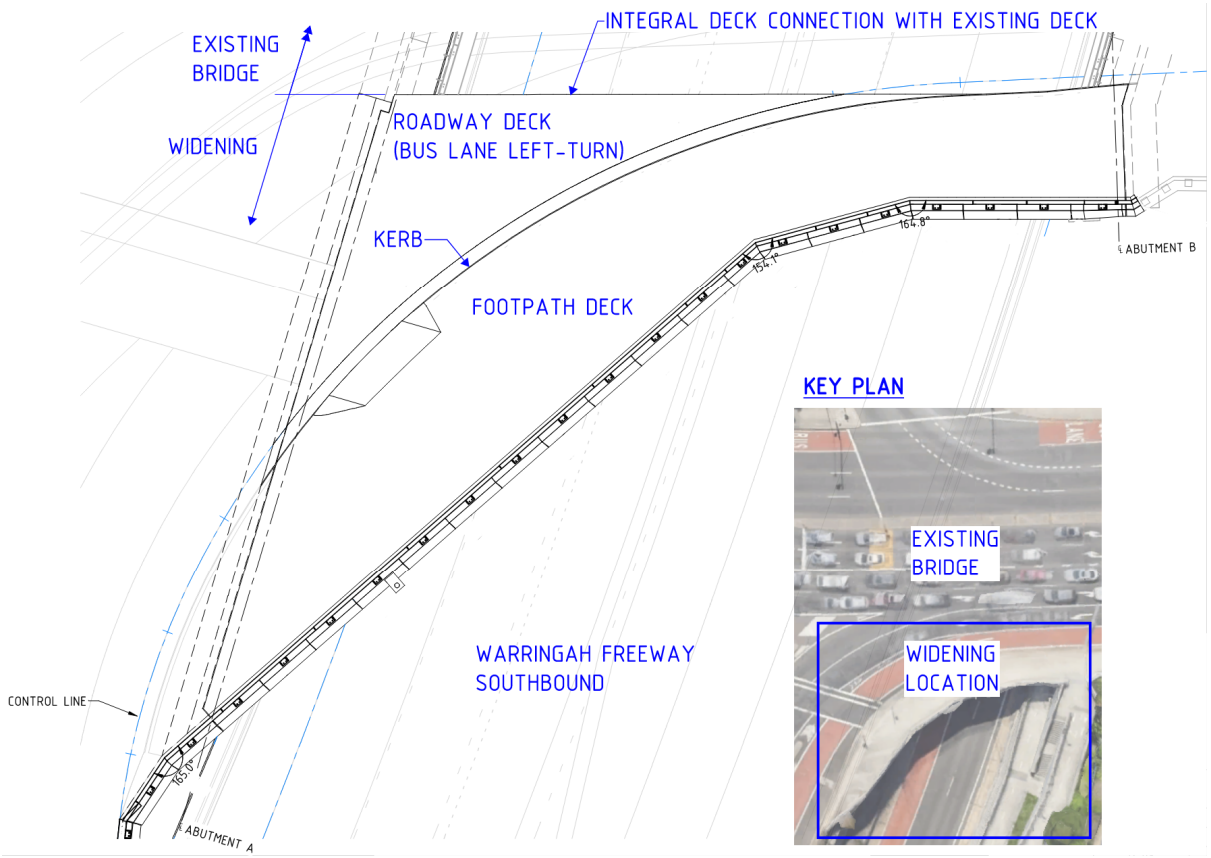
Falcon Street Bridge widening

Falcon Street Bridge is an existing structure comprising of two separate bridges constructed in 1969 over the Warringah Freeway. Bridge One, the western portion of Falcon Street Bridge, consists of three continuous spans of steel welded plate I-girders with non-composite reinforced concrete deck and is 81.9 m in length. Bridge Two, the eastern portion of Falcon Street Bridge, comprises a single, simply supported steel-composite I-girder span and has a span length of 27.9 m. The girders are supported on steel fixed and rocker bearings. The abutment sill beams are founded on rock.

Among the Lane Cove Tunnel (LCT) construction works in 2005, the southern part of Bridge Two was widened along the carriageway kerb line to service a shared path. Two concrete corbels were constructed at the rock face on the western end of Bridge Two to support the widening. Additional southbound lanes are being added to the Warringah Freeway under the Falcon Street Bridge as part of the WFU project, which required the concrete corbels supporting the LCT works to be demolished. As such, the southern widening of Falcon Street Bridge Two from the LCT works has been demolished and replaced with a new widening.

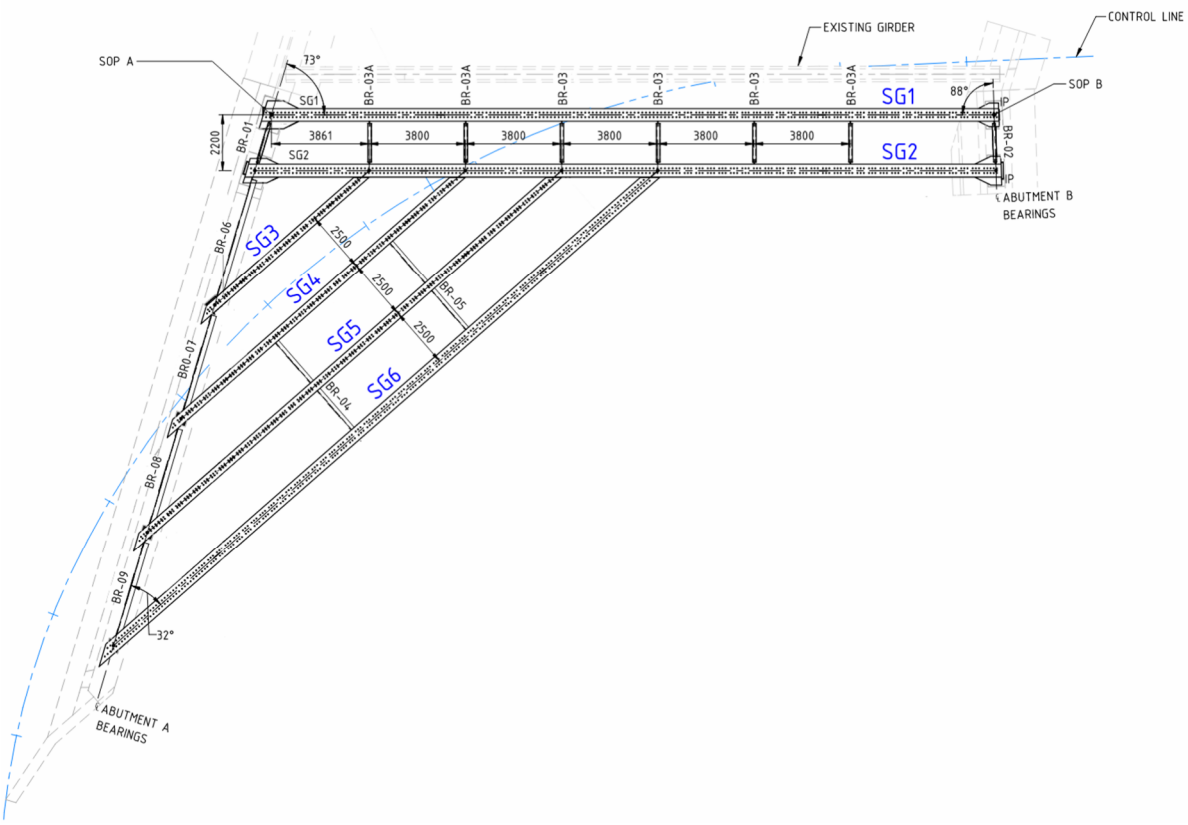
The new widening entails the reconstruction of the footpath, as shown in Figure 1. The unique geometry of the widening is driven by a bus lane left-hand turn from Falcon Street onto a new bridge (Falcon Street Bus Lane Ramp Bridge), which is an entry ramp onto the Warringah Freeway. A separate paper discussing this new bridge is also presented at this Conference.

Figure 1: Falcon Street Bridge widening general arrangement



The superstructure for the modified widening consists of two main steel I-girders (SG1 and SG2) parallel to the existing bridge girders and four splayed steel I-girders (SG3 to SG6). The layout of the girders is shown in Figure 2. All six steel girders have a depth of 1350 mm. The splayed girders are connected to SG2 via a bolted fin plate connection. The girders are made composite with a reinforced concrete deck through shear studs. K-frames (BR-03, BR-03A, BR-04 and BR-05) are provided between SG1 and SG2 and between SG4, SG5 and SG6 within the span. A K-frame end diaphragm is also provided at Abutment A (between all six girders) and at Abutment B (between SG1 and SG2). Girders SG1 and SG2 were lifted as a pair with K-frames pre-welded to the girders. The splayed girders were lifted individually and bolted to SG2, with K-frames bolted between the girders afterwards.

Figure 2: Falcon St Bridge widening girder layout



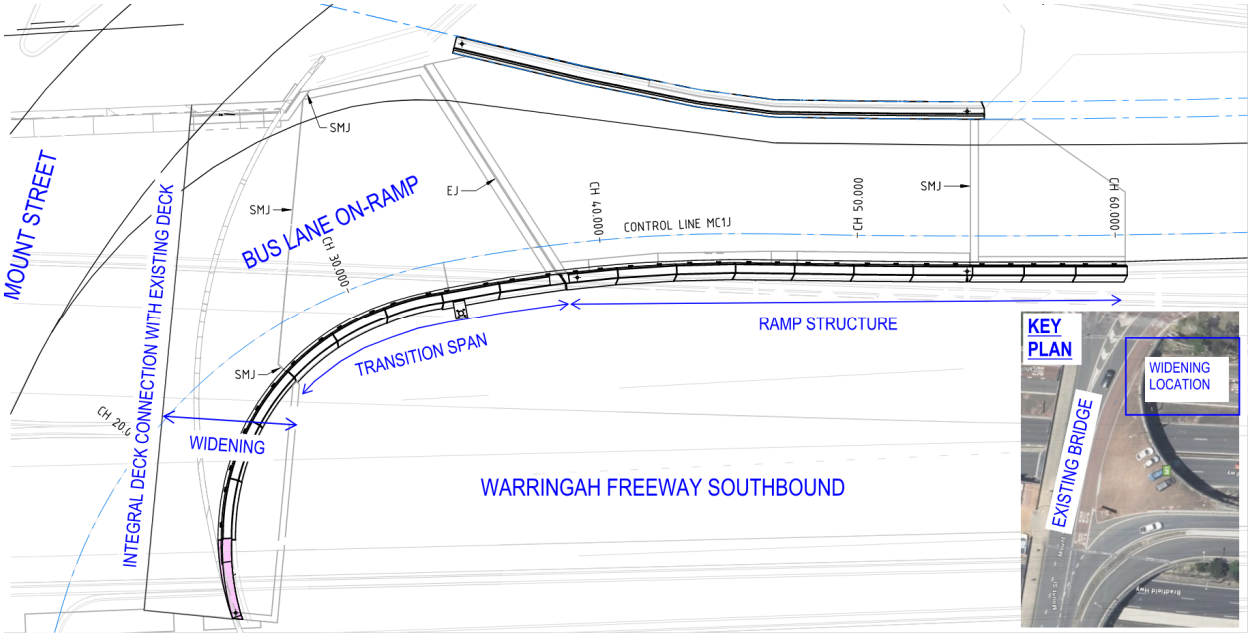
The southern portion of the existing Abutment A, including the wing wall, were demolished, and the abutment was extended to the south to support the new splayed girders. Reinforcing bars were drilled and grouted into the existing abutment to form an integral connection for the new extension. The new abutment extension at Abutment A consists of a reinforced concrete sill beam with spread footing founded on rock. The new Abutment A sill beam is wider than the existing sill beam to provide sufficient space for the larger spherical bearings and the provision for bearing replacement through jacking. There is a step in the new curtain wall at the interface with the existing abutment to accommodate the wider sill beam. Ground anchors were installed at the abutment extension for stability. The LCT abutment extension has been retained to support SG1 and SG2 at the eastern end.

Mount Street Bridge widening

The existing Mount Street Overbridge comprises two structures, Structure 1 spanning the western portion of the Warringah Freeway Northbound, and Structure 2 spanning the eastern portion of the Warringah Freeway Southbound and Cahill Expressway. Both structures are similar in geometry and structural form, that is, two span continuous steel I-girders with non-composite concrete deck. Structure 2 has a ‘wing’ hardstand portion to the south of Span 3.

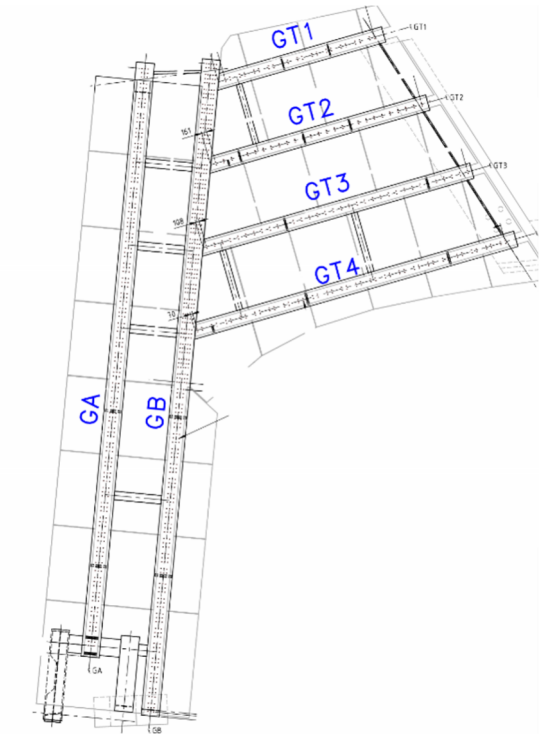
As part of the WFU project, Structure 2 of the existing Mount Street Bridge has been widened toward the south. A new ramp bridge connected to the widening facilitates a new bus lane right-hand turn from Mount Street heading southbound onto the Cahill Expressway. Figure 3 shows the bridge widening, transition span, and ramp structure arrangement.

Figure 3: Mount Street Bridge widening general arrangement



Both the bridge widening and the transition span comprise steel I-girders with composite in-situ concrete deck. The I-girders are custom-sized (depth and width) with plate thicknesses to suit an optimised design section. Except for Girder GB, all other girders have constant top flange, bottom flange, and web thickness along the girder. Girder GB has been optimised with variable thickness top and bottom flanges. The girders are braced with transverse cross beams to provide stability during construction of the concrete deck. A 220 mm thick situ-topping deck slab over 90 mm thick permanent formwork panels completes the superstructure. The girder layout is shown on Figure 4.

Figure 4: Mount Street Bridge widening girder layout

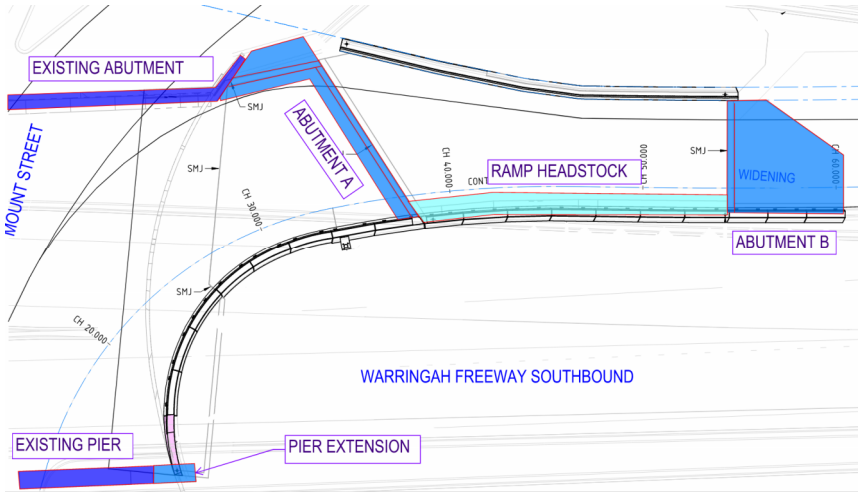


The transition span comprises four 610 mm deep girders with variable length ranging from 5.5 m to 10.5 m. The girders were delivered to site in pairs with bracings pre-welded. The girders were bolted to the new bridge widening edge girder (Girder GB) and supported on elastomeric bearings, which sits on the transverse headstock at the south end of the transition span. The cross bracings between the girder pairs comprise of standard universal beam (UB) section, with the exception of the diaphragms which comprise hollow sections in a K-frame configuration to improve maintainability and accessibility.

The bridge widening comprises two 1214 mm deep girders approximately 20 m long which are supported on elastomeric bearings. The girders are identified as GA and GB, the latter being the edge girder. The girders were individually lifted with bracings bolted on-site. The western end of GB is supported on a short extension of the existing pier headstock. Due to spatial constraints and the existing bearing articulation, a bespoke fork-like detail was developed for GA. This bespoke detail is discussed further in Section 4 of this paper. All new steel girders are supported on bearings at the pier extension, existing sill beam and new Abutment A sill beam.

Two new abutments are proposed along the transition span and ramp structure, that is, Abutment A and Abutment B as shown in Figure 5. Abutment A comprises a slightly skewed (relative to the existing abutment) sill beam directly adjacent to the existing Abutment D sill beam.

Figure 5: Mount Street Bridge widening substructure layout



The ramp structure comprises a reinforced concrete deck spanning between the longitudinal headstock and the existing rock top along the eastern face. Further details of the ramp structure are excluded from this paper as it falls outside the context of a bridge widening.

3. Design approach for bridge widenings

Generally, the following procedure is adopted for the design of short to medium span bridge widenings.

1. Collecting information about the existing bridge
2. Load rating
3. Establish design criteria
4. Structural analysis and design

These steps are explored below, with references to the Falcon Street and Mount Street Bridge widenings for examples.

Collecting information about the existing bridge

One of the first considerations in the bridge widening design process is understanding the level of existing build information available. As much information as possible should be gathered from as-built drawings, past inspections, condition assessments and load ratings, site survey, etc. Accurate and reliable survey is crucial to ensure the tie-in and interfaces are adequately incorporated in the design. Detailed survey is crucial to accurately identify the spatial constraints and limitations at the interface points.

The quality and accuracy of survey can vary significantly depending on factors such as survey method, equipment used, software, etc. The tolerance and accuracy of the survey must be well understood and accounted for in the design. Where ambiguity is present and the design is based on assumptions, these should be clearly stated in the design with requirements to validate the assumptions on site prior to construction.

For Falcon Street and Mount Street Bridge, the authors had access to the as-built drawings and previous inspection and load rating reports. During the design phase, point cloud survey was conducted with a general accuracy of ±100 mm, and increasing in accuracy to ±20 mm at the critical sections of the bridge. In addition, measurements around the existing bearing shelves were taken by hand to confirm spatial adequacy. For the Falcon Street Bridge widening, bearing plinths were detailed at the abutments to allow for bearing levels to be adjusted on site if required.

Load rating

In a bridge widening project, load rating of the existing bridge is an important part of the design process because it informs the overall design solution. A load rating of the existing bridge in its unaltered state should be conducted prior to the detailed design of the widening works. This informs the engineers and asset owner of what vehicular loading the existing bridge can carry, which can be used to set the design loading requirements for the widening. Following this, as the design is developed, load rating of the bridge in its temporary states during construction and in its final widened state is also necessary to account for changes in the global structural behaviour of the bridge. Because design development is an iterative process, several iterations of the load rating may be required.

Load rating allows engineers to determine whether strengthening is required to implement a new widening. The load rating outcome is also an important factor in the choice between adopting a bridge widening that is integral with or independent to the existing bridge. It is certainly possible to improve the load rating factor of some existing bridge elements between the unaltered state and final widened state without strengthening those elements. For example, an edge girder in an existing bridge would become an internal girder after bridge widening, and this alone could be enough to increase its load rating factor. Careful detailing choices and providing new elements with adequate stiffness can prevent unwanted load distribution into the existing elements. For wider existing bridges, there is usually very little change in the load rating factor for the elements further away from the widening between the unaltered state and the widened state.

Usually, a condition assessment of the existing bridge is conducted before the load rating. The findings of the condition assessment should be incorporated into the load rating, especially where material deterioration decreases the load-carrying capacity of the structural element. If material properties are not determined during the condition assessment, and there is a lack of information from as-built drawings, engineers can refer to Appendix A of AS 5100.7:2017 (Standards Australia[1]) for guidance.

Particular attention should be paid to load rating of the existing structure during construction of the widening. Depending on the widening solution, the existing deck cantilever may be demolished close to the flange of the edge girder. For girders designed to behave compositely with the deck, this will result in a temporary reduction in the load-carrying capacity and stiffness. Therefore, based on the outcome of the load rating, traffic restrictions may need to be implemented to keep vehicles away from the compromised edge girder during construction.

Specific load rating requirements are usually outlined in the project deed and the relevant codes and standards. A load rating for the existing Mount Street and Falcon Street Bridges was conducted in accordance with AS 5100.7:2017 for T44/L44 traffic loads.

In the case of Mount Street Bridge widening, the rating of two existing girders were negatively impacted with a drop in load rating factor to less than one, temporarily during construction. The primary reasons for this were the temporary / readjusted traffic staging lanes, as well as the partial demolition of the bridge deck causing a redistribution of dead loads to the adjacent span. Early discussions were held with the authorities, and considering several factors such as duration of construction, typical traffic activities, and degree of impact to load rating, the temporary drop in load rating factor was deemed acceptable by the road authority. The risk was then transferred over to the asset owner with appropriate risk management procedures undertaken.

Establish design criteria

Unlike with new bridges, which are typically required to be designed in accordance with the current Codes and Standards, establishing the design criteria for bridge widenings is not so simple.

Most existing bridges in Australia were designed for road traffic loads less than the current SM1600 design loads. For the widening of these bridges, there are a few potential scenarios:

1. Design the widening structure for SM1600 loads and strengthen the existing bridge to increase the load rating factor of each element to above one for SM1600 loads. This is the most economically expensive scenario in the short term and could be impractical in some cases but ensures a uniform risk profile across the entire widened bridge.
2. Design the widening structure for SM1600 loads, but do not upgrade the existing bridge to carry SM1600 loads. This scenario is more economical than the scenario above, but the structural reliability of the widened bridge is not improved. This scenario may be selected if there is an intention to strengthen the existing elements in the future.
3. Design the widening structure for the same road traffic loads as what the existing bridge can carry. A uniform risk profile across the entire widening bridge is achieved in this scenario.

Similarly, there are a few potential scenarios for establishing the design criteria for earthquake effects. Ultimately, the transport authority and asset owner set the design criteria for bridge widenings based on their asset management philosophy.

Typically for TfNSW projects, the Scope of Works and Technical Criteria (SWTC) stipulates that an integral bridge widening greater than 7 m wide should be designed to SM1600 loads whilst a widening of less than 7 m wide should be designed for the same loads as the original bridge, but not less than T44/L44.

Ambiguity in the application of road traffic design lanes can arise for bridge widenings that are irregular in shape, such as Mount Street and Falcon Street. In such scenarios, the configuration should be considered on a case-by-case basis in consultation with the transport authority to ascertain the requirements. In the case of Mount Street and Falcon Street Bridge, the road traffic design lane configurations shown in Figure 6 and Figure 7 were adopted respectively.

Figure 6: Traffic design lane configurations for Mount Street Bridge widening

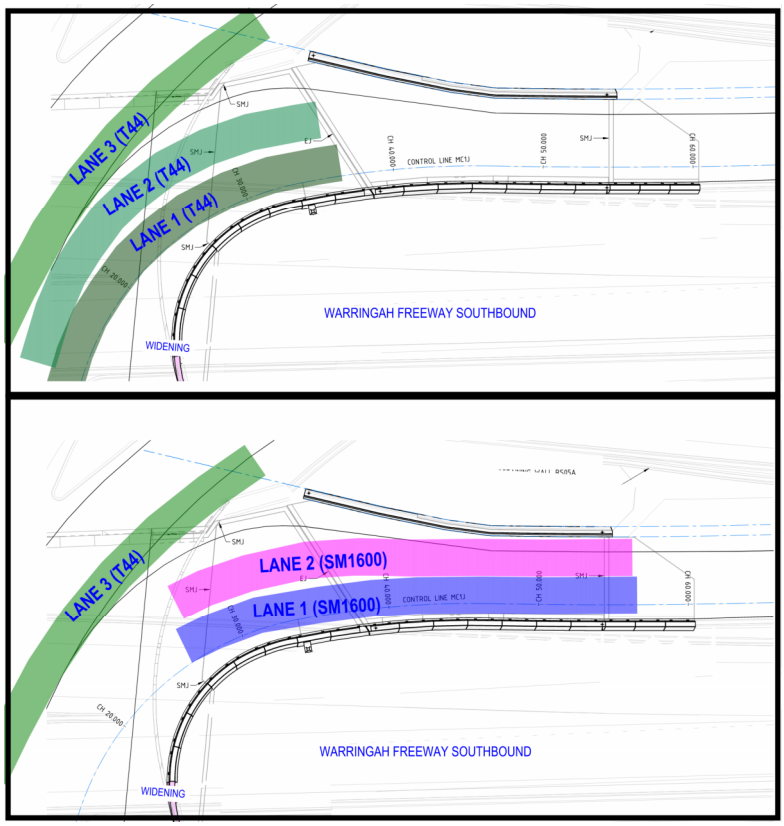
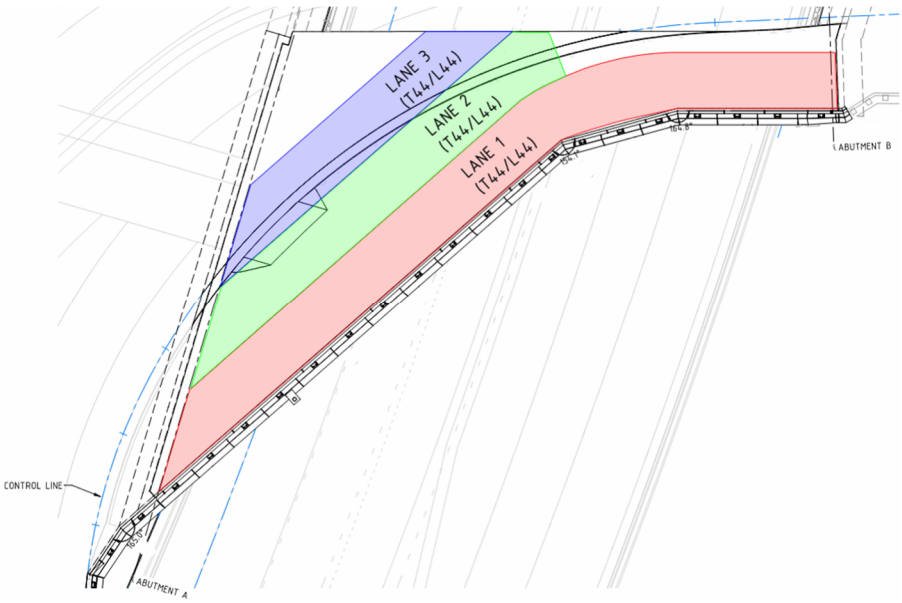


Figure 7: Traffic design lane configuration for Falcon Street Bridge widening



Structural analysis

In the structural analysis of bridge widenings, there are particular matters which require careful attention from the engineers. Some selected matters are discussed below.

Differential creep and shrinkage

By the time the widening is to be constructed, the effects of concrete creep and shrinkage should have fully occurred in the existing bridge. Therefore, concrete creep and shrinkage in the bridge widening are restrained, primarily in the longitudinal direction, at the deck interface. This effect induces axial tensile stress in the widening and axial compressive stress in the existing bridge. For prestressed concrete girders, particularly the girders closest to the new and existing deck interface, this leads to a reduction in prestress loss in the new girders and an increase in prestress loss in the existing girders. Since the restraint to creep and shrinkage is at the deck level, the eccentricity of this restraint causes hogging in the new girders and sagging in the existing girders.

To reduce the effects of differential creep and shrinkage in a bridge widening, the timing of the closure strip pour should be carefully selected (see Section 4 for further discussion about closure strip pours). If the closure strip is poured too soon after the widening deck concrete is poured on the new girders (or too soon after widening box girders are constructed), the differential creep and shrinkage effects will not be reduced sufficiently. If the closure strip is poured too late, extra hogging of the new girders due to prestressing will occur and may cause issues with tying into the existing deck. Besides, it may be impractical for construction to be halted for too long to wait for the closure strip pour. Therefore, a lower limit and upper limit for timing of the closure strip pour should be specified on the design drawings.

For steel-composite bridges, the girders are designed to be precambered to avoid sagging under permanent effects. The time-dependent deflection of the girders due to creep and shrinkage before and after the closure strip pour should be determined and included in the precamber value. In practice, the magnitude of time-dependent deflections in steel-composite girders may be outweighed by allowable precamber construction tolerances.

Differential settlement

For new bridge design, consideration of differential settlement between longitudinally adjacent piers and abutments is usually sufficient. In existing bridges, long-term settlements would have mostly occurred by the time they are to be widened. Particularly for bridges founded in softer ground conditions, as settlements start to happen in the widening structure, there is differential settlement transversely at the abutments and piers. Depending on the magnitude of the differential settlement, this can cause significant transverse bending in the closure strip deck, as well as headstocks which are joined together.

In such cases, it is very important that boreholes are taken at the bridge site so that settlements can be predicted more accurately by the geotechnical engineers during the design phase. Similar to dealing with differential creep and shrinkage, delaying the closure strip pour can reduce the magnitude of differential settlement.

Construction stage analysis

The structural analysis needs to consider the construction sequence of the bridge widening to accurately determine the action effects in each element. For example, whether the bridge barriers are installed before or after the closure strip pour can lead to different permanent action effects in the closure strip concrete, new and existing girders, bearings, and substructure. Especially for narrow widenings of shorter span bridges, stability of the new superstructure against overturning needs to be assessed if bridge barriers are installed prior to the closure strip pour.

The backfilling behind new abutments causes new earth pressure, whereas earth pressure is already acting on the existing abutments. This loading effect should be considered for the design of the connection between the new and existing abutments.

From the authors' experience, using an analysis software with construction stage analysis functionality, like Midas Civil, can be very convenient.

Load distribution and structural behaviour

During bridge widening design, there is an opportunity to manipulate the live load distribution within the widened bridge favourably by considering the relative stiffnesses between new and existing elements. For example, if the load rating factor of an existing edge girder needs to be increased, the new girders of the widening can be designed to be stiffer. This can be done by increasing their structural depth (subject to vertical clearance requirements), adopting a thicker composite deck for the widening, or increasing plate thicknesses in steel girders.

Once a bridge is widened and the overall weight of the bridge is increased, lateral forces from earthquake effects will increase. It is important to ensure the appropriate bearings / lateral restraint systems are in place to manage any increase in lateral forces.

4. Bridge widening design and construction solutions

Pier and Abutment Widening

As a bridge is widened, the new girder(s) may need to be supported on a new independent support structure or on a widened section of the existing support. When determining the support system for a bridge widening, it is important to understand the condition and capacity of the existing pier / abutment. Additionally, it is also crucial to understand the soil condition and any possible differential settlement issues should a new isolation pier be constructed for the widening.

A pier widening / modification is often a more efficient and cost effective solution compared to an isolated pier. Common methods of a pier extension include external steel corbel clamped to a pier headstock via post-tension stress bars, and reinforced concrete pier widening. Sheasby et al.[2] adopted a steel corbel extension method on the Western Distributor Viaduct modification works. Figure 8 and Source: *Google Maps*

Figure 9 below are two example images of pier widenings in Sydney.

Figure 8: Image of pier widening for Western Distributor Viaduct modification - Sydney



Source: Google Maps

Figure 9: Image of pier widening for Mount Street Bridge widening - Sydney



Source: Google Maps

Connection of new and existing decks and deck construction

Typically, a closure strip is used in bridge widenings to join the new bridge deck with the existing. There are several benefits of adopting this method of construction. Firstly, the new bridge elements can be constructed in isolation to the existing bridge, minimising traffic disruptions on the existing bridge. Secondly, the construction of the majority of the new bridge elements prior to connecting with the existing bridge ensures that there is minimal dead load transfer onto the existing bridge, which can be crucial for existing bridges with limited load-bearing capacity. Also, particularly for bridge widenings using prestressed concrete girders, the timing of the closure strip pour can be controlled to minimise the effects of differential creep and shrinkage between the new and existing structures, subject to construction timelines. For bridge widenings on softer ground conditions, delaying the closure strip pour can also be advantageous in reducing the differential settlement effects between the new and existing elements.

In many cases, it is not practical to completely close bridges to traffic during construction of the closure strip. Vibration of the closure strip concrete while it is setting, induced by vehicles travelling on the existing bridge, can have negative impacts on the performance of the concrete which are not easy to observe on site. These include reduced compressive strength (Furr and Fouad[3]) and reduced bond strength (American Concrete Institute[4]). Even for closure strips poured with ultra-high-performance concrete (UHPC), high amplitude vibrations can compromise the strength and bond (Yang et al.[5]). The explanation for the loss of bond is the reinforcing bars protruding from the new and/or existing decks moving relative to each other when the existing deck is subjected to vehicular loading, potentially forming voids around the bars which cannot be filled once the closure strip concrete has hardened to a certain extent (Manning[6]). Ng and Kwan[7] found that while it may be difficult to completely avoid cracking of the closure strip, if crack widths can be limited to below 0.2 mm, the reduction in bond strength is less than 5%.

Several bridge widenings in New South Wales in the past have adopted longitudinal joints between the new and existing decks. However, due to concerns around rideability, durability and maintenance, the current preference is to provide an integral connection between the new and existing decks where possible. On the WFU project, the SWTC from TfNSW required that an integral deck connection be implemented where possible. A longitudinal joint between the new and existing structure could only be used where the existing structure was found to be structurally inadequate.

The SWTC on the WFU project contains prescriptive traffic restrictions for bridges being widened to reduce vehicle-induced vibrations of the closure strip in its early age. These requirements were developed for typical precast concrete plank and girder bridges with spans up to 33 m and are summarised in Table 1.

Table 1: Traffic restrictions for closure strip on the WFU project.

Duration	Minimum strength gain (MPa)	Traffic distance x from closure strip (m)			
		x < 1.0	1.0 < x < 3.5	3.5 < x < 7.0	x > 7
< 24 hours	N/A	X	X	X	•
24 to 36 hours	15	X	X	•	•
36 hours to 28 days	20	X	•	•	•
> 28 days	50	•	•	•	•

Table 2 summaries the concrete properties and makeup for Falcon Steet and Mount Street Bridge widenings. The property and construction methods were in line with the project SWTC requirements as well as findings from Deery[8].

Table 2: Closure strip concrete requirements on the WFU project

i)	Closure strip width	900 mm to 1000 mm
ii)	Shrinkage	< 500 με at 56 days
iii)	Concrete grade	50 MPa
iv)	Curing	Wet cure and insulated - 14 days
v)	Vibration	Minimise vibration by adopting speed restrictions and other measures
vi) & vii)	Reinforcement	N16 longitudinal bars with 100 mm spacing within the stitch. Securely lap connect bars with triple ties.

The existing deck will need to be trimmed back for the closure strip to be constructed in-situ. The methods for deck connection considered for Mount Street and Falcon Street is listed in Table 3.

Table 3: Deck connection options considered for Mount Street and Falcon Street Bridge widenings.

	Method	Advantage	Disadvantage
1	Hydro-demolition of existing deck, retaining the existing bars. New and existing bars are lapped or joined using couplers.	Allows the existing bars to be retained and undamaged. Provides a true and sound integral connection. Minimal damage to existing deck.	Significant construction set up and access. A large amount of water is required and needs to be contained.

	Method	Advantage	Disadvantage
2	Saw cut the deck and drill new bars (top & bottom) into existing deck.	Fast demolition time.	The existing concrete is low grade and thin (170 mm thick). This makes drilling two layers of reinforcement complex. High risk of damage to existing concrete during drilling.
3	Saw cut the deck and drill centrally placed stainless steel dowels.	Fast demolition time.	Does not provide sound integral connection and creates a hinge point in the deck. Poor water tightness. Method not accepted by TfNSW.

Aside from the deck closure strip, the new deck construction can pose several challenges. Bridge widenings over traffic, waterways, valleys inherently increase the deck construction risk and complexity. Preformed deck panelling such as thin precast concrete panels or sacrificial GRP panels are often preferred means for deck construction. However, irregular shapes and large deck cantilevers often preclude the usage of deck panelling in its entirety. A combination of temporarily propped panels, full thickness in-situ deck and preformed deck panelling may be required, which was the case for Falcon Street and Mount Street Bridge.

A ‘Transfloor’ type precast permanent concrete formwork panel system was adopted in the bridge widenings, refer to Figure 10 and Figure 11 for deck panel layout. The precast concrete deck panels were designed to span one-way between the girder flanges and are not considered composite in the longitudinal direction.

Figure 10: Mount Street Bridge precast concrete deck panel layout

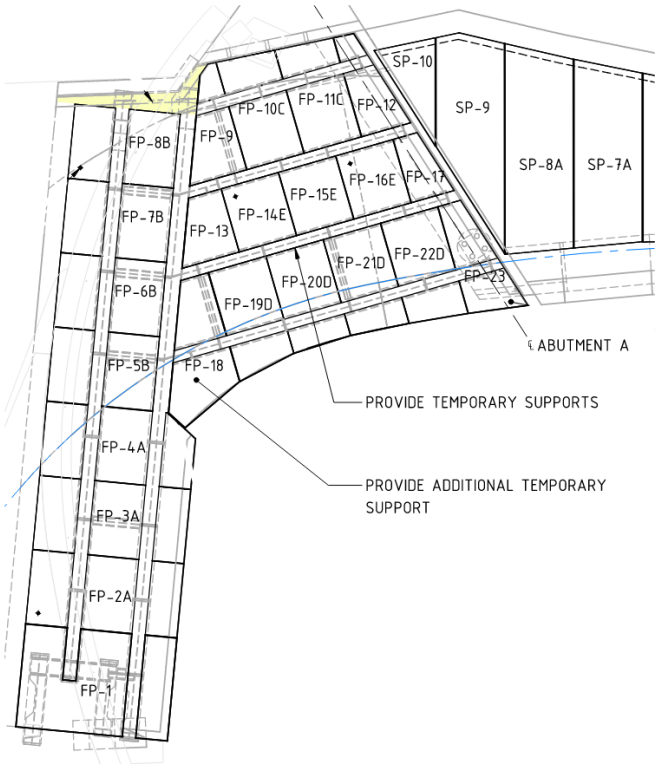
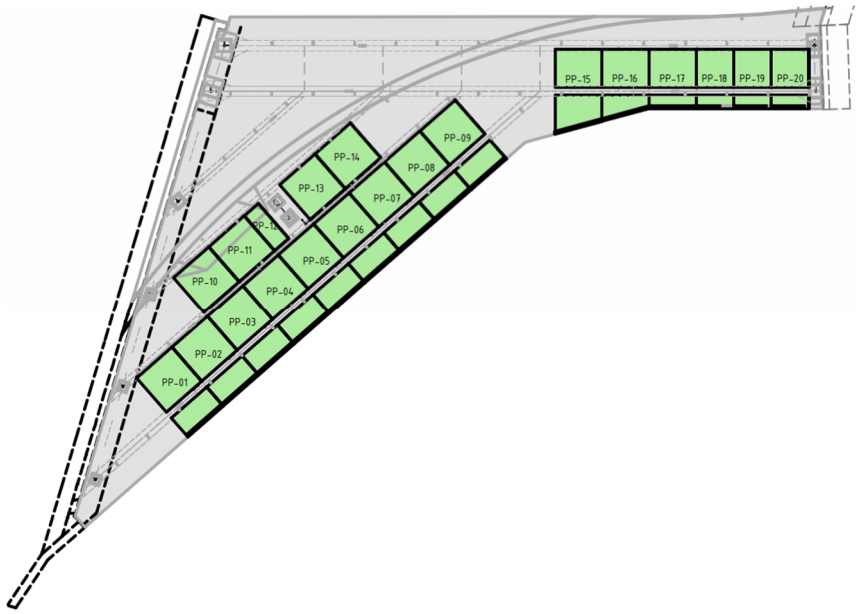


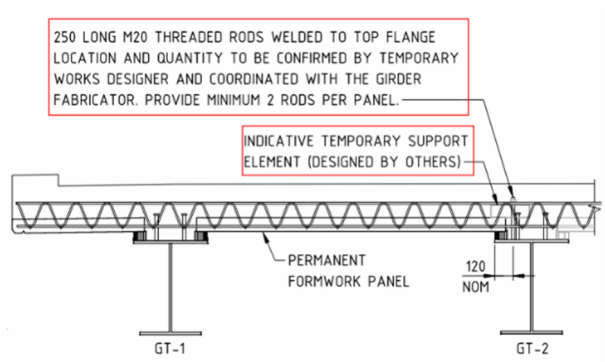
Figure 11: Falcon Street Bridge precast concrete deck panel layout



Falcon Street Bridge adopted a combination of precast concrete deck panels and conventional plywood formwork. The panels could not be used for the entire area of the deck due to the unique deck geometry. The deck cantilever panels were propped for stability by a temporary walkway structure installed on the edge girders (SG2 and SG6) to facilitate construction.

Mount Street Bridge adopted precast concrete deck panels with temporary supports or props required for fore the edge panels on the transition span (FP-9 to FD-12). M20 rods were welded to the top flange of Girder GT2 to allow for a temporary hold down systems to be implanted during construction, refer to Figure 12. Additionally, corner panels FP-18 and FP-23 requires external temporary support system due to its odd shape and large cantilever.

Figure 12: Precast concrete deck panel temporary support detail

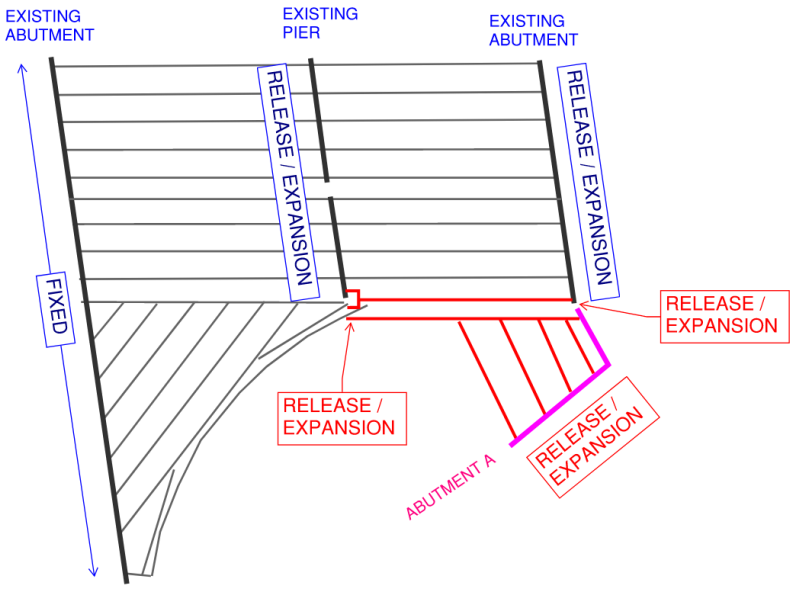


Bearing type and articulation

It is vital that the bearing type and articulation of the existing bridge is considered in the bridge widening design. The degrees of freedom at each support point (existing and new) should allow the widened bridge to move freely in the same direction as the existing bridge to ensure that the existing bearings retain their primary function. Special consideration may be required to ensure this is possible.

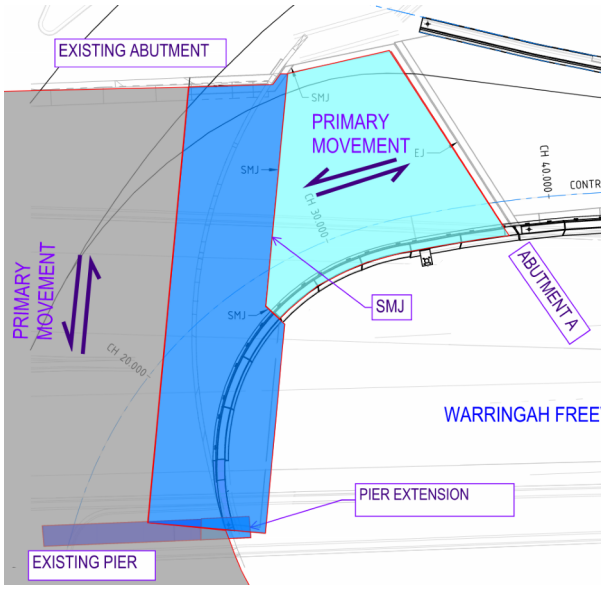
The existing Mount Street Bridge superstructure is supported on steel fixed bearings at the existing Abutment C and steel rocker bearings over the existing pier and at the existing Abutment D. The new steel girders are supported on expansion bearings. Thus, in the completed widened state, the overall articulation (fixed and free ends) is maintained, refer to Figure 13.

Figure 13: Mount Street Bridge bearing articulation



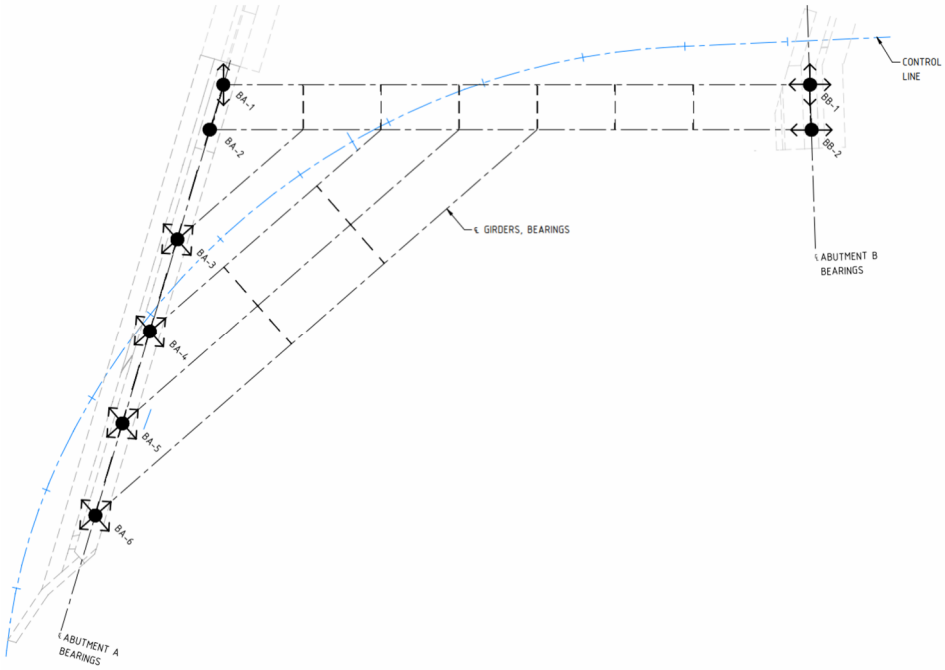
The two new widened girders run parallel to the existing girders while the splayed girders were orthogonal to it. This meant that the primary / longitudinal movement of the widened portion and the splayed deck portion were in opposing directions. To simplify the design actions and to mitigate complexity in directional movement, a small movement joint (SMJ) was introduced at the junction between the deck widening and the transition span deck. Refer to Figure 14.

Figure 14: Mount Street Bridge primary movement direction and deck joint



The existing Falcon Street Bridge superstructure is supported on steel fixed bearings at the existing Abutment A and steel rocker bearings at the existing Abutment B. The articulation of the widening matches this. SG1 is supported on a spherical bearing guided in the transverse direction at the western end and a free float spherical bearing at the eastern end. SG2 is supported on a fixed spherical bearing at the western end and spherical bearing guided in the longitudinal direction at the eastern end. The four splayed steel I-girders are supported on free float spherical bearings at the new Abutment A at one end and will be bolted to SG2 at the other end. Refer to Figure 15.

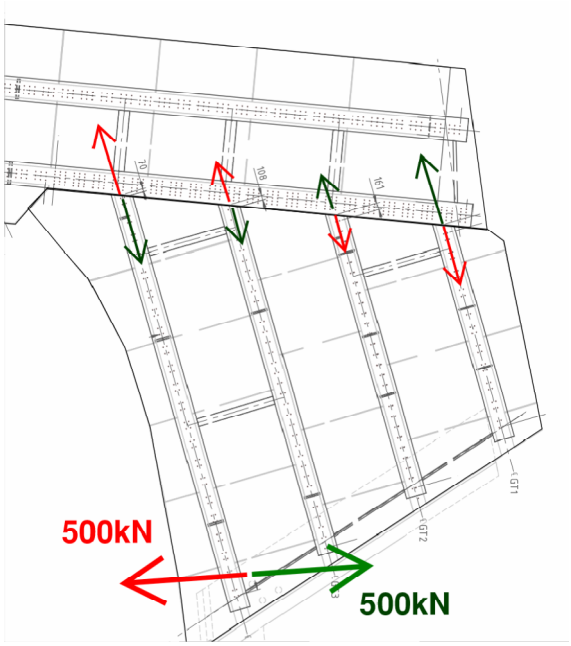
Figure 15: Falcon Street Bridge bearing articulation



Widening and changing the shape of a bridge and adding more loads can alter the lateral behaviour of the bridge. Primarily, the lateral actions of earthquake and minimum lateral restraint load should be considered. The existing bridge may not have been designed for minimum lateral restraint loads that meet current Standards and requirements. Additionally, the load transfer from lateral action may not be immediately obvious and deeper investigated into the lateral behaviour must be carried out.

On Mount Street Bridge, a 500 kN lateral restraint load applied on the southern abutment of the transition span resulted in an in-plan torsion of the deck. This torsion in the deck creates a push pull effect at the interface between the splayed girder and widening / edge girders, refer Figure 16. It was found that a lateral force transfer to the existing bearing of the eastern abutment would exceed the bearing capacity. To mitigate this, a lateral restraint bracket was introduced on the eastern end of the edge girder.

Figure 16: Mount Street Bridge lateral load distribution



Deck joints

As a bridge is widened, the existing expansion joint will need to be widened as well. The expansion joint of the widening deck should match the function, performance, and style of the existing joint. However, this may not be possible in all instances as historical joint systems become obsolete. As such, modern or more commonly used joints such as strip joints may be warranted. Where a change in joint type along the same joint line is proposed, it is important that the interface and end treatment of both the new and existing joint is designed accordingly. Bespoke end details are often required to suit, and thus vital that the treatment and detailing be discussed with a joint specialist / manufacturer.

Maintenance

The design should strive to maintain or improve the existing bridge maintenance strategy, particularly for the laterally widened portion of the bridge. For portions of the bridge that extend beyond the widening (transition span / ramp), the maintenance consideration should be in line with the relevant Standard and authority requirement.

The gap between the existing girder and the new girders should be such that there is sufficient space to carry out routine maintenance activities such as inspections and painting. At the girder ends, the choice of diaphragm / cross bracing configuration should be considered to maximise accessibility. For example, an X-brace or K-brace will provide better accessibility than a deep cross beam.

Propping of pre-composite girders

During the design phase, an opportunity was identified to prop the pre-composite steel girders at Falcon Street Bridge widening from the Warringah Freeway below. This was possible because part of the Warringah Freeway southbound carriageway under the bridge was closed to establish a construction work zone. A total of nine props were placed under the girders. This ensured that the deck concrete, a significant proportion of which had a thickness greater than 350 mm for the footpath, could be constructed in one continuous pour without increasing girder plate sizes. The axial stiffness of the props was assumed during the design phase based on the proposed propping system and verified during the construction phase.

Steelwork details

When dealing with a complex and highly constrained widening interface, bespoke steelwork detailing may be required. There were several unique steelwork detailing adopted on Mount Street and Falcon Street Bridge.

On Mount Street Bridge, the western end of Girder GA branched out on to two supports in a ‘fork-like’ manner. This forked girder arrangement was required due to the limited space available for a new bearing to be in line with GA. As such, the forked girder was supported on two smaller bearings to suit the available space. The steelwork of the forked girder comprises similar welded steel plate I-shaped beams with a stiff transverse beam section, refer to Figure 17 and Figure 18. Additionally, the bottom flange of both Girder GA and GB had coped bottom flanges to ensure that sufficient space is available for maintenance activities to be carried out.

Figure 17: Mount Street Bridge edge girder layout

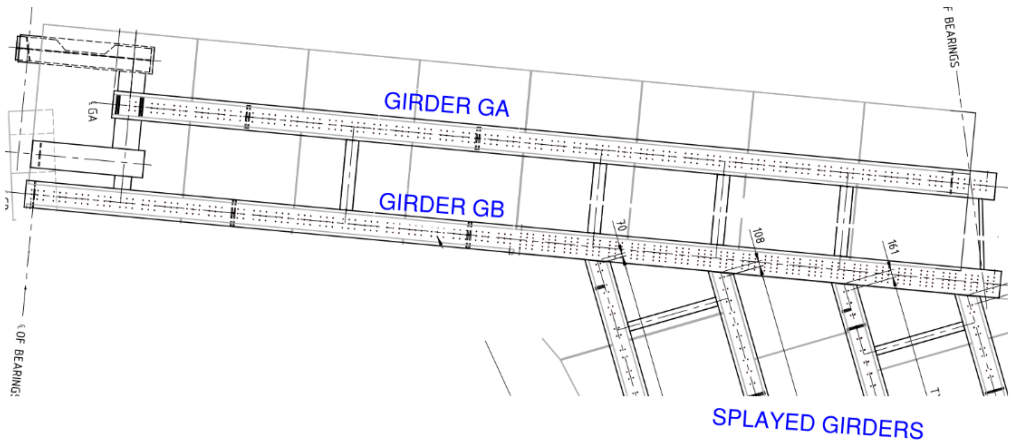
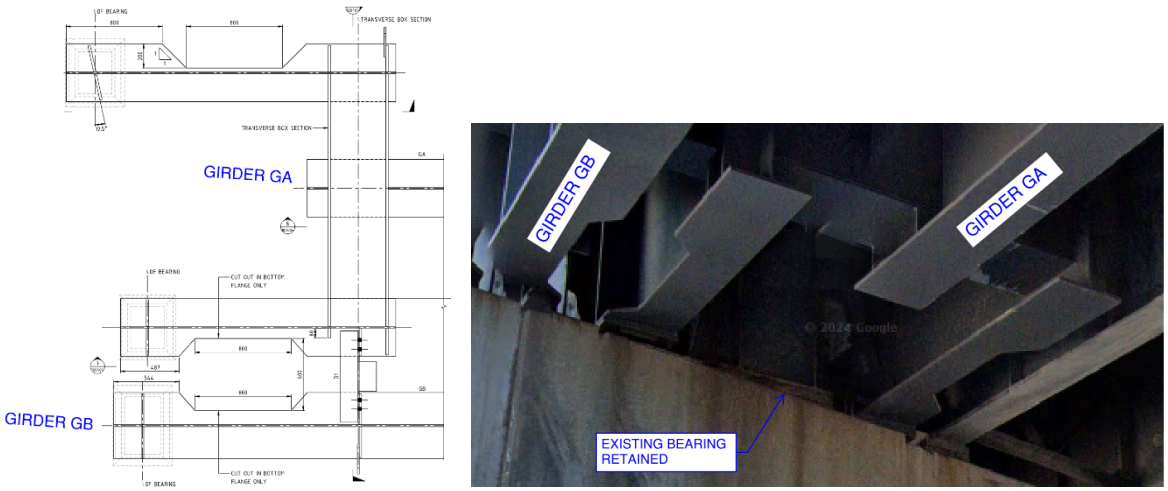
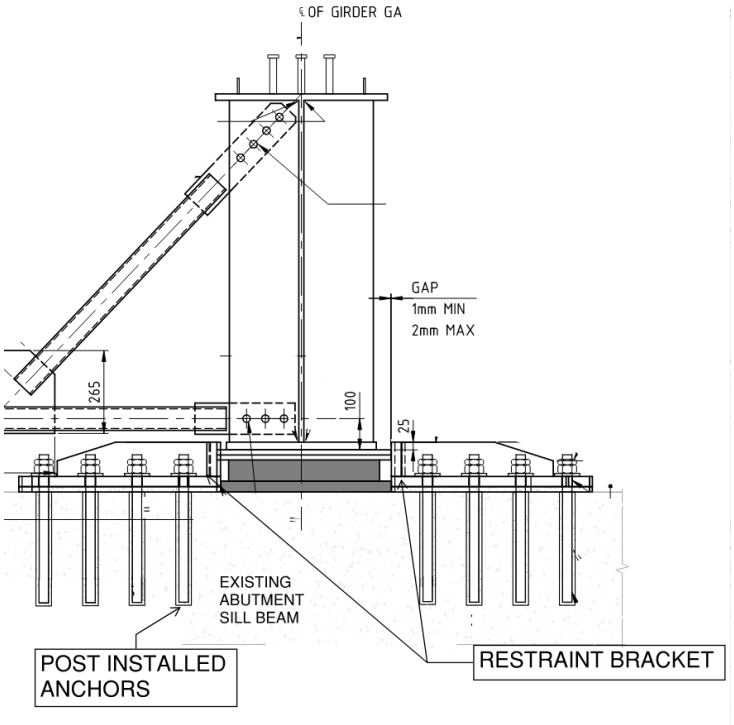


Figure 18: 'Forked' girder detail and image



A steel bracket system was also custom designed to provide lateral support to the bridge widening. The bracket was installed at the eastern end of Girder GA which is supported on the existing bridge abutment. The steel bracket comprises thick welded steel plates which are fixed into the existing concrete by chemical anchors. The bracket is designed to support 500 kN lateral load and is installed with a precise gap of 1-2 mm between the bracket and the girder bottom flange. This ensures that the bracket is mobilised should the girder displace under lateral load but also allows a small amount of freedom to avoid premature mobilisation of the bracket. Refer Figure 19.

Figure 19: Lateral restraint bracket detail



At Falcon Street Bridge, to accommodate girder end bracing at Abutment A between the highly skewed splayed girders, bent connection plates (Figure 20 and Figure 21) were used.

Figure 20: Bent connection plate detail

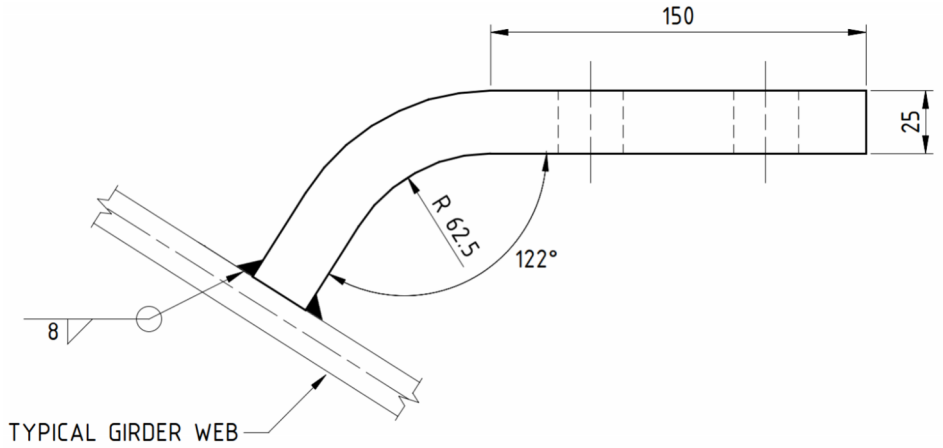
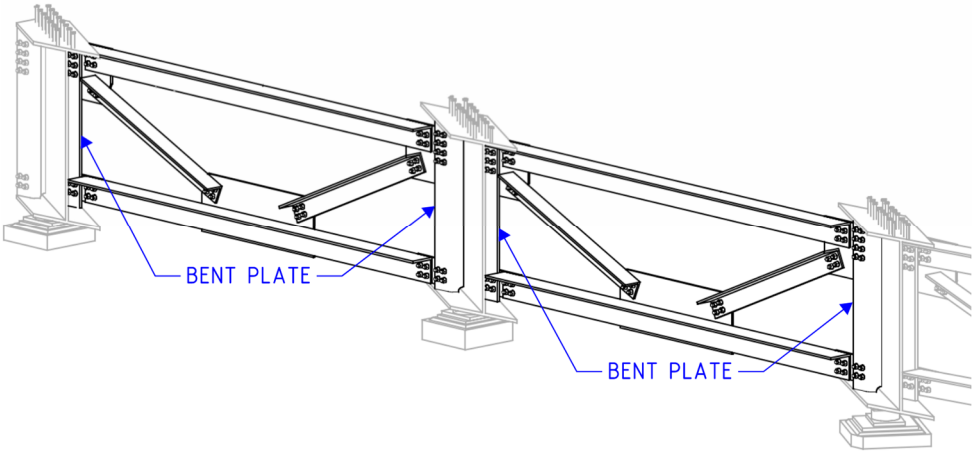
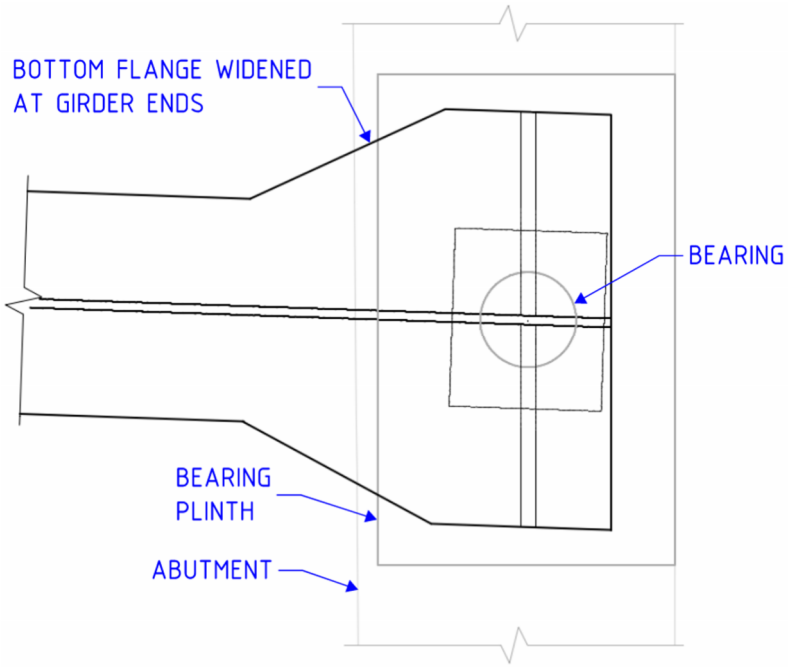


Figure 21: Isometric view of splayed girder end bracing



Due to spatial constraints at the abutment sill beams preventing hydraulic jacks from being placed in front of the bearings, for the main longitudinal girders SG1 and SG2, the bottom flanges were widened at the ends to allow a jack to be placed either side of the bearing (Figure 22). For the splayed girders SG3 to SG6, due to the skewed geometry, there was sufficient space on the Abutment A sill beam for jacks to be placed in front of the bearings. During construction, the girders were initially supported on hydraulic jacks placed in these positions prior to the girders being transferred onto the permanent spherical bearings. If jacking is required for future maintenance works, such as bearing replacement, hydraulic jacks can also be placed in these positions.

Figure 22: Girder bottom flange widening detail



5. Lesson learnt and recommendations

The key lessons learnt from the design and construction of Mount Street and Falcon Street Bridge widening are summarised below.

- When designing the traffic staging lanes to provide sufficient clearance to the deck closure strip, the load distribution to the existing girders will be impacted. This may temporarily negatively impact the existing girders. As such, conducting a loading rating assessment that includes the interim construction stage is crucial as this could be the critical case for the existing girders. Early communication with authorities is essential to ensure any temporary drop of load rating factor is acceptable.
- The new edge girders can be designed to be stiffer than the existing girders, particularly in steel girder bridges where plate thicknesses can be increased. The new stiffer girders will attract more loads, thus potentially improving the load rating of the existing girder(s).
- Significant spatial constraints around the interface and bearing shelf often poses big challenges. Accurate key at key interface locations should be sought after to ensure buildability and maintainability of the structure.
- With the final configuration of the widened bridge, it is important to acknowledge that the load paths may be impacted. Detailed analysis should be undertaken to fully understand its impact and implement design solutions accordingly. Solutions such as lateral restraint systems, introducing deck joints, and calibrating the stiffness of new elements may be adopted.
- With a widened deck, irregularly shaped deck, and / or adjoining ramp deck, the lateral actions and forces transfer to the existing bearing could be negative impacted. Positive lateral restraint systems may need to be considered to maintain mitigate any additional load transfer to the existing bearings.
- The method of integral deck connection is a key design element. To ensure the integrity of the connection, methods such as hydro-demolition is preferred where practical to allow the existing reinforcement bars to be exposed and retained without damaging them.

6. Conclusion

The design and construction of bridge widenings is uniquely challenging, as demonstrated in the Falcon Street and Mount Street Bridge examples from the WFU project. This paper discussed key aspects such as pier and abutment widening, deck connection method, and bearing articulation load distribution effects during construction. Design solutions and construction methods from the bridge examples including the use of deck closure strip pours, use of precast concrete deck panels, and customised steelwork, were crucial in addressing the challenges posed by irregular deck shapes and spatial constraints.

The lessons learned from the WFU project highlight the importance of thorough assessments, proactive communication with authorities, designing for changes in load distribution, and controlling the stiffness of new girders. By addressing these factors, bridge widenings can be executed successfully, ensuring that the existing and new elements of the widened bridge function cohesively while meeting project requirements and StaAndards for safety, durability, and maintenance.

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The opinions and conclusions presented in this paper are those of the authors and do not necessarily reflect the views of the authors' respective organisations.

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Challenging