WEATHERING STEEL RAILWAY BRIDGES IN NEW ZEALAND

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SUMMARY

This paper outlines the main design features of four all steel ballasted through plate girder (BTPG) railway bridges constructed in New Zealand during 2012. These design features were adopted from current Northern Hemisphere railway bridge design practice.

The following objectives were set as bridge span design criteria for these bridges:-

- Ability to be changed over online swiftly (<12 hours);
- To have a ballast deck;
- Suitable for sites with difficult terrain and access;
- Shallow superstructure depths to provide maximised floodway freeboard or roadway height clearances;
- Capable of long spanning to eliminate clearance width constraints;
- Suitable for standardised fabrication and mass production;
- Provide a durable and economic whole of life solution.

The main design features used in these bridge spans are:-

- Weathering steel superstructure material;
- Elastomer waterproofing membrane;
- Adapted North American ballasted through plate girder (BTPG) configuration.

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Introduction

In 2012 KiwiRail replaced four railway bridges in the Counties Manakau region of New Zealand. All these bridges featured (i) all weathering steel superstructure, (ii) cold liquid-applied elastomeric waterproofing deck membrane and (iii) the configuration inspired from the popular North American designed Ballasted Through Plate Girder (BTPG). The design of these bridges can be considered to be innovative as it was the first time any of these design features had been used in the New Zealand railway industry and for the most part within New Zealand. New Zealand had only one other weathering steel bridge, namely the Mercer SH1 Off Ramp built in 2007. Moreover these bridges have given KiwiRail another bridging option allowing them to tackle the considerable challenges that come with an aging bridge stock in awkward terrain, limited funding, and ever increasing rail traffic.

Firstly a brief overview of the New Zealand railway bridge environment is outlined, followed by more specific analysis of the bridge design issues pertinent to renewal of the 4 bridges that are the subject of this paper. The design features of these bridges are then described followed by comments on constructability issues. Some future improvements are discussed. A summary of the KiwiRail considerations made as the asset owner is then presented as these bridges prompted robust discussion and a deviation from the status quo. The paper is concluded by outlining the successful outcomes generated by these bridges.

1. New Zealand Railway Bridge Context

Kiwirail is the State Owned Enterprise (SOE) responsible for operating and maintaining New Zealand's railway. With regard to infrastructure KiwiRail is charged with maintaining about 4000km of track including approximately 1700 bridges. Seven hundred of those bridges consist of riveted steel plate girders (SPGs) on Australian hardwood timber piers (typically 3 or 4 piles supporting a timber cap). SPGs are 2 riveted ɪ shaped beam leafs with cross bracing between them. These leafs consist of a web plate and riveted angles to form top and bottom flanges. These spans are typically 20' (6.1m) to 50' (15.2m) long. The sleepers (ties) are fitted directly to the top flanges of the beam leafs. The average age of the timber pier bridges is about 80 years, with some over 100 years old. These bridges are rapidly approaching the end of their reliable service life and require large amounts of maintenance to keep them reliable and in service. It is this type of bridge that is regularly being renewed by KiwiRail. See Figure 1 below.

Figure 1: A typical KiwiRail railway bridge subject to high levels of maintenance and inevitable replacement. These bridges feature Steel Plate Girder (SPG) spans and hardwood timber piers often exceeding 80 years of age.

In addition to the large stock of hardwood timber pier bridges there has been increased customer focus by KiwiRail to match increased demand for rail freight. In particular freight volumes between Auckland and Christchurch, and Auckland and Tauranga have increased in recent years. As a consequence more freight trains are using these timber pier bridges allowing only limited opportunities for their planned replacement due to the single line nature of the KiwiRail network. Freight demands further restrict the duration of planned closures of the railway. That is both the opportunity and the duration for planned bridge replacements have been reduced with corresponding increase of rail freight traffic.

Alternatives to full bridge replacement such as selected pier or span replacement are considered but these are considered to be a life extension measure where the full benefits of a new bridge are not gained until all piers and spans are replaced. It is also noted that these existing bridges were designed and constructed several generations ago when load demands were lighter (14 tonne axles) and bridge building equipment such as piling rigs and cranes had lower capacity and were scarce when compared to present day design loading (25 tonne axles) and equipment. In other words efficient and economic pier/span configurations of 80 years ago are often not efficient today.

2. New Railway Bridge Project Scope Fundamentals

While there are many factors to consider in order to develop a range of viable schemes for a railway bridge renewal there is a smaller number of key decision points that essentially define the scope of a railway bridge renewal project and the methods employed for construction. These more dominant criteria are:

2.1 Track alignment: Online versus Offline

- Online bridge renewals maintain the existing horizontal alignment to the extent that the new bridge and its construction activities will disrupt train services during the construction phase.
- Offline bridge renewals are on a new track alignment sufficient distance away from the existing track alignment so as to significantly reduce disruption to current train services.
- The perfect railway alignment is straight and level. Deviations from these are considered compromised and therefore horizontal radii are kept as large as possible and grades kept as shallow as possible when the terrain is uneven as it often is in New Zealand. As a consequence offline renewal can considerably increase scope and cost of a bridge renewal project by the addition of newly constructed embankment as well as a new bridge.
- Online bridge renewals have no or little new embankment work associated with them but these projects are constrained by the planned line closure duration.

2.2 Deck Type: Direct Fastened versus Ballast Deck

- Direct fastened (or open deck) bridges have hardwood sleepers directly fastened to the top of the SPGs or to the floor system of Through Plate Girders (TPGs) or pre-stressed concrete spans. Direct fastened bridges are often the least costly deck system and free draining but the train live loads transfer more dynamic effects into the bridge than when compared to the ballast decks. The maintenance of the timber sleepers is very expensive and very time consuming.
- Ballast deck (or closed deck) bridges have the sleepers bedded into compacted granular rock ballast for drainage and track stability. Ballasted steel plate and concrete slab deck bridges are common in new railway construction in the Northern Hemisphere. However the 4 railway bridges under examination in this paper are the first steel plate ballast deck bridges in New Zealand as concrete slab decks have been used exclusively for ballast decks in New Zealand previously.
- While ballasted decks are more costly than direct fastening decks (because they carry heavier loads and contain more structural material) they require less maintenance both in terms of track and bridge. This is because the ballast absorbs and distributes the dynamic effects of the train live load in a less severe fashion when compared to direct fastened bridges. Ballast deck bridges are often used on lines with high traffic volumes to minimise future disruption due to maintenance or when the track alignment is curved. Also, ballasted decks can more easily accommodate small changes in track alignment (both vertical and horizontal) over time brought about by curve easing and changes in rail gradients.

2.3 Superstructure Depth: Shallow versus Deep

- Superstructure depth is measured vertically between top of rail level and the bridge soffit. The constraints on superstructure depth are from both the top and the bottom. Keeping track grades as shallow as possible and restricting track lifts to sections only where a lift would improve vertical alignment constrains the top of superstructure depth. Flood freeboard requirements (bridge over water situations) and headroom clearances requirements (bridge over road situations) constrain the bottom of superstructure depth.

- Moderately shallow superstructure depths can be achieved with direct fastened spans because no ballast is required. However with the SPG depth making up part of the superstructure depth; as the leafs are directly under the sleepers, the superstructure depth available dictates the maximum span achievable by using economic span-to-depth ratios (typically 10 to 16). This in turn affects the pier locations which are often subject to other site constraints. Through plate girders (TPGs) have a transverse spanning floor system; the depth of which dictates the superstructure depth. The floor system spans transversely between deeper side main girders to achieve longer spans for a constant superstructure depth. Therefore span length is independent of superstructure depth for TPGs. The TPG floor system increases the bridge cost significantly (steel weight increases over SPG's alternatives) while the limitations of direct fastening are retained.

2.4 Span Material: Pre-stressed Concrete versus Steel

- Traditionally in New Zealand all ballast deck bridge spans have been reinforced or pre-stressed concrete decks with a number of different configurations employed depending on track alignment, line closure duration and superstructure depth requirements. Direct fastened SPG's and TPG's were made from wrought iron up until the early 1900's and then from mild carbon steel after that. Carbon steel is still used today with yield strengths improving from less than 200MPa to 355MPa over the last century however it requires an applied protective coating at time of fabrication and 2 to 3 re-applications during its 100 year design life.

3. Four Railway Bridges

The four bridges replaced have KiwiRail titles of bridges 299, 300, 312 and 332 on the North Island Main Trunk (NIMT) between Auckland and Hamilton. This is the busiest section of the New Zealand railway network. Bridges 299 and 300 NIMT are located at Kellyville (between Mercer and Pokeno) crossing the Mangatawhiri River. These bridges are essentially side by side but at a skewed alignment to each other for one way traffic on each bridge. They are both identical to each other as 36m single span BTPG's carrying a single track. See Figure 2 below. Bridge 312 NIMT is located in Pukekohe adjacent to the southern end of Pukekohe Raceway. It consists of two 14m BTPGs side by side on common abutment piers. Each span carries a single track. See Figure 3 below. Bridge 332 NIMT is located at Papakura in southern Auckland. It consists of a single 17m BTPG carrying twin tracks side by side. All bridges are over waterways. See Figure 4 below.

Figure 2: Br 300 (left) and Br 299 (right) NIMT over the Mangatawhiri River near Kellyville, New Zealand. Each BTPG span is 36m long and weighs 150 tonnes.

Figure 3: Br 312 NIMT featuring two single track spans each 14m long and weighing 30 tonnes. The track centres are 5m apart.

Figure 4: Br 332 NIMT featuring a twin track span 17m long and weighing 95 tonnes. The track centres are 4m apart.

In terms of the key decision points outlined in Section 2 the following apply to all four bridges. The reasoning behind the above key design features is explored in the following sections.

- All were online renewals to minimise track embankment work and project costs.
- All were ballast deck for ease of track maintenance and reduced maintenance costs.
- All were shallow superstructure depth as only minimal track raise was achievable and to maximise available freeboard in flood conditions.
- All bridge spans are constructed from 355MPa grade weathering steel on the basis that:
  a) Shallow superstructure depth ballast deck bridges based on proven North American BTPG designs could be developed and value engineered with the contractor and the steel fabricator;
  b) Calculated corrosion rates were less than 1.5mm per surface per 100 years;
  c) Correct detailing was implemented to reduce debris collection details and therefore maximise surface drying to ensure minimal long-term maintenance.

The use of weathering steel (WS) makes these bridges the second to fifth WS bridges in New Zealand; the Mercer off ramp being the only WS precedent in New Zealand. Stemming from the fact that all bridges were online renewals on one of the busiest sections of the KiwiRail network the single most important design criteria was being able to changeover the bridges in less than a 12 hour planned closure.

4. KiwiRail's Vision: Bridge Standardisation

With the above project scope defined for these 4 bridge sites KiwiRail was also conscious of their many other timber pier bridges that would require renewing in the future. There was a desire to replicate the standardised approach to bridge construction that was present from 1900 to 1940 when SPGs on hardwood timber piers was the default solution. This modern approach would bring about the proof-of-concept for standardised railway bridging that not only dealt with:

- Online renewal to minimise the cost of embankment work;
- Ballast deck to ease future mechanised track maintenance;
- Shallow superstructure depth to deal with flood freeboard/road height clearances;
- Lower maintenance costs for bridges and;
- Speedy changeovers to minimise disruption to train services.

But also could cope with sites where:

- Limited site access/lay-down for bridge construction equipment is available;
- The constraints and characteristics of the site are such that long spans (>15m) are required.

While improving:

- Quality by maximising offsite fabrication and minimising site work to little more than the piles;
- Economy through economic span configurations so that total bridge cost can be optimised.

A standardised span concept was desired to suit mass-customisation manufacturing techniques that could cope with wide ranging site conditions economically.

5. Selection of Bridge Material and Type

The selection of weathering steel BTPG was based on the limitations of incumbent precast concrete ballast deck solution and the desire to achieve a standardised bridge solution to suit a wide variety of site conditions. Based on previous experience the shortest realistic changeover duration of a concrete ballast deck was 18 hours either by lifting or launching techniques in ideal site conditions.

Concrete ballast decks are better suited to offline construction. In terms of superstructure depths 1125mm to 1275mm was achieved with these 4 WS bridges. This compares to 1100mm to 1600mm for various suitable configurations of pre-stressed concrete bridges. Therefore superstructure depth was a factor but less significant than changeover duration.

The economic length of concrete ballast deck lengths is 12m to 16m. Longer spans up to 20m can be achieved while maintaining superstructure depths similar to that of the shorter spans but become restricted to transverse launching techniques because of their heavy lifting weight in an online renewal situation (e.g. a 20m concrete ballast deck weighs 180 tonnes compared to a 20m BTPG weighing 60 tonnes). All 3 sites under consideration required a single span solution to achieve the 12 hour planned changeover duration. The bridge sites at Kellyville required a 36m long bridge to meet hydraulic requirements. A single 36m span in concrete was neither practical nor economic at Kellyville. Concrete ballast deck solutions using multiple spans were feasible at the sites under consideration if longer 24 hour plus changeover durations were permitted.

Coupled with these limitations for the concrete ballast decks there was a growing recognition from modern publications, contractor feedback and consultation with railway authorities in the Northern Hemisphere that BTPGs were more economic in a developed world context like New Zealand. It was noted that steel deck BTPG's are of common use in North America while composite ballast deck BTPG's were of common use in Europe.

This led to an investigation into steel plate ballast deck bridges of North America. During this investigation weathering steel was suggested in lieu of painted carbon steel as this had become the bridge span material of choice for a number of North American private railroad companies because of commercial imperatives.

It was a necessary prerequisite to find a suitable waterproofing membrane to protect the steel deck of the BTPG from the rigors of near continual wetness and abrasive grinding ballast. British Rail in conjunction with a UK waterproofing company developed in the 1970s a cold liquid-applied elastomeric membrane precisely for this purpose. This type of membrane has since been approved by a large number of Rail Authorities around the world.

From the outset of this project KiwiRail had the foresight to allow a value engineering phase in this project whereby the representatives from the Kiwirail, the designers (Novare Design Ltd), and the selected contractor (Smithbridge Ltd) could work to together and refine the initial bridge concept. This resulted in an elegant solution albeit one with room for future improvement.

6. Weathering Steel

Weathering steels are high strength, low alloy steels that can provide corrosion protection without additional coating. Increase in alloying elements, primarily copper, provides an arresting mechanism to atmospheric corrosion in the material itself. This resistance is due to the fact that this steel will develop a durable, tightly adherent protective surface patina comprised of corrosion by-products that act as a skin to protect the steel substrate. Cycles of wetting and drying allow the patina to form. If WS is continuously damp or wet, its protective patina will not form. Surface corrosion loss of the order of 0.1mm can be expected before the patina sets up, but this is negligible to the structural performance. In terms of making allowance of a 100 year design life the New Zealand Steel Structures Standard (NZS3404.1:2009) provides a codified approach for determining site specific corrositivity. This was used to determine the surface specific corrosion categories at the 3 sites. The ISO 9223:2012 was used to determine the equivalent international corrosively category and then ISO 9224:2012 used to determine the corrosion loss based on the chemical composition of the WS. The 100 year design life corrosion loss of WS was determined to be less than 1mm corrosion loss for 100 years.

Given New Zealand's temperate climate, about 1.2m of annual rainfall at these sites, and windy nature then the corrosion loss of WS is expected to be much less than the design value of 1mm loss per exposed surface. A 6 yearly monitoring programme has been established to measure the parent metal thickness in the same precise positions on the bridges over the first 18 years of life in order to affirm the patina formation within the first 6 years and absence of corrosion loss over the subsequent 12 years.

The benefits to KiwiRail using WS are:-

- Initial cost savings of at least 5% over carbon steel with a thermally sprayed zinc coating (this cost saving is expected to grow as WS properties become inherent in higher performance 'bridge' steels being produced offshore begin to dominate the bridge fabrication market);
- Less whole-of-life maintenance and access requirements over coated structures;
- Reduced fabrication time if plate is in stock because no coating is required;
- Reduced maintenance costs as bridge remains in service and does not need a re-application of an applied coating;
- No site containment of blasted protective coating is required and less maintenance means greater safety for the structures staff involved with bridge maintenance in the rail corridor.

Fatigue is an important consideration in railway bridge design because of the larger live to dead load ratios and the greater transfer of dynamic effects into the structure when compared to the road bridging. Fatigue in WS is not of any more concern than with other carbon steel. Although the corrosion pits on a WS surface would lead to lower fatigue resistance in elements that are unwelded and free from holes; stress concentrations formed by connections inherent in welded details invariably govern fatigue life irrespective of WS being used.

The girders and connections were designed to encourage drainage and allow good ventilation. Specific design features include 1200mm spacing of transverse cross beams, intermediate web stiffeners terminated 50mm above top of bottom flange, and 50mm radius copes. Inaccessible or poorly ventilated sides of the pier cap (headstock) adjacent to the concrete abutment were fully enclosed and hermetically sealed to prevent moisture ingress. Weed mat, with overlaying quarry scalpings have been placed under the bridges around the abutments to prevent vegetation growth and to facilitate ventilation under the bridges. After over 1 year of service it is noted that bridges quickly dry after rain due to sun and wind. All bridges are fortunate to have an approximate north to south orientation to allow sun on both main girders and prevailing westerly cross flow breezes.

As part of the design, an inspection and maintenance manual has been developed and produced for these bridges. Considering the fact that WS is new to KiwiRail, the inspection requirements for the first few inspection cycles are very thorough. A KiwiRail Structures Inspector will check and report on the following: accumulation of dirt and debris, leaks, areas of permanent wetness (and their cause), excessive crevice corrosion at bolted connections, nearby vegetation preventing drying by sun or wind. The thickness of the plates will be monitored every 6 years and compared to the 'as-built' thicknesses to ensure that the patina is forming. The patina is expected to be fully formed after 6 years and remain tightly adherent thereafter. As KiwiRail learns more about the actual performance of the WS at the various sites in New Zealand, the inspection and maintenance requirements will be reviewed over time.

7. Elastomeric Waterproofing Membrane

Weathering steel will not form a protective patina when permanently wet. This is the situation at the interface between the underside ballast stones and the top and sides of the steel ballast tray. To protect this steel ballast tray interface from permanent wetness and abrasive grinding from ballast, a robust proven railway tough waterproof membrane was required.

In the selection of cold liquid-applied elastomeric waterproofing membrane the same philosophy that was used with the selection of the weathering steel and North American BTPG was adopted; that is to transfer the proven railway technology from the Northern Hemisphere to New Zealand.

The waterproofing system adopted is an elastomeric cold spray system based on methyl methacrylate resin. It comprises of a steel primer and two separately applied coats of membrane each of 1.5mm dry film thickness in contrasting colours. The primer is an anti-corrosive zinc phosphate that is applied within 3 hours of a Sa 2½ abrasive blasting to a ballast tray formed by deck and two kerb plates. See Figure 5 below.

Figure 5: The first layer (1.5mm d.f.t) being sprayed over a primed section of ballast tray. The ballast tray sections were later assembled on site and the site welds were locally abrasive ballasted, primed and protected by 3mm d.f.t elastomeric membrane.

The application of the elastomeric membrane is only permitted by the UK manufacturers approved applicators to ensure rigorous on-site QA procedures are followed without exception. These QA procedures include the confirmation of suitable application temperature and dew points, as well as adhesion tests on the primer and high voltage holiday detection on the finished membrane. The results were sent to the manufacturer and to KiwiRail for their records. The cold liquid-applied elastomeric membrane remains tightly adhered to the ballast tray. Should the membrane ever be perforated, any corrosion will be confined to the steel below perforation because of the tight adhesion. An additional protective heavy filter cloth was laid over the water proof membrane before the ballast filled the tray as an extra precaution against perforations resulting from filling the ballast tray from tip trucks and spreading ballast with small excavators operating on as little as 150mm thick ballast layer. KiwiRail requires a 300mm thick ballast layer to underside of sleeper.

Figure 6: Two adjacent ballast tray sections being site welded. The workshop applied elastomeric membrane coating stops short of the weld. After site welding is complete the weld is abrasive blasted, re primed and coated with a double layer of the elastomer which seamlessly adheres to the shop applied membrane.

8. Ballasted Through Plate Girder

The bridge span design selected was based upon the North American Ballasted Through Plate Girder or BTPG. This span type was in widespread modern use in North America and was selected to meet the following KiwiRail project objectives:

- High strength to weight ratio spans to allow:
  - Swift changeovers of just one single span that is light enough to either be lifted or launched into position during line closures of less than 12 hours;
  - Single long spanning bridge solution that be easily transported to, lifted and assembled on site with HSFG bolted connections;
  - Longer span lengths in order to equate the cost of superstructure to the cost of substructure to produce an economic bridge solutions and;
  - Reduced vertical and lateral loading demands on the piles for short spans.
- Ballast deck for ease of long term track maintenance and reduced bridge maintenance.
- Shallow superstructure depth to maximise flood freeboard without unnecessarily lifting the track and jeopardising the current vertical alignment.

- Weathering steel superstructures and pier caps for:
  - Low long term maintenance bridge solution;
  - Easily condition monitored and;
  - Provides a bridge span that is relatively easily repaired and strengthened if damaged.
- Built in quality construction with maximising controlled workshop fabrication with qualified iron-workers while reducing weather and train disrupting dependent site work.
- Design verification to the American Railway Engineering and Maintenance-of-Way Association (AREMA) guidelines which is a general KiwiRail requirement.

The overall bridge is 'U shaped' in cross section. Knee braces at each end of the transverse cross beams, forming a ladder deck in the plan view, also double as vertical web stiffeners for the longitudinal main girders. The knee braces provide a series of discrete partial lateral restraints to and along the top compression flange of the main side girders. This is technically known as U frame action and reduces the effective length of the top compression flange. The effective length is determined by a 'Beam on an Elastic Foundation' analysis outline in BS5400: Part 3: 2000.

The 20mm thick deck plate was welded to be composite with the cross beams by longitudinal fillet welds between the top flange outstand tips and the underside of the deck plate. There was no transverse weld between the top flange and deck plate to eliminate a possible stress raiser. There are no longitudinal stiffeners to the underside of the deck nor diaphragms between adjacent cross beams.

The cross beam to main girder connection detail via formed knee braces at the cross beam ends bolted through the main girder webs were developed after considering typical North American and UK practices. Continuing the cross beam top flange in a smooth radius to form the inner flange of the knee brace was selected to reduce stress raisers as the cross beams are loaded by every axle and therefore subjected to an extremely high number of stress cycles. The outer knee brace flange forms an end plate bolted to the main girder web, while the knee brace web doubles as main girder web transverse stiffener. The cross beams are at 1200mm centres. See Figure 8 below.

Figure 7: Inverted view of the cross beams welded to the deck during fabrication. The kerb plates are bolted to the deck plate and to the cross beam up stands.

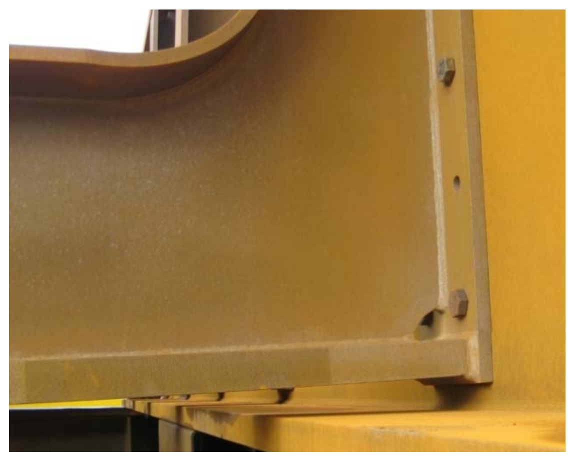

Figure 8: Close up of the cross beam and up stand connection during trial assembly. Note the 50mm clearances between the underside of the cross bottom flange and the top of the main girder bottom flange to prevent debris accumulation and to promote airflow to prevent permanent wetness.

Based on previous experience an economic span to depth ratio for the main girders was considered to be 13. Any lesser ratio would result in deep main girder unnecessarily protruding above rail level and becoming unwieldy for road transport. Conversely extremely shallow girders would result in very thick and wide flanges with resulting weight and fabrication inefficiencies. As it was the 36m spans required 100mm thick flanges. While not permitted in AREMA, the European practice of using doubler plates was used to form long flanges from two 50mm thick plate. This resulted in easier handling, less pre-heating requirements and the ability to curtail the doubler to achieve optimum structural efficiency. This resulted in a trade-off being given to the termination of the top flange (compression) doubler plate. The BS5400: Part 10:1980 on fatigue detailing provided guidance on the detail adopted to prevent fatigue due to longitudinal shear including tapering the width and rounding and tapering the end to make the termination gradual. See Figure 9 below. The bottom flange doubler continued for entire span length.

Figure 9: Curtailed top flange doubler plate detail in recognition of reducing moments away from mid span.

9. Constructability

The constructability or method of construction employed with these 4 bridges was all focused on achieving bridge changeover in less than 12 hours, even though longer track closures were made available, although not in the initial planning stages of this project. Developing swift bridge changeover was a key objective in the proof-of-concept approach adopted by KiwiRail for this bridge project.

Constructability is very much dependent on the contractor selected. Each contractor has their own set of past experiences, preferences, available equipment and personnel. These factors dictate the construction method as much as the site constraints or the bridge parameters do.

Railway bridge renewal constructability is invariably driven by duration of line closure. Due to the high volumes on traffic on the NIMT, line closures less than 12 hours could be made available on almost any weekend with sufficient planning and advanced notice. Longer closures are generally only available at Easter and between Christmas and New Year.

During the design process the overarching philosophy that was adopted to design these bridges was to minimise changeover duration. For this reason the design and designer proposed construction methodology was such that each bridge would maximise the work that could be done prior to changeover, and enable work to be done during changeover in 3 adjacent work areas simultaneously. That is at each of two abutments and the span installation. These three work areas would be available as soon as the existing bridge was removed on changeover day. Before the existing bridges could be removed the rail screws, running rails and guard rails were removed by KiwiRail track gangs. The rails were dragged off to one end of the bridges. With deck rails removed the contractor could lift out the existing SPG spans with sleepers remaining attached. This operation was greatly advanced by 'skeletonising' (removing all but the minimum required track fastenings) the bridge to the minimum for the safe operation of trains with temporary speed restrictions in the days leading up to changeover. The piles and wing-walls of the abutments were positioned at sufficient offset from the track centre line to enable them to be fully constructed prior to changeover. The head-walls that horizontally span between the abutment piles were precast and designed to be quickly lifted into place once the existing tracks were removed and the approach behind the headwalls was fully excavated.
While the bridge abutment design dictated the way a contractor would undertake this work, it was the span installation operation that was dictated by factors like contractor preferences, past experience and available equipment working within the site constraints.
Site conditions such as the hard-standing area and steepness of the surrounding terrain, the presence of overhead and under-ground services, site access and lay-down areas affect equipment that can be employed during a changeover. Three of the four bridge sites had sufficient space on site to allow

sufficiently heavy lift mobile cranes to be used to lift in the bridge spans. One of the bridge sites was sufficiently constrained and the twin track span sufficiently heavy (100 tonnes) to cause the contractor opt for the transverse launched approach to span installation. This allowed opportunity to evaluate two different methods of steel BTPG span installation.

Many of the future bridges to be renewed on the NIMT are either in the electrified section or have very steep surrounding terrain. While the transverse launching techniques have been successfully used for concrete ballast installation there was benefit in determining how the technology could be applied for a first time to a structure with steel pier caps.

The reason why steel pier caps were utilised in these bridges was that in many situations concrete piers would be required behind existing abutments and cannot be easily constructed in-situ and under the track. For this reason steel pier caps were designed for these four bridges that weighed only 5 tonne compared to an equivalent 25 tonne precast concrete pier cap. The crane demand to lift in a steel cap is very modest and relatively swift.

The final factor in constructability is equipment. The distinct advantage of steel spans over concrete is its relative light weight nature. The proliferation of large crawler (max. 600 tonne) and mobile (max. 550 tonne) cranes in New Zealand over the last decade is acknowledged. Ten years ago the largest crane available was 200 tonne and if constructed then none of these 4 bridges could have been lifted in. The use of relatively light steel spans becomes advantageous and speedy with the proliferation of large cranes.

10. Future Improvements

The three main innovations brought to the New Zealand railway industry by this project; namely the use of: weathering steel, the cold liquid-applied elastomeric waterproofing membrane and the BTPG concept prompted much discussion within the local bridge industry. This often caused a first principles re-examination of the concept, materials and details employed as there was no local precedent to follow and doubts and scepticisms were more easily raised than rational solutions developed. While it is acknowledged that these bridges are probably the first and most difficult step in a journey to building world class railway bridges in New Zealand it is still important that the next step builds on the lessons gathered from this project.

In summary these lessons are:

- The need to better understand the limitations of weathering steel and its actual tolerable proximity to the coast or body of sea water. In this regard overseas case studies of weathering steel close to estuaries and coasts with prevailing land to sea winds would allow a greater proliferation of weathering steel bridges in New Zealand. There is a large environmental difference between the tidal coast and 10km inland and yet they are often considered equally corrosive for weathering steel.
- The need to have documented case studies showing the condition of the particular cold liquid-applied elastomeric membrane under a ballast tray after say 40 years since its development. Suffice to say the manufacturer of the particular elastomeric membrane used has gained approval from railway authorities around the world for the use of its membrane, conducted rigorous tensile, abrasion, and accelerated aging testing, implemented strict QA/QC procedures, and developed a large customer/bridge base using it to give confidence to first time customers.
- Design refinement of the BTPG design to: gain greater structural efficiency, reduce large welds, reduce bolting, facilitate mass manufacture and span standardisation, ease transportation and simplify site assembly to reduce overall costs and fully utilise the strength to weight ratio of steel. This is likely to come about in the near future.
- Necessary prerequisites that cannot be understated for a successful BTPG bridge project are competent main contractors and quality focused steel fabricators. This project was fortunate to have these. High quality is well planned and does not happen by accident.
- For railway authorities fortunate to have pairs of heavy lift rail cranes, construction methods based around the following steps for online railway bridge renewal are thought to have merit because it utilises the existing linear nature of railways and reduces the significance of awkward site access and terrain, and the need

to mobilise heavy lift cranes, and reduces temporary staging works for both mobile/crawler cranes and the new spans. For KiwiRail there is merit in developing simpler means of new span installation given the propensity of awkward sites making large mobile/crawler crane access difficult and costly. The proposed construction methodology is as follows:

1. Conventionally construct new piers and abutments largely under the existing bridge with piling work outside the structural clearance gauge.
2. Transport to, fully assemble, and waterproof the BTPGs at a convenient siding within rail crane reach of the track.
3. Fasten temporary span supporting structure to one side of the new permanent piers.
4. With a pair of rail cranes (one at each end for long heavy spans) lift, transport, and position the new BTPG spans onto the temporary span supporting structures.
5. Plan and document the changeover thoroughly.
6. During the changeover remove the existing spans and cut down the existing piers as required. Using rail cranes lift across the new BTPG spans to the new piers with the rail cranes either located on the remaining existing bridge (may require temporary strengthening) or the approaches.
7. Fill the ballast trays and lay the tracks.

- The need to strain gauge and implement structural health monitoring systems on these new bridges in order to determine more accurately and quantify the effect of impact dynamics. Such validation information could lead to refinement of the BTPG floor systems (e.g. deck plate and cross beams).

11. KiwiRail Considerations

Wrought iron and carbon steel have been for a long time the preferred material for railway bridges in New Zealand. Protected by an excellent protective system based on lead paint these bridges have performed well over the last 80 to 100 years. However in recent years KiwiRail has come to realise the difficulty and costs associated with extending the life of painted steel bridges particularly around the need to remove the lead based paint system and apply a new protective coating system. On the other hand it must be emphasised that steel bridges offer distinct construction advantages over concrete bridges for railway bridges in New Zealand which run mostly a single track network through some very awkward geography. This means the option of relatively light, ballasted, shallow, long-spanning, durable decks that BTPG's from WS offer is particularly appealing.

After some detailed analysis both for and against KiwiRail came to the conclusion that the use of WS would deliver value for money even though the true value of these bridges may not be fully realised for another 30 years of service when alternative coated steel bridges are likely to be in need of further protection. While some uncertainties remain about the actual performance and durability of the WS bridges there is sufficient evidence from overseas experience to justify using this material in New Zealand.

The use of the elastomeric waterproofing membrane selected by KiwiRail was on the basis that:

- It was being used for the exact application that it was first developed for by its UK manufacturer and British Rail in the 1970's.
- It had been endorsed by a number of major Northern Hemisphere rail authorities.
- It had undergone a range of durability testing and has a stringent QA/QC regime including trained and approved applicators associated with it.
- It had been used extensively as a primary means of waterproofing decks of a large number of bridges all around the world with no known failures.

The BTPG configuration created robust discussion in an environment where only concrete had been previously used for ballast decks. Intense debate centred on the cross beam to main girder connection. Both what was thought to be common North American and UK practices were considered. To some extent what is believed to be a 'third' way was developed with the cross beams ending in a highly fatigue resistant up stand that doubled as a main girder web stiffener and partial lateral restraint to the main girder top flange to prevent buckling. The detailing was especially cognisant of the need to prevent debris accumulation and patches of permanent wetness on the weathering steel. While this detail appears to be expensive in terms of fabrication and not as easy for site assembly as was originally intended, it is considered durable if not overly cautious.

Conclusion

This project has taken KiwiRail and its designer Novare Design Ltd on a journey of discovery; challenging the status quo in terms of bridge solutions available to replace existing railway bridges online. The characteristics and constraints of the three sites were such that a new concept was required to achieve swift bridge changeover using long shallow spans that can carry a ballasted track. A new KiwiRail bridge design was born inspired from the North American BTPG.

KiwiRail was particularly conscious of the significant costs associated with long term maintenance of painted steel bridges and the limitations of both span length and online changeover time associated with concrete ballast trays. A new bridge solution was sought. Following an extensive research and review process the benefits and potential pitfalls were carefully considered along with the construction costs and life cycle maintenance costs. KiwiRail made an informed decision to proceed with this innovative bridge design. In terms of costs this new design is currently comparable to painted steel bridges but obviously cheaper in the long term and comparable to concrete bridges of the same parameters and site constraints.

KiwiRail have demonstrated visionary leadership in turning the idea of combining weathering steel, cold liquid-applied elastomeric waterproofing membrane and the BTPG into reality for the first time in New Zealand. After over one year of service there have been no technical issues with the bridges and the concept has been further considered and developed for other sites that are closer to bodies of seawater and to replace longer and higher multi-span bridges. In this next phase of development these newly developed spans will be tendered as an alternative to a coated steel BTPG's and to post-tensioned concrete ballast tray spans each in their optimum online replacement configuration. This is expected to give conclusive evidence that the weathering steel BTPG is also the most economic bridge solution.

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