COMPOSITE DOWEL BRIDGES IN WESTERN AUSTRALIA

Puentes mixtos de conectores dentados en Western Australia

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ABSTRACT

The introduction of composite dowels in Central Europe in the last decade has provided an economic alternative to prestressed bridge beams. After successfully completing a pilot bridge project in Australia in 2017, the concept has proven its simplicity which enables local contractors in more rural areas to install bridges without having to rely on the precast industry. Since then, multiple small to medium span bridges have been designed and constructed using the composite dowel technology. The development of a bridge system using mainly precast elements and minor in-situ stiches to create fully integral structures has resulted in a huge reduction in construction time.

RESUMEN

La introducción de los conectores dentados en Europa Central durante la última década ha proporcionado una alternativa económica a las vigas pretensadas. Tras la finalización exitosa de un proyecto piloto de puente en Australia en 2017, el concepto ha demostrado su sencillez, permitiendo a los contratistas locales en áreas rurales instalar puentes sin depender de la industria de prefabricados. Desde entonces, se han diseñado y construido múltiples puentes de pequeña y mediana luz utilizando esta tecnología. El desarrollo de un sistema para tableros que utilice principalmente elementos prefabricados y pequeñas uniones in situ ha reducido significativamente el tiempo de construcción.

KEYWORDS: composite dowel bridges, accelerated bridge construction, precast bridge system.

PALABRAS CLAVE: puente mixto, conectores dentados, construcción acelerada, tablero prefabricado.

1. Introduction

Steel-concrete composite beams no longer require shear studs welded to an upper steel flange to provide a shear connection to a concrete slab. Instead, composite dowels are formed by cutting an intended shape (steel-dowel) into the steel web providing a direct connection between the steel section and reinforced concrete slab or beam. The respective elements' best material behaviour of steel and concrete is maintained. However, the shear connection to create the composite action has become more effective by utilizing modern computer programmed continuous cutting methods. Compared to headed shear studs the higher load capacity and rigidity of the steel dowels adds economic advantages to the constructability and structural benefits to the design. The publication of several design guides and a general building authority approval [1] in Germany has provided the engineering tools to design this shear connector. A European

Technical Specification [2] has been drafted and will most likely be published with the second generation of the Eurocodes. Following the success of a pilot project in 2017 multiple small to medium span bridges have been designed in Western Australia using the composite dowel technology. The first successfully constructed Australian composite dowel girder bridge had some design, manufacturing and construction challenges to be resolved. Since then, construction time could continuously be reduced by increasing the use of precast elements. All bridge elements were modelled in 3D, including the space proofing reinforcement bars to eliminate problems during erections of the precast elements in the stich joint connections. As the composite dowel beams don't require prestressing, they can be cast in simple, cost-effective formwork set-ups (refer Figure 1) by any local contractor which suits the more rural and remote regions on Western Australia.

Figure 1. Simple formwork set-up for 18 m span beams

2. The composite dowel shape

The composite dowels provide a shear transmission between the compound materials concrete and steel. Years of research across Europe resulted in several published design guides [3], [4] and a general building authority approval [2]. The steel dowel geometry 'modified clothoidal dowel' (MCL) has been used for all bridges designed and installed in Australia (refer Figure 2), due to its improved fatigue capacity. The stress concentration factors for the simpler 'puzzle' shaped dowels are higher in all of the available design guides and were found to trigger shorter fatigue lives.

Figure 2. Steel dowels after cutting

3. Steel manufacturing to suit local markets

The European market offers a vast number of rolled-steel beam sections up to 1.1 m deep with flange thicknesses up to 64 mm. Steel mills are set-up to produce castellated beams. Having production lines capable of turning out rolled I-beams cut in half makes it a simple task to program the CNC oxy cutters to run a different cut profile.

Currently, the Australian Steel Industry does not offer deep rolled beams. Beams deeper than 600 mm must be ordered as welded beams, which removes some of the European market's cost effectiveness. Custom-made welded beams are mainly produced by local steel manufacturers who are usually set up with CNC oxy cutters. After some trials, it was found that providing the manufacturers the full length of the exact dowel cut shape as an electronic file was the most efficient route to a satisfactory result. A maximum surface roughness of 12 μm as per [6] (Table 6.5) could be achieved with minimal grinding – required to comply with a minimum 125 detail category as per [5] (Table 13.10.1(B)) and [1].

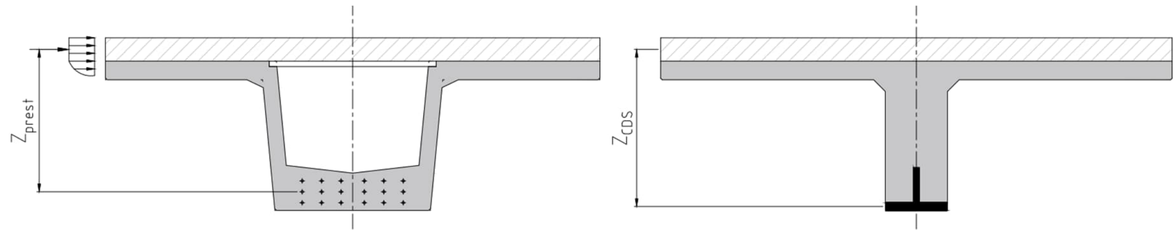

Figure 3. Structural depth of a typical pretensioned beam vs a composite dowel beam

4. Bridge beam cross sections

4.1 T-Beams and double T-beams

A halved structural steel I-section cast in the soffit of T-beams can be regarded as a reinforced concrete section with external reinforcement and has been used for all beams thus far. The major advantage of external reinforced beams, compared with conventional reinforced beams or pre-stressed beams, is the increased lever arm (refer Figure 3).

4.2 Flat slab

For slabs, the correlation to a filler-beam deck can be made. Research on this topic was conducted with an interesting outcome for flat-slab bridge beams [7]. Although only half the steel for cast-in T-steel sections compared to a filler-beam with cast-in I-beams is used, the bending moment capacity at ultimate resistance was just 6.7 per cent lower (a clear plastic deformation is evident).

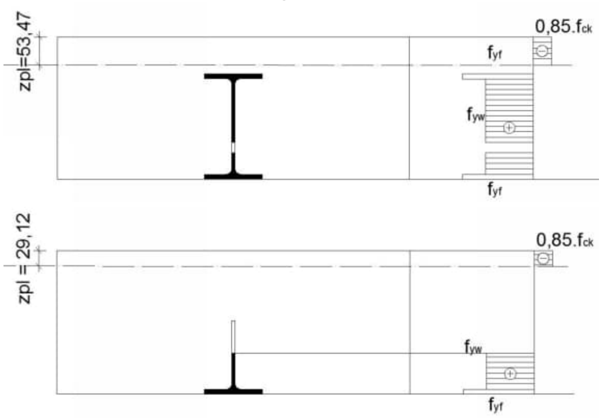

Figure 4. Filler-beam vs halved steel sections at full plastic capacity [7]

However, one of the conclusions in [7] was that "the composite action between steel and concrete in such deck structures remains problematic as the bonding between the two materials is not sufficient". The composite dowel addresses the composite action issue. The benefits of efficient structural steel T-section remain as discussed in [7] and were among the reasons for proposing a flat-slab beam with composite dowels for a slender bridge deck.

5 T-beam installed on bridge 0270A

Several options were considered during the concept design phase to replace an existing timber bridge at a remote site in Western Australia's South West region. The bridge articulation and length were governed by waterway requirements. The site topography prohibited longer-span options with deeper beams, hence shorter span options were used with more piers. Main Roads Western Australia decided to specify a fully integral structure to reduce whole-life costs by reducing maintenance and inspection requirements in this remote location. With a 54.5 m overall length (excluding approach slabs), this is the longest fully integral bridge constructed in Western Australia (WA) to date.

Transporting 15+ m precast beams from the nearest precast yard to site was investigated and found unsuitable due a distance of about 350 km on partially unsealed narrow rural roads. The possibility of constructing pretensioned or posttensioned precast beams adjacent to site was not investigated because of the onerous associated set-up costs for the low number of beams needed.

Figure 5. Bridge 0270A after completion

The decision to construct the first Australian composite dowel bridge was made after a contractor priced several superstructure options and the composite dowel T-beam option (refer Figure 6) returned the lowest cost [8]. On this pilot project, the span-to-depth ratio was conservative with just over 19 for the longer centre span. However, the aim was to test the T-beam's relative basic construction method with the composite dowel T-steel section forming the soffit. This arrangement required minimal upskilling of all trades.

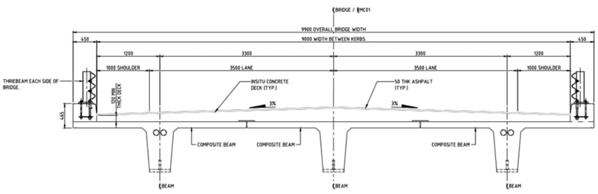

Figure 6 Bridge 0270A cross section

A total of nine T-beams 960 mm deep and 3295 mm wide were precast on site in sets of three at a time. A mobile concrete batching plant was set up on site to supply concrete purely for this project. To achieve the required pre-camber, temporary concrete plinths were used to shim the soffit of the steel-sections. The formwork had the pre-camber built into the top flanges to avoid any visual sag after all the concrete creep finished. Once stripped of the formwork, the beams were stored on site. It should be noted that, if not using elevated temperature curing, storage must be stress-free (e.g., supported at close intervals to suit the pre-camber) for at least 28 days. A mobile crane was used to install the beams onto the cast in-situ abutments and piers. The kerbs were precast with the beams and the steel barrier posts installed before the lifting operation. Temporary timber barriers were installed for safety. The concrete stitches at the piers and the abutments were cast as the next step. Lastly, the in-situ deck was poured.

Successfully completing Australia's first composite dowel bridge (refer Figure 5) demonstrated that after cutting the steel I-section with the dowel shape, it was business as usual for all trades involved. It laid the foundation for developing further bridge beams with this technology.

4. Flat slab elements installed on Bridge 0404A

When Main Roads WA had to replace an old 12.6 m-long, two-span timber bridge on a heavy haulage route, its condition and narrow width

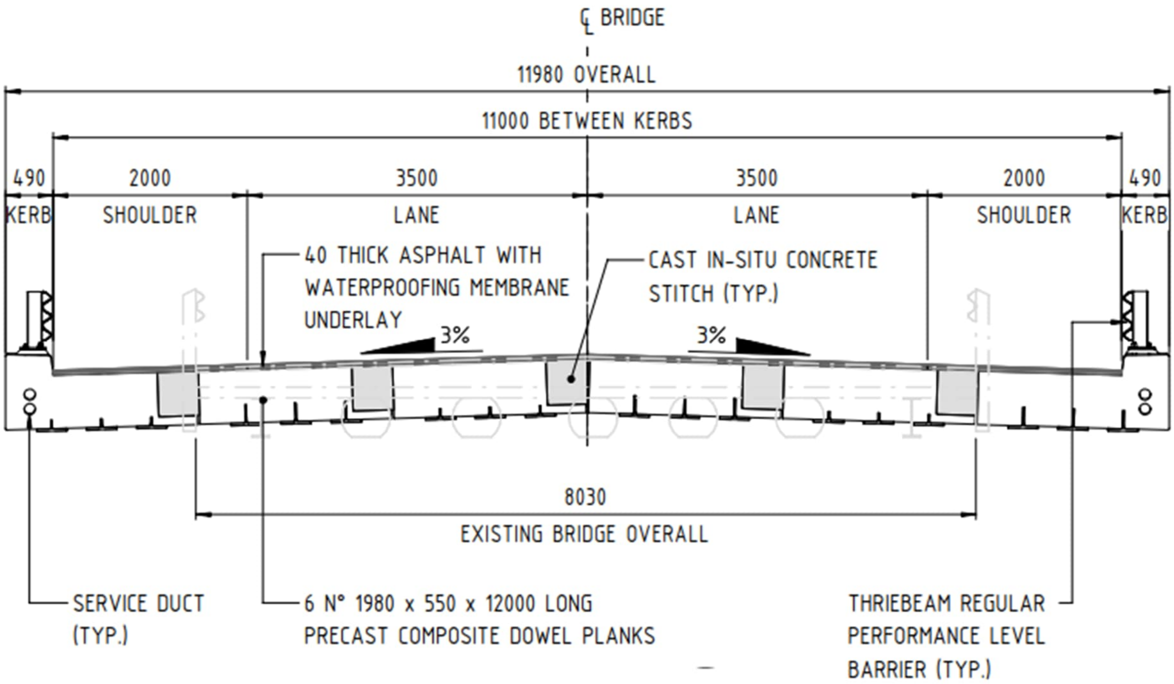

Figure 7. Bridge 0404A cross-section

required reducing the on-site construction time from the usual 6 months to about 2 months. Activities still had to include constructing a local bypass, demolishing the existing bridge, installing the new bridge, road works to accommodate the raised bridge deck levels, and removing the bypass. Usually such a bridge replacement is the sweet spot for the Main Roads plank or reinforced concrete box culverts. Ground conditions (9 m soft soils on granite rock) and likely settlement ruled out installing reinforced concrete box culverts on a reinforced cast in-situ flat slab. The superstructure had to be supported on piles. Galvanised UC steel sections were driven as end bearing piles on the granite rock.

Flood levels to achieve a 100-year (dry) average recurrence interval (ARI) serviceability, dictated the replacement bridge structure's soffit level. This required to raise the road alignment about 700 mm above the existing levels. A slim bridge superstructure needed to be developed that could be installed within shorter time frames than the available standard solutions. The remedy was to design a fully integral bridge, reducing sagging moments at the span centre. However, it seemed a push to use Main Roads WA's plank to install a fully integral bridge within 2 months. Wider precast elements were needed to minimise the number of on-site lifting activities, requiring less in-situ reinforcement concrete installed. To save even more time on site the replacement bridge also required precast abutment elements that could be joined to the deck elements with rigid moment connects to achieve a fully integral bridge. The benefits of the halved steel-rolled sections cast into a flat slab described in [7] were explored in combination with the composite dowel shear transmission to remove the insufficient bonding problem. It was found this could be a solution to achieve a slender deck. To use more available 250 t-rated mobile cranes for the installation of all precast elements a weight limit was set to 45 t. This resulted in detailing a fully integral bridge comprising 6 abutment and wingwall elements and 6 deck elements 1980 mm wide and 550 mm deep for a 12.4 m span (refer Figure 7). The deck is 18 per cent slimmer compared with the Main Roads WA pretensioned deck plank, and achieves a 22.5 span-to-depth ratio for a flat-slab bridge structure. Precast abutment elements had block outs for the steel piles. Moment rigid connection between steel piles and concrete abutments were achieved by filling the block-outs with in-situ concrete. Other in-situ concrete works were limited to stitching the precast abutments to the deck elements, stitching the deck elements, and casting the wingwall kerbs to suit the road levels. The precast abutment elements were joined with wire-rope loop boxes, providing shear and moment capacity transversely to resist surcharge loads from soil and traffic as well as guardrail collision loads. All bridge components are shown in Figure 8.

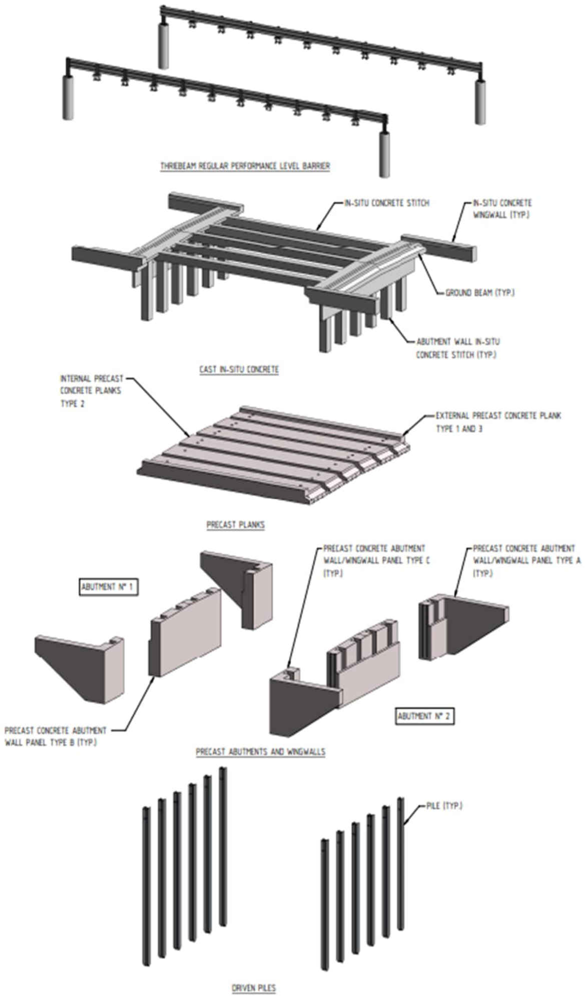

Figure 8. Bridge precast elements and in-situ stitches

Reinforcement from the precast deck elements and abutment elements had to overlap in the joints to form the moment rigid joints between those components. To avoid clashes between the overlapping reinforcement bars, it was essential to model all reinforcement in 3D, and to have a contractor or precast manufacturer who understands the importance of having the reinforcement bar installation tolerances to the called-up dimensions. This was easy for joints between the deck elements as the rolled UC steel sections' cut dowel shape resulted in two perfectly offset halves to place the transverse shear reinforcement (refer Figure 9, Figure 10, Figure 11).

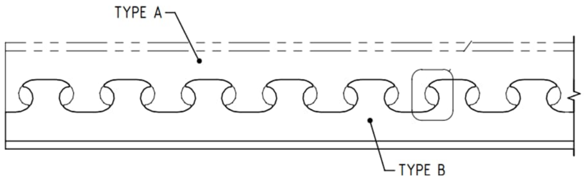

Figure 9. Type A and B dowels after cutting

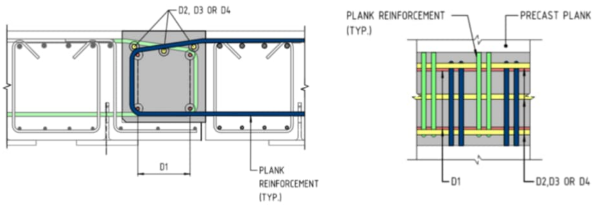

Figure 10. Overlapping transverse reinforcement in section and plan view on the drawings

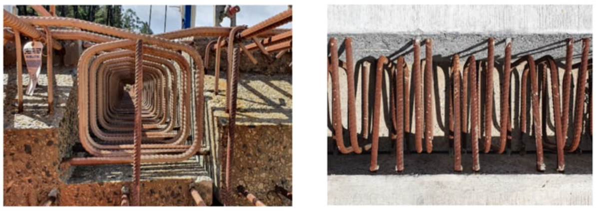

Figure 11. Overlapping transverse reinforcement in section and plan view installed on site

The solution to precast as many elements as possible for Bridge 0404's replacement structure, achieved the objective to replace this bridge within the 2-month timeframe. The bridge opened to traffic just before Christmas 2020. The project demonstrated the benefits of reducing the number of elements while maintaining a weight that a mid-size mobile crane can handle. The 3D reinforcement detailing, and the highly experienced precast manufacture's scheduling, guaranteed the elements' smooth installation. The few reinforcement bars were installed on site without issue and ensured all bending moments are accounted for on this fully integral bridge.

5. Double T-beam installed on Bridge 0235A and 0238A

The replacement structures for Bridges 0235 and 0238 were developed based on the benefits and lessons learned on Bridges 0270A and 0404A. To accelerate construction and reduce the time spent on site, all main elements were detailed as precast elements. The replacement structure for both bridges required a clear 18.0 m span over the waterway to achieve a 100-year (dry) ARI serviceability. Although one of them is on a rural road and the other is on a highway, the local Shire insisted on 2.0 m wide shoulders over the bridge in lieu of a dedicated cycle bridge.

To improve the span-to-depth ratio from 19 (used on Bridge 0270A) to 22.1 for the bridges but keeping the precast element width to comparable 3.2 m, a precast double-T beam with 650 mm depth was designed (refer Figure 12).

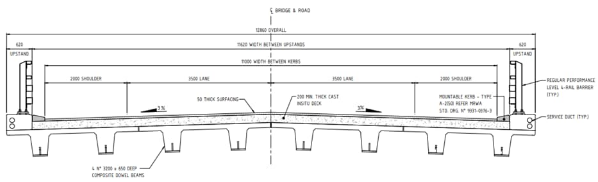

Figure 12. Bridge 0238A cross section

The maximum 50 t weight limit was another limitation for the precast elements, to allow precast manufacturers handling the beams by gantry cranes in their yards. However, when the bridge was tendered for construction, the precast industry's prices had significantly increased due to a spike in Western Australian infrastructure projects. The successful contractor decided to precast the double-T beams themselves and set-up moulds in a farmer's paddock near the bridge site (refer Figure 1). This reduced the superstructure's cost by $300,000.

On the previous bridges the steel elements were corrosion protected using an organic zinc coating system in lieu of hot-dip galvanising in response to the steelwork manufacturer's concern that hot-dip galvanising would warp the steel sections due to the residual stresses from welding and cutting. The double symmetric geometry of the welded I-beams before cutting them in half to produce the steel dowel beams posed less of a concern to the designers. Any locked-in stresses from cutting and welding are symmetric as the beam welding machines simultaneously weld the two web-to-flange fillet welds. On this bridge, Main Roads decided to hot-dip galvanise (refer Figure 13) the steel dowel beam sections to reduce touch-up works on a painting system post installation.

Figure 13. Steel beams with dowels after galvanising

The dowel cutting process resulted in a vertical deformation (sagging) of the steel beams with dowels due to the heat-shrinking effect, but no horizontal deflection was measured. As the steel dowel beams were detailed with the minimum allowable distance from top of the bottom flange to the dowel base, they were flexible enough to flatten out under self weight when continuously supported, as seen in Figure 1. No difference in the vertical nor the horizontal axis was measured after hot-dip galvanising of the steel dowel beams. No warping of the steel sections could be recorded.

Figure 14. Bridge 0235A storage of all precast elements

Manufacturing the individual bridge elements started in December 2021 and at the end of January 2022, bridge beams were installed on the abutments of the first Bridge 0238A. The precast elements for second Bridge 0235A were

Figure 15. Bridge 0235A installed

stored (refer Figure 14) and used a few months later to set a record for a bridge replacement, including 500 m of highway reconstruction.

6. Hybrid bridges

After repeating the slab bridge precast elements on Bridge 0191A and Bridge 0835A Main Roads was looking to implement the system on larger bridges. Especially the very remote regions in the Pilbara and Goldfields-Esperance started to see the benefits of this simple system that can be constructed by local work forces without having to transport prestresses elements from Perth for thousands of kilometres. Transport of the steel elements only is significantly simpler due to their light weight compared to prestressed precast beams. However, the demand for longer spans beams required the designers to improve on the efficiency of the beams. Based on the example of the 'Elblag' Bridge in [9] hybrid bridge beams with 35.2 m and 38.75 m length have been developed and designed for the Western Australian market (refer Figure 16).

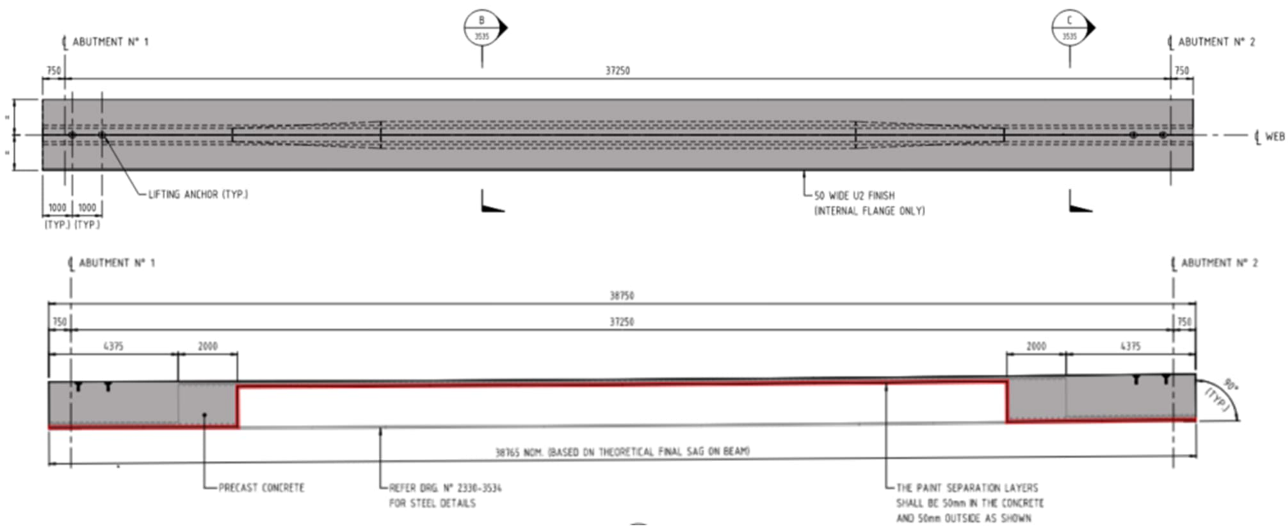

Figure 16. Plan and long section of a hybrid beam for Bridge 0997A

For those longer spans the beams need to be cut from welded I-beams in Australia which allows designers to modify the bottom steel flange width to suit the bending moment requirements (refer Section B and C in Figure 17).

With the availability of Grade 400 MPa weathering steel in Australia the bridge beams for those rural applications were detailed using the latest weathering steel design guidelines [10]. The use of weathering steel reduces the risk of damaging a corrosion protection system during transport of the steel beams and adds the benefit of less maintenance during the operation of the bridge. Those bridges are currently out in the market to receive prices from contractors to start constructing them in the next few months.

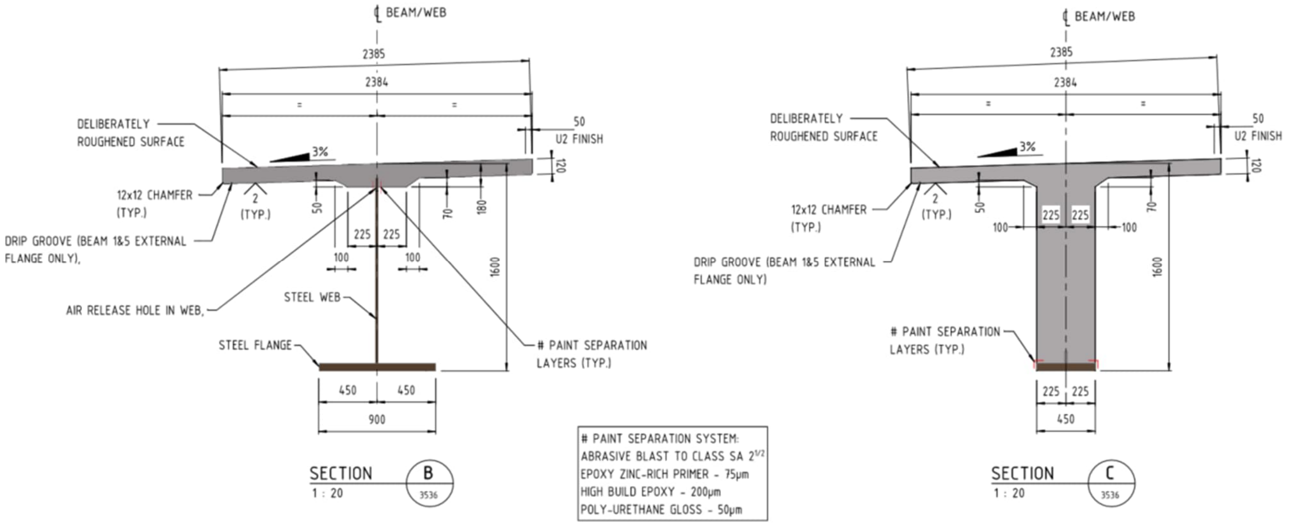

Figure 17. Cross sections of a hybrid beam for Bridge 0997A

7. Summary

For small- and medium-span bridge structures, composite dowel beams are a viable and cost-effective solution. Hot-dip galvanising of the steel dowel beams does not cause warping if produced from double symmetric welded I-sections. Prefabricating the beams does not require trades to learn new skills and provides the flexibility to manufacture them at remote sites or in precast yards. The composite dowel detailing offers the possibility of different forms of beam detailing, allowing structural engineers to devise innovative solutions. Where prestressed precast beams have limitations, precast hybrid beams offer solutions. The accelerated bridge construction method developed for Main Roads Western Australia can be adapted to suit available crane and transport equipment capacities.

8. Acknowledgements

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