# Innovation in Steel-Concrete Composite Bridges

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## ABSTRACT

Steel-concrete composite structures have been used in construction to benefit from the elements' best material behaviour. The interaction between the two materials and how to provide the most effective connection has seen multiple approaches. The latest evolution has been a steel concrete composite design method using composite dowels to transmit longitudinal shear forces between the compound materials steel and concrete. Composite dowels are formed by a steel rib consisting of an intended cut shape (steel-dowel) and the reinforced concrete that fills the recesses in the steel plate (concrete-dowel). Due to its load capacity, one composite dowel is able to replace a group of shear studs which adds economic advantages to the constructability and structural benefits of this detail. Years of research across Europe led to several bridges being constructed based on this innovative method and have proven its effectiveness and financial benefits. The design and construction challenges of the first Australian bridge applying the composite dowel design method will be discussed in this paper.

## INTRODUCTION

The composite dowel construction method represents the latest evolution in steel concrete composite design and construction method. This type of shear transmission between the compound materials concrete and steel allows composite girders to be detailed in multiple forms, providing bridge engineers with the opportunity to design tailored, cost effective solutions for short to medium-span bridge structures.

Years of research across Europe resulted in several published design guides [4],[8],[9] and a general building authority approval [10].

## CONCEPT AND BACKGROUND

The concept is based on the "Perfobond" shear connector developed for a bridge over the Caroni River in Venezuela in the late 80's by Leonhardt Andrä und Partner [7] where a stiffer connection between the compound materials steel and concrete was required to limit deflections. This proposed method lacked in cost and constructability with the main disadvantage being the positioning of the reinforcement. With the improved manufacturing method of computer numerical controlled (CNC) gas cutting the idea of the composite dowel was refined. The possibility of larger scale production reduced manufacturing costs. The revision of the original method of composite dowels, consisting of a steel plate with punched holes welded to an I-girder, to a steel rib consisting of an intended cut shape (steel-dowel) made installation of transverse reinforcements bars simple, e.g. preformed reinforcement cages could be lowered onto the steel beams, rather than having to have individual bars threaded through the holes.

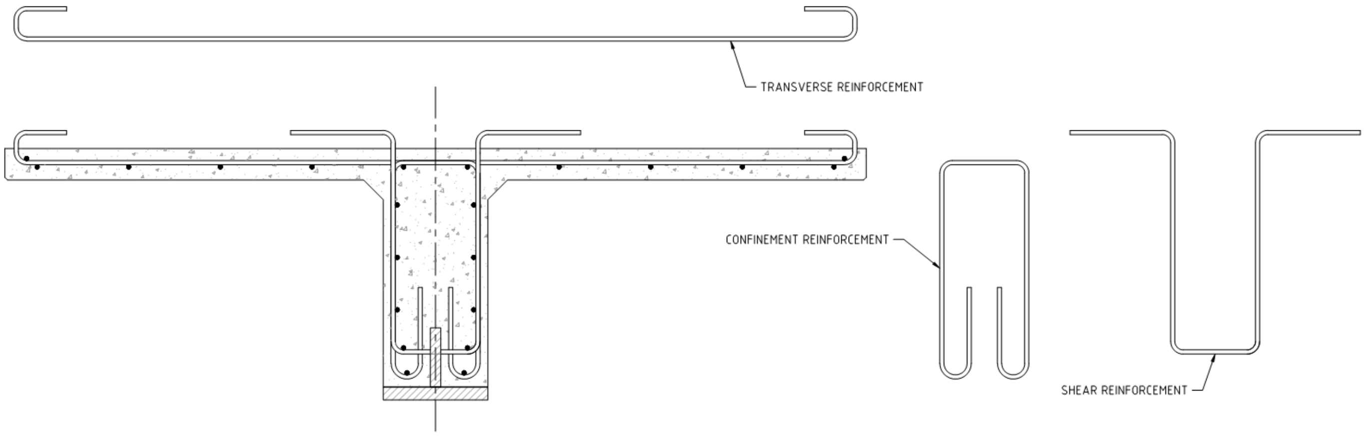



Plate 1: Typical reinforcement for a T-girder with a halved I-girder utilised as external reinforcement

Subsequent research concluded steel profiles without an upper chord (e.g. halved I-girders) cast in T-shaped girders are notable for the efficient use of material (refer to Plate 1). Further testing to refine the steel dowel geometry for improved fatigue capacity resulted in two recommended shapes being included in the general building approval [4] (refer to 2 & Plate 3).

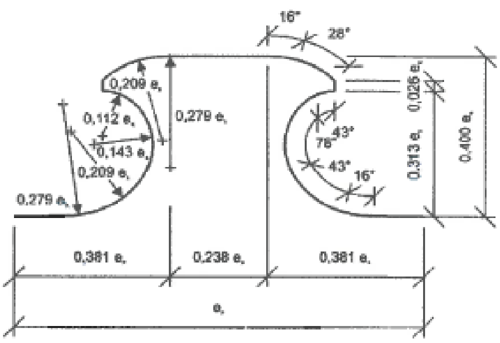


Plate 2: Clothoid

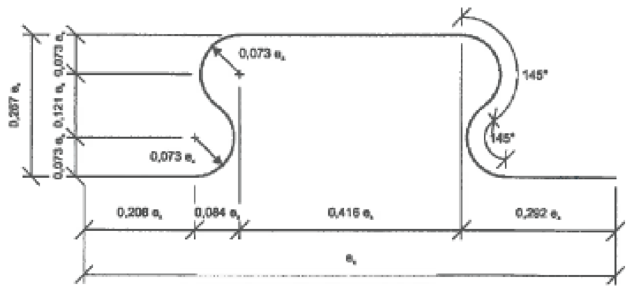


Plate 3: Puzzle

## ADVANTAGES

The T-shaped girder with a halved structural steel I-section cast in the soffit of the girder can be regarded as a reinforced concrete T-section with external reinforcement. The major advantage of external reinforced girders when compared with conventional reinforced girders or pre-stressed girders is the increased lever arm (refer to Plate 4). Geometric restrictions for heavily reinforced beams due to congested reinforcement do not apply when using external reinforcement. This leads to a considerable increase in stiffness and a very economical use of the compound materials.

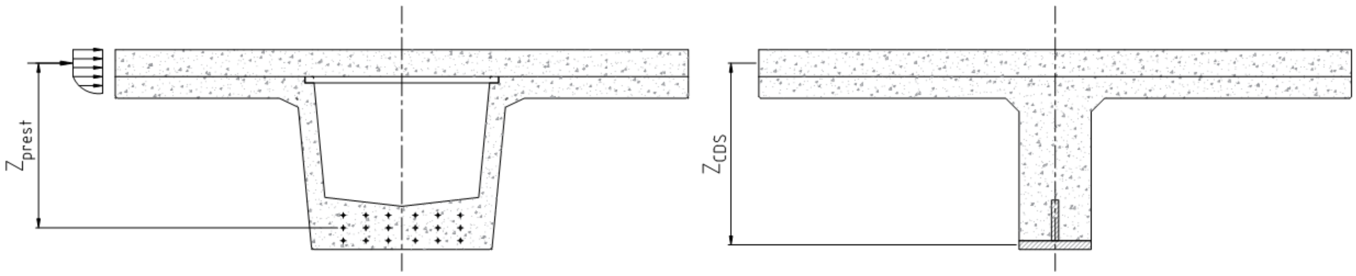



Plate 4: Effective structural depth

### Improved fatigue behaviour

The detail category is an important factor when it comes to the fatigue limit state design. Composite dowels can be manufactured to achieve detail category up to 140, with 125 being the minimum to be achieved by implementing sufficient quality controls. Compared with the detail category of 80 traditional shear studs offer this is an improvement. The simplistic nature of the steel composite dowel section reduces the locations that require fatigue assessment significantly when compared with conventional I-beam steel composites.

### Simplified detailing for integral bridges

In the substructure to superstructure framework corner region of integral bridges there is sufficient material available to accommodate the compressive forces without the introduction of additional plates into the concrete. During construction, the end plate detail caters for sufficient bearing capacity to place the prefabricated girders close to the support faces. This allows the detailing of relatively slender fully integral pier (refer to Plate 5) and abutment connections (refer to Plate 6).

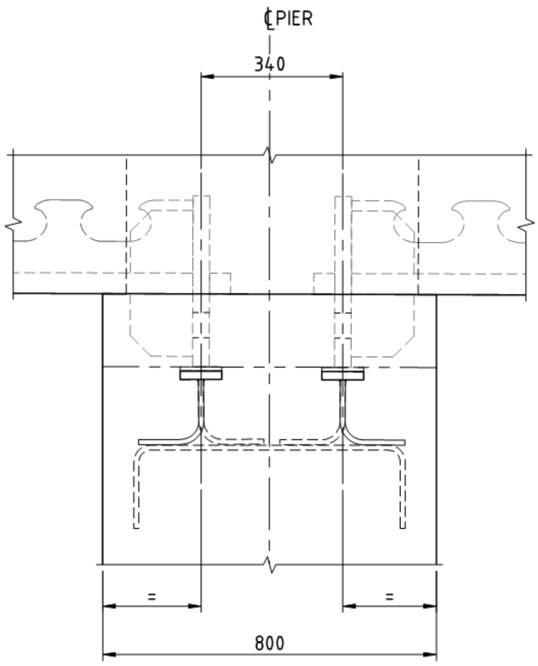



Plate 5: Pier set-up

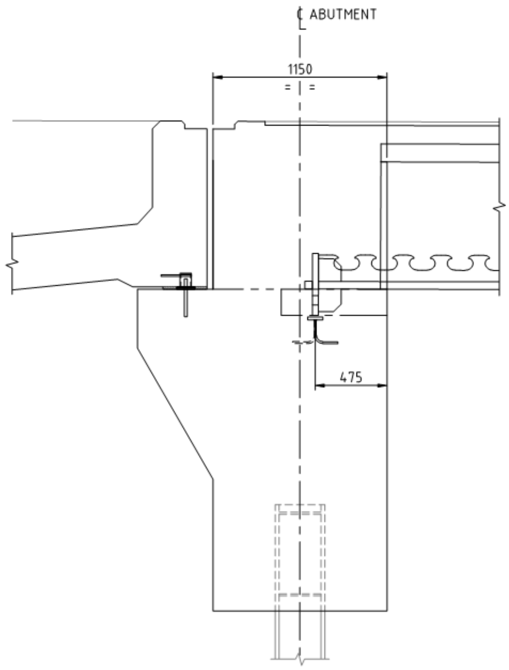



Plate 6: Abutment set-up

### Design for fire

The fire resistance of T-shaped girders is comparable to concrete encased composite sections. To increase the resistance to fire the experience for steel sections with encased shear connectors to achieve composite action can be considered. An embedded steel girder is generally well protected against fire. Higher bearing capacity can be obtained by higher reinforcement ratios. Those two conditions are met by the T-shaped girder. Therefor this girder is ideal for installations in areas with high bushfire risk and where design is to include fire effects in accordance with AS 5100.2 – 2017 [1].

**Safety in design**

There are some safety in design benefits the T-shaped girders with a halved structural steel I-section cast in the soffit offer over Teeroff-griders. Although prestressing is used daily it is still associated with a risk of tendons snapping, causing mayor injuries to workers. The open internal void of Teeroff-girders are usually covered by bondek permanent formwork on site. Before installation of this the open void causes a safety hazard to workers handling the girders and installing reinforcement. For Teeroff bridges in general, there is the requirement that the voids are self-draining, to remove any water that does enter the voids. Water ingress is generally caused by inadequate sealing of joints at service ducts, cracking of the deck allowing water to percolate into the void, and water ingress via the drainage hole in bridges over watercourses. Personal experience of one of the authors involved in 4 years Highways Maintenance activities in the UK, had found that clearing similar drain voids from voided bridge decks, unmaintained for 20 to 30 years had resulted in significant build-up of alkaline rich water, which not only causes injuries to maintenance operatives, but also, identified significant additional dead weight that the bridge had not been designed for. Thus, for low clearance bridges with exposure to repeated flooding, the adoption of non-voided type bridge decks has a long-term advantage in maintenance. By removing the void another detail requiring maintenance is eliminated.

When compared with traditional steel-concrete composite construction methods there are clear safety in design benefits the T-shaped girders with a halved structural steel I-section cast in the soffit offers. Nearly all welding and cutting is automated in the workshop. No shear stud welding is required. This reduces the manual welding to a minimum. No temporary bracing is required during construction which removes the requirement to install grip friction connection bolts on site which has seen some quality issues when tensioning the bolts in the past as well as the access issues and the difficulty of removing bracing at height with locked in stresses post installation of the concrete deck. Installation of transfloor permanent formwork is not required which minimises the handling and working at height risks during construction.

With the simplified detailing to achieve fully integral construction removes the requirement to inspect and maintain bearings and expansion joints.

It could be argued that having an exposed steel surface requires corrosion protection systems to be installed during the design life of the bridge. With appropriate durability planning this can be mitigated by the use of weathering steel (where the environment is suitable) or corrosion protection systems with a design life of 50 years.

Compared with traditional steel concrete composite sections where debris build up moisture pockets adjacent to stiffeners with snipes / cope holes cause accelerated deterioration of corrosion protection systems the clean lines of the exposed steel of the T-shaped sections are less susceptible.

## DESIGN GUIDELINES

The Research Fund for Coal and Steel (RFCS) of the European Community has co-funded a research project which has produced a design guide [3]. The Stahlinstitut VDEh has applied for a general building approval for the composite dowel with the German Institute for Construction Technics (DIBt) which was granted in May 2013 under the 'approval-number' Z-26.4-56 [10]. The design guides and general building approvals can be seen as an addition to the Eurocodes with the aim to further improve standards and as a preparation for the next generation. With the implementation of the revised Australian Standard 5100 Part 6 [2] being similar to the Eurocode 4 [5],[6] the design guides for the composite dowel can be easily followed.

Therefore, the application of composite dowel conforms as a shear connector for steel concrete composite construction if the material and geometric requirements are in accordance with [10]. The design concept included in [10] covers the ultimate limit state, the serviceability limit state and the fatigue limit state. The design concept for the static failure modes and the steel fatigue is based on sufficient data gained from lab tests. Concrete fatigue and concrete dowel loosening to avoid a softening of the shear connection is built in by a very conservative stress limitation

Subsequently, the Structures Engineering Branch of Main Roads Western Australia, agreed the research undertaken and the design guidelines published were sufficient to allow this construction technic be established in the Australian market if industry is set-up to manufacture the structural steel details. With a local WA steelwork manufacturer, Pacific Industrial Company, identified as having the required equipment and skills to manufacture the structural steel work for steel concrete composite dowel girders, it was concluded that the fabrication of the steelwork could be achieved without any additional industry setup and/or investment.

## ADJUSTMENTS FOR AUSTRALIAN STEEL MANUFACTURES

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. With the production lines capable of turning out rolled I-beams cut in half it was a simple task to program the CNC oxy-cutters to run a different cut-profile.

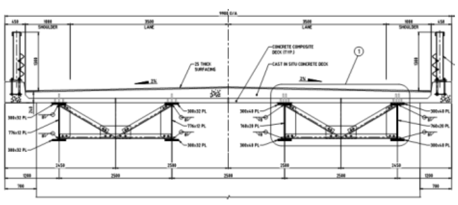
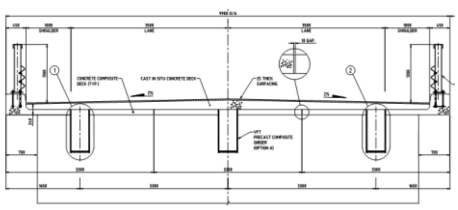
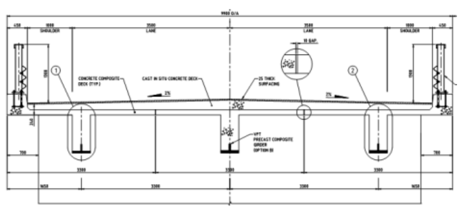
The Australian Steel Industry does not offer deep rolled beams. Deeper beams must be ordered as welded beams which removes some of the cost effectiveness the European market can offer. However, ordering custom made welded beams provides the opportunity to tailor cross sections and e.g. easily implement haunched girders.

## PILOT PROJECT BRIDGE 0270A

When Main Roads Western Australia required a design to replace an existing timber bridge at a remote site in the South West region of Western Australia, with several options being considered during the concept design phase in 2016. The bridge articulation and length was governed by waterway requirements and the topography on site ruling out longer span options with deeper girders and shorter span options with increased pier numbers. Standard Teeroff-grider construction (simply supported detailing) was ruled out due to the required depth (l/17). Fully integral detailing of Teeroff-griders would require the girders to be temporarily supported during construction and the supporting pier members to increase in size due to detailing requirements and was therefore not further investigated. In addition transport of 15+ m precast girders from the nearest precast yard to site was investigated and found to be an issue due to narrow rural roads. Three 3-span super structure options (refer to Table 1) with a centre span of 22.0 m and end spans of 15.7 m (refer to Plate 7) were designed and 50% drawings were handed over to a contractor to review and compare constructability and to prepare construction cost estimates.

The steel concrete composite dowel girder option was selected to be constructed at this site due to simplicity of construction and lowest cost. The lower cost for the steel concrete composite dowel girder is achieved due to fewer number of girders required for the same span to depth ratio when compared with traditionally constructed steel concrete composite girders. The removal of the shear stud welding and reduction in transport costs were other cost reducing factors.

Table 1: 3-span options bridge 0270A

| **STANDARD COMPOSITE** | **COMPOSITE DOWEL BOX** | **COMPOSITE DOWEL** |
|---|---|---|
|  |  |  |
| Superstructure cost estimates based on 50% drawings | | |
| $347,375.34 | $359,419.56 | $313,055.91 |

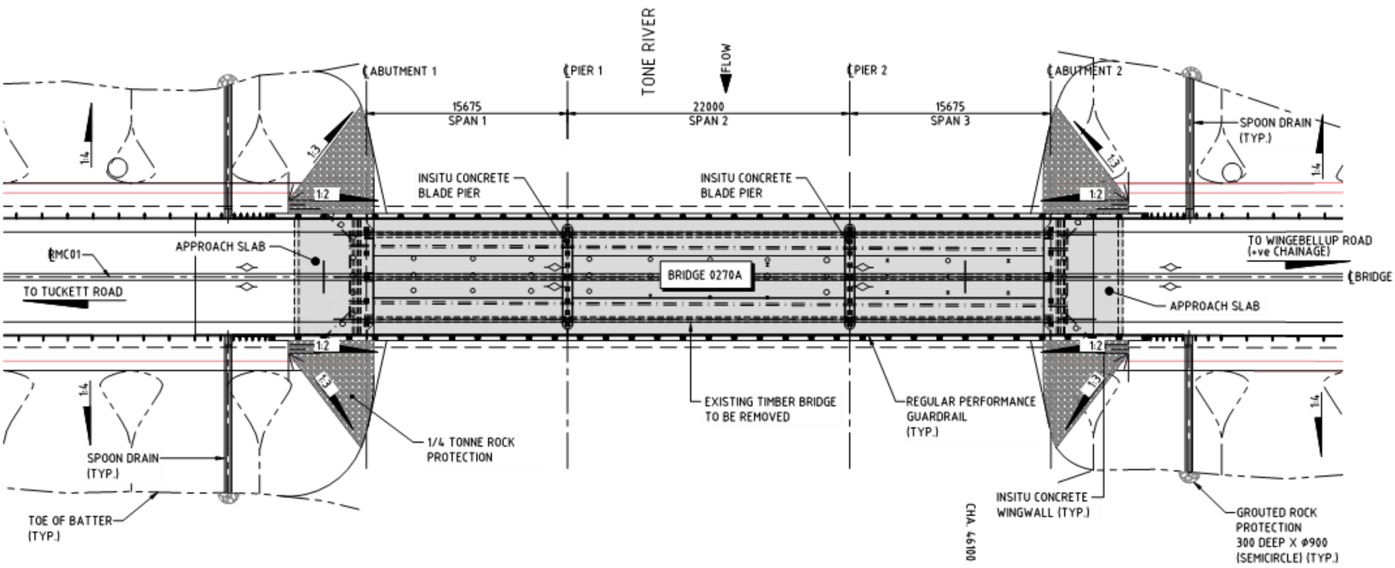



Plate 7: Plan view 3-span arrangement

The remote location of the bridge required the set-up of a batching plant to mix concrete on site, which was primarily associated for concrete to construct the substructure. The contractor therefore decided to cast the girders adjacent to bridge site. Compared with the set-up of a mobile mould with stressing bed to produce Teeroff-girders this was more economic. With suitably sized mobile cranes being available on site for other construction operations, the availability of plant to move the beams was also effectively cost neutral.

This had the benefit that only the fabricated steel plate would have to be transferred from Perth to site, involving just two vehicular trips, as opposed to 9, resolving the transport issues of large and oversized loads. Whilst it is acknowledged that the same tonnage of materials, e.g. concrete and reinforcement need to be transported, the aggregate for the concrete is sourced from regional facilities in Bunbury which is 170 km closer to the site.

## STEELWORK MANUFACTURING

CNC-oxy cutting also known as machine gas cutting is available in the Australian market. Larger steelwork manufacturers are equipped to cut steel plates in any shape. For the pilot project, several trial cuts (refer to Plate 8) were undertaken to review if a maximum cut surface roughness of 12 µm in accordance with AS/NZS 5131, Table 6.5 can be achieved with this shape. This is required to comply with a minimum detail category of 125 in accordance with AS 5100.6, Table 13.10.1(B) and [10]. Early engagement of the steelwork manufacturer and collaboration between manufacturer and design engineers resulted in successful trial cuts (refer to Plate 9) after WSP provided the cut profile electronically to the steelwork manufacturer.

Plate 8: Trial cuts

Plate 9: Trial cuts

After trail cuts were successful the methodology to manufacture the steel girders was discussed. The methodology was revised a few times and a final workflow was established which included manufacturing a welded beam (refer to Plate 10) prior to cutting it in half (refer to Plate 11) to improve efficiency. Tolerances on specified dowel sizes in accordance with [10] are generous and account for the expected heat distortion during the cutting process (+2mm/-4mm ('+' indicates size increase)).

As a result of modification of eigenstresses after the beam was cut longitudinally, the T-beams obtained required additional bending to form the defined pre-camber.

Plate 10: Welded beam before cutting

Plate 11: Welded beam after cutting in half, including the end compression plates

## FORMWORK

Originally the designers envisage the girder would be cast in a steel formwork and detailed the web to allow simple formwork stripping. However, with the formwork set-up in Plate 12 girder webs could have been vertical.

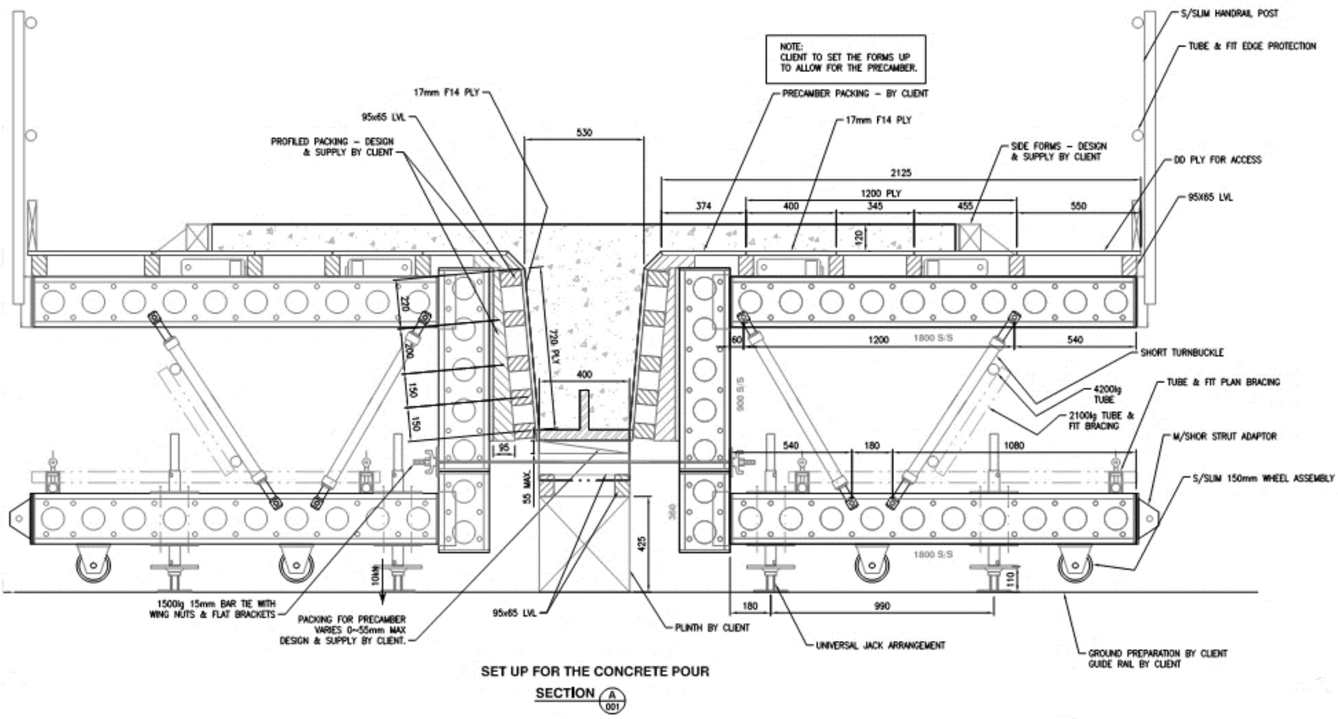



Plate 12: Formwork set-up

## LESSONS LEARNED

1. Increase web depth to reduce web thickness and remove the requirement for pre-cambering steelwork by utilising locked in thermal stresses;
2. The concrete web of the T-section, depending on fabrication method, e.g. moveable mould, vs lifting the beam from the mould, could be vertical to simplify detailing and formwork;
3. Outer girders with precast kerb profile should be asymmetric to modify the centre of gravity, so beam lift is vertical during installation and/or transport;
4. Close corporation between Client, Designer and Fabricator demonstrates that proposing alternative solutions need not be stopped in their tracks and be put in the “too hard basket” just because its not be undertaken before locally.

## CONCLUSION

For small and medium span steel-concrete composite structures, composite dowel girders are a viable and cost effective alternative to the prestressed precast options available. The construction method allows a very high degree of prefabrication but can also be used at remote sites where delivery of heavy and oversized loads is not possible. Modern integral construction to deliver sustainable infrastructure with clear safety in design benefits can be achieved with simple detailing.

## REFERENCES


[1] AS 5100 Part 2: *Design Loads*; Australian Standard; March 2017

[2] AS/NZS 5100 Part 6: *Steel and composite construction*; Australian/New Zealand Standards; March 2017

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[4] EUR 25321 — *Prefabricated Enduring Composite Beams based on Innovative Shear Transmission (Preco-Beam)*; European Commission; Directorate-General for Research and Innovation; Brussels; Belgium; 2013.

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[6] Eurocode 4 – *Design of composite steel and concrete structures – Part 2: General rules and rules for bridges*; Brussels; Belgium; July 2005.

[7] Leonhardt, F.; Andrä, W.; Andrä, H.-P.; Harre, W.; *Neues, vorteilhaftes Verbundmittel für Stahlverbund-Tragwerke mit hoher Dauerfestigkeit*; Beton- und Stahlbetonbau 82 (1987); Heft 12; S. 325-331; 1987.

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## AUTHOR BIOGRAPHY/IES

**Wolfram Schwarz** is a Chartered Professional Engineer with over 17 years' experience in building and civil structural design in Germany, Australia and New Zealand.  He is recognised as a technical reviewer and a trusted provider of engineering services with a passion for non-conventional design solutions.  He is the Team Leader of the Transport Structures Team in Perth acting as a principal technical resource and advisor providing solutions for clients.

**Neil Westmacott** has over 27 years of experience in the civil engineering profession.  He has extensive experience designing and assessing bridge structures in prestressed concrete, steel-concrete composite and prestressed-concrete composite.  He has been involved in bridge designs incorporating construction methods varying from heavy lift/transported structures, precast, trussed, cast-insitu and segmental construction.

**Nimal Jayasekera** has 32 years of career history as a Civil Engineer with wide range of Design, Construction and Project Management experience in road and bridge projects.  After completion of his Master's Degree in University of New South Wales, he started working for Main Roads Western Australia.  He has been working in Structures area for last 20 years delivering major bridge projects in Main Roads WA South West Region and is the Delivery Manager Structures for this region.