Investigating the most sustainable concrete bridge

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Abstract: Concrete is the primary bridge building material in the world. It is also of course the most successful. However, with the construction sector contributing to almost 20% of Australia's carbon footprint we are now beginning to see the traditional drivers for the design of concrete bridges (construction cost, durability, appearance, strength and ductility) be joined by considerations of carbon content. So what is the structure type that provides the lowest carbon emissions? This paper summarises the findings of an investigation into the carbon content of a typical 12.0 metre span, two-lane road bridge for a range of structure types including; traditionally prestressed concrete planks; reinforced concrete planks; prestressed concrete girders; geopolymer concrete planks; ultra-high performance concrete (UHPC) girders and concrete girders reinforced with higher strength steel (600N). General conclusions are drawn on the most appropriate option, assuming the minimisation of embodied carbon is the sole criteria for selection.

Keywords: concrete, bridges, sustainability, carbon emissions, adaptability

1. Introduction

Embodied carbon impacts of structural elements are not well defined by the industry. There is an opportunity to assess opportunities for emissions reduction through whole-of-life considerations in the early stages of a project. Simple design-related and cost-effective changes could be made that would have significant positive impacts on the carbon footprint of our bridge assets, such as material choice and structural form.

Embodied carbon emissions linked to Australian infrastructure, resulting from the production and transport of materials used in construction, contributed 5.9% (34.3 Mt CO2-e) of Australia's total greenhouse gas (GHG) emissions in 2018 as noted in ClimateWorks Australia2. As global populations continue to grow, material use is projected by the OECD3 to more than double from 79 Gt in 2011 to 167 Gt by 2060, all else being equal. This includes non-metallic minerals, such as sand, gravel and limestone, which are used widely in construction and represent more than half of total material use globally.

The following comprises a review of a range of different material and structure types for a typical small span rail bridge in order to compare the embodied carbon content for the construction of the superstructure.

2. The bridge form

The bridge chosen for the comparison is shown in Figure 1. It comprises a two lane road bridge in a rural setting crossing a small creek, 8.0 metres between kerbs and of a single 11.0 metre span measured between centrelines of bearings. The bridge is on a straight alignment with zero skew and a 2% nominal longitudinal grade. Regular performance traffic barriers are provided on each side of the bridge. The substructure consists of reinforced concrete abutment beams and wingwalls supported by reinforced concrete driven piles. The bridge is assumed to be located in rural Australia within 150 kilometres of a capital city.

A total of eight different superstructure material/structure types were developed as concept designs as noted below and tabulated in Table 2. Designs were undertaken in accordance with the relevant provisions of Australian Standard AS 5100 2017 Bridge Design, with SM1600 as the designated vehicle loading. The following elements were assumed to be the same for all bridge options assessed unless particularly noted; earthworks and scour protection, traffic barriers and kerbs, asphaltic surfacing and line marking, abutment beams and wingwalls, and piles. Minor items not considered in the comparison included elastomeric bearings, mortar pads and movement joints.

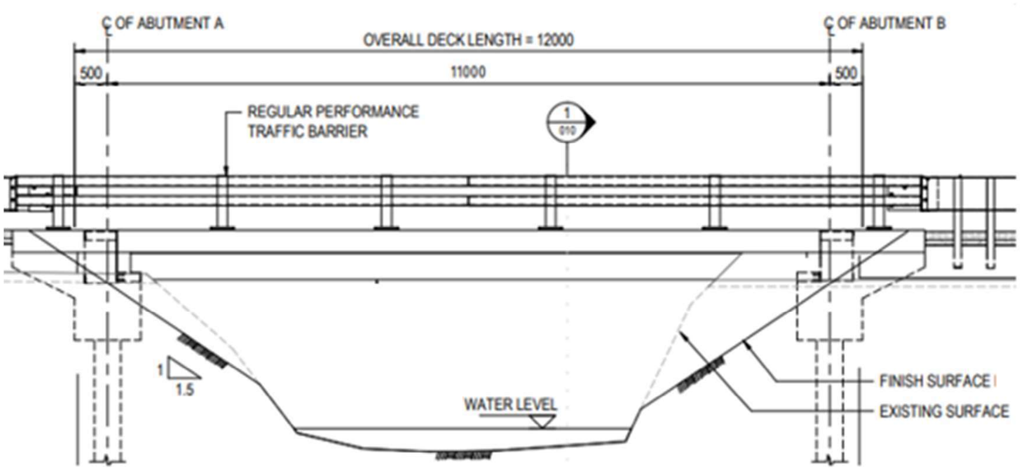

Figure 1 Bridge elevation

3. Options considered

Option A: Precast prestressed concrete planks with cast in situ concrete deck

For small span road bridges, a superstructure consisting of precast prestressed concrete planks laid nominally side by side and supporting a cast in situ concrete deck is the most common form of bridge construction throughout Australia and also in many parts of the world.

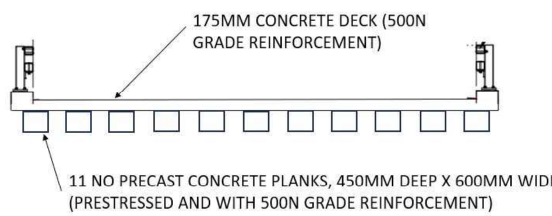

Figure 2 Concrete, Prestressed

The deck slab is graded for the road profile and is also designed to act compositely with the planks to support superimposed dead loads, (principally the surfacing, kerbs and railing), and truck loading.

The concrete for both the planks and deck slab has been assumed to comprise a 50 MPa mix with a cement material proportion of 70% GP cement and 30% fly ash. This blend is readily available.

Pretensioned strand to AS/NZS 4672.1, together with 500N grade reinforcement, provides the main flexural steel. For road bridges, the prestressing also has the advantage over fully reinforced plank options of better avoiding a permanent sag if the bridge is severely overloaded. For an 11.0 metre span a plank depth of 450 mm and a plank width of 600 mm is typical and was chosen. For this form of construction it is usually found more cost effective to separate the planks by approximately 300 mm clear with the advantage of both reducing the number of planks and mitigating against longitudinal cracking in the deck slab due to transverse bending of the deck under live load. Therefore, eleven planks are provided supporting a 175 mm thick concrete deck.

Option B: Precast steel reinforced (500N) concrete planks with cast in situ concrete deck

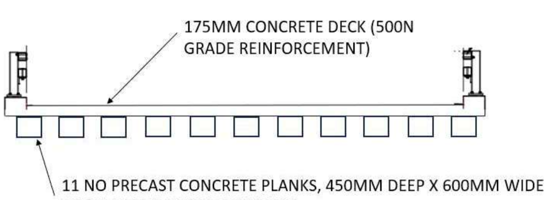

Figure 3 Concrete, 500N Reinforced

Options B and C are included to assess the embodied energy variation between prestressed and non-prestressed components.

For this Option the planks are not prestressed, and the planks and the deck slab utilise D500N Grade reinforcement to AS/NZS 4671.

Option C: Precast steel reinforced (600N) concrete planks with cast in situ concrete deck

This Option is similar to Option B but utilises the new higher strength D600N reinforcement in flexure and shear in lieu of the traditional D500N Grade. Higher strength steel was recently introduced into AS/NZS 4671 Steel reinforcing materials and is now included in AS 5100 Bridge design. For further details refer Ng and McGregor (2020).

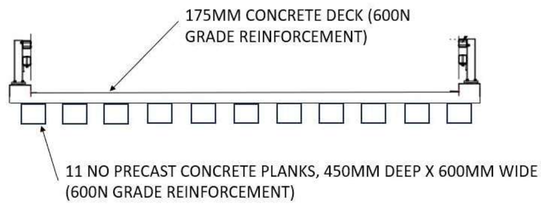

Figure 4 Concrete, 600N Reinforced

When using higher strength reinforcement particular care is required to assess whether crack width provisions and deflections are critical in the design. In this instance a serviceability check indicates that these provisions don't govern and the whole of the additional strength of the higher strength steel can be utilised.

It is noted that D600N reinforcement is fabricated from 100% recycled steel and utilises EAF furnaces which reduces carbon content from 1.58t(CO_2-eq)/t for 500N steel to 1.24t(CO_2-eq)/t for D600N steel.

Option D: Precast concrete planks with cast in situ concrete deck (all FRP Reinforced)

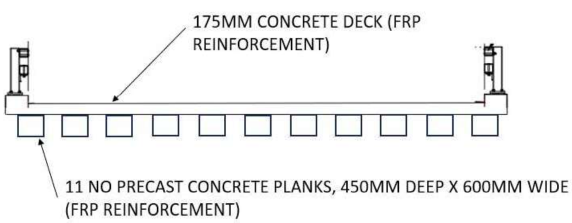

Figure 5 Concrete, FRP Reinforced

This Option is similar to Options B and C, except the reinforcement in both the planks and bridge deck consists of fibre reinforced polymer bars, specifically Grade 60 basalt fibre bars to AS 5204 and in accordance with ASTM D578/D578M. Main flexural reinforcement in the planks comprises FB60P24 bars (24mm diameter).

Two further benefits of FRP reinforcement are; easier to handle and place (22% of the equivalent mass of steel bars) and longer life.

It is noted that additional care is required in the design of concrete members reinforced with FRP bars. The elastic modulus of FRP is in the order of 30% of steel, so the strains required to develop similar tensile stresses are several times that of steel and crack widths are correspondingly much larger. Specifically, cracking of the concrete will be more extensive and pronounced if the FRP reinforcement is used to its full strength potential. Although this cracking will not lead to corrosion the appearance will be affected. For this design the serviceability limit state has governed.

Option E: Precast prestressed geopolymer planks with cast in situ concrete deck

Geopolymer concrete is similar to normal concrete except that the cement is replaced by industry by-products, such as slag, fly ash or rice husk ash, and the required chemical reaction is initiated by the promotion of alkali chemicals. In Australia this impetus is being led by Wagners (Glasby, 2013) who are supplying a proprietary geopolymer concrete.

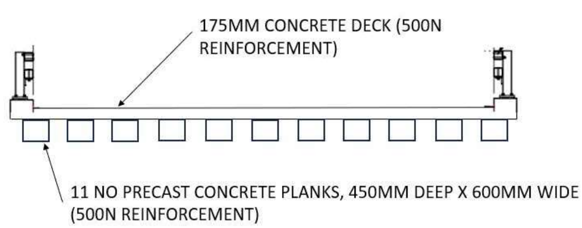

Figure 6 Geopolymer Concrete, Prestresses

In this instance, the geopolymer is made from a combination of ground granulated blast furnace slag (GGBS) and fly ash, making the binder system nearly entirely recycled, providing a 60% reduction in carbon emissions compared to Portland cement.

Option F: Precast, prestressed concrete girders with cast in situ concrete deck (500N reinf.)

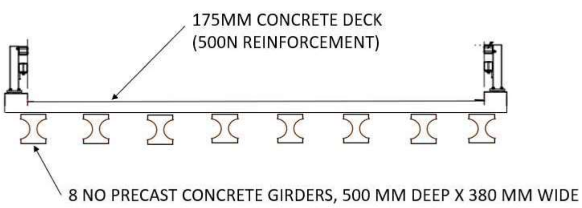

Figure 7 Concrete Girders, Prestressed

This Option is similar to the typical prestressed plank option (Option A) except that precast prestressed girders are provided instead of rectangular prestressed concrete planks. In this way the concrete volume is reduced by both the introduction of a more efficient girder section (in lieu of the solid rectangular planks) and a a reduced number of longitudinally spanning units (from 11 to 8). It is noted that the cast in situ deck utilised for Option A is sufficient to span the greater distance between girders for Option F without modification.

Option G: Precast, prestressed concrete girders with cast in situ concrete deck (600N reinf.)

Option G is the same as Option F, with the exception that the 500N steel reinforcement is replaced by the new 600N grade reinforcement described in Option C. This has the effect of producing a lower total embodied energy by both the higher strength of the reinforcement and the lower carbon content per tonne.

Option H: Precast, prestressed UHPC girders with cast in situ concrete deck

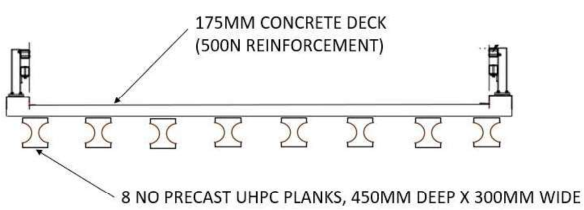

Figure 8 UHPC, Prestressed

UHPC (Ultra High Performance Concrete) was developed in the 1990s with typical compressive and flexural strengths of over 180 MPa and 40 MPa, respectively (Foster, 2015). Typically, UHPC comprises Portland cement, silica fume, superplasticers, and steel fibres generally 1-2% by volume. UHPC has a very low binder/water ratio and no coarse aggregate is used.

Excellent durability of UHPC girders is achieved as a result of the increased particle packing density. The steel fibres produce a material of excellent ductility without relying on conventional non prestressed reinforcement to achieve this. For the concept design shown in Figure 8 the only reinforcement provided for the girders is longitudinal prestressing to achieve the required flexural strength, and bars through the top flange to achieve composite action with the conventionally reinforced concrete slab. No shear ligatures are provided; excellent ductilty is provided by the steel fibres.

4. Carbon Emissions

Embodied carbon emissions factors that were adopted for each of the various constituent material types are noted in Table 1, below. These factors account for the “as constructed” embodied carbon of the structure and do not take into account replacement or renewal of any elements. Where possible, Environmental Product Declarations (EPDs) were used. An EPD is an independently verified and registered document that communicates transparent and comparable data and other relevant environmental information about the life-cycle environmental impact of a product. Total carbon content for each option is noted in Table 2.

Table 1 Carbon emissions per material type

Material	Options	Emission factor	Reference
Precast 50 MPa Concrete (30% SCM) excluding reinforcement	A-C, F-G	0.181 t($CO_{2\text{-eq}}$)/t	(ISC 2023)
Cast insitu 50 MPa concrete (30% SCM)	A-K, N	0.181 t($CO_{2\text{-eq}}$)/t	(ISC 2023)
50 MPa Geopolymer concrete	E	0.118 t($CO_{2\text{-eq}}$)/t	(TFC 2020)
D500N Grade reinforcement	A-B, E-F, H-K, N	1.58 t($CO_{2\text{-eq}}$)/t	(Infrabuild 2022)
D600N Grade reinforcement	C, G	1.24 t($CO_{2\text{-eq}}$)/t	(Infrabuild 2022)
Prestressing steel	A, E-H, M	1.98 t($CO_{2\text{-eq}}$)/t	(Infrabuild 2022)
Fibre reinforced polymer (FRP)	D	3.88 t($CO_{2\text{-eq}}$)/t	(Wagners 2023)
UHPC	H	0.498 t($CO_{2\text{-eq}}$)/t	

Table 2 Total carbon content for each option

Option	Option description	Carbon content tonnes (CO_2-eq)
A	Precast Prestressed Concrete Planks, Cast Insitu Concrete Deck	35.5
B	Precast Reinforced (500N) Concrete Planks, Cast Insitu Concrete Deck (500N)	43.7
C	Precast Reinforced (600N) Concrete Planks, Cast Insitu Concrete Deck (600N)	37.0
D	Precast FRP Reinforced (FRP) Concrete Planks, Cast Insitu Concrete Deck (FRP)	40.9
E	Precast Prestressed Geopolymer Planks, Cast Insitu Concrete Deck	38.5
F	Precast Prestressed Concrete Girders (500N), Cast Insitu Concrete Deck (500N)	27.7
G	Precast Prestressed Concrete Girders (600N), Cast Insitu Concrete Deck (600N)	24.9
H	Precast, Prestressed UHPC Girders, Cast Insitu Concrete Deck	26.7

5. Discussion

The benchmark is Option A (11 closely spaced precast prestressed concrete planks with cast in situ reinforced concrete deck) , as this is generally the go-to solution for small span road bridges. This is a cost-effective solution; precast plank moulds and stressing beds exist from a range of suppliers in all Australia states and construction methods are straightforward and well established. The principal components of; prestressing strand, 500N steel reinforcement and 50 MPa concrete are readily available. Supplementary cementitious materials (SCMs) such as fly ash (by-product of coal powered power stations) and ground granulated blast furnace slag (GGBS, a by-product of steel production) in a blended cement offer substantial advantages in reducing carbon content and concrete mix comprising 70% Portland cement and 30% fly ash has been assumed for both the precast and cast in situ concrete component in all options. Circular economy outcomes are also realised through the recycling of fly ash and GGBS as waste products into new materials.

Other plank options considered were Option B (500N reinforced), Option C (600N reinforced), Option D (FRP reinforced) and Option E (Geopolymer concrete). Depending on the Geopolymer mix, creep may be an issue for prestressing losses. For any Geopolymer mix, the creep credentials will need to be established.

Even though prestressing strand has a higher emission factor than reinforcement this is offset by its higher strength, so the carbon content increases for either Option B or Option C. Substituting the steel prestressing and steel reinforcing in the concrete planks with FRP reinforcement (Option D) did not produce a lower carbon content. This is principally due to limitations on serviceability stresses to limit crack widths due to the reduced elastic modulus of FRP reinforcing bars. For the reinforced only plank solution, the use of geopolymer concrete (Option E) in lieu of traditional concrete (30% SCM) was beneficial in reducing the carbon content.

A substantial advantage of the plank solutions is that once the planks are placed an immediate work platform is created for placing deck reinforcement and placing and finishing deck concrete. However, this construction advantage comes at a premium to carbon content. The concrete girder (Option F) is a much more efficient section than the plank options described above with the total mass of the spanning units reduced by more than 50% and the carbon content for this option reduced from 35.5 tonnes to 27.7 tonnes. It can also be seen from Option G that the carbon content can be further improved, to 23.3 tonnes, by utilising the new higher strength 600N reinforcement in lieu of traditional 500N reinforcement.

The higher strength UHPC girders (Option H) produces a relatively low total carbon content of 26.7 tonnes. UHPC also has the advantage of a longer service life in comparison with concrete girder options (Option F and Option G), and a much lower lifted girder mass. The carbon content saving of UHPC compared to normal concrete is expected to increase with increasing span due to the lower self-weight of UHPC.

5. Conclusions

This conversation is timely. Governments and private investors are spending record amounts of money on new infrastructure. At the same time, infrastructure is facing pressure to prepare for net zero emissions on two fronts:

- All Australian states and territories have set commitments or aspirations to achieve net zero emissions by 2050, or earlier; and
- Private investors are increasingly aligning investment portfolios with net zero emissions in order to future-proof economic value and investment returns. (ClimateWorks Australia 2020).

Most long life engineering projects are a compromise between initial cost, lifetime, and lifetime cost, and this same principle can be applied to carbon: initial embodied carbon (to supply and construct); embodied carbon in replacement and renewal; and lifetime carbon including transport of material to site, deconstruction and waste management carbon ‘costs’.

The assessment undertaken for this paper provides a summary of the as-constructed carbon “cost” of a variety of structures suitable to service the generic design considerations of the proxy bridge we are considering. This assessment is intended to serve as a starting point during options assessment, to be considered alongside both traditional cost factors, as well as the further considerations outlined in this paper.

The lowest carbon “cost” of the concrete options was Option G, comprising precast prestressed concrete girders (not planks), a cast insitu concrete deck and 600N grade reinforcement and Option H (UHPC).

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