Concrete Bridge Design and Construction series

This series is authored by the Concrete Bridge Development Group (CBDG).

The group aims to promote excellence in the design, construction and management of concrete bridges. With a membership that includes owners, designers, academics, contractors and suppliers, it provides a focus for the use of best practice, innovation, training initiatives and research and development. Further information on the CBDG can be found at: www.cbdg.org.uk

No. 6: Concrete bridge construction methods – *in situ*

Figure 1
Stolma Bridge, Norway

Introduction

This article from the CBDG's Technical Committee examines the *in situ* construction methods for a concrete bridge. The first three articles[1-3] in the series looked at the general parameters surrounding the design and construction of concrete bridges, while the most recent two[4-5] looked at the particular types of bridge that are available and when they might be used. The next article will describe the various precast techniques.

In situ concrete bridges

As noted in *Types of concrete bridge*[4], there are four basic types of *in situ* concrete bridge:

- solid or voided slabs – cast on a scaffold system or a series of beams/girders
- twin ribs – cast on scaffold/beams or using travelling gantries
- span by span box girders – cast on scaffold/beams or using travelling gantries
- balanced cantilevers – short box sections cast using a travelling formwork system

The choice between precast or *in situ* construction was outlined in *Introduction to concrete bridges*[1], but these *in situ* options tend mainly to be used on projects where the speed of construction is not critical, or where the lower costs of the *in situ* works justify a slightly longer programme. Figure 9 in *Types of concrete bridge*[4] shows that *in situ* bridges cast on scaffolding are produced at a rate of about 10m/week, which is about half the rate that can be achieved with many precast solutions. Once there is sufficient length of bridge to justify some capital investment in using travelling gantries, this rate can easily be increased to 25m/week, which is similar to all other methods, except the most specialised ones. A CBDG Technical Guide on fast construction gives general guidance on many of these production issues[6].

In situ slab and twin rib solutions tend, therefore, to be used on smaller projects with modest spans in the range 10-40m. In these situations, it will not be possible to justify the use of the more sophisticated precast solutions, as these methods will need considerable investment in specialist equipment. However, precast beam solutions are generally perfectly valid and the choice between precast and *in situ* will largely depend on the assessment of programme and costs (outlined in the previous articles).

For longer spans of 40-80m, box girder solutions are generally required. *In situ* box girder bridges cast on scaffolding or on gantries though are relatively rare, as the casting of long lengths of box can be quite slow, requiring the box section to be cast in two or three phases, i.e. bottom slab, followed by webs, followed by top slab; or bottom slab and webs, followed by top slab. These casting issues are usually resolved by casting the box in shorter lengths than the span, e.g. by using *in situ* balanced cantilevering or by using some of the precast solutions. With *in situ* balanced cantilevering, the bridge is formed from short *in situ* units (or 'segments') each 3-5m long and cast in a travelling formwork system. The production rates for this technique are quite slow at about 5m/week for each pair of travelling forms, but this rate can be accelerated by using multiple sets of forms. So, whereas *in situ* boxes cast on scaffolding or gantries tend only to be used for spans of 40-80m, *in situ* balanced cantilevering can be used from 40m up to 300m. The longest concrete beam

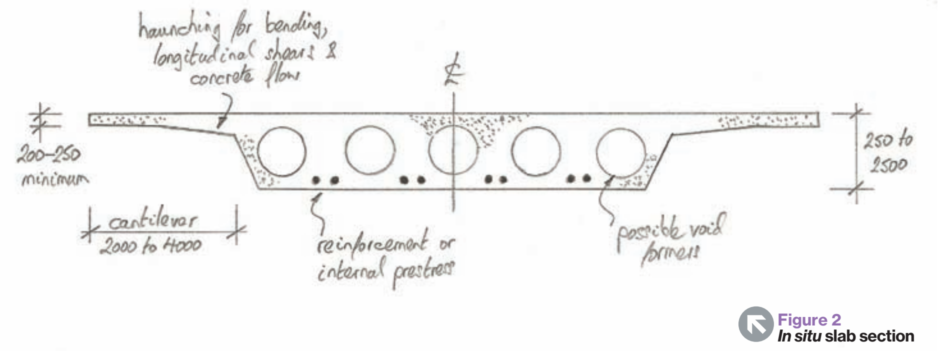

Figure 2
In situ slab section

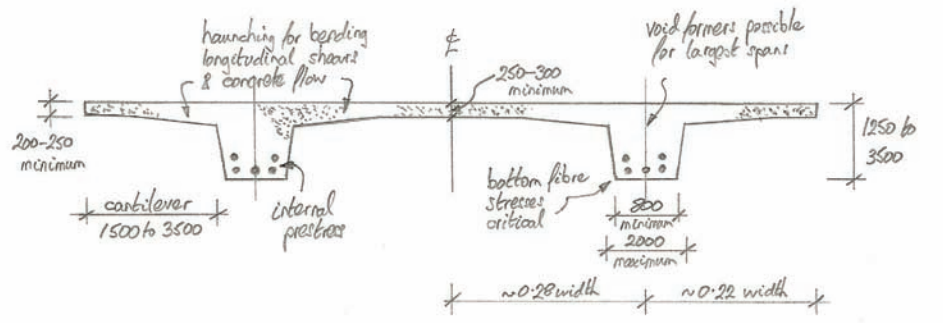

Figure 3
In situ twin rib section

bridges in the world have all been built by this method, with the Stolma Bridge in Norway holding the current record span of 301m (Figure 1). Once the spans get above about 150m, all precast solutions generate units that are too heavy for transportation, and thus the only viable option for beam bridges becomes *in situ*.

In situ slab bridges

In situ slab bridges have very simple cross-sections that are easily cast (Figure 2). Typical spans range from 5-20m for solid slabs and from 20-40m for voided slabs. Prestressing is generally used with spans over 20-30m. Span to depth ratios for highway bridges are typically 18-24, depending on whether the bridge spans are simple or continuous. This type of bridge deck represents a very flexible solution for any site, with a clean aesthetic, which is best suited to low sites over land with good access.

Spans are usually constructed using plywood formwork and simple falsework systems, based on scaffolding or proprietary props, often just sat on sleepers, concrete blocks or blinding concrete. The system is relatively sensitive to ground conditions and once the simple methods noted previously are no longer adequate, further ground improvements may be needed. Beams are used to span over openings for traffic through the site, or over live carriageways, though more substantial girders and piers with proper foundations will need to be used for bigger openings. As these bridges are often cast span by span, the common configuration is to cast a span plus a short cantilever into the next span (of 0.2 to 0.25 of the span). This ensures that the as-built moments in the deck are close to the final moments. With smaller spans, it would be possible to cast several spans at the same time, in one continuous pour. Timber forms of this size can be used 10-50 times before needing to be refurbished.

With the larger spans, voids should also be incorporated, both to reduce the self-weight and to increase the efficiency of the section (the ratio of kern height to overall height η - discussed in *Prestressing for concrete bridges*[3]). These voids are generally made from polystyrene formers, which need to be held rigidly in place, with care taken to ensure that the concrete flows around them. As a result of these issues, the cost of these void formers can often be more than that of the concrete they replace, but the benefits in reducing the amount of prestressing justify their use.

The flat soffit of the deck makes the formwork, fixing and concreting very simple, but the deck is relatively uneconomical in terms of concrete volume and main reinforcement or prestressing tonnage. Overall, bridges of this nature have relatively low construction costs, provided there is good access.

In situ twin rib bridges

In situ twin rib bridges have a more efficient section than flat slabs but they maintain a simple external profile that is easy to cast (Figure 3). Typical spans range from 20-50m and prestressing is generally used. Span to depth ratios for highway bridges are typically 14-18. Even though they need a slightly deeper section, twin rib bridges still represent a flexible solution for any site, with a good aesthetic (Figure 4). If a scaffold system is being used as the falsework, they are best suited to low sites over land with good access, but once a travelling gantry system is used, they are suited to all sites, even those with poor access.

Twin rib bridges can accommodate deck widths up to about 20m, beyond which additional ribs can be incorporated. Transversely, they rely on the interaction between the transverse stiffness of the deck slab and the torsional stiffness of the ribs to carry eccentric traffic loads. Though not as efficient as a box girder in this regard, they still perform well in spreading load between the ribs. No diaphragms between the ribs are needed in the span to help with this behaviour. Diaphragms might be needed in some pier locations where the lateral loads are high (due to wind, traffic loads or seismic effects) but adding them will generate significant additional torsions in the rib, which is undesirable.

Figure 4
South Holland Bridge, Lincolnshire, UK

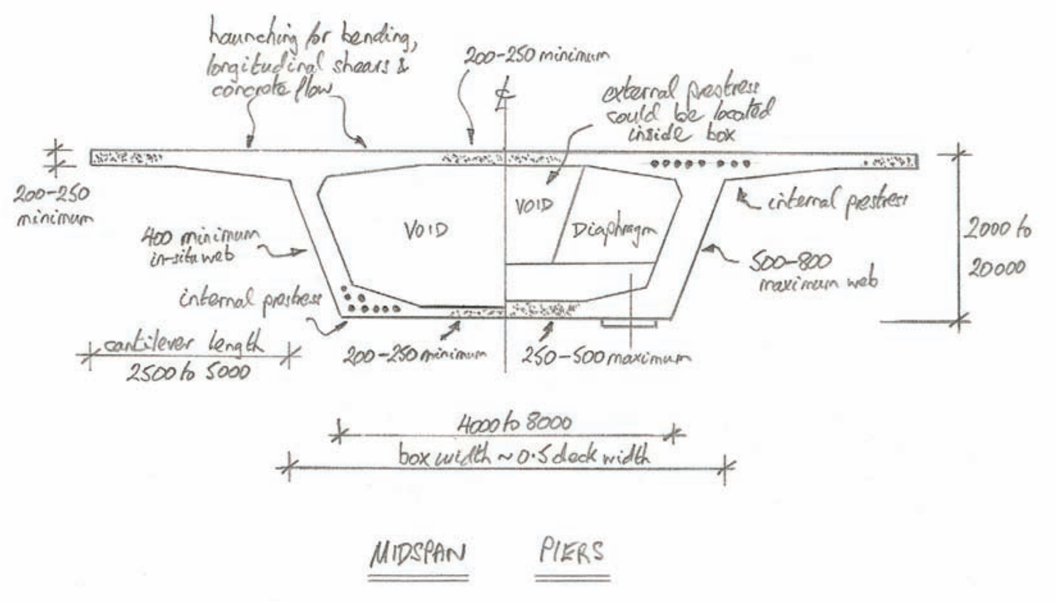

Figure 5 ***In situ* box section**

Figure 6 **River Taw Bridge, Devon, UK**

Diaphragms are also a nuisance for the construction process as they prevent the easy use of the soffit forms, and thus should only be used at the ends of the bridge. The ribs are sized to provide torsional stiffness and will generally be at least 800mm wide, but they may be 1.5-2m wide. The ribs are best spaced across the width such that there is no permanent torsion on the rib; splitting the width approximately in the ratios 0.22:0.56:0.22. The soffit of each rib is generally the critical area for the design, both at SLS and ULS.

As with *in situ* slab bridges, twin ribs are usually cast span by span in one continuous pour. For shorter lengths, the falsework would be the same as used for slab bridges, i.e. scaffolding. Once a large enough area of deck exists (>10-20,000m^2), it becomes economic to mechanise the process by using a gantry falsework system, which spans from pier to pier, or from the previously built deck to the next pier. Steel would then be used for the formwork for these 20-50m long pours, as the material can accommodate the casting of 20-100 units. These gantries can be either overhead or underslung, and be as mechanised as the project allows.

The simple soffit of the deck makes the formwork, fixing and concreting easy. The deck is more economical than a slab in terms of concrete, though it is still relatively expensive in terms of prestressing, due to the eccentric load distribution and section efficiency both being inferior, when compared to a box section. Overall, bridges of this nature still have relatively low construction costs, depending on the degree of access.

In situ span by span box bridges

In situ box girder bridges have a very efficient section but the internal shape of the box does cause some issues with the casting process. Typical spans range from 30-80m and prestressing is always used. Span to depth ratios for highway bridges are typically 16-22. Even though they have a more complex cross-section (Figure 5), box girder bridges represent a good solution for many sites, with a clean aesthetic. If a scaffold system is being used as the falsework, then they are best suited to low sites over land, but once a travelling gantry system is being used, they are suited to all sites.

The minimum slab thicknesses are 200-250mm. The top slab is primarily governed by transverse bending effects from traffic, and therefore the slab thickness increases over the webs. The webs would generally be positioned at about ¼ points of the deck width. Typical rules of thumb for a highway bridge would show a top slab thickness over the webs of (cantilever length)/8 or (box width)/16-18, both of which generate about the same figure. This greater thickness helps the flow of concrete during casting, and is also a means of creating an area at the top of the webs where internal cables can be located. This haunching of the slab also controls longitudinal shears. The variable depth of the top slab therefore serves multiple purposes, though the longitudinal compressions in the top slab at midspan rarely govern this thickness, as the deck width is invariably sufficient to control these stresses.

For ease of casting, the webs of the box should ideally be vertical, though inclined webs are much more elegant. Such shapes also reduce the width of the bottom slab, which is beneficial in self-weight as it rarely needs to be as wide as the top of the box. The minimum web thickness for an *in situ* box is about 400mm for both concreting purposes and the use of internal vibrators. The web thickness is then governed by shear and torsion at the pier locations, where the typical thickness increases to 500-800mm. The only requirement for the bottom slab at midspan is to close the torsion box – the slab is therefore best kept as narrow and slender as the codes allow. It should still be thickened where it connects to the web to help the flow of concrete during casting and to provide a location where internal cables might be located. At the pier locations, the slab may need to be thickened to carry the longitudinal compressions, though it rarely needs to be more than about 500mm thick. Diaphragms are only ever needed at pier locations and should generally never be used in the span, as the distortional behaviour of a concrete box is rigid enough.

The easiest form to create is a single-cell box, which can accommodate widths up to about 20m. Boxes generally need internal access for both maintenance and stressing operations; meaning they should be at least 2m deep, which determines the minimum span of about 30m. Multi-cell boxes, though possible in some locations, should be avoided wherever possible as they are awkward to construct, with too many pours and difficulties in operating the many internal shutters (unless each cell is made at least 4m wide). They also tend to have too much web and bottom slab, making them inefficient in self-weight and prestressing.

As with *in situ* slabs and twin ribs, these boxes are usually cast span by span. For shorter lengths of bridge, timber forms supported on scaffolding would be used. As previously noted, such bridges are quite rare, as the box section has to be cast in two or three phases; generally bottom slab and webs, followed by top slab. However, it is quite difficult to move the long lengths of internal shutter that form the inside of the box, making the operation slow and more expensive.

The deck is very economical in terms of concrete and prestressing, due to the excellent eccentric load distribution and section efficiency. Overall though, the box section makes the formwork, fixing and concreting more complex, which is often reflected in higher construction costs.

In situ balanced cantilever bridges

The issues related to casting long lengths of box are resolved in this method by casting the bridge in short lengths. Typical spans range from 40-300m and by definition, are always continuous. Span to depth ratios for highway bridges are typically 18-20 for constant depth schemes. However, variable depth is very common and would generally be a necessity for all spans over about 60m (Figure 6). In this case, span to depth ratios for highway bridges are typically 12-18 at the pier locations and 25-40 at midspan.

Each box section is cast within a travelling formwork/falsework frame (known as a 'traveller'), which needs a minimum deck area of about 3,000m^2 to justify its procurement. Ideally, to simplify the formwork, the bridge should be of constant width. The aesthetics are very good, particularly with variable depth girders and inclined webs. The method is well suited to all sites, especially ones with poor access from below. *In situ* balanced cantilever bridges are used extensively worldwide and are ideally suited to the typical 3-span or 5-span crossings of a river - locations where the cost of conventional falsework can be prohibitive.

Figure 8
River Dee Viaduct, UK: balanced cantilever pair

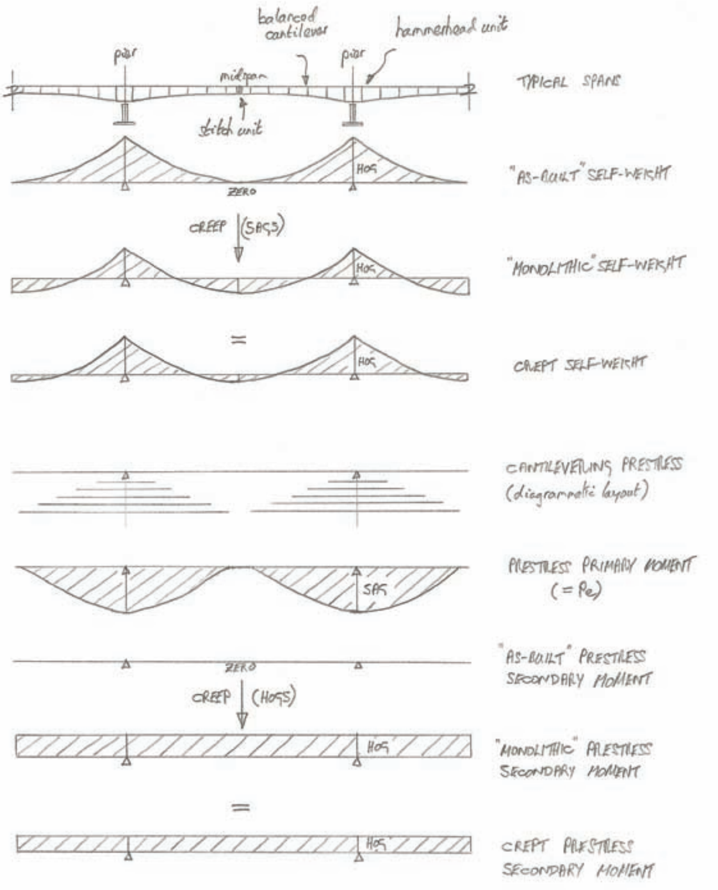

Figure 7
Creep of moments

The sizing of the box girder is as described previously. The section is again best developed as a single-cell box, with each 3-5m long unit poured in one complete operation. The maximum box width is also about 20m but the minimum box depth is now 2.5m to allow easy use of the internal formwork. Ideally, the webs of the box should be vertical as this allows better use of the side shutters with a constant width bottom slab. Inclined webs, however, are much more elegant and often used, even though the bottom slab formwork has to accommodate a variation in width. As each new pair of units is cast, the balanced cantilever grows until it reaches the midspan of each adjacent span. The self-weight of the bridge is thus primarily produced while the bridge is statically determinate. Significant creep of these as-built moments then occurs as the bridge creeps toward moments that would have existed if it had been built in one phase, i.e. monolithic moments. There will also be significant creep of the prestressing secondary moments. Fortunately, the creep of the self-weight and the secondary prestressing moments is in the opposite direction, negating the need for too much precision in the calculation of the creep factor (Figure 7), unless the spans are very large.

Each pair of units is cast either side of the pier location – typically on a weekly cycle – to create a balanced cantilever (Figure 8). The unit formwork is generally supported from an overhead traveller that is attached to the end of the last unit. Formwork is generally plywood as each traveller will cast 10-50 units. Underslung travellers, which keep the top of the deck clear, are also used as they allow the unit reinforcement cage to be pre-fabricated and lifted in as a single piece. This allows the casting cycle to be reduced to less than a week, though at the cost of a more expensive traveller. In most cases, the pair of units is cast on a Friday and left to cure over the weekend, allowing the deck to be prestressed on the following Monday. The travellers can then be moved forward on Monday afternoon. Cantilevering prestress is applied to each balanced pair until the whole cantilever is complete.

The entire construction cycle tends to be operated by a composite gang of labour who do all the traveller operations, rebar fixing, stressing and grouting, with additional labour used for the weekly concreting phase. As each traveller is a mechanised piece of formwork/falsework, it needs to be operated with a careful sequence of striking, moving, fixing and casting. There are many operations in each cycle, which require a thorough set of checking and signing-off procedures to ensure safe use. Construction starts from the top of a pier with a 4-12m long hammerhead unit that is cast on a falsework system that sits on the permanent foundations or is supported off the piers (Figure 9). This unit then forms the initial platform for the travellers (Figure 10), while temporary props are used to provide stability to the balanced cantilever until further continuity of the spans is achieved. Once two cantilevers meet at midspan, a stitch unit is poured to close the span. The same travellers are used to form this stitch unit, though additional falsework is also required to hold the cantilever ends stable during the pour. Once continuity is made and the stitch concrete is up to strength, further prestressing cables are added and stressed across each span to make the bridge continuous. Similarly, end span units are cast to reach the abutments, thus completing the whole bridge length.

The main advantage of *in situ* balanced cantilever construction is the use of a bespoke travelling formwork system that is used many times on a regular production line cycle, obviating the need for falsework from the ground. Construction can also be started at several piers at the same time, thus reducing the programme further. The deck is also economical in terms of concrete and prestressing. Thus, *in situ* balanced cantilevering should deliver very competitive construction costs.


Figure 9 Hammerhead unit cast on scaffolding: River Taw Bridge


Figure 10 River Taw Bridge: hammerhead unit with travellers

Conclusions

Various methods for the *in situ* construction of concrete bridges have been described, which allow both the smallest and simplest slab bridges, and the biggest and most complex beam bridges in the world, to be built.

Subsequent articles will examine more precast bridge types in greater detail. A forthcoming CBDG Technical Guide (TG 14) will contain further information about the detailed programming and costing of 15 different *in situ* and precast bridge types, including the ones described here, allowing teams to select the best bridge solution at an early stage.

References and further reading

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3) Concrete Bridge Development Group (2014) 'Concrete Bridge Design and Construction series No.3: Prestressing for concrete bridges', *The Structural Engineer*, 92 (3), pp. 48-52

4) Concrete Bridge Development Group (2014) 'Concrete Bridge Design and Construction series No.4: Types of concrete bridge', *The Structural Engineer*, 92 (4), pp. 45-50

5) Concrete Bridge Development Group (2014) 'Concrete Bridge Design and Construction series No.5: Concrete bridge formwork and falsework', *The Structural Engineer*, 92 (5), pp. 42-46

6) Concrete Bridge Development Group (2005) *Technical Guide No. 5: Fast Construction of Concrete Bridges*, CBDG and The Concrete Society: Camberley, UK

Further reading

Benaim R. (2008) *The Design of Prestressed Concrete Bridges, Concepts and Principles*, Abingdon, UK: Taylor & Francis

Concrete Bridge Development Group (2014) *Technical Guide No. 14: Best construction methods for concrete bridge decks*, Camberley, UK: CBDG (publication in 2014)