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. 4: Types of concrete bridge

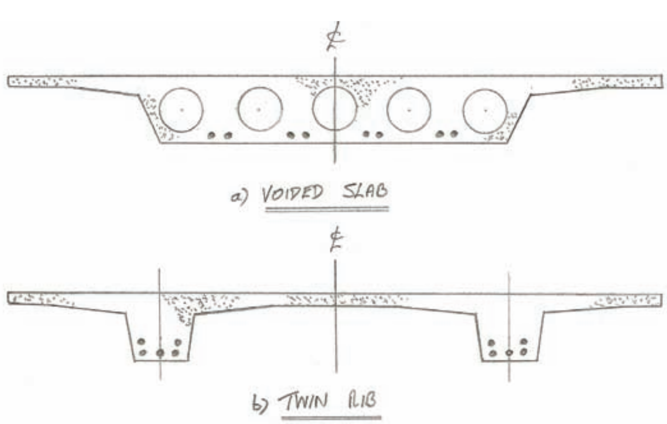

Figure 1
In situ voided slab and twin rib

Introduction

This article examines the selection process for the most suitable type of concrete bridge. The general parameters of the scheme such as typical spans, overall deck area, clearance requirements, alignment and the overall aesthetic will start to suggest which type of bridge deck and construction methods might be appropriate. However, the final choice will depend on other particular parameters, many of which could be related to construction, programme and cost. The CBDG's forthcoming *Technical Guide No. 14: Best construction methods for concrete bridge decks* will give further information about all these key parameters, especially programme and cost.

Bridge types

There are several types of concrete bridge deck, each of which should be used in different circumstances. The two key parameters used in selecting a bridge type are the construction method and the typical span, though many other parameters come in to play. Table 1 in Part 1 of this series[1] shows a layout of Bridge Types vs Span, which gives a broad outline of the options. The bridge types may be split into the following *in situ* and precast options:

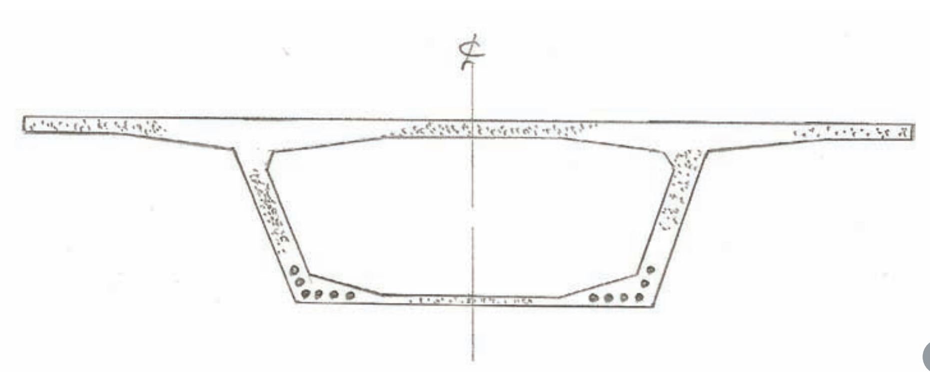

Figure 2
In situ or precast box girder

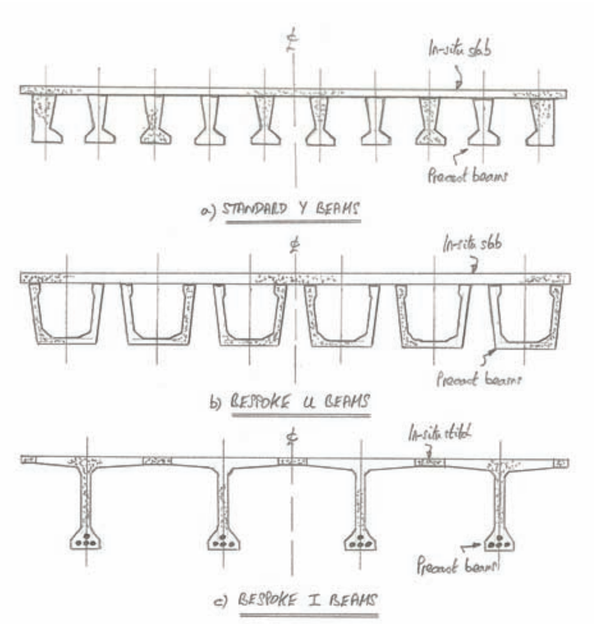

Figure 3
Standard and bespoke precast beams

Figure 5
Casting a concrete beam (Banagher Precast Concrete)

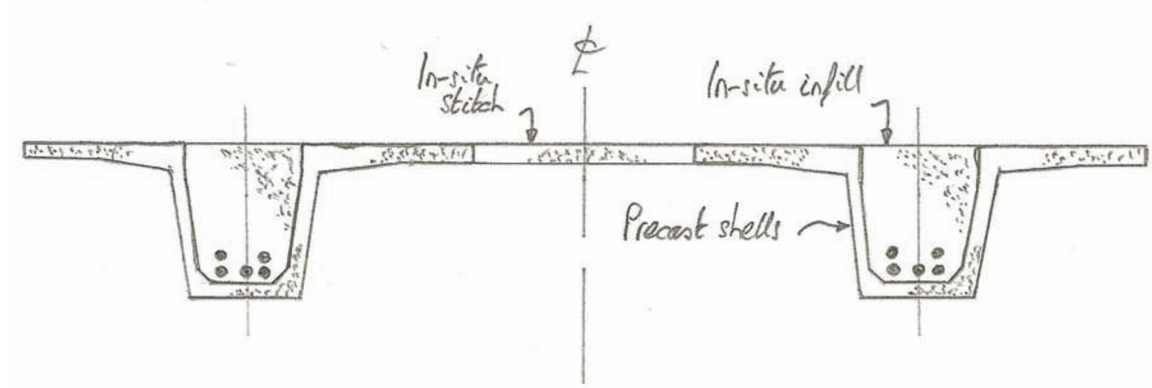

Figure 4
Modular precast shells with *in situ* infill

- ***In situ* solid or voided slab** – cast on a scaffold system or a series of beams/girders
- ***In situ* twin rib** – cast on scaffold/beams or using travelling gantries
- ***In situ* span by span box girder** – cast on scaffold/beams or using travelling gantries
- ***In situ* balanced cantilever** – short box sections cast using a travelling formwork system

- **Standard precast beam** – inverted T/Y or U beams erected by crane
- **Bespoke precast beam** – T, I or U beams erected by crane or using a gantry system
- **Precast segmental box girder** – short segments erected with cranes or gantries
- **Whole span precast box girder** – erected span by span with gantries
- **Incrementally launched box girder** – erected using sliding equipment
- **Modular precast** – short shell segments erected on scaffold/beams or launched into place

Basic cross-sections of each type are shown in Figures 1-4. Further details of these bridge types will be provided in future articles.

Selection of bridge type

It is often the construction method that determines the actual design solution, as no bridge can really be designed without knowing how it will be built. The construction method influences the forces in the bridge deck, as well as shaping the cross-section and many of its details. It is also determined by the site constraints, with the overall programme and the speed of the actual construction method playing a key part in the breakdown of cost. Ultimately, it is the optimum cost solution that will be built, but a skilful team should ensure that this solution is also the same scheme that delivers best value to the owner.

The deck construction process can be split in to three broad stages; casting, transportation and erection. Casting relates to the formwork and mould issues (and to the falsework for *in situ* schemes), all of which will be covered in the next article. It also relates to the choice between *in situ* and precast bridge options, which were discussed in

Figure 6
Transporting a concrete beam (Afon Hydfron Bridge, UK)

a previous article[1]. Casting (Figure 5) needs to consider the amount of land that is made available for casting areas and storage of any units. Transportation relates to the precast options, all of which involve the movement of units from the casting area to the erection area. This will involve the use of low-loaders, straddle-carriers, wheeled-bogies or rail systems (Figure 6). Erection entails the use of mobile or site cranes, or various falseworks, to move and then support the precast units (Figure 7). These falseworks will be in the form of scaffolds, beams, girders or trusses that need to travel from span to span as the construction evolves. This movement can be via a dismantling and re-erection process, or by using gantry systems that travel forward. The bridge and all its falsework must remain stable during all these operations, which will often need several other items of temporary works to ensure that stability is not compromised or that the permanent works are not adversely affected.

Access for all these items of construction plant is important for both buildability and the speed of construction, with the ease and degree of access being crucial to the way in which the project is programmed. The programme will also need to take account of utility diversions or installations, and any traffic management, which can be either on the bridge, over it or underneath it. The particular supply of materials, labour and plant will vary from site to site, and in relation to the site's remoteness.

Programme issues

Many of the choices concerning which bridge deck to use are driven by the need to increase the speed and simplicity of the construction process. Faster construction also leads to cost savings through reduction in the duration of the overheads, and thus any steps to improve the speed will also generate savings over and above the overall operational benefits. Alternatively, faster construction may be driven by the need to minimise disruption to traffic or other users. In extreme cases, more expensive construction methods might be adopted in order to realise such benefits, e.g. within the railway environment, where possessions are very costly. Many of these topics are discussed in more detail in CBDG TG 5[2].

Design decisions must be made with buildability in mind and thus the involvement of construction team members during the design process (such as in 'design and construct' contracts) will yield significant benefits. The resulting details will reflect the contractor's requirements, while safety issues can be better recognised and the cost implications of decisions can be readily assessed. Sufficient time must be allowed for designers, contractors, sub-contractors and suppliers to adequately design, plan and execute the scheme in relation to any restrictions. The owner will be an essential part of this process and will have an active part in the discussions, resolving any issues with third parties. Simplicity is a key element for efficiency - simple and standardised detailing should allow easier and more rapid construction.

Reinforcement rationalisation should eliminate unnecessary variation by simplifying, reducing complexity and taking advantage of the opportunities provided by prefabrication. The team should identify typical reinforcement arrangements that will be suitable for many elements. Though this process may lead to some over-design, there will be subsequent economies in terms of the ease and speed of fixing the reinforcement. Prefabricated cages can be made on site, in timber or steel jigs, to allow the precise positioning of every bar. Cages can be produced in a factory environment, with repetitive and safe operations, and then lifted straight in to the mould (Figure 8). Welded cages are rarely used in bridge decks due to the fatigue issues, though some welding can help to stiffen the cage. The careful integration of prestressing anchorages and ducts within the cage is crucial. Such areas can become congested, and each bar is best

Figure 7 Erecting a concrete beam (Southern Ring Road, Limerick, Ireland)

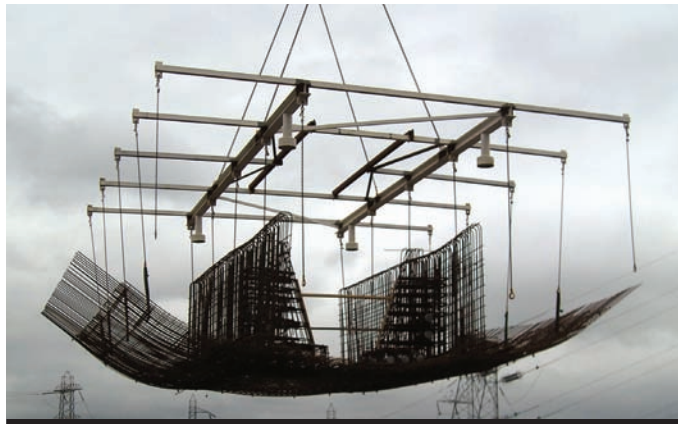

Figure 8 Clackmannanshire Bridge, UK: reinforcement cage assembly

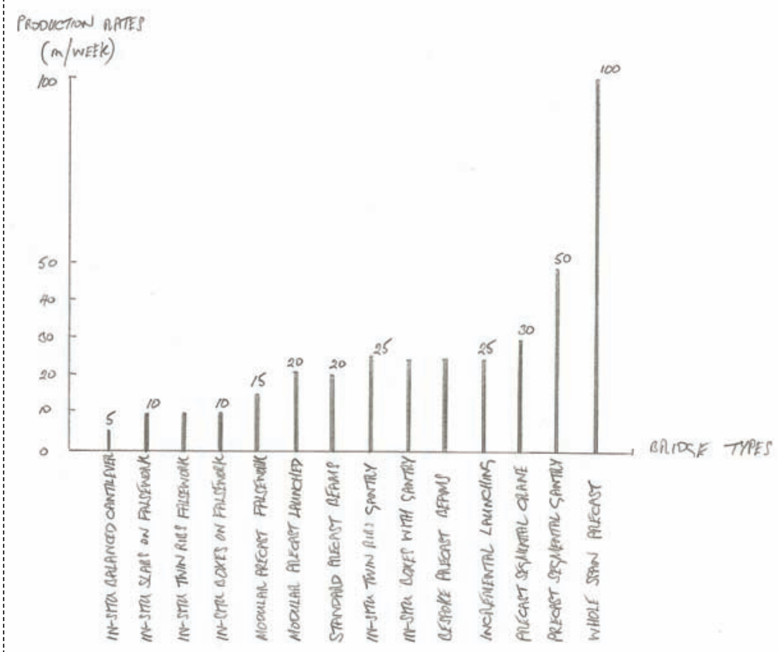

Figure 9 Typical production rates (by bridge type)

designed and detailed by sketches or 3D models, to ensure that they can all be placed with speed and ease.

Connections between precast units and *in-situ* concrete, or between *in situ* concrete pours, will require lengths of reinforcing bar projecting from the elements, which then need to be lapped. The detailing of these 'starter' bars needs as much care as other congested areas, as they can form both a hazard and a hindrance to site operations. The temptation for operatives to bend any high-yield steel bars out of the way must be avoided, in order to prevent unacceptable stresses in these bars. Mild steel 'bend-out' bars are still used in some countries, but in Europe it is more common for couplers to be used. Couplers can play a major role in allowing fixing operations to be safe, easy and rapid, though they can be expensive and should only be used when all the implications are understood. Various types of coupler are available, though the most common are threaded, requiring the ends of both bars to be machined. These couplers have a relatively poor fatigue performance and should not be used in areas close to repeated traffic loads. Couplers have a diameter that is larger than the bar itself, which must be accommodated in the detailing.

Road closures, or railway possessions can significantly affect the speed of construction. On a railway (or waterway), the usual method is to close the route for the duration of the works, whereas on a highway, it is more common to divert traffic. Such closures or diversions have to be arranged many months in advance, and so the role of the owner is again crucial. Railway possessions may need 12 months' notice, or more, whereas highway diversions may need only 2 months' notice, though on major routes this may be closer to 6-12 months. The phasing of the works to suit these diversions or closures should be carefully considered at an early stage, otherwise several methods might become impractical. A single box across the whole carriageway would not be possible, for example, if the highway needed to be built in two phases, and an alternative beam section might be preferred.

The forthcoming CBDG TG 14 has been prepared by examining typical production rates for all concrete bridge types. These have been based on comparisons to multiple sources of data from bridge schemes worldwide. As a starting point, Figure 9 shows typical production rates (in m/week) for each bridge type. In order to examine the overall programme, it is also necessary to include mobilisation, substructure, finishes and a learning curve for the production. Learning curves generally add around 25% to the production; varying from 10-15% for projects with many cycles, to over 50% for projects with limited cycles. One of the benefits of precast solutions is the ability to cast the deck before, or at the

Figure 10
Blackwater Viaduct, Ireland during launch

same time as, the substructure. Only the deck erection needs to wait for the substructure to be finished, or partly finished. So for precast schemes, there is also the need to assess the casting rates (with a learning curve too) – the balance between the casting and erection rates then determines the amount of storage needed for the precast units, or vice versa. The production rates vary from 5m/week for the relatively slow balanced cantilever method (which can be accelerated by using multiple sets of travellers) to >100m/week for the sophisticated whole span precast system.

Risk issues

The whole team need to ensure that the project falls within the health and safety regime of the particular site, though best practices should always be used in all locations. Whatever decisions are made on the various construction methods, their adoption must never compromise site safety. Besides the usual factors related to working with concrete, there will be others relating to the construction method, such as working next to traffic, stability of temporary works, or transportation and erection of heavy elements, including working at night or in adverse weather conditions. Factory methods that form part of many techniques can significantly improve the safety regime by shifting the works to a more regular and controlled series of operations, with a workforce who have become familiar with the process. Many of the methods also reduce the need to work at height, by using cranes or other heavy lifting equipment. Launching techniques in particular, require limited numbers of men to work at height, as the majority of activities take place behind an abutment (Figure 10).

To address these issues, the owner should adopt a formal approach to health and safety, and to risk management, and share all this information with the designer and contractor, who will also use it throughout their considerations. Health and safety risk assessments need to consider the residual risks related to construction, operation, maintenance and demolition of the bridge. But commercial risk assessments should also be considered, where factors are applied to both the programme and costs in order to achieve greater surety of safety, quality, delivery and final price.

Cost issues

The deck quantities should always be checked against historic data for typical bridges. It is easy to calculate the effective thickness of the deck, defined as the total concrete volume divided by the total deck area. Charts exist in a number of publications[3-5] which show a reasonably linear relationship between effective thickness and typical span. For typical highway (or light rail/metro) bridges, the effective thickness (mm) is approximately $350 + 4.5L$, where L is the typical span (m). So, for spans ranging between 30-60m, the effective thickness of an efficient box or beam section should be 500-600mm. Great care needs to be exercised with such simple rules, but in the hands of experienced bridge engineers, it is a useful means of checking the quantities. The figure can easily vary by +/- 100mm, depending on local conditions and bridge types. Heavy or high-speed rail bridges, or bridges with unusual traffic loads, will have a greater thickness. The quantities of prestressing and reinforcement can be expressed in kg/m^3, i.e. the total tonnage divided by the total deck concrete volume. The prestressing rate is generally independent of span and is around $45kg/m^3$, with a typical range of +/- $10kg/m^3$. This figure equates to fully prestressed highway bridge decks – it will be less for partially prestressed decks and more for more heavily loaded decks. This figure directly relates to the average axial prestress of the section, which is generally $4\text{-}7MN/m^2$. The reinforcement rate also tends to be independent of span, with values of 170-200 kg/m^3 for fully prestressed decks with internal cables (or 200-230 kg/m^3 for external cables). The rates will be 120-170kg/m^3 for sections with a higher effective thickness. These rates increase for partially prestressed decks, where the longitudinal reinforcement is also used to carry loads. Once there is no prestress, and the section becomes reinforced concrete, the rates will be 200-300 kg/m^3 or more.

Once the quantities are confirmed, it is possible to calculate the costs of the bridge deck. The concrete, reinforcement and prestressing rates to be used are the gross rates inclusive of all elements, i.e. to include material, supply, and the labour for the placing or fixing – this includes all the ducts, anchorages, jacking and grouting for the prestressing. Approx. rates in the UK are:

- Concrete - £120/m^3
- Reinforcement - £1,100/t
- Prestressing - £3,000/t

However, the main difficulty with concrete bridge decks is the pricing of all the works necessary to get the concrete into place, i.e. the combined cost of the formwork and falsework. The difficulty arises because there are a large number of different construction methods available, each one needing to be priced separately. Such a combined formwork/falsework rate needs to be calculated using the breakdown of the principal stages in the construction process:

- Casting – moulds/formworks, precast factory/storage, falseworks, labour, cranes/gantries
- Transport – vehicles, labour, cranes
- Erection – falseworks, beams/girders, towers, jacks, labour, cranes/gantries

The typical range of these combined formwork/falsework costs is currently £50-150/m^2 of the total formwork area. The wide range in these costs and lack of available data, is addressed in the forthcoming TG 14, which will define the details, programmes and formwork/falsework costs for a range of fifteen different concrete bridge decks. These cover all the options previously described. Each option, priced with the assistance of the chief estimators at Bam Nuttall, is shown as a 15m wide deck with a length dependent on the minimum desirable length for each of the particular construction methods. The total price for each scheme has then been converted back into typical formwork/falsework rates, which can be applied to the total formwork area. The rates are then shown as they might be applied to a 50m, 150m or 600m long bridge, allowing teams to pick the most suitable rate for their project. So, in conjunction with the concrete, reinforcement and prestressing rates, teams will now be able to price the full range of suitable concrete bridge decks, for any size of scheme. For detailed pricing, a thorough programme and cost exercise would still need to be carried out, but these broad rates will allow teams to consider all the options at an early stage. Often in the UK, concrete schemes have been too readily dismissed, or not considered, as teams did not have any reliable cost information. All these rates can be adjusted *pro rata* over time or into different locations, to suit the prevailing conditions in each market.

In order to make comparisons with other schemes, especially lighter steel-composite bridges, the substructure costs should also be included. Rates for these items are well defined and there is no need to discuss them further here. In general though, the differences in substructure costs between concrete and steel-composite decks are not as large as might be thought. Even if the self-weight of a steel-composite deck is close to half that of concrete, the combined differences at foundation level (including finishes, eccentric traffic loads, lateral loads and substructure loads) are usually only 15-20%. As the substructure might represent about 30% of the total bridge cost, the effects of the reduced weight of the steel scheme are then only around 5%, which certainly needs to be accommodated but is not dominant.

Finally, if a real cost estimate is needed, rather than just a comparison in order to select a solution, the costs need to be factored for preliminaries, overheads and profit. Such factors might add another 25-40%. It is then useful to check the overall cost of the bridge per m^2 of deck area. These costs/m^2 vary reasonably linearly with typical span, but are very dependent on bridge types and local conditions. Very roughly, total bridge costs (£/m^2) are currently about 1,000 + 15L, where L is the typical span (m). These figures apply up to spans of about 150m and need to be treated with great caution as the variation could easily exceed +/- 25%. Beyond 200m spans, the costs become closer to 1,000 + 10L.

Conclusions

Construction methods have been shown to play a huge role in the selection of the most appropriate bridge types, with the detailed assessment of the programme having a major influence on the final costs. The CBDG's forthcoming Technical Guide (TG 14) shows a detailed breakdown of the critical formwork and falsework costs, allowing teams to select suitable concrete bridge types at the very earliest stages of the project. Concrete is used for the majority of bridges worldwide as its competitive initial construction costs are coupled with low levels of inspection and maintenance, ensuring a very attractive whole-life cost for the owner. Future articles in this series will examine the whole range of particular bridge types in more detail.

References and further reading

1) Concrete Bridge Development Group (2014) 'Concrete Bridge Design and Construction series No. 1: Introduction to concrete bridges', *The Structural Engineer*, 92 (1), pp.41-46

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

3) Menn C. (1990) *Prestressed Concrete Bridges*, Berlin, Germany: Birkhauser

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

5) Hewson N. (2012) *Prestressed Concrete Bridges, Design and Construction*, London, UK: Thomas Telford

Further reading

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