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. 2: Concrete bridge layouts

Figure 1
Blackwater Viaduct: example of straight launched bridge

Introduction

This second article from the Concrete Bridge Development Group's technical committee, examines the initial parameters that might determine the best layout for a new bridge.

The owner will have described the basic requirements in relation to establishing the best location for the bridge. This choice of location will be governed by the type of crossing that is required (highway, railway or footbridge), and over what sort of obstacles the bridge needs to cross (water, highways, railways or utilities). The alignment of the bridge, and the required loadings that it has to carry, are likely to be determined at this early stage too. Careful thought about the best construction methods must also be accommodated even at this stage, as several perfectly sound methods might be eliminated through an inappropriate early decision. For example, a launched bridge scheme (Figure 1) might be excluded if the alignment is made too complex. Or, if only one short end of the bridge needs to be widened to carry a slip road, then the costs of the project are likely to be considerably more as the bridge deck will need to be made flexible enough to allow for such a variation. It may be much better to re-consider the alignment and road layout in order to produce a bridge that can be made more uniform and repetitive, and thus become more economical.

In simple terms, it is the deck area and the length of the typical span that determine many of the bridge options. Larger schemes (e.g. those with deck areas over 10,000m^2) can accommodate several methods (such as precast segmental techniques) that would be inappropriate for smaller deck areas. The range of construction methods for bridges with typical spans between 50m and 100m (such as *in-situ* or precast balanced cantilevers) can be quite different to those with spans between 20m and 50m (such as *in-situ* slabs or beams, or precast beams).

The availability of sufficient working access and space can also help to simplify and speed up the construction process. The owner should therefore be aware of all the available construction methods (such as the need for on-site casting and storage areas), as these issues could easily determine the amount of land that needs to be purchased, or temporarily acquired.

Opportunity should therefore be made for involvement from the whole team (owner, designer and contractor) at this early stage, so that decisions are made with a clear understanding of all the issues, with the owner's priorities being fully understood. The owner should try to leave as many of the parameters as flexible as possible, such that the designer and contractor can consider all the available construction methods – this strategy will lead to the optimum solution. A forthcoming CBDG Technical Guide (due to be published this year) will highlight many of these key construction issues, and how the programme and costs might vary between different bridge options.

Figure 2 Medway Crossing Viaducts: 152m spans over deep water

Figure 3 STAR LRTS Viaducts, Kuala Lumpur: 35m spans over land

Spans, articulation and fixity

Span layouts can often be determined by the obstacles that are being crossed, but it is then generally possible to rationalise the spans to generate either a more typical layout throughout, or a more aesthetically pleasing one, or ideally both. Decisions taken at this stage will fundamentally affect all future components of the scheme and it is therefore imperative that they are taken by the most skilful and experienced engineers in the team, who appreciate the impact upon the overall value of the project, to both the owner and society.

Pier locations should be chosen to be clear of water wherever possible, both to avoid the need for cofferdams or other marine works, and to reduce the restrictive effects on navigation, wildlife, floods or tidal variations. Columns that are positioned well clear (more than 5.7m) of highways and railways can also be designed without the additional costs of impact forces.

The overall substructure layout will also affect the best choice of bridge type. The wide range of available foundation and pier options are well documented in other publications[1-2], and are hugely dependent on the precise and particular geology of the bridge location. The costs and programme for particular substructure options will need to be considered in the overall package of options, which will ultimately allow the most suitable bridge type to be chosen. In areas of difficult foundations, such as over deep water, the bridge tends to be optimised with longer spans over about 80m (and up to 300m or more) (Figure 2). Intermediate spans of 50-80m tend to be used in poorer ground or over shallow water. In areas of easy foundations, such as over land and good ground, the spans tend to be 20-50m (Figure 3).

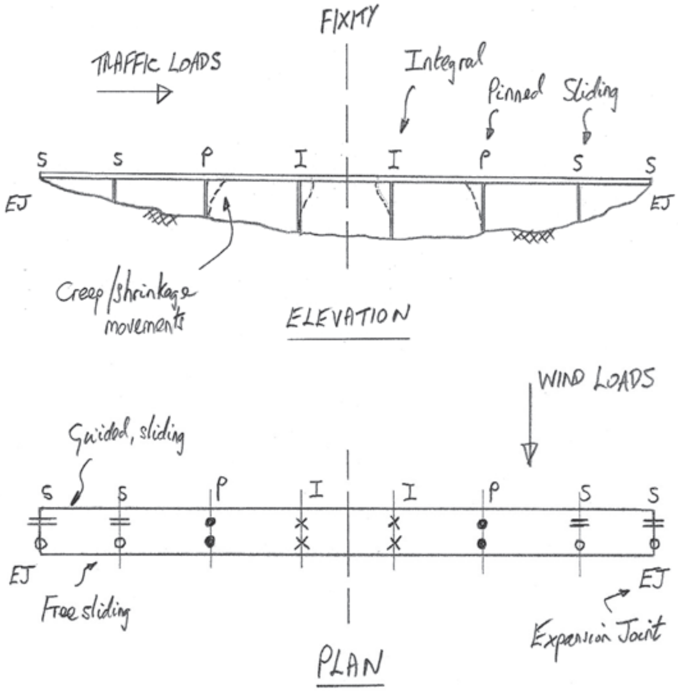
These shorter 20-50m spans are best progressed as *in-situ* slabs or twin-ribs, precast beams, *in-situ* boxes, precast segmental or incrementally launched boxes, whole span precast units or as the modular precast concrete bridge. The intermediate 50-80m spans are best as *in-situ*, precast segmental or incrementally launched boxes, whole-span precast units or as *in-situ* balanced cantilever boxes. The longer spans (over 80m) are best as *in-situ* or precast balanced cantilever boxes, or as extradosed or cable-stayed schemes. It is common with long bridges with regular spans, for the span to be chosen by the foundation size and type. For example, where a particular pile cap solution works well with four 1.5m diameter bored piles, or even with a single 2.5m diameter pile, it may be best to select the span to exactly match the capacity of that foundation.

Concrete bridges expand and contract with temperature changes; they shorten under creep and shrinkage, and they deflect under applied loads, prestress and temperature gradients. However, bridges also need to be held safely in all directions at all times, including during construction, when subjected to wind, traffic forces, seismic activity or various impact loads. The articulation of a bridge is therefore the measures taken to control its overall position while allowing it to move and deflect.

Most bridge decks are generally best fixed transversely at all piers, usually with a guided, sliding bearing that allows longitudinal movement but is rigid transversely. Longitudinally, it is often best to fix the deck upon a central pier, or group of piers – this minimises the differential friction forces that arise from the group of sliding bearings and equalises the movements at each end (Figure 4).

Alternatively, the bridge can be fixed at one of the abutments, which does enable all the piers to be kept quite slender. However, this option significantly increases the longitudinal fixing forces (as the fixed bearings have to carry the sum of all the friction forces on all the other bearings) and concentrates them at a location where the vertical reactions are small, which can make it much more difficult to accommodate the fixity.

Figure 4 Fixity and bearings



In seismic regions, shock absorbers can be used – these allow normal movements under creep, shrinkage and temperature, but lock up under seismic accelerations, thus spreading the load over more of the substructure. Alternatively, one can isolate the deck from the substructure with the use of elastomeric bearings. The thickness, and hence the shear stiffness, of each bearing can be adjusted such that, in combination with the elasticity of the piers and foundations, the distribution of all the longitudinal forces is under control.

Joints and bearings

Bridges are generally best formed as continuous structures with no joints, other than at the ends. If the deck is very long, it may be necessary to divide it into several expansion lengths by using intermediate joints. Concrete highway viaducts can often be more than 1km in length, without intermediate joints, with the longest in the UK believed to be 1.75km (Figure 5). This absence of joints also provides a better ride quality and structural performance through the redundancy. As such, the distance between structural expansion joints on highway bridges should be maximised wherever possible. The railway environment is different, as more frequent joints in the structure are often preferred so as to eliminate any rail joints, which can be expensive and need regular maintenance.

Some construction methods are better suited to forming simple spans, such as when standard or bespoke precast beams are used. But even schemes that are built as a series of simple spans can be subsequently joined together to reduce the number of joints – this might be via a structural connection that then makes the whole deck depth continuous, or it might be via a system that makes only the deck slab continuous. This latter option is common, with long viaducts built using whole span precast units where the main structure remains determinate but the deck slab becomes continuous, allowing a better road surface by eliminating the joints.

For prestressed concrete bridges, it can be shown that the balance between using either simple or continuous spans is quite close for spans around 25-50m, though continuity generally saves prestress. This better performance of a continuous deck in distributing loads is partly eroded by the secondary effects that arise from continuity, such as differential settlement and temperature. However, the choice of the most appropriate construction method will generally dictate the best solution. For spans over about 50m, concrete bridges should always be continuous.

The elimination of joints should be high on the designer's list of priorities, as historically they have been the source of many bridge maintenance issues. Joints also need to be inspected regularly, requiring good access and space beneath the joint for this purpose. CBDG CPS 5[3] gives details of the various expansion joint options and CBDG TP 6[4] gives details about the formation of sound concrete joints.

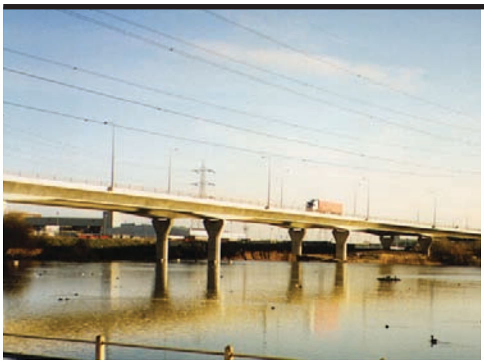


Figure 5 A13 West of Heathway Viaduct: 1.75km long with only end joints

Figure 6 River Dee Viaduct: built-in central piers

Figure 7 Pinned bearing: Broadmeadow Estuary Bridge

It is generally beneficial to also reduce the number of bearings, both to enhance durability and to reduce the maintenance. In areas that are close to the longitudinal fixity, bearings can generally be eliminated and, as long as the piers are flexible or made flexible enough, the deck can be built in to the pier and made integral (Figure 6). Though this detail may appear to be more complex from a construction point of view, it can also provide significant additional stability during the temporary phases of the construction. At greater distances from the fixity, it will be possible to fix the deck using pinned bearings, and only when the piers are more than 50-100m away from the fixity will it finally be necessary to provide sliding bearings, dependent on the pier height and flexibility. Once bearings are required, pinned bearings are the most economical solution, having the least amount of mechanical components (Figure 7). Sliding bearings are necessarily more complex, requiring a polytetrafluoroethylene (PTFE) top to the bearing and a stainless steel plate attached to the deck soffit, both of which work together to form the low-friction sliding surface, which usually has a design friction of 4-5%. Guided, sliding bearings are yet more complex as they also need to carry transverse forces. Any bearings that are chosen should be of the simplest variety, with a strong preference to use rubber pot or elastomeric bearings as opposed to the more mechanical types. Good access for inspection and maintenance of the bearings must always be provided, including the need to provide space, and adequate strength, for the jacking operations that will be needed to replace the bearings. Bearings (and joints) have a much shorter life (20-30 years) than the life of a bridge.

Integral bridges

The ultimate development in the thinking behind eliminating joints and bearings, is to make the bridge integral. As noted previously, integral piers are required to be flexible enough to accommodate the

Figure 8
Various types of integral abutment

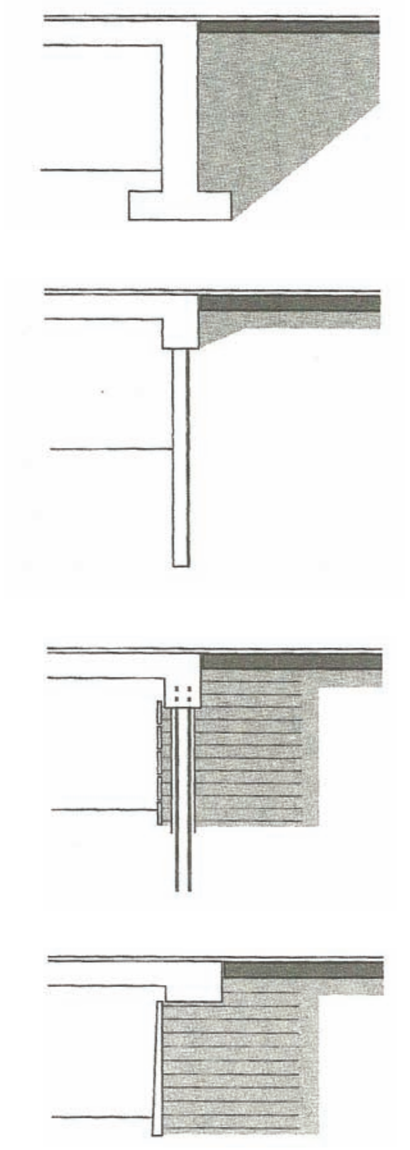
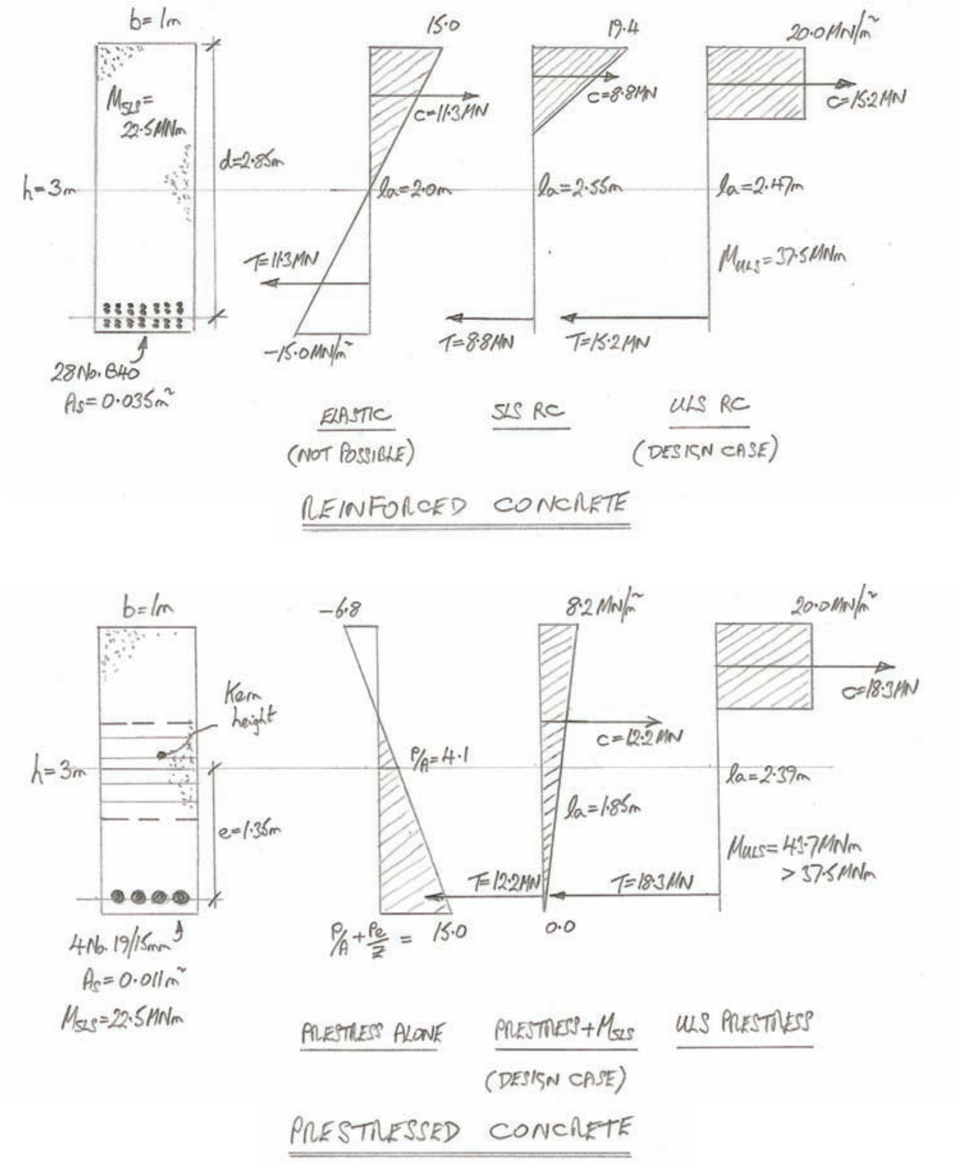


Figure 9
RC vs. PSC comparison



movements. This is generally achieved through the height of the pier, but can also be realised by splitting the pier into two leaves. This use of integral piers is more complex to design due to the interaction between the deck and the substructure, and between the substructure and the soil, but the benefits for the owner are significant. As such, the designer needs to have a good appreciation of all the imposed deformations that might occur due to prestress, creep, shrinkage and temperature, in order to deliver a robust solution.

Integral abutments should also be used for smaller bridge lengths. Fully integral bridges are generally required to be used for all lengths less than about 60m, but can also be used for lengths up to around 100-120m, depending on the exact levels of prestress, creep, shrinkage and temperature (Figure 8). Often the abutment becomes like a typical pier in order to attain sufficient flexibility, while the soil is then retained by separate mechanisms, such as reinforced earth. For intermediate cases, where a fully integral bridge cannot be achieved due to longer bridge lengths or high skews (where soil loads will cause deck rotations), it is possible to use semi-integral abutments, where the deck joint is eliminated but a bearing is retained. Further information on the use of integral bridges can be found in CBDG CPS 3[5] and CBDG TG 1[6]. CBDG TG 13[7] outlines a typical set of integral bridge calculations in accordance with Eurocode 2[8]. Some of the research background to the design of integral abutments is also shown in CBDG TP 2[9] and TP 10[10].

Reinforced and prestressed concrete

Reinforced concrete (RC) is a passive system that relies on the composite action between concrete (strong in compression) and reinforcing bars (strong in tension). In bridges, reinforced concrete would only be used for spans shorter than about 20-30m. For spans longer than this, prestressed concrete (PSC) must generally be used. Prestressing is a technique that enhances the capacity of a member that is weak in tension, but strong in compression, to carry loads. It effectively creates a new construction material which is strong in tension. Alternatively, prestressing can be seen as an improvement to the technique of reinforced concrete.

Figure 9 shows an interesting comparison between the two sections carrying the same moment. The RC section is designed at ULS and checked at SLS, whereas this PSC section is designed to be fully compressed at SLS and then checked at ULS (where it is found not to be critical). Note that the ULS stress patterns are very similar, but the SLS stresses, forces and lever arms are quite different. Further details on the various prestressing options will be provided in the next article in this series, but the principal advantages of the technique include:

- Greater economy, if well designed and built
- Reduced weight of steel to be handled and fixed
- Reduced steel congestion, leading to easier and quicker concreting
- Greater stiffness and an elastic behaviour
- Generally compressed under permanent loads
- Greater durability due to the absence, or reduced incidence, of cracking
- Being an active and more efficient system, opposing the applied loads
- Carrying a large element of the shear force
- Lighter and more slender members
- Improved appearance

Reinforced concrete can still be used for slightly larger spans than 20-30m, but as well as the lack of economy and elegance, the large deflections and the increase in these deflections caused by creep, prevent such a solution being sensible. Indeed, it was the extensive research carried out by Eugene Freyssinet between 1910 and 1930 on such topics, that allowed him to fully develop the idea of prestressing. The technique only really came to the fore though in the 1950s, once high strength prestressing steel had become commercially available (Figure 10). Prestressing steels are required to have a sufficiently high strength (f_{pk} of around 1,800 MN/m^2) such that the long-term losses in the prestress force due to relaxation of the steel, and creep and shrinkage of the concrete, are not more than about 10-15% of f_{pk}.

As prestressing is an active system, considerable skill and care must be taken in its design. A designer has to have a deep understanding of the range of actions, the effects of creep and shrinkage, the difference between internal and external forces, and the difference between loads and imposed deformations. One cannot simply add more prestressing steel in order to be conservative, as the addition of prestress is just as likely to be as detrimental to the section as that of its removal. Further discussion on these topics can be found in the 2012 Milne Medal paper[11].

Conclusions

It is very important that the best bridge layout is chosen at an early stage, while the greatest benefits are still available to the owner. CBDG's forthcoming Technical Guide will help designers select the scheme that provides this highest value.

Figure 10 Freyssinet's Changis-St Jean Bridge (1951)

However, the design team must employ the skills of the most experienced bridge engineers at this early stage, as once an inappropriate solution has been chosen, it will be difficult to optimise it later. The key factor is to get on the right path in the first place. This process requires a team with a thorough understanding of bridge design, prestressing and the various construction methods available.

The design team should strive to eliminate joints and bearings wherever possible. An integral bridge should always become a scheme that is more economic and elegant, while requiring significantly less maintenance.

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