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. 8: Concrete bridge construction methods — arches and frames

Introduction

This article examines the various methods for the design and construction of concrete arches, frames, tunnels and jacked boxes, which cover the whole range of bridges from the smallest culverts to the largest concrete spans in the world. This text should be read in conjunction with the previous two articles in the series, which describe the various *in situ* and precast techniques for beam bridges[1,2]. The basic types of bridge described here are:

- Arch bridges – standard precast arches/portals and bespoke arches
- Frame bridges – beam bridges supported by inclined legs
- Tunnel bridges – standard precast box culverts and cut-and-cover tunnels
- Jacked portal and box bridges – whole spans that are slid or rolled into place

CBDG Technical Guide No. 5 on fast construction also gives general guidance on many of these bridge types[3].

Arch bridges

Arch solutions cover a wide range of spans from the very small (5m) to the very largest (over 400m). They can be conveniently split into two types – the standard precast arches (or portals) that can span up to 25m and the bespoke arches (which may be *in situ* or precast) that can span anywhere up to 400m or more, but which are generally used in the 80–200m range.

Standard precast arches

Figure 1 Standard precast arch: Maryville Railway Bridge, UK

The choice of standard precast arches tends to suit single earth-retaining spans of 5–25m (Figure 1). Arches are very efficient structures that carry the traffic and fill loads to the foundations with little effort; primarily using axial compressions in the arch. Great care is needed in their actual design though, and in the backfilling/compaction methods that are used, to avoid any excessive bending moments in the arch. Typically for these earth-retaining structures, the span/rise ratios are 2–3, but can vary from 1–4 depending on the amount of overburden being supported (with around 500mm being the normal minimum level of cover). Span/thickness ratios are 25–50, giving arch thicknesses of 200–400mm. The structures are quite flexible in relation to the ground and therefore tend to be designed using soil springs to represent the appropriate ground movements, subject to non-linear behaviour close to the active and passive horizontal earth pressure limits (K_a and K_p). Additionally, arches often have a lower curvature around the crown (where the pressures are less) and a higher curvature towards the springings (where the earth pressures are greater) – this creates an intrados profile that better suits the required clearances.

These arches are generally cast off site in precast factories and then transported to site. They can also be cast on site though; enabling sections to be chosen that exactly match the requirements of the location. In this case, simple steel moulds would be required on site, together with suitable storage facilities.

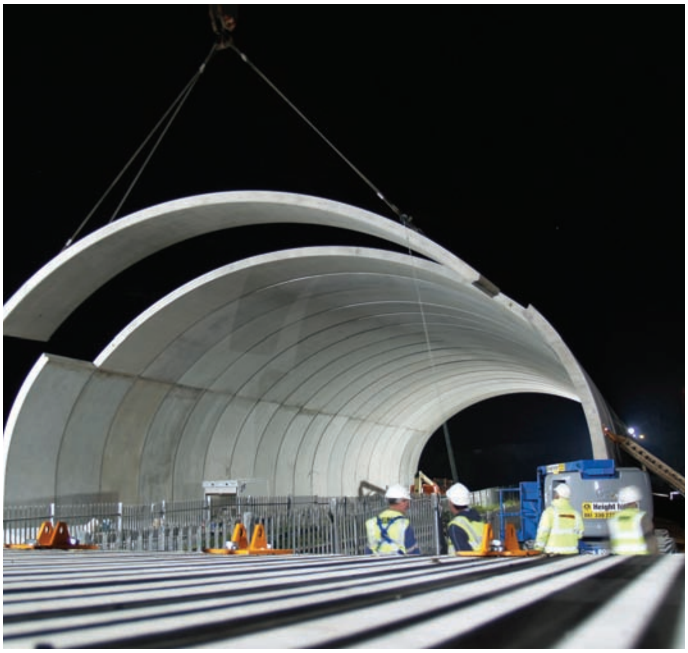

Figure 2 **Cahir Railway Bridge, Tipperary, Ireland: precast arch unit erection**

Figure 3 **Bloukrans Bridge, South Africa (272m main span)**

The precast units will usually be made from solid concrete sections, 2–4m wide, and erected using two, three or four elements to form either 2-pin or 3-pin arches. Each pin has a male/female concrete socket detail, specially designed to resist the high stress concentrations at the bearing points – the detailing of these areas is similar to the areas around prestressing anchorages, which will all be covered in a future article. The units weigh 10–35t, allowing them to be simply erected by crane, or pairs of cranes (Figure 2).

No temporary works are generally needed, as most types of arch system are designed and manufactured as stable structures. However, there are other types that can be supported by cranes throughout, or are designed to rest against each other in the short term. With some types of arch, the units may be stitched with *in situ* concrete at a later stage, often at the crown, either to provide continuity, a simple restraint at the joint or to mitigate the impact of shallow overburden. Using these methods, 20–40 units can be installed during a working day, which is a very fast erection rate. Once waterproofing is applied to the joints and the external surface, the backfilling can be installed. This is applied gradually, so that both sides of the arch are backfilled evenly to avoid any sway effects. Areas close to the arch itself are protected by being compacted by hand-operated, non-vibratory plant. Portal solutions are also available in a very similar format to the arches, though they tend to have a much more rectangular intrados, enabling even better clearance profiles to be achieved for railway or highway crossings.

There is also an innovative precast concrete block system (developed by Macrete and Queen's University) that is delivered flat to site, but once lifted into place it takes the form of the required arch, and can span 3–15m. A polymeric fabric is fixed against all the voussoirs of the arch, holding all the blocks in position. There is no other reinforcement, making it an extremely durable solution – a return to the traditional un-reinforced arches that have survived for centuries, but this new system is built without any centring[4].

Overall, precast arch units are produced on a regular cycle in controlled, factory conditions and can be erected in an efficient manner, as long as there is good access for craneage. River crossings, highway and railway bridges, as well as pedestrian underpasses, waterway, vehicle and rail tunnels can all be built successfully using this very simple form of construction. Arches also have a very calm aesthetic, which is widely appreciated by the general public. Further details can be found in CBDG CPS 8[5] and CBDG TG 12[6].

Bespoke arches

Away from earth-retaining structures, longer span bridges can be supported on discrete arches. These bespoke arch structures are often tailored to suit particular sites that involve a large single span (often in a cutting) and good foundations, though they can also be used in many other locations. As for the precast arches, the arch is a very efficient structural member carrying much of the load in direct compression and thus ideally suited to be constructed in concrete. These concrete arch spans tend to start at around 50m and can be used successfully up to around 400m, with the current world record sitting at 420m. These bridges carry the highway or railway traffic on separate decks, which can be above the arch (supported on columns as in Figure 3), below the arch (supported by hangers), or a combination of these two systems. With the deck below the arch, the arch thrust can be resisted by the deck in tension, creating the tied arch.

The aesthetics of the arch are quite complex and great care is needed to ensure the right balance between the depth of the deck and the depth of the arch, both of which intimately affect the distribution of forces in the system. From a visual point of view, it would be best to avoid having deck and arch depths that are too similar, i.e. any moments in the system caused by asymmetric or concentrated traffic loads should primarily be carried by either the arch or the deck, not by both – the symmetric and uniformly distributed self-weight and traffic loads are mainly carried by the simple thrust of the arch. The junction between the arch and deck also needs very careful design and detailing. Well designed details can be truly stunning (Figure 4). Various construction methods can be used to form the arch but the decks, which are generally supported by the arch at regular intervals and thus have shorter spans (10–40m), tend to be beam structures such as *in situ* slabs or twin ribs, precast beams, precast segmental or incrementally launched boxes – all of which were described in the previous two articles of this series[1,2].

Typically for these bespoke arched structures, the span/rise ratios are about 6–8, but can vary from 4–12, whereas the span/thickness ratios are 40–100, giving thicknesses of 1–5m. As was seen with prestressing in an earlier article[7], these deeper arches are best formed as box sections, as the section becomes more efficient under the axial arch compressions as more material is removed from the centre of the member.

These larger arches are usually built as fixed-end structures, without any pins, making them more rigid and easier to build. However, shortening of the arch under elastic deformations, creep, shrinkage and temperature effects, causes the arch crown to drop – which then generates sagging moments at midspan and hogging moments at the springings. These moments are minimised by using as thin an arch as possible. This shortening of the arch is the main reason to avoid the arch being too flat, as once the span/rise ratio is greater than about 12, its length becomes very close to the chord length, and thus much more sensitive to this shortening. Buckling of the arch also needs to be considered, both in-plane and out-of-plane, but in both cases, the deck provides additional stability, requiring the whole system to be analysed.

Modern casting and erection methods can now be used to form these arches, instead of the classical (and expensive) centring methods used historically. Such techniques include balanced cantilevering with cable-stays using *in situ* or precast segments (Figure 5), or casting the arch vertically above the abutment (in a similar way to slipforming) and rotating the arch downwards, or casting the arch horizontally above the abutment (on the ground) and rotating it sideways in plan. These latter two techniques would also need support from temporary towers and cable-stays.

Frame bridges

Whereas beam bridges mainly carry the loads in bending, and arch bridges mainly carry the loads in compression, frame bridges can be seen as a intermediate position, with major loads carried in both bending and compression. So, whereas an arch might have a curved (ideally parabolic) intrados, a frame structure will have a clearly pronounced polygonal intrados, formed from the legs and the deck. As a result of these similarities, frame bridges are often used in locations where both beam bridges and arch bridges might be appropriate. As with the longer arches described in the previous section, frame bridges are frequently tailored to suit particular sites that involve a large single span, or where the aesthetics are particularly awkward due to the peculiarities of the site (Figure 6). Due to these constraints, frame bridges will generally be cast *in situ*, as precasting might not suit the variations in deck and leg section that could be needed. Casting would therefore tend to take place on scaffolding or on other falseworks, such as sets of beams/girders resting on temporary towers. They can also be built over the land, in the same way as arches, and then rotated horizontally into position – Ove Arup's famous Kingsgate Footbridge in Durham was built in this manner.

Tunnels

Tunnel solutions cover spans from 1–2m up to 20–30m. As with arches, they can be split into two types – the standard precast tunnel (or box culvert unit) that can span up to about 6m, and the bespoke cut-and-cover tunnels that can be up to 50m wide, with intermediate walls.

Standard precast box culverts are best suited to single earth-retaining spans, with spans of 1–6m (Figure 7). As earth-retaining box structures, the span/depth ratios are typically 10–15, giving wall and slab thicknesses of 200–500mm. The structures are quite stiff in relation to the ground and therefore tend to be designed using 'at rest' horizontal earth pressures K_o. Box culverts are cast off site as 2–4m long units and are then transported to site, where the 10–35t units are crane erected. Once all the units have been positioned next to each other, waterproofing is applied to the joints and the external surface and the backfilling can then be placed. These standard precast units, which are left as jointed structures, are ideal for small waterways, pedestrian underpasses or small vehicle access roads.

Box culverts are a smaller example of the larger cut-and-cover tunnels, which are all generally cast *in situ*. The design of these cut-and-cover structures is dominated by the geotechnical considerations and the precise methods of construction. As much of this information is well documented elsewhere[8,9], only the basic structural

Figure 4
Robert Maillart's beautifully detailed Salginatobel Bridge, Switzerland

Figure 5
Sungai Dinding Bridge, Malaysia: balanced cantilever erection

Figure 6
Framed legs: River Tyne Bridge, UK

Figure 7
Standard precast culvert units

Figure 8
Singapore Central Expressway: 'bottom-up' construction

parameters are described here.

With these larger spans, the effects of the earth and water pressures are much more dominant and due care should be taken of the soil-structure interaction, and the way in which the flexibility of the structure affects the possible range of earth pressures. Flotation of the whole structure will also often become an issue and measures will need to be taken to prevent any upward movements. These measures might include the provision of sufficient levels of overburden, positive means to optimise the side friction, or tension capacity from the side walls or other forms of vertical piling.

The simplest method to construct any underground tunnel is to build it in open cut. Such box structures are simply cast *in situ* on the ground and are then backfilled on completion. The base slab is cast first, followed by the walls and finally the roof slab. The roof slab will be cast using scaffolding or proprietary formwork systems that allow the rapid movement of each shutter panel after the concrete has gained sufficient strength. Panel lengths are often chosen to suit standard reinforcement bar lengths and arrangements, and thus will often be around 11m long. Care needs to be taken with heat of hydration and shrinkage cracking between adjacent pours, and the overall water-tightness of the box is then completed with the addition of waterproofing at the joints and on the external surface.

If open cut is not possible, the next best method is to build the tunnel 'bottom-up' within a temporary cofferdam (Figure 8). The cofferdam, which can be formed from sheet piles or bored piles, creates a hole within which the tunnel box can be built in exactly the same way as with the open cut method previously described. The cofferdam will almost certainly need to be propped (or anchored back) during the works to carry all the horizontal pressures until the permanent box is completed. In urban or restricted sites, it will be necessary to build the tunnel 'top-down' (as this method is significantly stiffer than bottom-up construction) in order to limit the settlement of any adjacent properties. In this case, bored pile or diaphragm walls are installed first, and the deck or roof slab is then cast on the ground.

Although the excavation that follows is more expensive in the more confined space, it does allow the excavation to proceed with much greater control of the adjacent ground movements. Some temporary propping of the walls may still be needed. The tunnel box is then formed from the deck or roof slab, the piled walls and the base slab. In some cases, where the water pressures are controlled and/or the piled side walls are extended to a deeper level, the structural base slab might be omitted or simply replaced with a propping slab. This situation could also apply to a bridge deck cast on the ground (Figures 9a and 9b).

Each of these bespoke tunnels is designed to suit the particular geotechnics of the site and thus it is not really possible to quote any general guidance rules, except that walls and slabs tend to have quite small span to depth ratios of 10–15, which produces roof and base slabs that can be 0.5–2.5m deep and walls that can be 0.5–1.5m thick. With larger spans, it also becomes economic to haunch the roof and base slabs, in the areas where the slabs intersect the supporting walls (Fig. 8).

Jacked portal and box bridges

This section describes the special cases where portal or tunnel box bridges are either slid or rolled into place. Typical spans of such structures can reach approx. 25m. Where an existing bridge needs to be replaced or a new bridge is to be installed under live traffic, it is increasingly desirable to limit the disruption to the existing road or railway by building the new structure alongside. A short but large disruption can often be more preferable than a long series of minor disruptions. The traffic management in the area can be greatly improved by avoiding the phased or piecemeal construction of traditional replacement operations. Though these options may appear to be more expensive, the greater degree of programme certainty and the reduced level of risk, as well as the unhindered deck construction, will often make these solutions faster, and therefore more economic. They may be the only possible solutions in the railway environment.

Concrete portal or box structures are then built in an adjacent casting area. In a single road or rail closure, over a weekend for example, any existing bridge is slid or lifted away to allow its demolition off the critical path. Alternatively for new bridges, the embankment is partially removed during

Figure 9a A350 Canal Aqueduct, Wiltshire, UK: 'top-down' construction

Figure 10 Completed jacked box: A43 Bridge (under the M1), Northamptonshire, UK

Figure 9b A350 Canal Aqueduct: completed

this long possession period. Either way, the new structure is then slid or rolled into place during this possession, generally on slide tracks that have been previously installed underneath the embankment in pre-bored mini-tunnels. The new deck can be either pulled into place using strand jacks, or pushed into its final position with long-stroke jacks. In a similar manner, large wheeled transporters (self-propelled modular transporters – SPMTs) can be used to move complete portals or decks from adjacent casting areas to prepared substructure locations.

In the most special cases, jacked concrete boxes can also be slid or jacked beneath embankments, obviating the need to close the railway or highway above at any stage (Figure 10). These boxes are also formed in adjacent casting areas and are then pushed into the embankment using jacking points in the casting area. A steel or concrete shield is used to support the advancing front face beneath the embankment. The frictional load on the box can be limited either by the use of proprietary anti-drag systems, or by the prior installation of a steelwork grillage that supports the traffic above[10].

All these jacking techniques use the advantage of unhindered deck casting away from the critical locations, followed by a concentrated burst of erection activity. These solutions would all be developed to speed up the construction process and to minimise disruption at the most sensitive bridge sites.

Conclusions

Various methods for the design and construction of concrete arches, portals, frames and boxes have been described, covering both the smallest span culverts and the largest concrete arch bridges in the world. A future article in this series will examine the other remaining concrete bridge types, including cable-stayed, extradosed and stressed ribbon bridges.

References and further reading

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Further reading

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