17

The design and construction of arches

17.1 General

Loads may be carried to the foundations of a bridge by compression, tension or bending/shear, Figure 17.1, or by combinations of these three actions. Arches which work principally in compression, are among the most beautiful of structures, effortlessly spanning great distances. They may also be among the most economical, as they may be made from cheap and readily available materials such as stone or concrete, while tension and bending both require expensive materials such as steel or fibre composites.

However, arches can be labour intensive to build, and consequently had somewhat fallen out of favour. More recently, the growing awareness of the concept of sustainable development has renewed interest in this form of construction that minimises the materials employed, and has stimulated the search for more economical methods of construction.

A special feature of arch bridges is that they do not need any back span; if a large span is flanked by terrain that is suitable for much shorter spans, arches have a significant economic advantage. Most other types of bridge require side spans either side of a main span, which extends the costly long span technology over additional length.

Large-span stone and concrete arches have been used very extensively in China, where it is reported that some 70 per cent of all highway bridges are of this form of construction [1]. Chinese engineers have developed a variety of innovative methods of construction.

17.2 Line of thrust

A useful concept for understanding arches is the line of thrust. Any loads applied to an arch will create a line of thrust. If the arch is made exactly the same shape as the line of thrust, it can carry the loads without bending moments. The shape of the line of thrust may be visualised by applying the loads to a weightless suspended cable, Figure 17.2 (a). The shape of this loaded cable is known as a funicular diagram. Clearly, the sag of the loaded cable, and its tension, will depend on how taut it was before application of the loads. If the cable tension is varied, an infinite number of similar funicular diagrams may be drawn. This is an exact analogy to the line of thrust, Figure 17.2 (b), as the compression in the arch is inversely proportional to its rise.

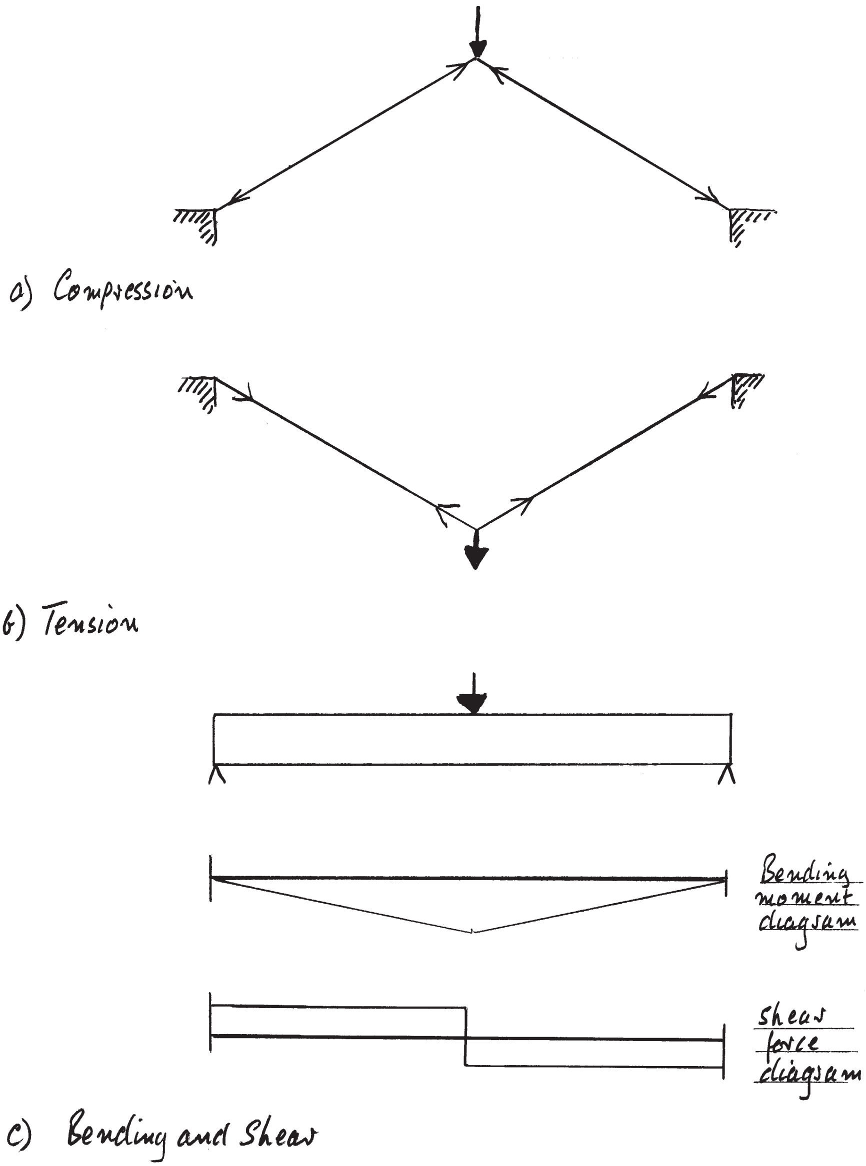

Figure 17.1 Compression, tension and bending

If the arch shape does not correspond exactly with the line of thrust, a local bending moment will be generated; M = N×d, where *N* is the force in the arch at that point, and *d* is the distance between the neutral axis of the arch and the line of thrust, Figure 17.2 (c).

If the arch has hinges in its length, the bending moment must be zero at the hinge positions, which means that the line of thrust must pass through those points. If the arch has three hinges, typically at the springings and at the crown, it is statically determinate. In this case, the line of thrust is also determinate, and can be drawn, superimposed on the arch. The line of thrust shown in Figure 17.2 (b) may be scaled

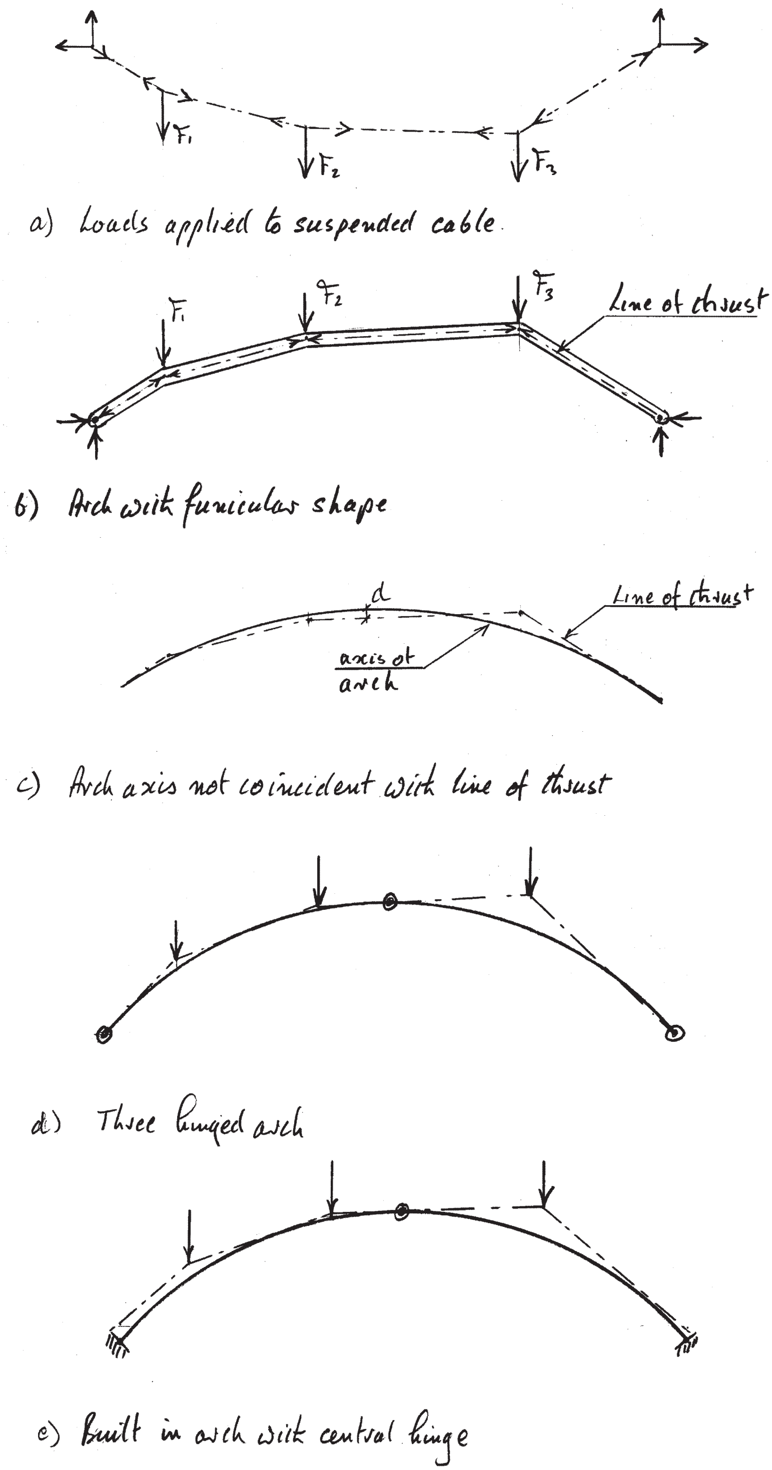

Figure 17.2 Concept of line of thrust

so that it passes through the three hinges, Figure 17.2 (d). The thrust at the arch springings and the compression at any point along the arch may then be calculated by simple statics. The bending moment at any point of the arch may also be calculated by taking moments about that point, or by measuring the distance between the line of thrust and the neutral axis of the arch.

If the arch has less than three hinges, and is consequently indeterminate, the line of thrust may not be drawn precisely without elastic analysis. Thus, for a fixed-ended arch, the line of thrust will not pass through the springings, where there will be a moment in the arch, Figure 17.2 (e). However, the line of thrust will always be a 'best fit' to the shape of the arch neutral axis, and so can be drawn approximately, allowing an early rough estimation of the bending moments in the arch, and also allowing a first approximation to the best shape for the arch.

The correct shape for an arch carrying a uniformly distributed vertical load is a parabola. For an arch of constant thickness carrying only its self weight, the correct shape is a catenary (which is very close to a parabola). For an arch carrying its self weight and external loads, the best shape is a compromise between a catenary and the funicular diagram of the loads.

17.3 Unreinforced concrete and masonry arches

The stability of a masonry arch is given principally by its shape and its thickness. When the shape of the line of thrust differs from the shape of the arch, the arch ring needs a finite thickness to contain it, Figure 17.3. Where the line of thrust is within the middle

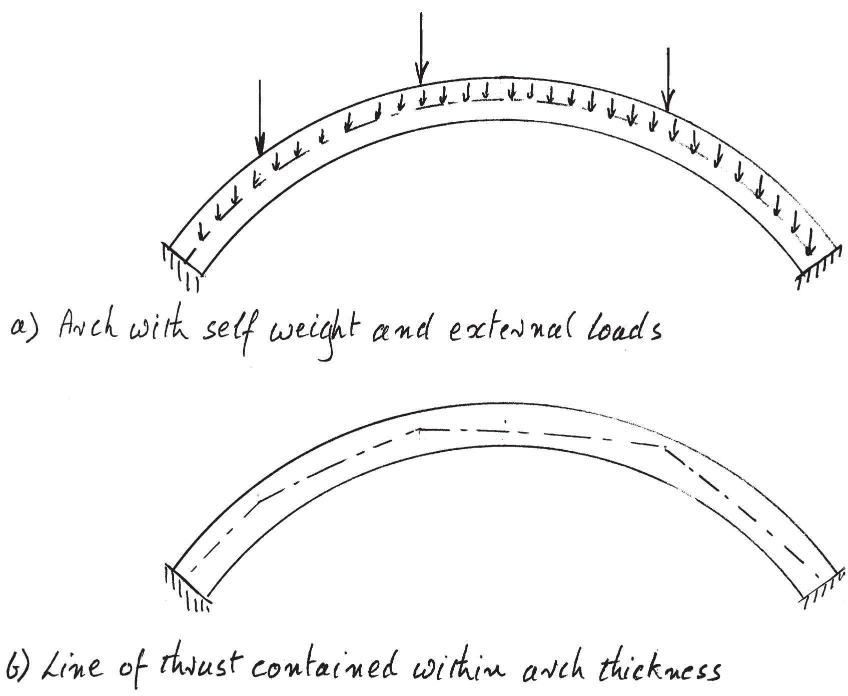

Figure 17.3 Masonry arch with external loads

third of the arch ring, the complete cross section of the ring will be everywhere in compression. If the line of thrust is locally outside the middle third, one face of the arch ring at that section will be in tension, and the arch will crack. In stone or brick arches these cracks usually occur in the joints and may not be noticed. If the line of thrust touches or crosses the intrados or extrados of the arch, a hinge will form at those points. When four hinges form, the arch will become a mechanism and fail. However, as a certain thickness of material is necessary to resist the thrust, a hinge will in fact form when the line of thrust is at a finite distance within the arch structure. For masonry arches the cause of failure is almost always the mechanical instability described, not the inadequate strength of the masonry.

An unreinforced concrete arch will behave very much as a masonry arch. However, it should be remembered that if the line of thrust lies significantly outside the middle third, visible cracks are likely to occur. The arch is not threatened, but the cracks may be unsightly.

Masonry arch bridges have been built with spans up to 120 m, such as the Wuchao River Bridge in Hunan Province in China.

17.4 Flat arches

An arch does not have to be 'arched' in shape. Consider a flat 'arch' of constant depth spanning between rigid abutments, Figure 17.4. The line of thrust for a uniform load, for instance, will be parabolic. If it is possible to draw such a line of thrust within the rectangular profile of the arch with a rise/span of at least 1/10, the loads will be resisted in arch action. Clearly the line of thrust will be outside the middle third over much of the length, and the structure will crack. In fact, there is an 'incorporated' arch which is a finite thickness of material drawn around the line of thrust. The material above and below this incorporated arch is redundant, and could be removed, without affecting the performance of the arch.

If the arch was made of concrete, and reinforced as for a beam in bending and in shear, the shortening of the arch ring under the compression, and the consequent deflection of the arch, would induce bending action. The loads on the 'arch' would then be shared between arch and bending action, see *3.12* and *9.3.5*.

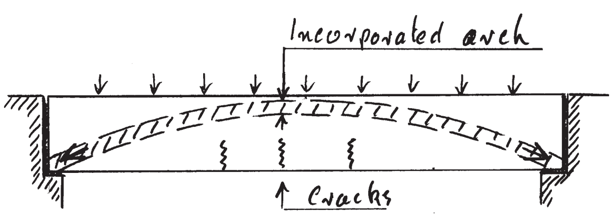

Figure 17.4 Flat arch

17.5 Reinforced concrete arches

17.5.1 General

Reinforced concrete arches differ from masonry arches principally in that they can resist bending tension, and consequently can remain stable with a line of thrust that lies outside the arch. They do not depend on their thickness and shape to give them

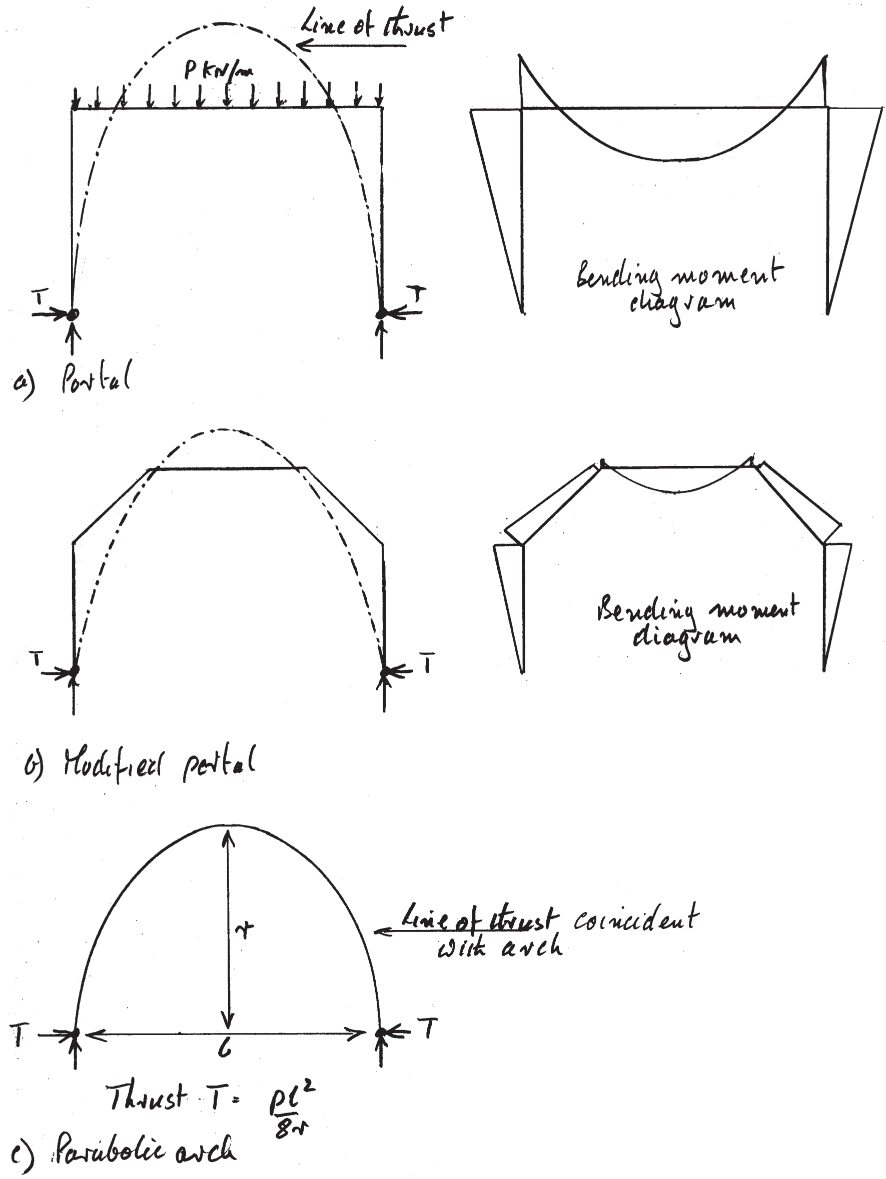

Figure 17.5 Transition of portal to arch

stability, but on their resistance to combined compression and bending. However, their economy depends on their shape being close to that of the line of thrust.

A two-pinned portal may be seen as a crude approximation to an arch. When subjected to a uniform load, the superimposition of the parabolic line of thrust on the portal illustrates graphically the bending moments that are proportional to the distance between its neutral axis and the line of thrust, Figure 17.5 (a). The loads are carried by a combination of arching action that are represented by the thrust at the arch feet, and bending. If the portal is refined by deflecting the cross-beam, Figure 17.5 (b), the distance between the line of thrust and the centroid of the portal frame is reduced, and the bending moments drop in consequence, with more of the load carried in arching action. Finally, if the portal is further modified to become a parabolic arch, the line of thrust and the neutral axis of the frame become coincident and the moments disappear, Figure 17.5 (c). At the same time the thrust *T* will increase as the rise of the line of thrust decreases, and as all the loads are carried in arching action.

17.6 Short-span reinforced concrete arches with earth fill

A thin reinforced concrete arch covered in earth fill is a very economical structure for carrying highway loads. The presence of the fill distributes point loads, reducing the bending moments on the arch.

If solid abutments are available, the arch may be simply an economical replacement for a slab roof. A good example is the 600 m long Byker Tunnel, part of the Tyne & Wear Metro in Newcastle-upon-Tyne, Figure 17.6, designed by the author when at Arup [2]. The 200 mm thick arch spanned 9.4 m, with a rise of 2.3 m, and the road above was subjected to full UK highway loading (45 units of HB + HA). The arch is three-centred, that is it had a larger radius over the central section than over the

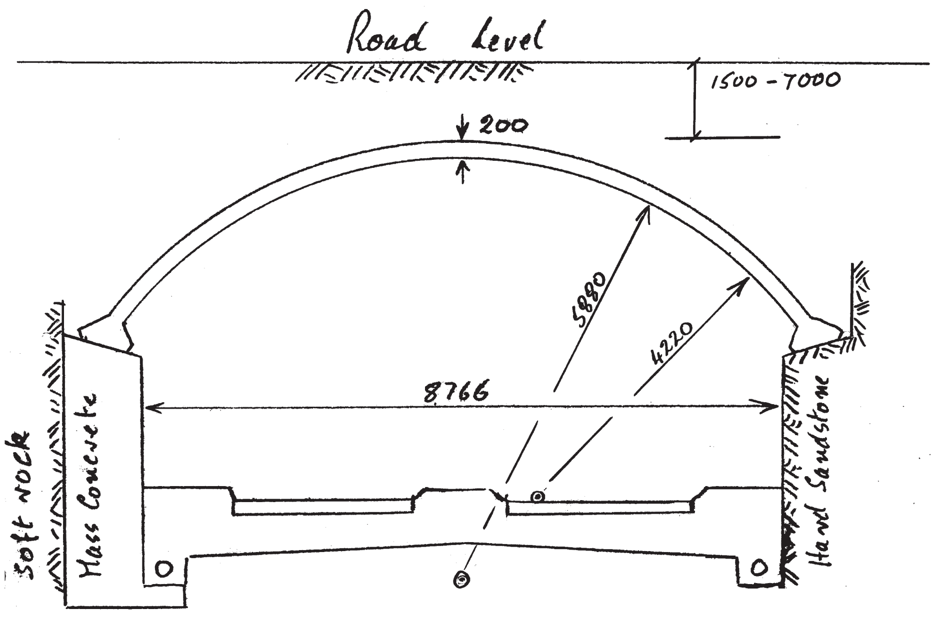

Figure 17.6 Byker Tunnel

Figure 17.7 Byker Tunnel under construction (Photo: Robert Benaim)

haunches, where there is a greater weight of earth. Over most of its length it rested on abutments cut into massive sandstone. As the hard rock fell away, it was replaced by unreinforced concrete walls, either dressing the soft rocks of the coal measures, or for short lengths acting as cantilever retaining walls.

The arch was cast in-situ on a set of steel travelling shutters, Figure 17.7. As the slope of the arch at the springings exceeded 18°, a partial top shutter was necessary. Such an arch needs only light reinforcement, and the bars should if possible be of small diameter such that they will lie to the arch radius without pre-bending, preferably under their own weight.

Two alternative designs carried out by Benaim demonstrate the economy of reinforced concrete arches. Both carried the M74 motorway in Scotland on very skew crossings of twin-track railways, Figure 17.8. The New Cowdens Bridge was 190 m long with an arch span of 21 m and crossed the electrified main line from England to Scotland, while the Maryville Bridge had a span of 16 m and crossed a lesser line. The arch thickness for New Cowdens was 450 mm, and 300 mm for Maryville. The greater thickness of the former was adopted to allay concerns about the impact resistance of the structure in the event of a derailment. These alternatives consumed approximately one-third of the materials of the conforming designs they replaced, Figure 17.9. The precast arches were erected in a matter of days, and once in place they protected the railway from the remaining construction activities. This minimised possession times and reduced the risk to the railways. An additional advantage of such arch bridges is that they require less maintenance; in particular they do not need roadway expansion joints.

The arch profiles consisted of two radii; a tighter radius is required over the lower part of the arch to accommodate the increasing weight of earth and lateral pressure.

Figure 17.8 New Cowdens arch (Photo: Alister Lynn/Balfour Beatty Civil Engineering Ltd)

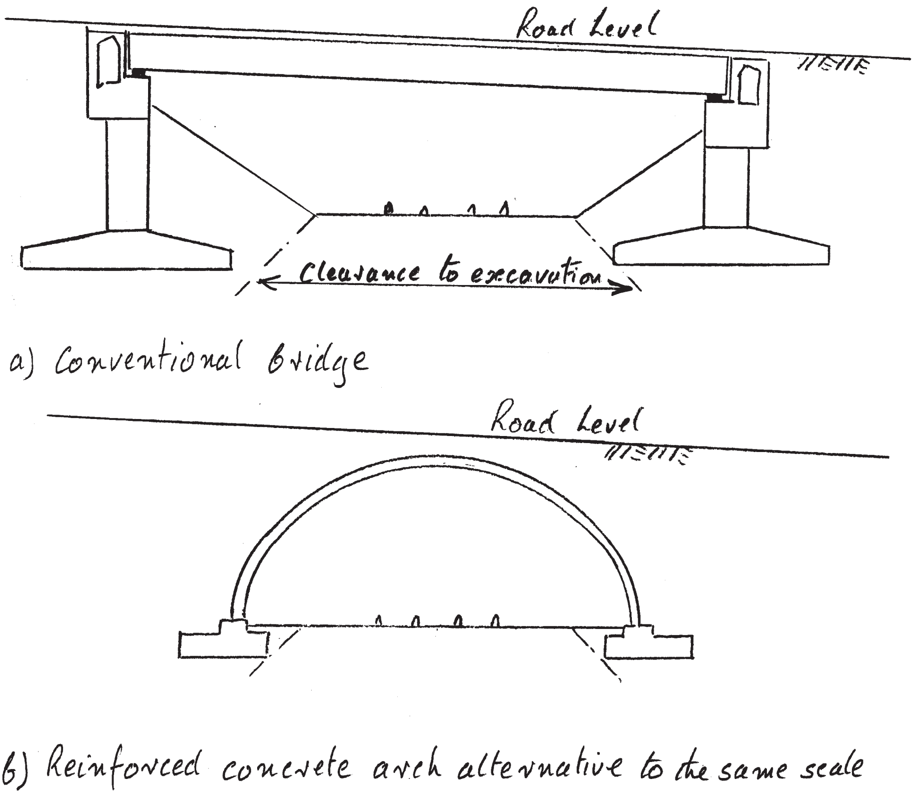

Figure 17.9 Comparison of an arch with a conventional bridge

However lateral earth pressure is not a unique value, varying over a range between the extreme limits of active and passive pressure. It is advisable to design for pressure at rest (K_o), and to check the sensitivity of the design to reasonable variations in the pressure. Heavy vehicles over the haunches will increase the lateral earth pressure on the arch as well as the vertical pressure. Such eccentric loading will cause the arch to sway sideways, away from the load, creating a countervailing earth pressure on the unloaded side. This may be simulated in analysis by modelling the soil as a series of springs. The arches also had to be designed for the situation near the portals where the embankment ramped down on one side.

The structures were precast in half arches 3.2 m long, and erected in pairs without falsework, Figure 17.10. They were placed in sockets on the foundations, on carefully levelled packs, and then grouted in. The precast units were then stitched at the crown to complete the structure. At the request of the client, on New Cowdens they were also stitched all the way down the arches to create a monolithic roof. Both arches were entirely covered with a waterproof membrane.

At the portals it is necessary to retain the earth above the arch. This may be done by building a conventional spandrel wall. However, this causes some difficulties, as the arch ring is likely to be too slender to provide moment fixity for a cantilevered retaining wall. One solution is to allow the spandrel wall to span horizontally between counter forts over the arch springings. Alternatively, the spandrel wall may be made of reinforced earth. There is also a need for wing walls to contain the fill in the approach to the arch.

Figure 17.10 Maryville arch under construction (Photo: Benaim)

Figure 17.11 Bridge on A16, France (Photo: Robert Benaim)

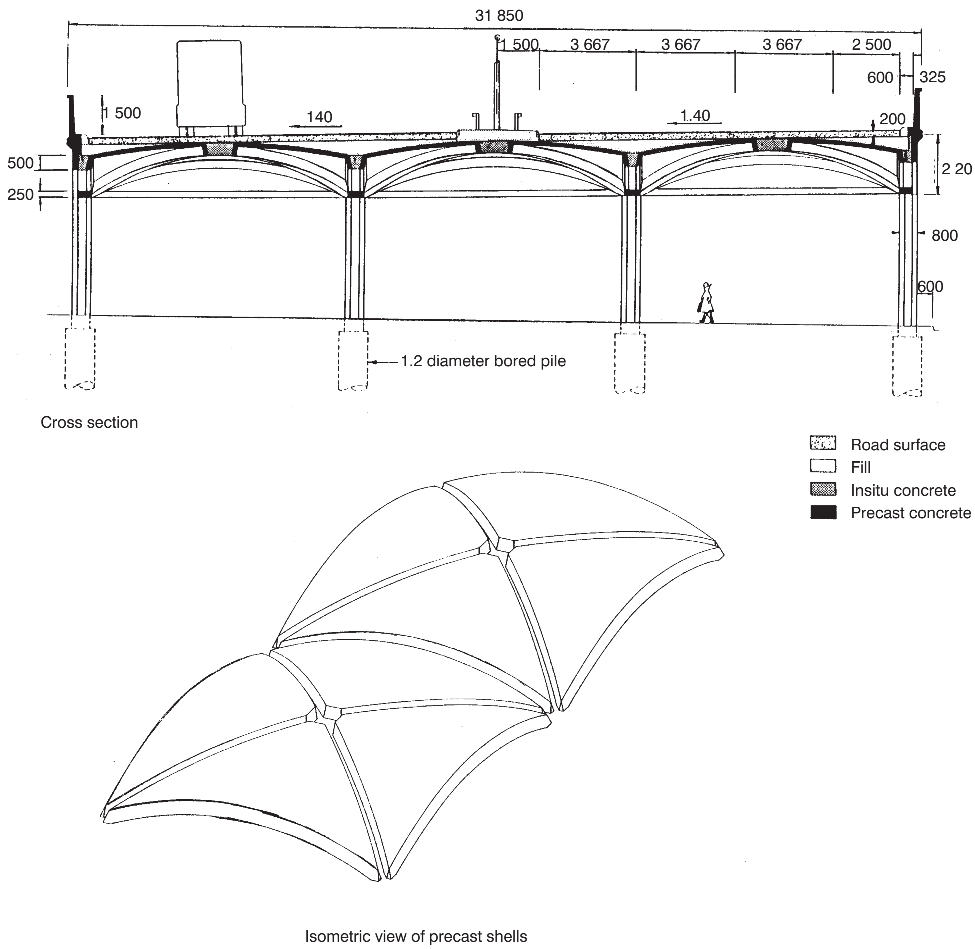

Figure 17.12 Project for Station Viaduct Middlesbrough

A spandrel wall can be avoided by extending the arch and allowing the earth to spill forward at its angle of repose. This solution was adopted for the bridges over the A16 motorway in France, Figure 17.11. An elegant way of detailing this last solution is to terminate the arch with an inclined plane at the angle of repose of the ground.

An original use of thin reinforced concrete vaults for a bridge deck was the project for the Station Viaduct in the heart of Middlesbrough, carrying a dual three-lane motorway between the railway station and a shopping centre, Figure 17.12, designed by the author when at Arup. The deck consisted of precast ¼ vaults, made of a 150 mm thick reinforced concrete shell. Each ¼ vault was trimmed with downstand permanent shuttering for arched stiffening beams. When assembled, the precast components created a series of 10 m square vaults with stiffening beams on the diagonals and around the perimeter, with the heads of the columns linked by a grid of prestressed concrete ties. The structure was completed by casting the core of the stiffening beams in situ. There were three vaults across the 30 m width of the motorway. PFA was placed above the vaults to provide the road platform. The use of precast arches led to a very economical structure, which would have competed favourably with more conventional bridge deck technology, while providing a useful and attractive space beneath the viaduct. Unfortunately this project was never built in this form.

17.7 Longer span reinforced concrete arches supporting bridge decks

17.7.1 Length changes of arch bridges

Arch bridges where the roadway is built on fill do not need expansion joints, as the length changes in the arch due to temperature variations are taken up by changes in the geometry of the arch; its crown rises or falls with the temperature. Longer span reinforced concrete arches generally carry a separate deck which requires provision to accommodate its length changes. Either the deck may be a series of statically determinate spans with joints every span, or it may be made continuous with expansion joints at the abutments. In the latter case, the columns linking the deck and the arch must either be sufficiently flexible to follow the deck movement, or must be pinned top and bottom, or must carry sliding or elastomeric bearings.

17.7.2 Relative stiffness of arch and deck

Highway and railway loads include both distributed and concentrated loads. Whereas distributed loads applied over the full length of the arch cause principally compressions in the arch, distributed loads applied over only part of the length and concentrated loads cause significant bending moments. As the arch ring and the deck are linked together, they will inevitably share these bending moments, in proportion to their stiffness.

The designer has a choice of designing the bridge such that the greater proportion of the bending moment is carried by the arch or by the bridge deck. For instance, if the deck is made deep and hence stiff in bending, while the arch is made as thin as possible, the greater part of the bending moments will be carried by the deck, and vice versa, Figure 17.13. Benaim's short-listed entry to the Poole Harbour competition, designed with the architectural assistance of Wil Allsop, Figure 17.14, was provided with a stiff deck, allowing the arch to be made as thin and unobtrusive as possible. On the other

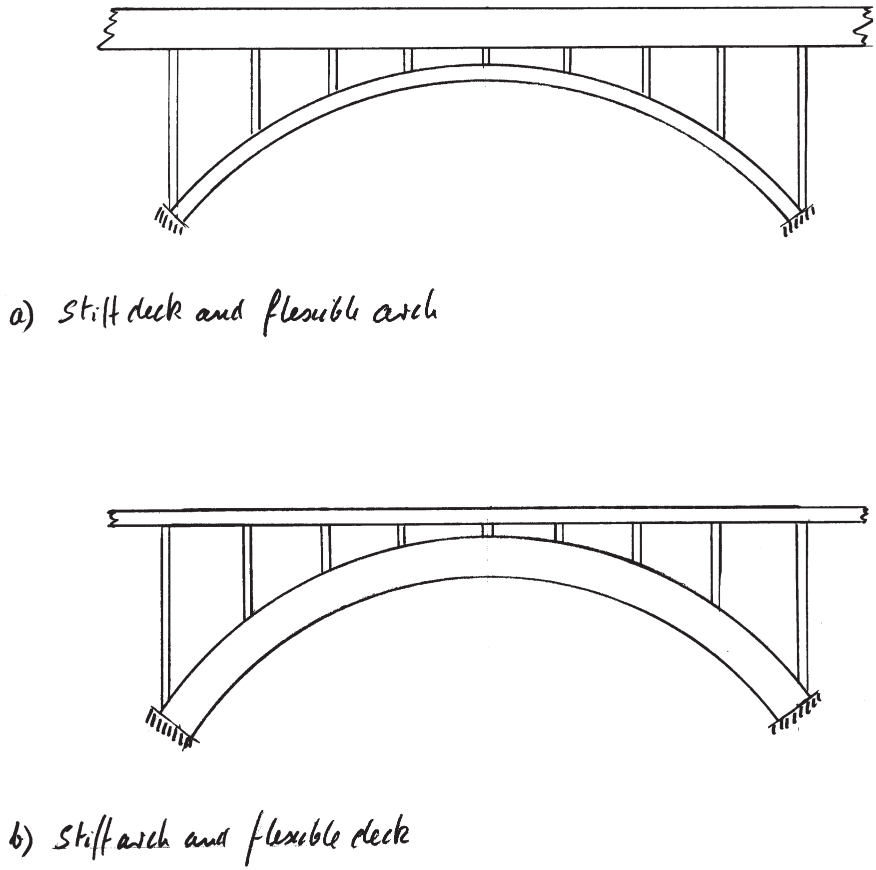

Figure 17.13 Relative stiffness of arch and deck

Figure 17.14 Benaim entry to the Poole Harbour Crossing competition (Image: David Benaim)

hand, Benaim's Sungai Dinding Bridge in Malaysia, Figure 17.16, which had a slender steel composite deck, and Maillart's Salginatobel Bridge, Figure 1.18, are examples of bridges where the arch ring has been designed to carry most of the bending moments. It is also possible to design the bridge such that the bending moments are shared more or less equally.

For long-span bridges, such as the Krk Bridge, Figure 17.19, the arch needs to be deep to resist buckling and it naturally carries the bending moments. When the deck consists of a series of statically determinate spans, it clearly cannot relieve the arch of any bending moment.

17.7.3 Effect of shortening of the arch and spreading of the abutments

Reinforced concrete arches must be designed to resist the effects of shortening of the arch ring due to elastic and creep deformations under compression, concrete shrinkage and temperature drop. These effects cause the crown to drop and induce sagging bending moments at mid-span and hogging moments at the springings of a monolithic arch. Spreading of the abutments as a response to the thrust causes bending moments similar to those due to arch shortening. The thicker and stiffer the arch, the greater these moments will be. Consequently, it is important to keep the arch as thin as possible, compatible with stability and with the strength necessary to carry the bending moments due to point loads.

Reinforced concrete arches generally have a span/rise ratio of between 4 and 8. However arches with a rise of span/10 or even flatter can be designed. The flatter the arch, the greater the effects of shortening will be. This may be easily understood by the fact that the length of an arch with a rise of 1/5 is about 10 per cent greater than the span, while for a rise of 1/10, it is only 2.6 per cent greater.

The arch shortening/spreading of foundations are imposed deformations that can cause cracking, but in most cases cannot cause collapse. However, these actions change the geometry of the arch, and so induce second order effects. For arches with a span/rise ratio of about 8 or less, these second order effects are not significant. However, for very flat arches, the changes in geometry may be significant, increasing the bending moments in the arch and even threatening its survival.

17.7.4 Instability of arches

As arches are in compression, they must be checked against buckling instability. Generally, when the bridge has been designed so that the bending moments are carried by the arch, a thickness in the plane of the arch of span/60 at the crown is likely to provide a satisfactory factor of safety as the arch shape inhibits in-plane buckling. When the bending moments are carried by the deck, the arch thickness is governed by criteria other than general buckling, such as compressive stress, bending moments, local buckling between points of liaison with the deck or stability during construction.

Buckling perpendicular to the arch plane is similar to conventional strut behaviour, and the arch rib should be checked and reinforced as a strut as a first approximation. However, due to the curvature of the arch, its torsional strength is mobilised in any lateral deflection. A slenderness of 1/30 for an arch fixed in the plane of buckling, and 1/20 for a pinned structure are likely to be satisfactory, although more slender

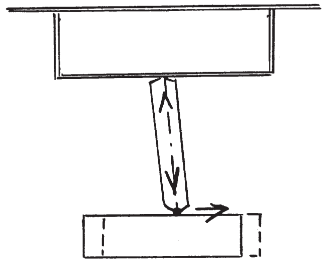

Figure 17.15 Lateral instability of arches

structures are possible. Lateral wind loading is also likely to be relevant to arch stability. A detailed analysis of stability in both planes is always required. For an arch consisting of several ribs, the critical condition for stability may well arise during construction before the links between ribs are in place.

Out of plane buckling of an arch cannot be considered in isolation from the bridge deck carried. If the deck is above or below the arch and consists of statically determinate spans without overall transverse stiffness, it will follow any lateral displacement of the arch and reduce its stability, in the same way as a weight on top of a cantilevered column will reduce its stability. A continuous deck has transverse stiffness and the effect on the arch will depend on the nature of the link between the deck and the arch. If it rests on the arch through columns effectively pinned at each end, the lateral deflection of the arch will incline the columns, imposing a horizontal disturbing force on the arch, decreasing its stability, Figure 17.15. However, if suspended from the arch, transverse movement of the arch will incline the hangers, applying a restoring force, Figure 17.21 (b), (*17.10*).

The stability of a concrete arch is affected fundamentally by creep under sustained loads. Preliminary elastic calculations of stability may be carried out using a Young's modulus of one-third of the short-term value, and a load factor of 3 against the critical load. Energy methods are very appropriate for a calculation of the stability of arches as are non-linear finite element programs, as long as the designer has thoroughly understood the statics of the problem, and is capable of checking the accuracy of the results. There are also charts available [3].

17.8 Construction of arches

Traditionally, arches were built on timber centring which were often major engineering structures in their own right. Removing this centring and allowing the arch to carry its own weight is a delicate operation. As the concrete is stressed in compression, the arch must shorten as it takes up its self weight, leading to a drop in the level of the crown. Ideally, the centring should be lowered incrementally over the full span simultaneously, so that potentially ruinous bending moments due to the self weight being applied over only part of the span are not introduced into the arch. This clearly is a difficult task for a timber centring consisting of a large number of members or for a large span. At the Plougastel Bridge with three 180 m spans, designed and built by Freyssinet in 1930, the problem was solved by the novel technique of introducing flat jacks into the cross section of the arch which, when expanded, lifted it off the centring.

The same method was used to strike the 305 m span Gladesville arch in Sydney, in 1964. The arch, which has a rise of 41 m, consists of four adjacent box section ribs, each 6 m wide, 4.25 m deep at the crown and 7 m at the springings. Each rib was made up of a series of precast voussoirs 3 m long jointed with cast-in-situ concrete, and was built on centring. It was struck by inflating flat jacks at the quarter points. The centring was then slid sideways for the next rib. The arch acts as an unreinforced concrete structure for its overall actions, and when built was the longest span concrete arch in the world. If the same arch were to be built today, it would be considered more economical to counter-cast the segments, avoiding the need for a jointing operation.

The cost and the time involved in building the centring, striking the arch and then removing the centring are one of the reasons that large-span arches have not been used more extensively. However new methods of construction avoid the need for centring.

For instance, Benaim's Sungai Dinding Bridge, Figure 17.16, had 13 arches with spans that varied from 45 m at the river banks to 90 m at the centre, plus approach viaducts. The arch ring was a box section, 8.8 m wide, with a depth that varied from 1.6 m for the smaller arches to 2.25 m for the largest. The arch spans were built in cast-in-situ balanced cantilever from each pier. A pair of half arch rings was temporarily hinged at the springings and suspended by stays from temporary falsework towers, Figure 17.17. When completed, the trailing half arch was stitched at the crown to the completed portion of the deck, and one of the two falsework towers could be leapfrogged forwards to the next pier. As each arch was completed, the temporary hinges were locked by cast-in-situ concrete. In this way the arch was built span by span, Figure 17.18. The deck was of continuous steel composite construction.

The 390 m span Krk Bridge had a rise of 60 m, and the arch was a constant 6.5 m deep and 13 m wide while the deck consisted of precast 'T' beams. It was built by cantilevering from the two abutments, Figure 17.19. A central box section was built first, from precast flange and web members stitched in-situ. The concrete and precast members were delivered by cable crane. The falsework was in the form of a truss, with the arch constituting the compression flange and the tension and shear members in

Figure 17.16 Bridge over Sungai Dinding (Photo: Benaim)

Figure 17.17 Bridge over Sungai Dinding: balanced cantilever construction of arch (Photo: Benaim)

Figure 17.18 Bridge over Sungai Dinding: span-by-span erection of arches (Photo: Benaim)

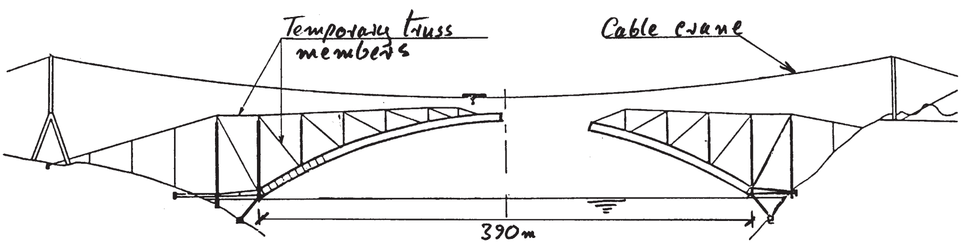

Figure 17.19 Construction of Krk Bridge

Figure 17.20 Construction of Yajisha Bridge (Photo: Engineer Leo K.K. Leung, Executive Director of Hopewell Highway Infrastructure Ltd (Hong Kong Stock Code: 737))

steel. Once this pre-arch had been closed, the steel falsework could be removed and the box was extended by adding two side cells.

Arches may also be prefabricated in sections weighing hundreds of tons, and assembled in cantilever using cable cranes. The Chinese have significant experience of this type of erection. Another method of erection for large-span arches used extensively in China is to erect a pre-arch consisting of steel tubes braced together which are subsequently filled with concrete that acts compositely with the tubes. The tubes are erected in cantilever with tie backs, or by cable crane. Clearly the falsework is much lighter than that required for the erection of the finished arch.

A recent example of this method of construction is the 360 m span Yajisha (an alternative rendition of Ah Kai Sha) Bridge over the Pearl River close to Guangzhou, Figure 17.20. Half arches consisting of steel tubes were built on falsework on either bank, and then rotated about a vertical axis into their final position. During the rotation, the steel half arches were counter-balanced by short concrete arches supporting the approach span. Once in position, the steel arches were filled with concrete [4]. This single-deck dual-carriageway bridge was built instead of the Ah Kai Sha twin-deck four-carriageway cable-stayed bridge designed by Benaim (*18.4.11*).

Yet another method of building large arches is to build each half arch vertically over the springings, and then to rotate them about a horizontal axis, lowering them into position. This requires restraining falsework of similar capacity to that required by cantilever erection, but for a much shorter time. The construction of each half arch may be carried out by slip-forming or jump-forming techniques that may be more economical than building in cantilever.

When an arch is built in cantilever, the temporary masts and cables have to carry the full weight of the arch before it is joined. These costly temporary works may be significantly reduced by building a structure that is hybrid between the arch and the truss. The total restraining bending moment needed to ensure stability is of course dependent solely on the weight of the composite structure, but economy is derived from the fact that much of the temporary works are incorporated into the permanent works. It should always be an ambition of the engineer to use his ingenuity to minimise the purely temporary components in a construction procedure. In addition to reducing the temporary works, this method of construction also builds the deck and the arch at the same time, giving the opportunity to reduce the overall construction programme. Many such bridges have been built in China [1].

It is hoped that this brief summary of the various methods of building large concrete arches will stimulate the imagination of the designer, as clearly other possibilities exist

17.9 Progressive collapse of multi-span arch bridges

The Romans designed each span of their multiple arch bridges to be stable in the event of the absence of an adjacent arch, either due to a span-by-span construction sequence, or to the destruction of a single span in war. Consequently, everyone else did likewise until the late eighteenth century when Perronet discovered that he could greatly lighten the piers of his bridges by building all spans at once. Thus he could design the piers only for the difference in thrust from adjacent spans. Now, modern engineering practice has returned to Roman concepts as it is considered prudent to design to limit the risks of progressive collapse, or of disproportionate damage in the event of a local accident. Thus a multi-arch bridge should be capable of carrying its self weight plus normal working live load without collapse in the event of the removal of one span.

In the Sungai Dinding Bridge described above, the progressive construction method imposed pier foundations that were designed to resist the unbalanced thrust of the dead weight of an arch. In fact, as the piers were designed for ship impact, the foundations did not require significant strengthening.

17.10 Tied arches

Conventional large-span arches require foundations to resist their thrust. If the ground is poor, such foundations are likely to be very expensive, and may rule out a conventional arch option. This problem can be overcome by providing a tie between the arch springings, leaving only vertical reactions on the foundations, Figure 17.21 (a). The tie is usually incorporated into the bridge deck that is suspended from the arch by hangers. The bridge must rest on bearings that allow for its length changes.

As the self weight of the arch is a significant proportion of the total load, it is likely to be economical to use very strong concrete working at high stress to reduce its size and weight. This is possible as the buckling of the arch may be restrained by the deck, as long as this has adequate bending strength in both planes. Any lateral deflection of the arch due to incipient buckling is resisted by the deviation of the hangers, which provide a restoring force, Figure 17.21 (b). However, although greatly improving the stability of the arch, this arrangement does not totally preclude buckling. Before the hangers can exert any restoring force the arch must deflect incrementally sideways. It needs to be proven by analysis that there is a stable outcome and that the deck can resist the small lateral loads that this action will impose on it, or that it will not deflect

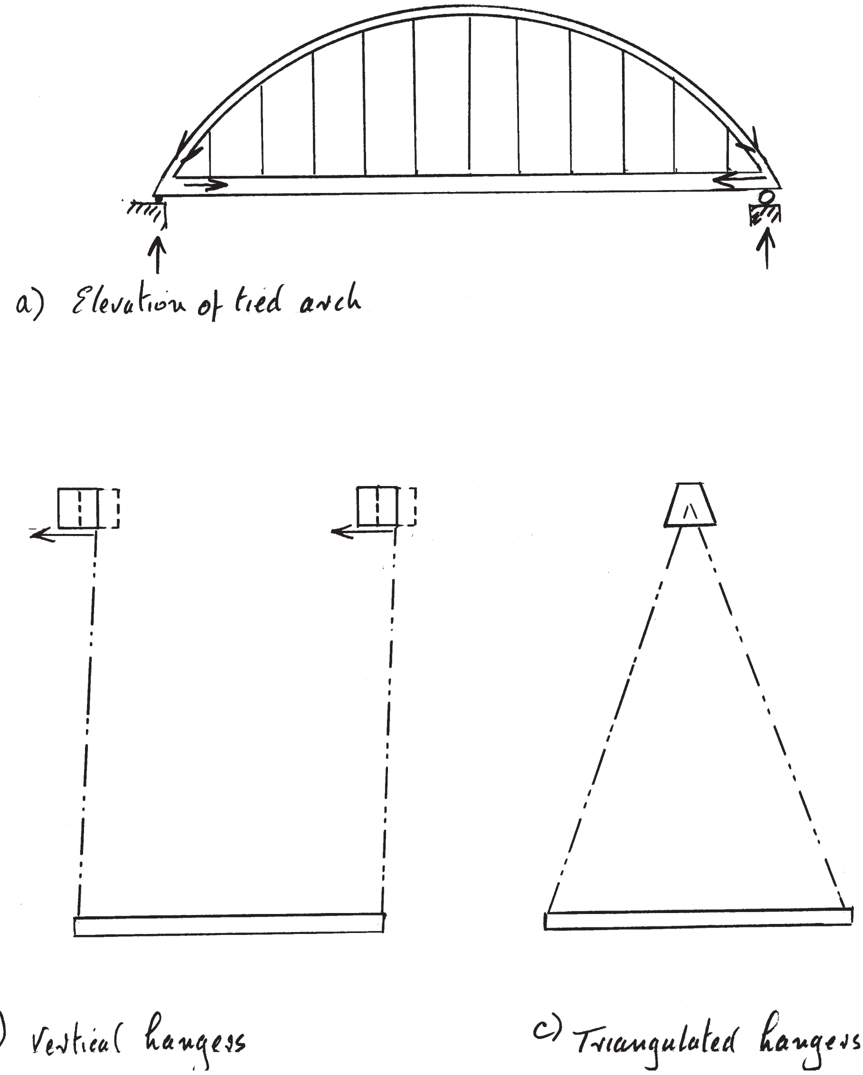

Figure 17.21 Tied arch

laterally so much that its stabilising effect is reduced. Any normal continuous highway deck is likely to fulfil these conditions, but light footbridges may not. If the hangers are effectively triangulated transversally, meeting at an apex at the arch, and if the deck has suitable torsional stiffness, the arch may be completely stabilised against lateral buckling, Figure 17.21 (c), allowing the most slender of structures. Even a narrow angle of triangulation will be effective in providing this stability, as the first incremental sideways movement of the arch immediately encounters a horizontal component of hanger force.

The bridge must of course be capable of carrying concentrated live loads which, if applied to the arch, would generate bending moments in it and significantly increase its required depth and weight. The logic of the tied arch is to provide a stiff deck that carries the moments, allowing the arch to be as light as possible.

The construction of a tied arch is dominated by the problem that it cannot be erected unless the tie is in place; but as the tie usually consists of the bridge deck, it needs the arch to carry it. Various solutions, other than ground-based falsework, are available.

For instance, the arch foundations may be designed to carry a small amount of horizontal thrust by the bending of vertical piles, augmented if necessary by temporary inclined ground anchors. A pre-arch made of steel or thin concrete shells may then be erected whose thrust is within the capacity of the foundations. The pre-arch may be erected in cantilever supported by temporary stays, or may be prefabricated in large sections and erected by crane. Once the pre-arch is complete, a tie would then be installed. One option for the tie consists of temporary cables in tension. However, as such cables would be much more flexible than the foundations any increase in thrust due to additional weight added to the arch would extend them, transferring most of the additional horizontal thrust to the foundations. This may be avoided by progressively increasing the tension of the cables to keep the horizontal force in the foundations between predetermined limits.

This is a fussy operation, and may be avoided if ties are installed that can also carry some compression. These may be slender steel or concrete tubes that cannot buckle, due to the internal prestressing (*4.2.8*), or the ties could be a first stage of the construction of the suspended deck. These ties would initially be compressed by the cables. The increasing thrust from the arch as it is completed will then de-compress them, with little elongation, hence adding only small additional horizontal thrusts to the foundations. However, ties capable of taking compression will be heavier than cables, and the thrust of the pre-arch due to this additional weight has to be taken by the foundations.

An alternative method of construction would be to erect the deck on temporary supports, either by launching or span-by-span, and then to use this as a platform for erecting the arch. If such temporary supports were acceptable and economical, it would of course beg the question as to whether the arch was indeed necessary.