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. 12: Management of concrete bridges

Figure 1 Anti-carbonation coating

Introduction

The final article in this series examines the long-term management of concrete bridges. Previous articles discussed the durability of concrete bridges[1], the importance of minimising the number of bearings and joints, and the use of integral bridges[2]. The specifications for bridge concretes need to identify the required concrete strength, the cover to reinforcement, the water-to-cement ratio and the cement type, all of which will depend on the particular site and environmental conditions. Working to these specifications will ensure that the concrete is best suited to its location in the bridge, and provide a long and low-maintenance working life. Here, we discuss the inspection and assessment of a bridge over its entire life, maintenance requirements and possible strengthening to upgrade the bridge to a new load configuration or revised layout.

Deterioration mechanisms

Although concrete is considered a durable material (because it is thought of as 'hard' and has been around in its basic form since Roman times), it can be prone to deterioration caused by local environmental conditions. Concrete is a highly alkaline material and provides a protective environment for steel reinforcement due to the formation of a passivating film on the surface of the reinforcement. The passivating film can be reduced by external factors such as penetration of atmospheric gases or chloride ions from de-icing salts or seawater. The speed at which this reduction occurs is dependent on the properties of the concrete, such as its water-to-cement ratio, permeability and electrical resistance. In some conditions, these factors can lead to the onset of corrosion in the reinforcement.

The principal deterioration mechanisms affecting concrete structures are:

- carbonation
- chloride ingress
- sulphate attack
- corrosion of reinforcement
- alkali-silica reaction
- freeze-thaw cycle
- impact

Secondary problems, such as thermal, bacterial and radiation damage, are unlikely on concrete bridge structures. The principal deterioration mechanisms, and preventive/repair techniques used to address them, are described in the following sections.

Carbonation

Carbonation is a slow reaction process, caused by carbon dioxide in the atmosphere, which starts at the surface of the concrete and slowly works its way inwards. Carbonation decreases the alkalinity of the concrete and thus reduces its resistance to steel corrosion. Testing for the presence of carbonation involves the application of phenolphthalein to the surface of the concrete; a violet hue indicates that the concrete remains alkaline. It is good practice to apply this indicator to a piece of freshly broken concrete, so the depth of carbonation can be assessed. Increased carbon dioxide in the

Figure 2
MCI application

atmosphere, due to climate change, may lead to more carbonation in the future.

Anti-carbonation coatings are available; these can be sprayed or applied with a brush to form a protective barrier (Figure 1). Maintenance of the coating should be included in the bridge maintenance plan. In addition to the coating, a migrating corrosion inhibiter (MCI) can be installed. These act by suppressing the electrochemical corrosion reactions that may occur on the surface of reinforcing bars[3]. The MCI is usually applied by brush or sprayed onto the surface of the concrete (Figure 2). Due to their migrating properties, MCIs are able to penetrate the concrete to protect the steel reinforcement from chloride attack. Other versions are available in tablet form; these can be placed in holes drilled at regular centres in the concrete.

Chloride ingress

Chloride ingress occurs primarily due to the use of de-icing salts, although it also occurs in marine environments. In the past, chloride-based additives were also included in the concrete mix to accelerate curing; however, their use was prohibited in bridges in the early 1970s. Traffic speed and volume have created problems with chloride-saturated spray affecting bridge piers and deck soffits. Poor maintenance of movement joints allows chloride-laden rainwater to penetrate the ends of decks and bearing shelves. Chloride ions can diffuse through concrete pores in solution and attack the passive film protecting the steel reinforcement, causing corrosion. The corrosion product, rust, has a greater volume than steel and, as a result, provides an expansive force that will eventually cause the concrete cover to delaminate and spall, making reinforcement visible. Repairs will be needed to prevent further deterioration.

The extent of repair will depend on the extent of chloride contamination and the condition of the reinforcement. Chloride-contaminated concrete will need to be removed, usually by hydro-demolition (Figure 3), which reduces the risk of damage to reinforcement and to concrete being retained (Figure 4). Reinforcement may also need to be replaced or supplemented, depending on the amount of section loss and structural capacity. Concrete behind the reinforcement bars must be removed to ensure that the embedded chloride is eradicated and that the new concrete – whether sprayed, poured or hand-placed – has a key around the bars. Care must be taken if spraying, as voids can form in the shadow of reinforcement. It is essential that the source of chlorides is removed in locations such as bearing shelves; movement joints will often need to be replaced. Deck waterproofing will prevent ingress of chlorides and is a requirement on all new bridge decks in the UK (Figure 5). It is good practice to apply a red sand carpet over the waterproofing membrane to alert any future surfacing operations to its presence (Figure 6).

Sulphate attack

Sulphate attack is most common in buried structures where groundwater contains sulphates. The problem generally occurs in clay soils, although there are other sources, including gypsum. The molecular structure of the concrete changes, with ettringite being formed within the cement paste. The concrete becomes sandy in appearance and soft to the point that it can be scraped away easily with a handheld tool. There is also a type of sulphate attack which occurs under very specific wet conditions in clay soil; a thaumasite mineral gradually replaces the cement paste matrix of the concrete. Repair will often mean complete replacement of the item, as it is not possible to reverse the effect. When considering reconstruction, BRE publications give recommendations on minimum cement contents depending on the sulphate concentration, and sulphate-resisting cement is also available. Buried structures are usually specified to have a coat of bituminous waterproofing prior to backfilling to help with this resistance.

Corrosion of reinforcement

Corrosion of reinforcement may occur as a result of the effects described previously, but insufficient cover to the steel can also be a cause. In recent years, cathodic protection (CP) has increasingly been used to protect reinforcement from further corrosion. It is particularly relevant to chloride-contaminated concrete, allowing concrete to remain in place if it is sound, which avoids the need for extensive removal and replacement. There are two principal types of CP system available for use in the bridge environment: sacrificial

Figure 3
Hydro-demolition

anode and impressed current. The decision on which system to use is usually influenced by a number of factors including, but not limited to, the condition of the structure, the owner's budget and the anticipated life expectancy of the structure following the repairs. A case study on the use of sacrificial anode CP is discussed in CBDG Technical Paper No. 11[4].

Sacrificial anodes have been used to protect steel in concrete from corrosion since the 1990s. The initial application was to protect patch repairs from 'incipient corrosion' of the surrounding reinforcing steel. The principle is similar to that of sacrificial anodes applied to ships and pipelines, in that an anode attached to steel will corrode in preference to the steel and thus protect the steel from further corrosion. Sacrificial anodes used in concrete repairs can contain either a zinc or aluminium core, which is surrounded by an activator to avoid passivation, and are placed around the periphery of repairs to offer protection to the steel in the adjacent chloride-contaminated concrete. The sacrificial anode current output responds to the nature of the environment, increasing current delivery in warm, moist, chloride-contaminated concrete. These materials are incorporated into the European Concrete Repair Standard[5]. The simplicity of these sacrificial anode systems offers an attractive corrosion control option for the bridge owner.

In a further development, a hybrid anode system has been developed which utilises a temporary initial impressed current treatment followed by a long-term sacrificial anode protection phase, using a single anode. The hybrid anode system utilises the advantages of impressed current by applying an external current for a short period in order to stop steel corrosion by re-passivating the steel. Once re-passivation is achieved, the anode system is connected directly to the steel in order to behave as a sacrificial anode system and maintain the passive condition of the reinforcement steel. This simple principle is based on data obtained from 15 years of electrochemical treatment of concrete structures and offers a straightforward solution to ongoing corrosion problems. The requirement for a permanent power supply is eliminated and the hybrid system offers the simplicity of a sacrificial anode requiring minimal long-term maintenance. A further substantial benefit, in terms of corrosion risk management, is the facility to re-apply further current through the installed anode system at any point in the future.

Figure 4
Exposed reinforcement after hydro-demolition

Figure 5
Application of waterproofing membrane

Figure 6
Red sand carpet over waterproofing

Impressed current CP differs from galvanic CP in that it derives its source of electricity from a DC power supply rather than the potential difference of two dissimilar metals. Where galvanic anodes have a finite lifetime, determined by the type and weight of material and the environment in which they are deployed, impressed current anodes are inert and can be used under a much wider range of environmental conditions. As a result of this fundamental difference, impressed current CP can be set to maintain a uniform protection level regardless of the operating conditions. Impressed current CP has therefore found use where chloride concentration may be particularly high (typically greater than 0.8% by weight of cement), in carbonated concrete and where an extended design life is required (approx. 50 years). Impressed current CP systems for concrete structures make use of inert anode materials, typically titanium with a mixed metal oxide activator, connected to the positive pole of a DC power supply unit, with the structure (the cathode) connected to the negative pole. Anodes can be either embedded or surface-mounted, and come as rods, ribbons, surface-mounted mesh and paints among other forms.

All CP systems should be designed with a method of performance monitoring to ensure adequate protection is being achieved. For impressed current CP, it is typical to install a number of half-cell reference electrodes which provide a standard fixed potential against which to measure the influence of CP on the potential of the reinforcement. To cater for differences in concrete conditions, such as reinforcement quantity, geometry and environmental exposure, it is common to design a system in a number of independent anode zones, with each zone comprising an anode system, monitoring devices, DC wiring system and DC power supply unit. DC power supply units for CP are typically bespoke units which tend to incorporate

Figure 7
Resin injection

data-logging equipment and telemetry for monitoring system performance. The power consumption of a typical four-zone impressed current CP system is in the order of 400W.

Alkali-silica reaction

Alkali-silica reaction is caused by a reaction between the hydroxyl ions in the alkaline cement pore solution in the concrete and reactive forms of silica in the aggregate (e.g. chert, quartzite, opal and strained quartz crystals). The reaction creates a gel substance that increases in volume and cracks the concrete; the gel often exudes from the crack. The problem often reveals itself where water runs onto a surface, such as at joints, upstands, plinths and drip features. In unrestrained concrete (without any reinforcement), the reaction causes characteristic 'map cracking' or 'Isle of Man cracking'. If the concrete remains dry, the reaction may not occur. Where the damage caused is slight or not structurally significant, it may be appropriate to seal any cracks arising and allow the problem to stabilise once the water ingress has been stopped. Where damage is severe, demolition and replacement is the only solution. For new concrete, current specifications limit the alkali content for cements in which aggregates include any reactive forms of silica.

Freeze-thaw cycle

Freeze-thaw cycle damage occurs when water has penetrated the matrix and expanded upon freezing, sometimes cracking the concrete in the process. Upon thawing, the cracked concrete spalls. This is a progressive process and, in general, the higher the strength of concrete, the more resistant it is to this problem. In the late 1970s, air entraining became popular. An admixture is used to create air bubbles in the mixing process (typically 0.4mm diameter); these bubbles cut off the capillary action of the concrete hydration pores (typically 0.025mm diameter), so water is not 'soaked up' by the concrete. Repairs to frost-damaged surfaces involve removal and replacement of the affected material.

Impact

Impact damage is often severe due to the energy imparted and its distribution throughout the structure. Structural integrity may be compromised, creating an immediate danger of collapse. However, repairs are often local. Consideration must be given to the effects on reinforcement, or prestressing tendons where present, as they may have been damaged. The treatment is to remove any loose material and check reinforcement and tendons. Where reinforcement or tendons are damaged, structural capacity must be checked and repair, replacement or strengthening carried out as necessary before applying a suitable cementitious repair material. Edge beams are most likely

Figure 8
Application of sprayed concrete

to suffer in the event of an impact and this can cause particular issues in relation to the capacity to redistribute loading.

If the majority of the structure is sound, various repair techniques are available. This applies to all areas of deterioration, not only damage. The affected concrete should be removed by percussive methods or hydro-demolition. Resin injection can be used for sealing cracks (Figure 7). Exposed reinforcement can be assessed for loss of area and either re-used or replaced. New concrete can be cast *in situ* or sprayed (Figures 8 and 9). Other treatments, as described previously, can then be applied as required.

Investigation works

Bridge owners are normally required to undertake principal inspections at regular intervals; if problems are observed, it is good practice to carry out a more detailed investigation of the cause and/or thorough condition survey[6,7]. Risk-based assessments can be carried out to adjust the time interval between inspections, but this is not currently common practice. During an investigation, the following checks are performed in order to assess the extent and effects of the possible problems described earlier:

- detailed visual survey
- carbonation analysis
- chloride content analysis
- sulphate content analysis
- cement content analysis
- reinforcement cover survey
- half-cell potential survey
- visual check

A **detailed visual survey** will accurately record all physical defects to the structure and will be used to determine the locations and extent of the subsequent investigations. It will also include ancillaries such as bearings, parapets, fixings and joints. **Carbonation** depth is readily assessed on-site by spraying phenolphthalein onto a freshly broken concrete surface. **Chloride content** is determined by drilling into the concrete and collecting dust samples for analysis, noting the depths at which they were taken. **Sulphate content** is determined in a laboratory from samples obtained from site. **Cement content** can also be determined from a concrete sample obtained from site and is required to enable a more meaningful determination of chloride and sulphate results. It will also provide an indication of the quality of the original concrete.

A **reinforcement cover survey** should only ever be required once in the life of a structure, because reinforcement does not move. Cover surveys are normally carried out using electromagnetic cover meters. However, data collected should be calibrated by breaking out to expose reinforcement locally. This can often be combined with breakout required to make electrical connections to reinforcement for half-cell potential surveys. **Half-cell potential surveying** is a technique for determining where the probability of reinforcement corrosion is highest. This method measures the electrode potential of steel reinforcing bars in concrete compared to the known potential of a reference electrode (usually a copper/copper sulphate or silver/silver chloride). The electrode potential of the steel is an indicator of the likelihood of corrosion activity. The survey is carried out by making an electrical connection to the reinforcement and taking measurements on the concrete surface.

Strengthening

An increase in the weight of heavy goods vehicles on the UK's roads has required a programme to assess almost all highway structures. In general, most structures are satisfactory because the 12t permissible axle load has not increased; only the number of axles has increased. However, impact effects on bridge parapets have increased and it is sometimes necessary to re-form the parapet edge beam. Similarly, the number of axles on a structure may necessitate shear enhancement near supports and possible bending capacity enhancement near midspan. This has also been known to increase bending capacity on deck cantilevers due to the increase in the overall weight of heavy vehicles.

Shear enhancement

Shear enhancement involves increasing the amount of vertical reinforcement in a deck; this is achieved by retrofitting bars through holes drilled in the deck. Holes are cored through and high-tensile-strength threaded studs are placed in the holes. A large spreader plate is placed at each end

Figure 9
Sprayed concrete with anode positions

and the void is filled with grout. After the grout has cured, the studs can be tensioned by applying a designed torque to the nuts. Carbon fibre strengthening can also be used to add reinforcement and to aid transverse distribution, thereby enhancing shear capacity.

Bending enhancement

Bending enhancement usually comprises fitting external reinforcement in the form of cables, bars and steel or carbon fibre plates. The concrete surface needs to be cleaned of all laitance, dirt and grease – ultra-high-pressure water jetting or grit blasting will achieve this effect. A primer coat of resin is then applied, followed by a layer of resin onto which the steel or carbon fibre plates are placed. One problem with steel is the weight of plates, as this form of strengthening is generally applied to the deck soffit. Some form of bolted end anchorage is required while the resin cures. When strengthening deck-edge cantilevers, it is usual to apply the plates on the top surface under the asphalt road construction[8–10].

Consideration needs to be given to fire protection of the strengthening arrangement. The plate may be left exposed if the risk of fire is low. However, a fairing coat of cementitious material could offer protection should a fire occur. When used at a location which people can access (such as subways), the plates need to hidden from view to reduce the risk of vandalism. Columns have successfully been strengthened by applying carbon fibre fabric in layers wrapped around the column. This technique is ideal for circular columns, but a radius will need to be formed on any faceted columns.

Conclusions

Concrete is an ideal structural material for use in bridges. It is relatively easy to handle, mix and place, and offers a robust form of construction, partially due to its mass. A concrete structure should perform for its minimum design life of 120 years without significant problems, providing attention is given to its environment and use, good detailing is applied, the right constituents, finishes and reinforcement cover are selected, and it undergoes routine maintenance of drainage and joints. However, it is the responsibility of the asset owner to ensure maintenance is carried out to limit the ingress of water and deleterious materials arising from blocked drainage or leaking joints. A responsible owner will keep these issues under control with a maintenance regime that will keep the bridge functioning as it was intended.

References and further reading

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