

ENGLISH HERITAGE  
PRACTICAL BUILDING CONSERVATION

# CONCRETE



ENGLISH HERITAGE

ASHGATE

*This chapter covers the principal methods which can be used for the repair and preservation of concrete, and provides guidance as to when particular treatments might be appropriate.*

Rigorous diagnosis of the causes of deterioration and damage is a precondition to successful long-term maintenance of concrete buildings. A programme of intervention needs to be robust, transparent and accountable, and based on an understanding of the building's history, significance, condition, local environment, and any risks arising from the way it is to be used. **➤BASICS**

Sustainability considerations, as well as conservation requirements, make it necessary for the useful life of our built environment to be maximised. Unless there are good reasons to the contrary, the first aim of any repair programme should be to keep as much of the original fabric of the building as possible.

A second overall aim should be to maintain the appearance of the building, but this is not always possible. Some remedial treatments will effectively conserve the character and appearance of a historic building, but more invasive and visually disruptive work may be needed to secure its continued survival and use. Matching repairs to maintain the aesthetics of exposed concrete creates particular challenges, and if efforts are to be made to reinstate the original appearance, then it is important to establish exactly what this was.

Once deterioration becomes widespread, repair and remedial work to concrete are expensive and disruptive to the normal use of the building. Methods for reliable long-term repair of deteriorating concrete are only slowly being developed. As with other materials, this requires good knowledge of the material and the way in which it deteriorates, along with the appropriate skills needed to carry out repairs.

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## THE PRACTICAL BUILDING CONSERVATION SERIES

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This series of *Practical Building Conservation* technical handbooks supersedes the original five volumes written by John and Nicola Ashurst, and published in 1988.

The series is aimed primarily at those who look after historic buildings, or who work on them. The ten volumes should be useful to architects, surveyors, engineers, conservators, contractors and conservation officers, but also of interest to owners, curators, students and researchers.

The contents reflect the work of the Building Conservation and Research Team, their colleagues at English Heritage, and their consultants and researchers, who together have many decades of accumulated experience in dealing with deteriorating building materials and systems of all types. The aim has been to provide practical advice by advocating a common approach of firstly understanding the material or building element and why it is deteriorating, and then dealing with the causes. The books do not include detailed specifications for remedial work, neither do they include a comprehensive coverage of each subject. They concentrate on those aspects which are significant in conservation terms, and reflect the requests for information received by English Heritage.

Building conservation draws on evidence and lessons from the past to help understand the building, its deterioration and potential remedies; this encourages a cautious approach. New techniques, materials and treatments often seem promising, but can prove disappointing and sometimes disastrous. It takes many years before there is sufficient experience of their use to be able to promote them confidently. Nonetheless, understanding increases with experience and building conservation is a progressive discipline, to which these books aim to contribute.

The volumes also establish continual care and maintenance as an integral part of any conservation programme. Maintenance of all buildings, even of those that have deteriorated, must be a priority: it is a means of maximising preservation and minimising costs.

Most of the examples shown in the books are from England: however, English Heritage maintains good relations with conservation bodies around the world, and even where materials and techniques differ, the approach is usually consistent. We therefore hope the series will have a wider appeal.

Dr Simon Thurley  
Chief Executive, English Heritage

## ABOUT THIS BOOK

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Despite some public antipathy towards its appearance and concerns about its longevity and environmental impact, the importance of concrete to the nation's architectural heritage is gradually being acknowledged. Many concrete buildings have now been listed: from farm buildings, sculptures, houses and churches, to large structures such as factories, bridges and even whole housing estates. A number of buildings have been conserved to wide acclaim and this is helping to temper the perceived 'ugliness' of concrete, as well as successfully extending the lifespan of the buildings themselves.

The vast majority of iconic 20th-century structures have used concrete in some part of their construction, even if this may not be readily visible. Many concrete structures have been built to a very high standard; others (for reasons of economy, lack of knowledge, expediency and poor workmanship or supervision) have been less well constructed, but are nonetheless of architectural or historic importance and so may require conservation. The maintenance of this built infrastructure is socially important and, given that premature demolition and new construction are neither economically or environmentally sustainable, its conservation also has considerable environmental benefits.

This volume considers how historically significant concrete buildings should be treated, both in terms of preservation and repair. The interaction of the composite materials that make up concrete provides additional complexities that do not exist in homogenous materials. Furthermore, the approach to conservation, both in material and aesthetic terms, may be different to that adopted for more traditional historic materials, such as stone, timber and plaster. For those materials, retention of a certain amount of surface decay and weathering is acceptable and perhaps desirable, but on a more modern concrete building, technical issues and design intent may preclude this, even though patina can play an important part in its appearance.

One of the problems with conserving this complex material is that, as yet, the number of concrete conservation projects is small and there has been little opportunity for long-term monitoring of the results. Materials and methods will continue to evolve, through improvements in understanding and technology, and as monitoring of treatments reveals more about good and bad practice.

The book begins with a history of the use and development of concrete as a building material. The second chapter, **Deterioration & Damage**, looks at the ways in which concrete degrades or breaks down, and the third covers the **Assessment** of concrete buildings as a prelude for determining approaches to their conservation. **Treatment & Repair** describes the range of methods that can be used to deal with the causes and consequences of deterioration and damage. This is followed by a chapter of **Case Studies**, where specific examples are used to illustrate some of these general principles of repair. The final chapter, **Care & Maintenance**, gives guidance on how to maximise the preservation of concrete buildings whilst minimising long-term costs.

## STRATEGIES FOR REPAIR

Inherent in the British Standards for concrete is a design life of 50 years for general construction, and 100 years for important bridges and buildings; with appropriate care and maintenance, the best-designed and best-built concrete structures are likely to last far longer. Unfortunately, many concrete buildings have had to be demolished because of premature deterioration.

Effective treatment and repair strategies should aim primarily to address the underlying mechanisms of deterioration. As with other construction materials, it is exposure to moisture that is the basis for most decay.

In some cases, works are needed because the building has been neglected or because previous interventions have failed; in others, because of the inevitable progressive deterioration that develops in concrete when reinforcement begins to corrode.

In the 1970s and 1980s a growing realisation that concrete was not a ‘maintenance-free’ material led to research on the processes of deterioration, techniques of investigation and diagnosis, and remedial methodologies to repair structures, strengthen them, or control rates of corrosion and deterioration.



Opened in 1966, the concrete at the Tricorn Centre, Portsmouth, deteriorated quite rapidly partly due to design issues, but also due to the wet coastal climate. Attempts to get it listed as a fine example of Brutalist architecture were turned down and it was demolished in 2004, despite an active campaign for its preservation.

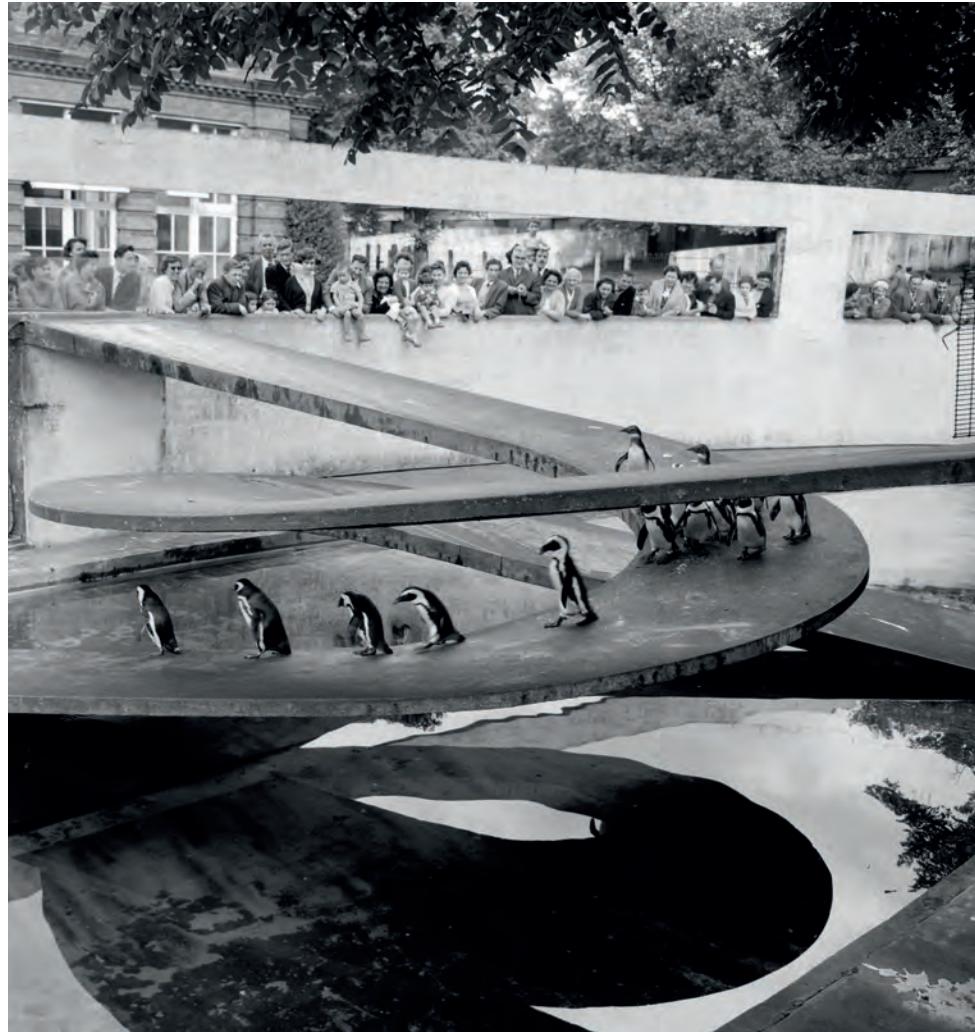


One influential figure from this era was Berthold Lubetkin. He and Tecton built Highpoint I (comprising 56 flats) during the years 1933–35. This construction utilised a method developed by engineer Ove Arup, in which floor slabs spanned external load-bearing walls and spine beams rested on a central row of columns, thus limiting the free plan. By 1936, however, when Lubetkin and Arup began Highpoint II, this problem was resolved. They used a different construction, with double-height living rooms at the centre of the luxury flats. By making the internal cross walls and floors structural – using a box frame – the elevations were free to be light and highly glazed; this technique was to transform post-war building construction.



Highpoint I, Highgate, London, 1933–35. The flats were originally commissioned to house staff from the Gestetner company. Corbusier described them as *“an achievement of the first rank”*.

The Penguin Pool at London Zoo was built in 1934 and brought together two pioneers in the concrete construction: the architects Berthold Lubetkin and the engineer Ove Arup. The pool is based on an egg shape with two spirally intertwining ramps. It was extensively conserved in the 1990s.



Lubetkin also used concrete expressively, as at the Penguin Pool at London Zoo from 1934, with its two intertwining helical ramps, one of the most enduringly popular and flamboyant examples of concrete innovation.

The preservation of buildings from this period presents particular challenges. Often, concrete buildings of the 1930s have very thin walls. Furthermore, a range of waste materials and poor-quality aggregates were used in concrete in the early 1920s, and some innovations were to prove problematic in the long term. One of these was high-alumina cement [HAC], first imported into England in 1922 and used widely in pre-cast elements well into the 1970s, after which it was banned for structural work because it was subject to a loss of strength over time.





# TYNEMOUTH COASTAL BATTERY

## NORTH TYNESIDE, TYNE & WEAR

### BACKGROUND

#### SUMMARY

Mass concrete can be more difficult to repair than reinforced concrete, since the steel can help mechanically bond new patches to the original material and prevent repairs cracking. Previous repair methods for historic concrete were based on shuttering being fixed (or ‘plugged’) into the original concrete, leaving holes which needed to be filled; these were impossible to conceal. A programme of repairs on the Tynemouth Coastal Battery tested less-invasive ways of shuttering.

#### HISTORY

The coastal battery at Tynemouth dates from various periods (from the 1880s to the 1940s) and includes concretes of various compositions, including different textures and surface finishes. The battery has considerable significance, not only for its use of materials but for its historical role in the defence of Britain during two World Wars; as a result, it is a scheduled monument.

#### CONDITION

The absence of reinforcement had allowed different concrete pours to move and settle relative to each other; the resulting cracks had allowed water ingress. It also meant, however, that the concrete had not been subject to the corrosion of reinforcement expected in this marine environment after prolonged exposure. Other deterioration had occurred due to surface degradation (loss of outer cementitious layer revealing the aggregate), and mechanical damage from the scrap merchants who removed many of the embedded steel fittings when it was decommissioned.

The coastal defences at Tynemouth were put in place to defend the north of England's main outlet for oil and coal. There are many phases of building on the site, including this late-Victorian gun emplacement, the pit of which was filled with a concrete store during the Second World War.

## CHOOSING APPROPRIATE REPAIR OPTIONS

In reality, most concrete deterioration arises due to a combination of causes, and therefore most repair will involve a combination of remedial actions. The table below shows the advantages and disadvantages of repair options, and the implication of their use, with regard to the significance and appearance of the building. The table summarises conservation best practice; for each case the most appropriate repair option can only be established once the reasons for decay have been understood and assessed.

Repairs that are not proven or inappropriate for historic concrete buildings (for example, corrosion inhibitors, re-alkalisation) have not been included in these options. Structural repairs (including crack filling) have also been omitted because they will need specialist assessment.

| CAUSES OF DECAY & CHOOSING THE APPROPRIATE TREATMENT & REPAIR  |  |   |  |
|--|--|---|--|
| REPAIR OPTION  | ADVANTAGES   | DISADVANTAGES   | CONSERVATION IMPLICATION   |
| <b>Exposure to damp internal or external conditions for concrete with developing corrosion due to carbonation</b>              |  |   |  |
| Patch or large-scale repair to match original and leave uncoated   | <p>Provides short- to medium-term solution depending upon the reasons for the deterioration</p> <p>Can be combined with moisture reduction to slow deterioration in adjacent areas</p> | <p>Further repairs will be required at some stage in the future</p> <p>Any new external repairs will require time to weather and establish microbiological growth to match the original</p> | Aesthetically acceptable for scheduled monuments and some listed buildings   |
| Surface coatings (paints and anti-carbonation coatings) combined with local repairs using like-for-like or proprietary repairs | <p>In some locations can reduce ingress of water to slow deterioration</p> <p>Can reduce rate of carbonation</p> <p>Hides repairs and inconsistencies</p>                              | <p>Can trap water within the concrete to increase corrosion rates by preventing evaporation</p> <p>Needs periodic re-application</p> <p>Changes appearance</p>                              | <p>The change in appearance that results from a new surface coating may not be acceptable for a listed building</p> <p>Decisions will have to be based on assessment of this change against the possible extension of the lifespan of the concrete</p> |
| Surface impregnation and sealants  | <p>Reduces ingress of water</p>  | <p>Reduction of moisture may increase carbonation</p> <p>May change surface appearance slightly (by reducing reflective properties of the concrete)</p> <p>Needs periodic renewal</p>       | The slight change in appearance may be acceptable, but regular re-application becomes a maintenance issue  |
| Erect ventilated rain-screen cladding  | <p>Prevents the ingress of rainwater and encourages drying, thus reducing the corrosion rate</p> <p>Hides repairs and irregularities</p> <p>Provides long-term solution</p>            | <p>May increase the rate of carbonation of the original concrete</p> <p>Changes appearance</p>  | The significant change in appearance means that this is the last available option to be used when the interior of the building or its elements are more important than the overall appearance  |



| <b>CAUSES OF DECAY &amp; CHOOSING THE APPROPRIATE TREATMENT &amp; REPAIR</b>   |   |   |  |
|--|---|---|--|
| <b>REPAIR OPTION</b>   | <b>ADVANTAGES</b>   | <b>DISADVANTAGES</b>  | <b>CONSERVATION IMPLICATION</b>  |
| <b>Exposure to damp internal or external conditions for concrete with developing corrosion from chlorides (calcium chloride, marine spray or de-icing salts)</b> |   |   |  |
| Cathodic protection  | <p>This provides an alternative to patch repairs and coatings itemised above</p> <p>In conditions where uniform current density can be achieved with moderate voltage it can control corrosion rate in the long term</p>                            | <p>Concrete still requires repair</p> <p>Requires periodic maintenance</p> <p>Requires embedded anodes which will require concealment</p> <p>Can cause embrittlement of steels</p>  | If the anode can be suitably concealed, this can provide a visually acceptable long-term solution; however, in many cases, this will require the concrete cover to be replaced or overcoated |
| Patch repair using matched or proprietary repairs  | <p>Provides short- to medium-term solution depending upon the reasons for the deterioration</p> <p>Can be combined with moisture reduction and measures to stop spread of contamination with chlorides, to slow deterioration in adjacent areas</p> | <p>Only appropriate where chloride ingress and corrosion is localised</p> <p>Further repairs will be required at some stage in the future</p> <p>Any new external repairs will require overall coating or time to weather, and establish microbiological growth to match the original</p> | Can be acceptable for scheduled monuments and some listed buildings  |
| <b>Water ingress from defective rainwater goods, leaking roofs, pooling</b>  |   |   |  |
| Checking rainwater systems (hoppers, downpipes, surface drains and so forth) are working properly  | <p>Keeps rainfall from penetrating into dry carbonated concrete where it can cause corrosion</p> <p>Reduces risk of frost damage</p>  | None  | Should be part of ongoing maintenance  |
| <b>Water ingress into exposed and vulnerable areas</b>   |   |   |  |
| Install flashings and covers   | Diverts water away from vulnerable areas to reduce microbiological growth and discolouration, and risk and rate of deterioration  | May require alteration to original fabric such as installing overflow chutes or cutting chases for flashing   | This might be an acceptable intervention although may lead to architectural changes; for example, flashings will provide a hard visible edge where none was intended                         |
| <b>Water ingress from design defects such as in-built rainwater pipes or undersize hoppers</b>   |   |   |  |
| Amendment of design faults; improvements to detailing  | Reduces future decay  | Changes original architecture   | May alter building appearance, and thus compromise its significance and authenticity   |

## ELECTROCHEMICAL METHODS TO PREVENT CORROSION

The corrosion of steel reinforcement is electrochemical in nature, and involves the movement of charged ions and electrons between anode and cathode. This means that electrochemical methods offer a way of controlling the migration of charged ions (such as chloride, sodium and hydroxyl ions), and therefore stopping or delaying the corrosion reaction of the iron.

### Cathodic Protection [CP]

Cathodic protection is not a new process. In 1824, Sir Humphrey Davy presented a series of papers to the Royal Society describing how CP could be used to prevent the corrosion of copper sheathing on the wooden hulls of British naval vessels by using iron as a corroding sacrificial anode. This was successfully adopted, and since then CP has expanded into many other areas as an option for corrosion control and prevention. Over the past 40 years the technology has been selectively applied to concrete to control corrosion of the steel reinforcement; although it has proved successful in some suitable conditions, it can be an expensive option. Initially, most of the applications were on bridges, car park decks and buildings in marine environments; all situations where damp chloride-affected concrete had caused the development of severe corrosion. CP has been used in other situations, but any benefit is hard to separate from that which may be attributed to other repairs (for example, patch repairs and preventing water ingress) carried out at the same time. The long-term performance of all aspects of the repair needs to be accurately monitored and evaluated to reach conclusions as to the success of CP.

In CP systems the reinforcement to be prevented from corroding is supplied with electrons from an external source (by means of a small DC current) so that the entire metal surface is forced to act as a cathode (hence the term ‘cathodic protection’). It is essential that CP systems are designed by a suitably qualified specialist, and are tailored and controlled to suit the specific configuration and variability of the structure and the developing corrosion.

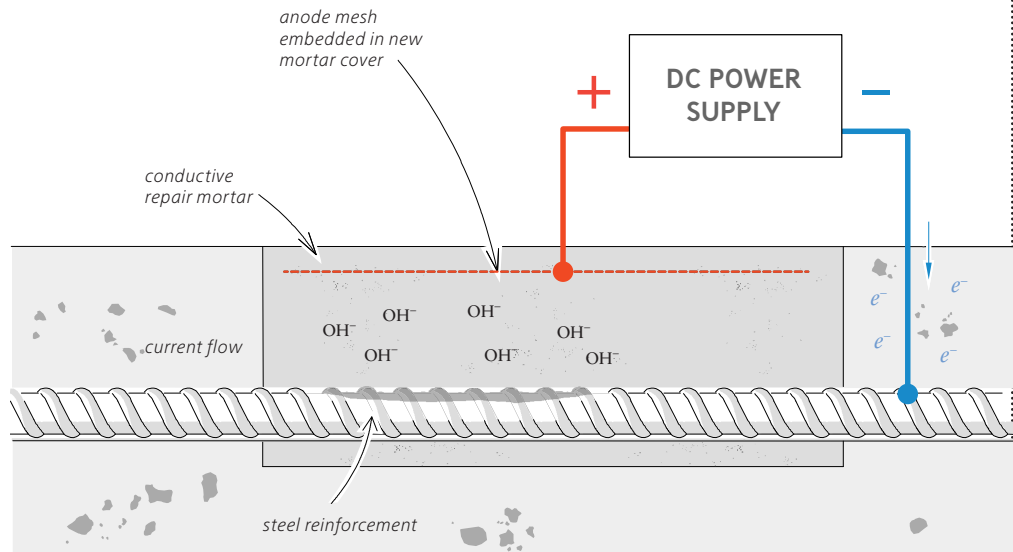
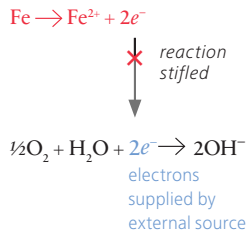
The primary technique used for concrete is impressed current cathodic protection [ICCP]. These are complex systems, that can protect large areas of embedded iron and steel, including steel reinforcement, I-beams, columns and supports, and be used even where the concrete has a high electrical resistance. They use non-corroding anodes located close to the embedded reinforcement to provide part of the current pathway, and an external power supply – usually mains-powered transformer rectifiers – to provide a DC current to the steel being protected.

ICCP can be continuously monitored and has been effective where chloride concentrations in the concrete are high. Although installing ICCP systems can be disruptive, these systems once in place can be relatively discreet, especially where the anodes can be positioned on internal surfaces.

**CATHODIC PROTECTION**

**SCHEMATIC DIAGRAM**

The external flow of electrons from the embedded steel satisfies the reaction at the cathode, forcing the corrosion reaction to cease.



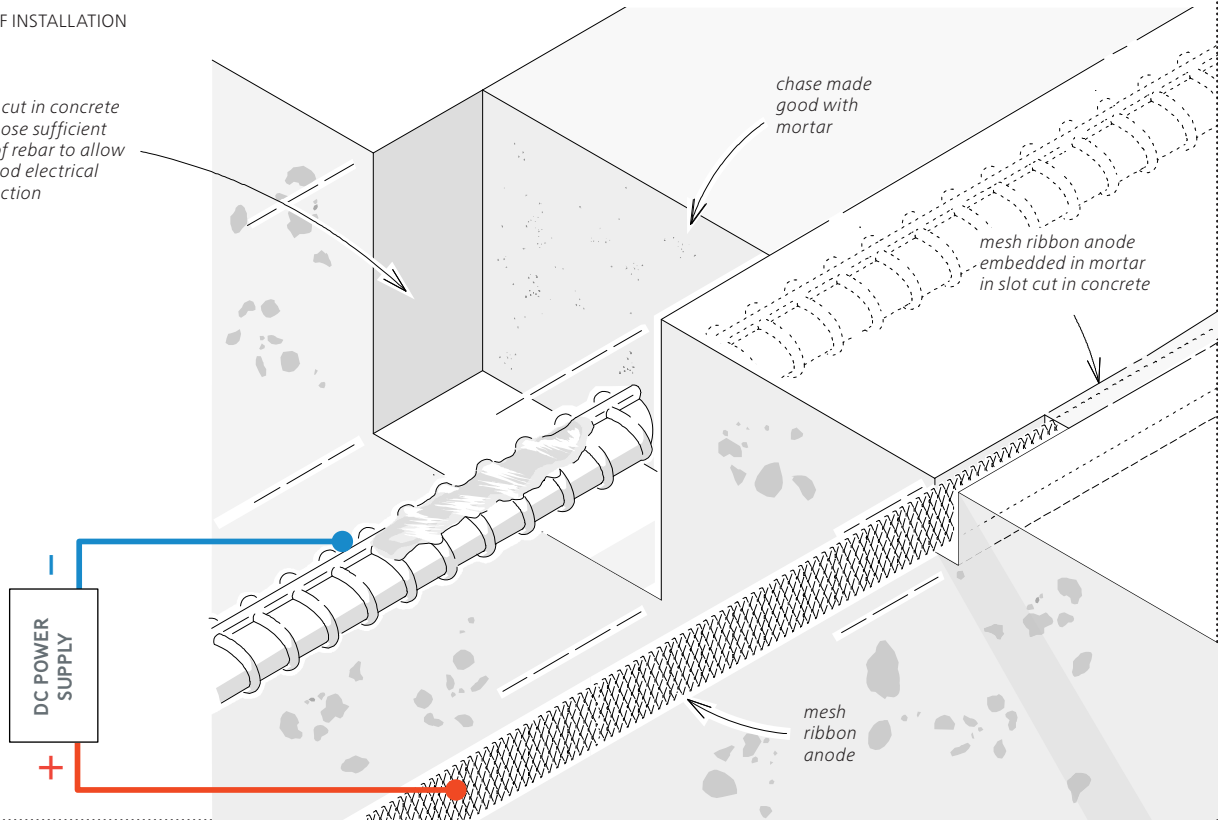
**EXAMPLE OF INSTALLATION**

chase cut in concrete to expose sufficient area of rebar to allow for good electrical connection

chase made good with mortar

mesh ribbon anode embedded in mortar in slot cut in concrete

mesh ribbon anode





## Surface Coatings

There are a range of coatings and surface treatments which have been applied to concrete as a barrier to further carbonation or surface absorption of chlorides, or to lower moisture level in the concrete; provided they are applied early, these can be used to improve the durability of concrete.

When applying surface treatments to concrete it is important to consider not only the appearance of the coated concrete, but the effect of the coating on moisture movement and the ongoing maintenance requirements (re-application may be needed every 10 to 15 years).

It is essential to ensure that the treatment is applied when the concrete is in a suitable condition, in particular at the correct temperature and with sufficiently low surface moisture content.

Although surface coatings can provide effective treatment, they usually radically alter the appearance of the concrete, so careful weighing of all options is required; if retaining the original uncoated surface is important, other treatments should be considered first. Once corrosion has started, coatings will be less effective, as they can trap moisture within the body of the concrete. The evaluation of all coatings should take into account their possible influence on moisture content and corrosion rates, especially if the corroding reinforcement is already in a carbonated or high chloride zone.

In all cases, before coatings are applied, there should also be a quantitative evaluation of changes in moisture content and corrosion conditions that might arise as a result of other remedial works. Such changes might occur from:

- heating and ventilation of the interior environment
- improvements in drainage and rainwater shedding
- improvements in the thermal properties, water and vapour permeability of the interior walls or roof
- alterations to the thickness of the wall or roof.

### *Anti-Carbonation Coatings*

Anti-carbonation coatings are intended to restrict the further ingress of carbon dioxide. The simplest rating of their effectiveness is to find out the equivalent depth of additional concrete cover provided. They need to be applied before carbonation has reached the reinforcement and spalling has started; once the average carbonation depth has reached the average depth of cover, it is much too late for an anti-carbonation coating to provide any significant benefit. Although there is evidence that, in some circumstances, after the application of an effective coating there is a marginal migration of alkalinity outwards, this only slightly reduces the depth of carbonation.

A number of remedial treatments were trialled at Park Hill, Sheffield, to try and overcome corrosion problems. The intention was to develop a range of repairs which would maintain as far as possible the appearance of the buildings; these included hydrophobic treatments, like-for-like patch repairs, anti-carbonation coatings and selective replacement. The anti-carbonation coatings were matched to the colour of the cleaned concrete, but still have a significant aesthetic effect as shown in the top of the image. There were powerful local demands for the demolition of the whole estate because of increasing social problems and its deteriorating appearance. A drastic solution was needed and listed building consent was eventually given for a scheme which kept the structural frame and essential form of the buildings, but replaced the walls, windows and interiors.



A good anti-carbonation coating may be effective at limiting further damage if spalling is the result of a few near-surface reinforcement bars corroding due to insufficient cover, and where the majority of reinforcement is set deeper and remains passivated. Effectiveness is enhanced if the coating is combined with local patch repairs to the areas of spalling.

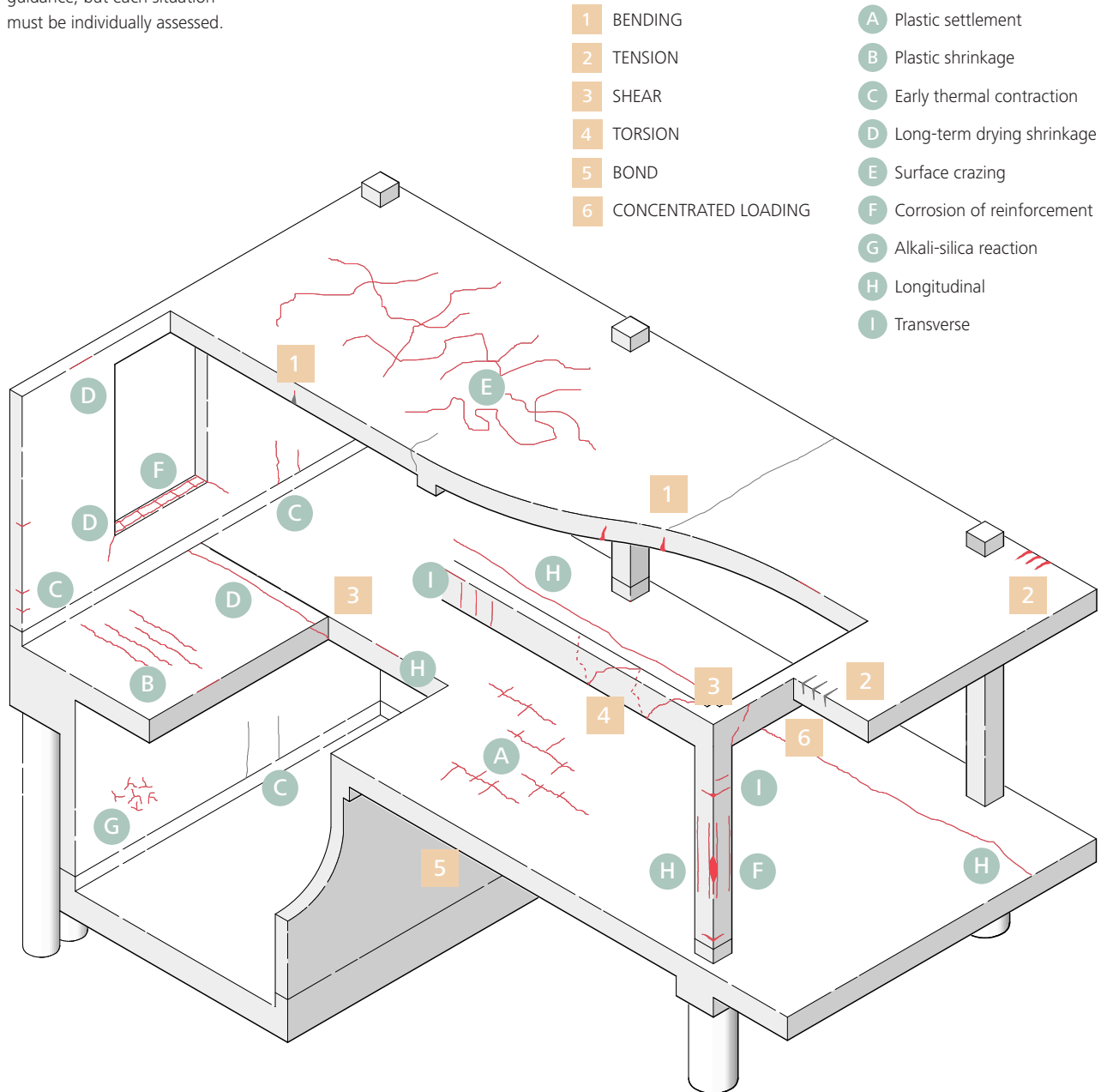
Anti-carbonation coatings should not be specified until the results of detailed tests to establish carbonation depths, cover and spalling patterns are available, and show that it is not too late for them to be of value.

Anti-carbonation coatings come in a range of colours and shades, but all will change the surface texture of concrete, particularly on board-marked finishes. Clear coatings may look unobtrusive when first applied, but coated surfaces will weather very differently to the existing concrete. Preliminary trials of the colour and texture on test panels should precede trials on the building, since removing coatings without causing blemishes is very difficult.

| COMMON TYPES OF CRACKS IN CONCRETE |   |  |
|------------------------------------|---|--|
| NAME                               | DESCRIPTION   | POSSIBLE CAUSES  |
| LONGITUDINAL CRACKS                | Cracks formed after the concrete has hardened, aligned parallel to the reinforcing bars   | Corrosion of steel reinforcement<br>Shrinkage of slabs formed with high cement content<br>AAR in columns and beams   |
| TRANSVERSE CRACKS                  | Fine flexural transverse cracks, most common in columns and beams; follows the line of the secondary reinforcement<br><br>Generally precedes longitudinal cracking  | Corrosion of steel reinforcement<br>Shrinkage<br>Thermally-induced movement  |
| SHEAR CRACKS                       | Cracks formed after the concrete has hardened: unusual  | Movement or loading of the structure<br>Demands closer structural investigation  |
| PLASTIC SHRINKAGE CRACKS           | Appear on the surface of fresh concrete soon after it is placed<br><br>Often parallel to each other and relatively shallow  | Excessive evaporation of water from the setting concrete   |
| PLASTIC SETTLEMENT CRACKS          | Formed within the first few hours after pouring<br><br>Usually regularly spaced and following the line of the uppermost reinforcement, giving a series of parallel cracks<br><br>May also be shorter cracks at right angles over the bars running in the opposite direction | Settlement of fresh concrete has been restrained, causing differential settlement of the aggregate and cementitious mix<br><br>As water moves upward through the mixture, the denser constituents move downward; this downward movement may be obstructed by the top layer of reinforcement or by the shuttering |
| SURFACE CRAZING                    | Fine random cracks or fissures on the surface of concrete mortar; rarely more than 3 mm deep  | Usually due to poor or inadequate curing<br><br>The mix being too wet or excessive floating allows for excessive concentration of cement and fine aggregate at the surface   |

### TYPICAL LOCATION & APPEARANCE OF STRUCTURAL & NON-STRUCTURAL CRACKING

This diagram provides general guidance, but each situation must be individually assessed.



## NON-STRUCTURAL CRACKING

Non- structural cracking is a characteristic feature of reinforced concrete, and in most cases has little effect on strength or durability. Much of it develops during the construction process and thereafter stabilises, and so it is distinct from the slowly developing cracking due to long-term deterioration.

The shrinkage of cement paste relative to the reinforcement and aggregate is a significant factor in cracking and micro-cracking. Wetting and drying produces a cycle of swelling and shrinkage of the paste, and allows moisture transport in the surface layers of the concrete. This often produces surface crazing due to the differential between the surface and the more stable interior.

The constituent materials of concrete have differing thermal coefficients of expansion; together with temperature and moisture gradients, these are major factors in the 'non-structural' cracking of reinforced concrete.

| THERMAL EXPANSION OF CONCRETE COMPONENTS |   |
|--|---|
| MATERIAL                                 | COEFFICIENT OF THERMAL EXPANSION<br>$\mu\text{strain}/^{\circ}\text{C}$ |
| Cement paste                             | 18–20   |
| Steel                                    | 11–12   |
| Igneous aggregate                        | 6–9   |
| Limestone aggregate                      | 6   |
| Sandstone and quartzite                  | 11–13   |

Another cause of non-structural cracking can be in the shutter construction and timing of its removal; this has a major influence on the hydration of the concrete surface. If it does not dissipate, the heat generated by the hydration of cement raises the temperature of a typical concrete mix (350 kg/m<sup>3</sup> of cement; 1:2:4 cement:sand:aggregate) by 37°C over about three days; from, say, 10°C to 47°C. Small elements with steel shutters rapidly lose this heat, but large elements, especially ones with shutters of wood or some other insulating material, will develop a hot core with a gradient of cooling towards the surface. When the shutter is removed, particularly if this is done before the concrete has set, the surface cools by evaporation of moisture, and the resulting temperature differential can lead to surface crazing.

As it cools, concrete contracts by 0.37 mm/m (370  $\mu\text{strain}$ ) relative to any adjacent pours cast previously. Early age cracks 1–2 mm wide can develop as a result of this shrinkage.

*Facing page:* The cracks on this wall at Dudley Zoo are likely to be due to a combination of plastic settlement cracks and the lack of movement joints.

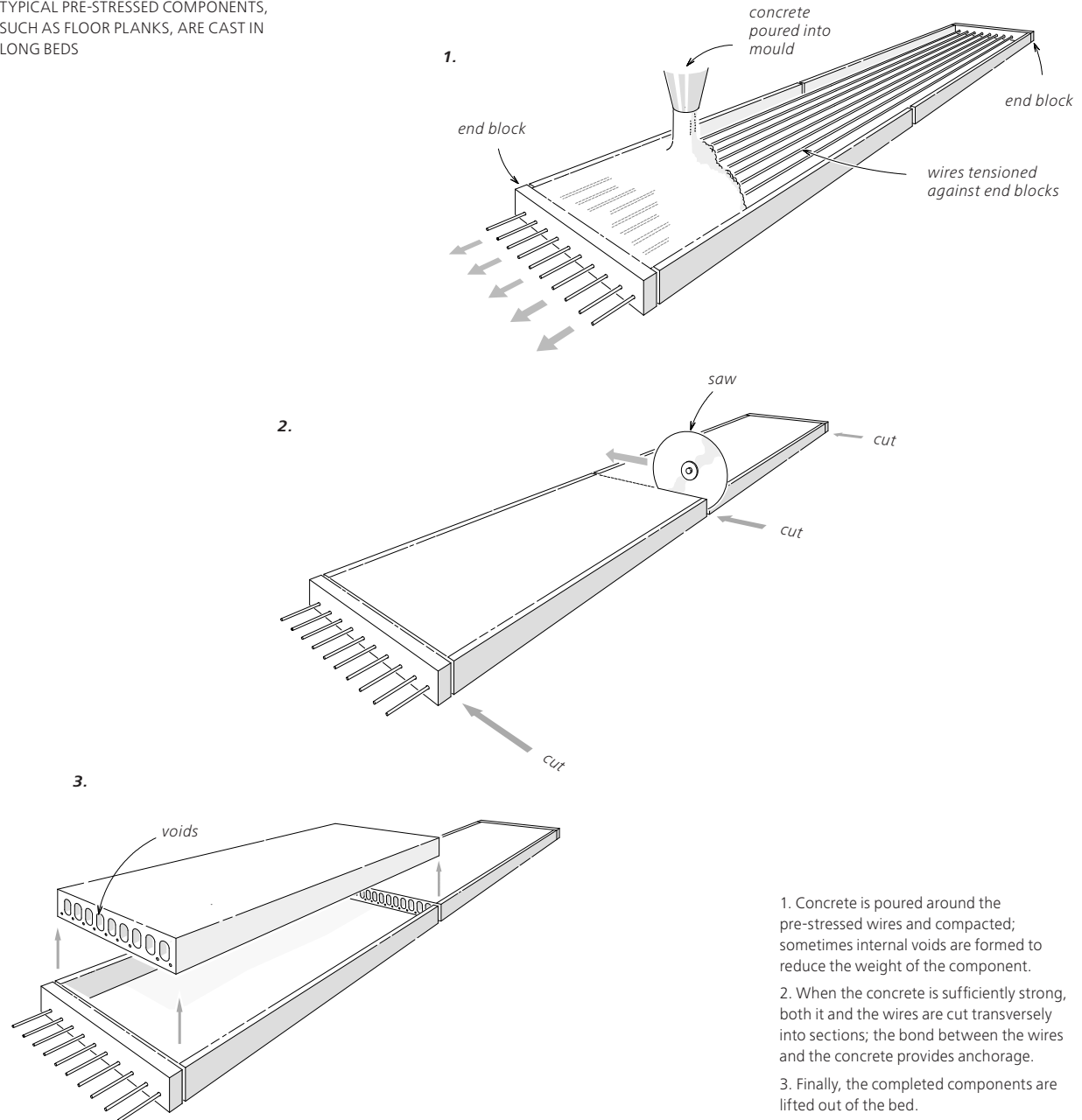






## PRE-TENSIONED PRE-STRESSED CONCRETE

TYPICAL PRE-STRESSED COMPONENTS, SUCH AS FLOOR PLANKS, ARE CAST IN LONG BEDS



1. Concrete is poured around the pre-stressed wires and compacted; sometimes internal voids are formed to reduce the weight of the component.
2. When the concrete is sufficiently strong, both it and the wires are cut transversely into sections; the bond between the wires and the concrete provides anchorage.
3. Finally, the completed components are lifted out of the bed.

For larger structures such as bridges and large floor slabs, post-tensioned pre-stressing is normally used. Internal ducts are formed within the concrete prior to setting, and the reinforcement strands are then threaded through and stretched with jacks to tension them, before being anchored at the end. Normally the ducts are then filled with grout and left to set. Additional reinforcement is almost always provided, especially around the highly stressed anchorages. For major structures, pre-cast elements or elements cast *in situ* can be clamped together with post tensioning.

Post-tensioned concrete is rare in conventional buildings, but was exploited by architects for many of the more adventurous buildings of the second half of the 20th century.

## Other Materials Used for Reinforcement

Since the 1970s there has been growing interest in alternatives to steel for reinforcement in both construction and remedial works. Some of these aim to improve durability, others to provide surface reinforcement or new approaches to pre-stressing. A number have proved successful in niche applications, but others have failed to perform satisfactorily, often because of a fundamental lack of compatibility with concrete's alkalinity or physical properties (such as Young's modulus, thermal expansion coefficient, creep and relaxation, or the movement of moisture).

Innovative materials can lead to fundamental changes in behaviour and treatment of the concrete. Stainless steel of the appropriate grade performs well in severe chloride conditions, but bond strength is reduced, which affects the detailing; stainless steel must not be used in contact with ordinary steel, because of the possibility of galvanic corrosion. Zinc coatings are effective in delaying corrosion of steel in air, but in damp carbonated concrete the protective zinc layer is soon lost, and so only a small delay in corrosion initiation is achieved; the widespread failures of galvanised wall ties in brickwork proved to be an expensive cautionary tale. The poor durability of galvanised fixings in carbonated or chloride-contaminated concrete and mortar, and the subsequent corrosion of the underlying steel, will give increasing problems in future years. [☞ METALS](#)

The introduction of short fibres into concrete, if well mixed and compacted, can significantly improve tensile strength and resistance to cracking within the fibre-reinforced zone. Until the health risk became apparent, asbestos fibres were a popular choice, and 'asbestos cement' was used widely for roofing sheets, ducting, fireproofing and many other purposes. Stainless-steel fibres are compatible in stiffness and thermal properties with concrete, but many of the other fibres that have been used are not.

Glass reinforced cement [GRC], which was once promoted as a new wonder material with widespread applications, faced problems from cracking due to high shrinkage, rigid fixings and differential stresses caused by irregular shapes. There is also a severe loss of tensile strength as the alkalinity of the cement attacks and embrittles the glass fibres. Niche applications have now been found for GRCs made using alkali-resistant glasses and low-alkali cements.



## BUILDING WITH CONCRETE

### REINFORCEMENT & PRE-STRESSING WITH STEEL

Concrete has a high compressive strength, but a very low tensile strength. If it is to be used to span any distance, this can be overcome by installing steel reinforcement (colloquially known as ‘rebars’) within the concrete. The success of steel reinforcement derives from three factors:

- the close match of thermal expansion coefficients between steel and concrete ( $10 \times 10^{-6}^{\circ}\text{C}$  and  $7\text{--}12 \times 10^{-6}^{\circ}\text{C}$  respectively)
- the higher stiffness of steel (Young’s modulus of 210 kN/mm<sup>2</sup>); this attracts the load to it, and limits the tensile strains in the concrete (Young’s modulus of 14 kN/mm<sup>2</sup>)
- the strong alkalinity of uncarbonated concrete, which has a pH greater than 13; this passivates the steel, and prevents corrosion. [METALS](#)

By the time the pioneers of reinforced concrete were putting steel into concrete at the beginning of the 20th century, mild steel had become widely available. This ductile metal could be easily bent to form a reinforcement cage consisting of straight or bent bars introduced to resist bending stresses, and bent bars (known as ‘stirrups’ or ‘links’) to resist shear stresses, and to constrain the main reinforcement in columns.

Mild steel was used almost exclusively for reinforced concrete construction until the 1950s, when higher strength bars of ‘high yield’ steel reinforcement (Grade 50 carbon steel, supplied as deformed round bars) were introduced; this had an impact on the detailing since they could not be bent to the same radius as a mild-steel bar. An increase in radius of one-third was common, and this often led to the cross-sectional area of the element having to be increased to achieve the required depth of cover. The 1950s also saw the introduction of standard-sized sheets of welded reinforcement, fabricated from hard-drawn wire possessing similar material properties to high-yield steel bars. This reinforcement greatly simplified the design of some structural elements, such as floor slabs.

### PRE-STRESSED CONCRETE

In pre-stressed concrete, the reinforcing bars are stretched prior to the concrete being poured. Pre-stressing can be applied either during the manufacture of pre-cast concrete sections (‘pre-tensioned pre-stressing’), or after the sections are cast and cured (‘post-tensioned pre-stressing’).

Pre-tensioned pre-stressing is the most common method. Steel rods or wires are stretched through a line of moulds, and anchored at each end. The concrete is then placed in the moulds and cured. When the concrete has achieved sufficient strength, the strands or wires are released from their anchorages; as they elastically relax, a load is imposed on the concrete, and this produces the required compressive stress. The strands remain fixed in the concrete by the bond strength that has developed at the steel-to-concrete interface.





## POST-WAR BUILDING

The years after 1945 saw materials in short supply, effectively rationed by a system of licensing that restricted building largely to schools, housing and industry. A shortage of American dollars limited the import of Scandinavian timber; in the early 1950s, it was actually easier to obtain hardwoods from around the British Empire, as they could be paid for in sterling. Concrete was used in buildings of this period, particularly for details such as porches, window sills and roof trusses that would normally be made of timber.

In most 'Modern Movement' buildings of the 1930s, large amounts of reinforcement had been contained in the external walls, but the post-war period saw structure put into the internal walls. Arup refined the technique used at Highpoint after the Second World War for several buildings in London: firstly at Brett Manor (private flats in Hackney), and then in 1950 at Fry and Drew's Passfields in Lewisham; while Lubetkin and Francis Skinner used a box frame at Spa Green Estate in Islington (listed Grade II in 1998). Box framing allowed for complex internal plans where living rooms and bedrooms could be stacked up, so a simpler cross-wall technique was sufficient. This change explains the variety of materials used in post-war façades, with concrete contrasted with brick, tile and large areas of glass. Lubetkin's designs were likened to the carpet patterns of his native Georgia, while Park Hill in Sheffield, developed with the artist John Forrester, demonstrated the idiom on a massive scale. As a result this is now listed Grade II\*.

### Park Hill, Sheffield

Park Hill was originally constructed of an exposed concrete frame with contrasting yellow, orange and red brick infill panelling. Although remaining structurally sound, over time the fabric of the building has decayed and social disadvantages of the estate meant that tenants were hard to find. Recent repair has conserved the concrete frame, but replaced the brick with glass and aluminium panels.

*Facing page:* Park Hill in the 1960s. The concept of the flats was described as 'streets in the sky'. Broad decks, wide enough for milk floats, had large numbers of front doors opening onto them. Each deck of the structure, except the top one, has direct access to ground level at some point on the sloping site. The site also allows the roofline to remain level despite the building varying between four and 13 storeys in height.



The actual finish of the concrete matters very little in these buildings. Locally available aggregates were generally used (with hazardous results in the case of seaside coastguard cottages, where the sands used were full of salt). An early exception is the remarkable church of St John the Evangelist and St Mary Magdalene in Goldthorpe, near Doncaster (which is listed Grade II\*), built in 1914–16 at the behest of the Second Viscount Halifax to serve a growing colliery district. Quite why reinforced concrete was chosen is unknown, though wartime steel shortages may have been a factor, but the result was a tall, grand design with an Italianate campanile. There are concrete trusses and concrete walls 200 mm thick; the shuttering lifts are very visible, and on the exterior there is a strong difference in finish between the frame and infill. The interior, where even the altar and sculptural decoration are of concrete, was always painted. Goldthorpe is discussed in some detail in **Case Study 3**.

Historical significance is perhaps paramount for the structures produced for military use during and between the two World Wars. The concrete itself was necessarily rough and raw. One example is the listening post at Loftus, near Redcar in North Yorkshire, which dates from 1916 and was constructed from rendered cast slag concrete; this is listed at Grade II.



The church of St John the Evangelist and St Mary Magdalene, Goldthorpe.

## CONCRETE

THE DEVELOPMENT & USE OF CONCRETE

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