Achieving sustainable resilience in new precast concrete structures

Taking precast concrete to a new level

A collaborative research report from Buildoffsite and CIRIA

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Publisher

Buildoffsite is a membership organisation with members from a wide range of UK and international client, supply, professional services and academic organisations.

Buildoffsite is a UK-based business organisation that promotes:

- Increased use of offsite methods across all sectors of the UK construction market.
- Innovation in the development of offsite solutions.
- More effective promotion of business and project benefits by offsite solution suppliers.
- Improved understanding by clients and suppliers of the benefits of offsite solutions.
- Education and skills development in the use of offsite solutions.
- Debate, discussion and knowledge transfer relating to the use of offsite solutions.

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Buildoffsite's mission is to be the trusted, independent voice of the UK construction industry with respect to offsite and pre-manufacturing, and to provide all relevant support to our members and other stakeholders to enable them to feel confident to promote and adopt the same.

Vision

A permanent, positive, transformation of the UK construction industry – enabled through the increased adoption of offsite and pre-manufactured solutions to drive increased productivity.

Buildoffsite is a specialist network within **CIRIA**.

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Contents

Figures

Tables

Abbreviations

AACMs	Alkali activated cementitious materials (including geopolymers)
AAR	Alkali aggregate reaction
ACI	American Concrete Institute
ASR	Alkali-silica reaction
BAS	Building automation systems
BFRP	Basalt fibre reinforced polymer
BS	British Standard
BSI	British Standards Institute
Capex	Capital expenditure
CE	European standards conformity mark (conformitė europëenne)
CEM I-VI	Defined Portland cement-based blends
CFRP	Carbon fibre reinforced polymer
CIRIA	Construction Industry Research and Information Association
CO_2e	Carbon dioxide equivalent
CP	Cathodic protection
DCF	Discounted cash flow
DOT	Department of Transportation
EAD	European Assessment Document
EAF	Electric arc furnace
EN	European norm (standard)
EPD	Environmental product declaration
ESG	Environmental, social and (corporate) governance
ESR	Environmental and social responsibility
FRP	Fibre reinforced polymer
GCP	Galvanic cathodic protection
GDP	Gross domestic product
GFRP	Glass fibre reinforced polymer
GHG	Greenhouse gas
HMI	Human-machine interface
ICCP	Impressed current cathodic protection
IRR	Internal rate of return
ISO	International Standards Organisation
MAU	Modular anode unit
MPA	Mineral Products Association (UK)
NACE	National Association of Corrosion Engineers, NACE International
NOAA	National Oceanic and Atmospheric Administration (US)
NZC	Net zero carbon
Opex	Operating expenditure (revenue costs)
PAS	Publicly Accessible Specification (published by BSI)
PREN	Pitting resistance equivalent number
RCA	Recycled concrete aggregate
RIBA	Royal Institute of British Architects
RICS	Royal Institute of Chartered Surveyors
SCC	Social cost of carbon
SHM	Structural health monitoring
UKCA	United Kingdom Conformity Assessed mark
UoM	University of Miami
US	United States (of America)

Foreword

Approximately 70% of global structural degradation in industrialised countries is reportedly[1] due to corrosion. This is avoidable but has created a legacy where it is estimated that, globally, there are US$2.5 trillion of repairs to be carried out on infrastructure and buildings due to corrosion[1]. The surprisingly high (if largely hidden) cost of corrosion represents approximately 3.4% of Global GDP. This is massive by any standard but potentially avoidable in the future. It also represents significant damage to prior carbon investments in affected structures.

This report aims to help construction clients, architects, engineers, main contractors and precast manufacturers reduce the impact of corrosion in future. It does this by signposting methods for combatting the root causes of corrosion using sustainable materials and methods, which, combined, deliver enhanced resilience and reduced whole life cost and carbon for a structure.

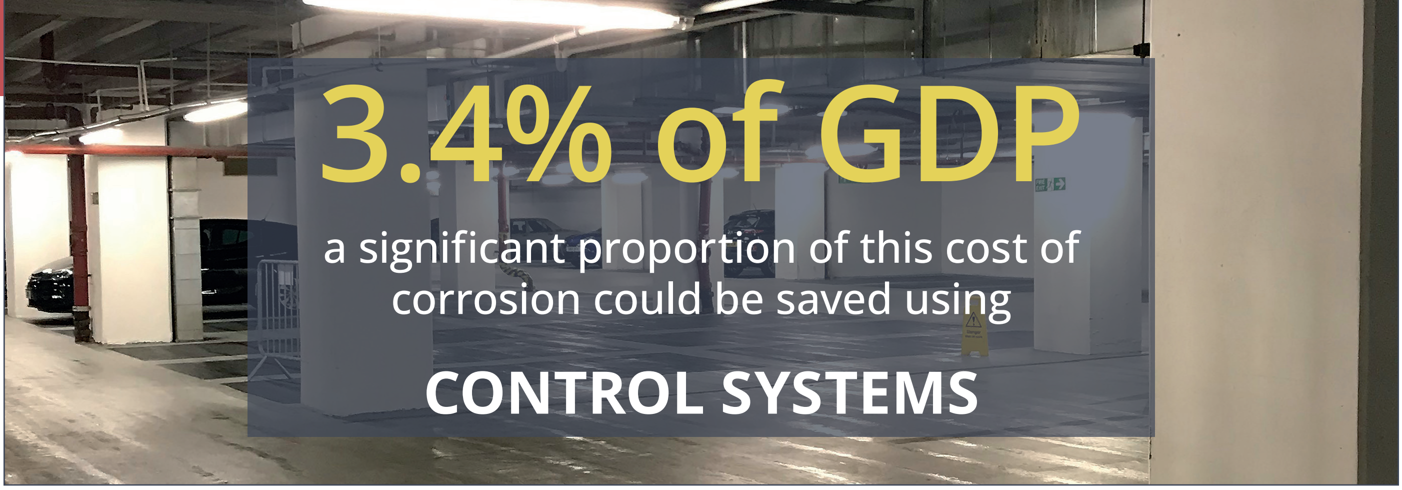
Much of the emerging guidance on reducing the carbon footprint of reinforced concrete in projects focuses upon using lean, efficient designs, incorporating less concrete and steel. In this context, it becomes increasingly important to protect that steel and concrete from corrosion, to ensure that design life intent is met. Monitoring and control systems have a role to play here and are more cost effective when installed from the outset.

The largest risks to corrosion propagation in concrete structures come from unintended water penetration, chloride-induced acceleration from de-icing salts and marine exposure, and longer-term carbonation of the concrete cover to reinforcement steel.

Climate change is forecast to accelerate degradation of structures[30] due to greater thermal cycling and heat-accelerated chemical reactions. Increasing carbon dioxide levels in the atmosphere may reduce the alkalinity in natural waters, which, in turn, would increase acidic degradation of the concrete by promoting more rapid carbonation of concrete cover and resultant corrosion[30].

"The effect of a high CO_2 concentration will not change the carbonation process at all, since carbonation will occur instantly, thereby maintaining a CO_2 concentration of zero at the reaction front. The only effect of the high CO_2 concentration is a faster transport of the CO_2 molecules to the pore air–pore solution interface and thus a faster reaction process"[3].

Climate change consequently represents some major safety and cost issues. In extreme conditions, if left unmaintained, these could lead to more bridge and building collapses similar to those cited as follows.



The conventional approach to designing reinforced concrete needs to be re-assessed for climate change.

Modern methods of construction are constantly evolving, including the offsite precast concrete sector. Robust designs and effective, low carbon protection technologies are available but need to be employed more widely.

With expert input from the design, precast, materials science and corrosion engineering communities, Buildoffsite is signposting a route to more sustainable, resilient buildings and infrastructure that will reduce the probability of earlier than intended repairs, premature demolition, or failure due to condition degradation. Indeed, it opens up the prospect of optimising designing for indefinite life[4].

At the time of producing this report, the UK Government has published a requirement for the *"golden thread of information for buildings to be managed throughout the life of a building"* (see **Appendix A** for further details):

https://www.gov.uk/government/publications/building-safety-bill-factsheets/golden-thread-factsheet

Methods proposed in this report could help achieve this, building on lessons learnt from the restoration and heritage sectors, which are experienced in addressing corrosion issues.

Governments, major construction clients and their funders around the world are progressively attributing a social cost to carbon emissions. Investments increasingly need to take this into consideration. These ESG requirements do not only apply to organisations, such as banks, they are being applied to assessments of their customers and supply chains as well. This too is starting to drive change in how structures are designed.

Nobody sets out to design for corrosion, but the reality has been that it happens far too frequently and prematurely, causing disruption for users and operations, costly repairs, loss of embodied carbon or worse, loss of life. This guide outlines steps that may be taken to significantly reduce these risks with a focus on sustainable materials to achieve resilience. These will help produce and maintain the golden thread of information that will increasingly be required for both buildings and infrastructure going forward.

Executive summary

In the main, reinforced concrete structures are well-constructed and built to last. However, when problems develop, they can be catastrophic, as seen from bridge collapses at the Urdaneta Bridge in Venezuela in 1964, and the Morandi Bridge in Genoa, Italy in 2018. Indeed, from 2004 to date, 12 bridges/overpasses have collapsed in Italy alone. This is also not an exclusive problem to bridges, as has been seen in the buildings sector in June 2021 in Miami.

It is generally accepted for structures to be considered resilient that they can withstand extremes of weather and environmental impact over time. Their collapse is often caused by multiple contributory factors, some consequential of others. It should not be unexpected, for example, that an extreme weather event impacting an already corroding structure could result in its collapse.

It has been rare, however, that structures have built-in control functions to prevent the debilitating effects of corrosion over time despite the billions invested in constructing these assets and their safety criticality to life.

The challenges of corrosion are significant given it is the cause of 70% of infrastructure damage. Traditionally, these challenges demand huge sums for maintenance and repair, to ensure safety, as well as bearing major costs in terms of disruption, and carbon. The tragic loss of life stands above the loss of asset value, economic activity and embodied carbon, but all these are felt when structures collapse or need to be demolished due to deteriorated condition or poor maintenance.

These factors combined with environmental, social and governance (ESG), a UK Government policy that must be factored into all procurement projects since January 2021, mean the sector is challenged with choosing an effective whole life strategy. In addition, the Construction Playbook[5] encourages innovation whilst remaining respectful to the environment and securing embodied carbon.

Figure 1 Car park constructed out of precast concrete beams and planks

This report focuses on how corrosion can develop and identifies technology that can be incorporated from initial construction that improves the whole life performance of structures whilst minimising maintenance requirements and targeting low carbon materials to achieve longevity.

Offsite construction in factory-controlled conditions for precast concrete generally allows for better quality control to reduce some of these risks. It also offers the ideal conditions to integrate technology to control the initiation and propagation of future corrosion.

When designing a precast concrete structure, there are opportunities to make each element more resilient and lower in carbon impact. The opportunities and challenges presented by alternative green steel production, alkali-activated cementitious materials (AACMs), certain recycled aggregates, and non-metallic reinforcement are examples explored in this report. There is significant ongoing R&D of methods for improving reinforced concrete that will also need to be considered when they emerge and reach the market.

The benefits of designing-in corrosion protection measures, such as impressed current cathodic protection (ICCP) and structural health monitoring (SHM) systems are also discussed. Enabling remote data-driven performance management throughout service life provides futureproofed control for structures without disruption, providing a golden thread of information through the life of the facility.

Design for sustainable resilience using precast concrete, manufactured from low carbon materials and processes with protection management systems built-in from conception, offers an exciting and deliverable legacy to reduce both the whole life cost and preserve embodied carbon for structures indefinitely and safely.

Introduction

1

Precast concrete modular components are widely used in construction and the quality of finishes has been improved to the extent that they are frequently a design feature. The speed of erection can be transformational for a project, even in an infrastructure context. Concrete is a very versatile material which can be formed into a variety of wonderful shapes. There are, however, a few challenges, namely:

- The amount of embodied carbon in the manufacture of Portland cement-based concrete components.
- The risk that joints may become exposed to water ingress over time, exacerbated by increasing rainfall and exposure to storm surges.
- The longer-term risk of carbonation of concrete, a natural process, likely to accelerate with increasing carbon dioxide levels.
- The heightened risk due to ingress of chloride ions from de-icing roads and marine exposure.
- Ensuring that the required protective concrete cover of steel reinforcement is consistently achieved.

The latter four points potentially lead to corrosion of steel reinforcement contained within components.

This collaborative study set out to:

- Demonstrate the technical feasibility of avoiding corrosion risks in precast reinforced concrete structures.
- Consider the commercial and carbon cases for doing so with associated added value in the context of environmental, social and governance (ESG) aspects, a growing focus of investment[6].
- Highlight the opportunities to make structures more resilient and sustainable, whilst increasing the probability of extending service life and repurposing rather than demolishing them.

This report aims to provide guidance to designers, manufacturers, precast producers, contractors and construction clients on the current state of the art in this area (in 2022). It also aims to demonstrate how the precast sector can help suppliers deliver the whole life cost and carbon requirements of clients that are increasingly being set and that are subject to carbon reduction and construction efficiency targets. This is likely to be driven by targets set by infrastructure sector regulators, the use of the Construction Innovation Hub's Value Toolkit[7] for procurement decisions and UK Government departments implementing the Construction Playbook[5].

Readers of this report will gain insight for designing, operating, monitoring, controlling, reporting and thereby valuing the health and performance of these structures, optimising whole life cost with low carbon choices. This will include:

- context and background to the issues and inter-related benefits
- low carbon materials and component choices
- emerging innovations in cement and reinforcement choices
- approaches to designing for resilience
- advanced products for preventing and controlling corrosion
- performance monitoring and management technologies
- data-driven service life knowledge
- benefits and impact on economics by adopting innovations to achieve sustainable structural resilience.

Figure 2 Reservoir constructed using precast wall panels

Causes and costs of structure degradation

Paul Lambert and Chris Atkins, Mott MacDonald

2

The built environment represents the biggest investment in current society. In addition, there are considerable on-going operation and maintenance costs, often exacerbated by inadequate durability requiring periodic repair or replacement. While capital expenditure remains dominant in determining how structures are designed, built and maintained, there is increasing awareness of operational costs and sustainability issues.

Corrosion of steel

Steel has a similar life cycle to the people who use it, with its life influenced by how it is treated and employed. Corrosion is a loss of embodied energy, so from a sustainability point of view should be managed. It is the natural consequence of exposure to the atmosphere and can be accelerated by contaminants, such as chloride ions and carbon dioxide. As well as losing section and reducing load bearing capacity, the corrosion products can occupy a volume up to ten times greater than the metal they came from. This can induce stresses, disrupt coatings and displace adjacent materials, such as masonry or concrete.

Figure 3 Testing precast beams shows a cover survey being undertaken on precast concrete beams

Deterioration mechanisms of reinforced concrete

The majority of reinforced concrete around the world performs adequately and gives few problems. A minority of structures have deteriorated due to either the action of aggressive components from the external environment or incompatibility of the mix constituents. Problems can arise as a result of inadequate understanding of the exposure, poor design, badly specified concrete, inadequate training and supervision and the resultant poor workmanship.

Deterioration may occur due to several individual mechanisms on which a large body of literature already exists. These include:

- Corrosion of reinforcement, due to:
  - chloride ions
  - carbonation
  - change in the rebar environment (for example, impinging cracks).
- Sulfate attack of concrete.

- Salt recrystallisation/freeze thaw.
- Soft water/acid attack of concrete.
- Alkali aggregate reaction (AAR).
- Shrinkage.

All these factors must be considered during design and specification.

Figure 4 Prestressed beam suffering from corrosion of the reinforcement

Factors influencing rates of deterioration

The environment provided by good quality concrete for the embedded steel reinforcement is one of high alkalinity (generally >pH 13 in new concrete), generated by the hydroxides of sodium, potassium and calcium released during the various hydration reactions. In addition, the bulk of surrounding concrete acts as a physical barrier to most of the factors that could result in premature degradation of the reinforcement.

Provided this environment is maintained, the steel remains passive and any small breaks in the stable protective oxide film are self-repaired. However, if the alkalinity of the surroundings is reduced, for example by reaction with atmospheric carbon dioxide (carbonation), or if chloride ions are made available at the surface of the steel, then corrosion may be initiated, resulting in propagation and eventual loss of steel section and spalling of cover concrete.

It is also possible to lose the passive oxide film in conditions of low oxygen availability, such as may be encountered in buried or submerged structures, although rates of metal loss are negligible.

Depth of cover

Inadequate cover is invariably associated with areas of high corrosion risk due to both carbonation and chloride ingress. Controlling cover during manufacture is, therefore, an essential step in ensuring optimum protection of the steel reinforcement from corrosion.

Presence of chloride ions

Chloride ions can enter concrete in two ways. They may be added during mixing, either deliberately as an admixture or as a contaminant in the original constituents. Or, they may enter the set concrete from an external source, such sea water and de-icing salts. In some areas of the world, chloride free aggregate is not available, and washing rocks with drinking water is not environmentally sound.

Once sufficient chloride ions have reached the reinforcement, they will de-passivate the steel, breaking down the protective oxide layer. The concentration of chloride ions required to initiate and maintain corrosion is dependent upon the alkalinity. It has been shown that there is an approximately linear relationship but with many factors influencing the exact chloride threshold levels[8].

Carbonation

Carbon dioxide present in the atmosphere combines with moisture and results in a reduction in alkalinity of the concrete. The rate at which this neutralisation occurs is influenced by factors such as moisture levels and concrete quality. Poor quality concrete exposed to moderate levels of moisture is at the greatest risk. This process is sometimes claimed to reduce carbon dioxide emissions from cement, but it is merely reabsorption of carbon dioxide released during manufacture and risks premature corrosion of reinforcement with reduction in service life. Atmospheric carbon dioxide levels are increasing, and this will accelerate the rate of carbonation and, therefore, corrosion. See the “Rust” thought piece on page 7.

Environmental considerations

The micro-climate to which the reinforced concrete member is exposed directly affects the likelihood and extent of reinforcement corrosion. Factors such as chloride levels and pH have already been discussed. The most important aspect is, arguably, the moisture level. Carbonation, chloride ion ingress, resistivity and corrosion rate are all greatly influenced by the degree of saturation and wet/dry cyclical exposure and the availability of oxygen for the cathodic reaction.

Global changes in climate, resulting in more extreme temperature and rainfall events, threaten to aggravate the extent and severity of such factors.

The cost of corrosion

Based on the NACE International’s data[1], the global cost of corrosion is estimated at US$2.5 trillion, equivalent to 3.4% of global GDP and similar to the annual value of the global infrastructure market.

The appropriate application of current corrosion control practices could save between 15% and 35% of this cost of corrosion, plus additional benefits in terms of improved safety, reliability and sustainability.

For reinforced concrete, controlling the quality of the concrete and maintaining minimum cover would be sufficient to avoid the majority of problems resulting in loss of service life.

Figure 5 Coated precast concrete segmental bridge

Potential benefits of precasting and offsite manufacture

While there is considerable understanding of the factors that govern the optimum performance of structural materials, there remain significant challenges with ensuring that the designer's requirements are correctly translated to the finished structure on site.

Historically, pre-fabrication of concrete has not necessarily translated into high-quality and durable products, as speed and cost of production were the main governing factors. Offsite fabrication of steelwork and precasting of reinforced concrete elements, under controlled factory conditions, provide routes to ensuring the necessary quality and consistency is achieved to deliver optimum service life, but details need to be carefully considered.

The increased adoption of offsite construction may be expected to result in a greater number of joints and connections, features often associated with vulnerabilities in conventional structures, allowing ingress of a potentially aggressive service environment. The design of such features must take full advantage of developments in more durable materials and improved methods of construction, handling and long-term protection to avoid increased risk of corrosion and degradation and achieve an extended low-maintenance service life that justifies the investment in energy and materials during manufacture.

Some thoughts on ...

Rust

Climate change is happening. CO_2 levels are rising. This will reduce the pH of atmospheric exposed water; this also reduces dissolved oxygen levels. A significant change in the chemistry of the planet is not a good thing, as we all live in a slowly interacting complex system.

Corrosion could be seen as an interaction between manufactured products and the environment. It happens really slowly so it can be quite difficult to assess. How we think things corrode, and hence how we predict future life of products, is based on past experience, but that may not work very well as the environment changes.

From construction's point of view, most things are made out of steel or concrete. The steel will want to turn into rust, so we may coat it, we may galvanise it, or we may use it as part of reinforced concrete. Steel normally doesn't rust in concrete as its protected from the atmosphere by a layer of concrete called the cover. It will rust in reinforced concrete if the concrete gets salt in it, or it carbonates. In the UK carbonation normally isn't a problem, but up until the mid-80s that was based on concrete exposed to <350ppm CO_2 (see **Figure 6**) Levels are currently over 400 and rising, so carbonation is going to get worse. The increased dissolved CO_2 will also be bad for concrete exposed to water in general. Concrete is alkaline, so a reduction in pH is a bad thing for it, if it has steel reinforcement. The alkaline environment passivates the steel reinforcement and if the alkalinity is reduced then the passivation is reduced, which may lead to rusting. The normal way of getting concrete to last longer is to up the cover or up the cement content, both of which would increase the CO_2 produced during concrete manufacture, so it is probably not a good thing.

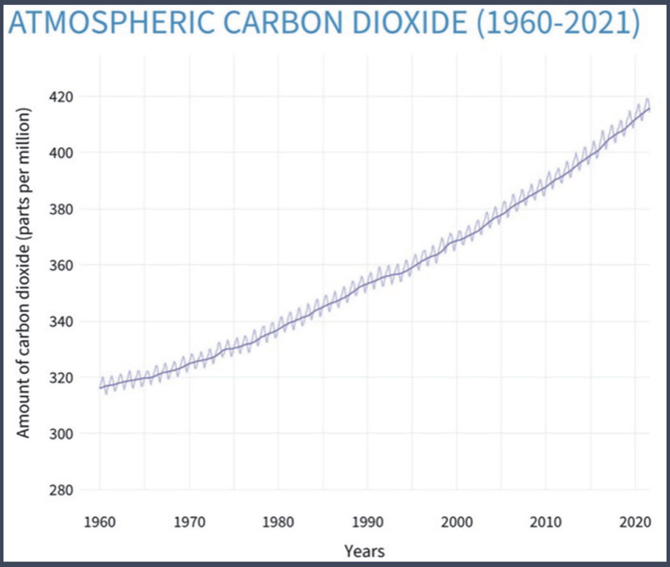


Figure 6 The evolution of carbon dioxide in the atmosphere (courtesy NOAA climate.gov)

It is not all bad news from a corrosion point of view. For submerged steel, generally a reduction in dissolved oxygen would be expected to reduce corrosion rates. It reduces the current demand for cathodic protection that can protect buried and submerged steel, but lower oxygen levels could affect the wonderful world of microbial induced corrosion. Galvanising typically forms a carbonate film, so might end up more durable.

The tricky bit is the design codes for durability are typically based on experience, and our experience is based on a different world. Probably time to have a serious think about structural durability.

Article first published on LinkedIn by Chris Atkins, January 2022

Designing for sustainable resilience in precast concrete

Graeme Jones, C-Probe Systems Limited and Chris Hirst, Orlimex Limited

3

Introduction

There are many factors that relate to resilience of structures. Often design for resilience is considered for extreme conditions and natural disasters, such as fire and flood.

For the purposes of this guidance report, we are considering mainly the effects of corrosion and design measures that can be taken to provide low carbon solutions to achieve "sustainable resilience". To that end, innovations are not exhaustive but are highlighted to contribute to achieving lower carbon elements and, where applicable, how these can offer corrosion control. It is also the case that materials such as alternative cements (for example AACMs defined in PAS 8820:2016[9]) can overlap with these other resilience issues in concrete by offering improvements to fire resistance, for example, whilst also being low carbon in their manufacture.

In 2018 Angst[10] identified issues that industrialised nations are facing and will face in the future. Recent market FIDIC data[11] estimates a global need for infrastructure investment at $7trillion per annum. These issues are likely to be dominated by the need to restore existing infrastructure growing a reported six-fold to 2060, where most structures will come to meet the end of their expected service life and some prematurely.

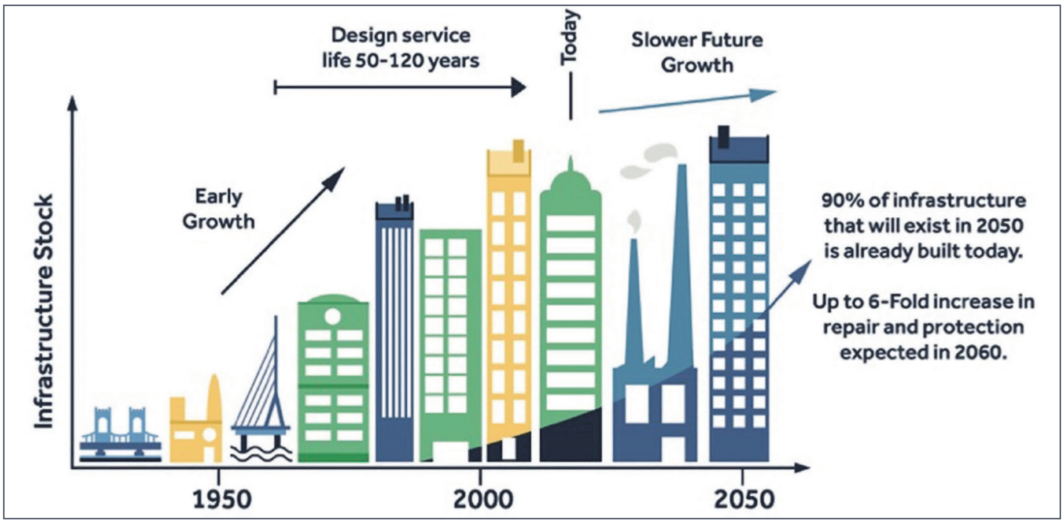


Figure 7 The structural resilience of existing infrastructure and a business as usual approach to design in industrialised countries (based upon reference 10)

Demolition of all these structures is not an option and would cause immense environmental damage in terms of loss of embodied carbon. It would seem imperative to use innovation to prevent new constructions from facing unmanaged risk of deterioration in the future, to maintain the structure's health with control functions and to achieve this sustainably with performance data.

For emerging nations, the emphasis is different. The opportunity to expand new infrastructure with low carbon materials is a chance to prevent issues experienced by industrialised nations being copied in these new infrastructures. This is not to ignore the need to restore existing infrastructure in these geographical areas, as that will be needed given the growth of construction from the 1980s to now.

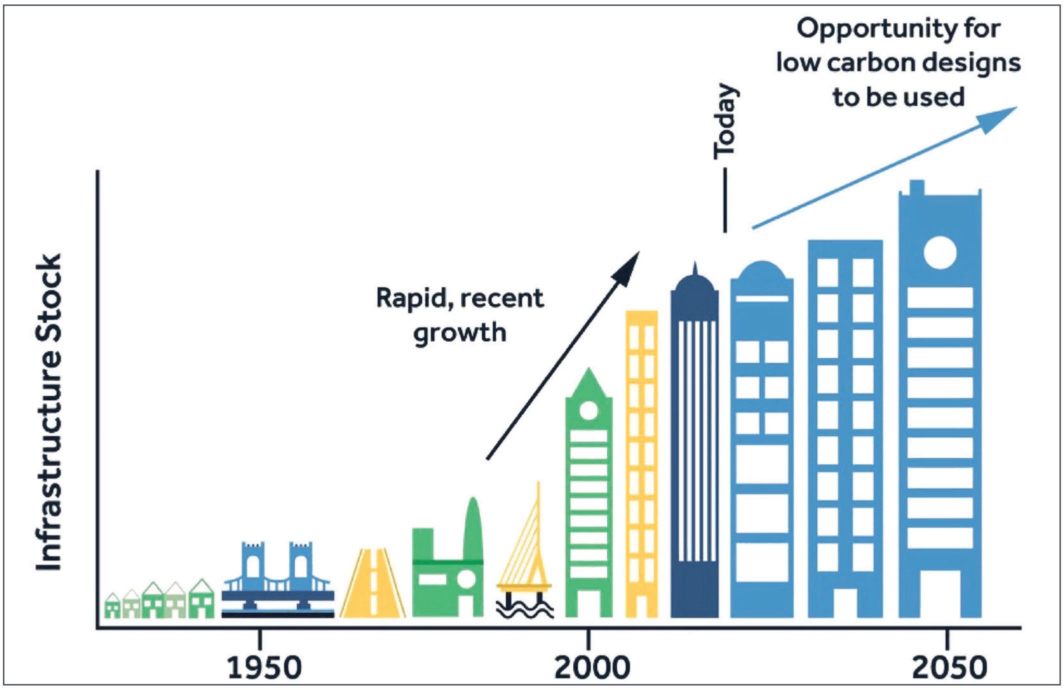


Figure 8 Potential for improved structural resilience of new infrastructure[10]

Sustainability is influenced by the materials chosen and by adopting technology to achieve resilience.

Sustainable resilience can be achieved by consideration of the following components of a precast structure:

- design
- reinforcement
- aggregates
- cements
- admixtures
- water
- proactive corrosion protection.

Designing-out risk

The first areas to consider may be to design-out details that result in potential vulnerability in structures, as well as designing-in components that can actively offer protection through the whole service life of the structures (see **Chapter 3**).

Identifying the at-risk areas on any structure should be made at the design stage. An action plan should be put in place to develop future planned preventative actions, or to apply during construction if technically and cost beneficial. Taking account of the life cycle cost can be valuable in this assessment (see **Chapter 5**).

An example of designing-out features may include bridge joints over structural sub-structures, where leakage can cause consequential damage to the support element. Issues can arise from the failure of a small element of the design causing significant cost, disruption, and damage that, if addressed at the design stage, could avoid such issues arising.

Precast water-retaining structures inevitably comprise a large number of joints between adjacent panels. These need to be carefully considered to meet the required performance characteristics. This may require the use of compressible seals, or additional *in-situ* grout of concrete. Low carbon options for such materials are emerging and should be considered where possible.

Reinforcement

Recycled mild steel and stainless steel

Recycled steel maintains the inherent properties of the original steel and the quality can also be improved on recycling, whether used in bar or fibre forms for precasting. Steel can be infinitely recycled and is 100% recyclable without loss of quality. Lower value steel scrap can be converted into high value steels by using appropriate processing and metallurgy.

Similarly, the structural design can address the arrangements and quantity of steel to be used within a construction to minimise use without compromising safety, thereby providing carbon and cost savings.

UK processes historically used blast furnaces to process and manufacture steel. The UK has significantly increased its use of electric arc furnaces for rebar, with 97% of steel procured from UK sources using this process.

Stainless steel has been used as a corrosion prevention strategy with precast elements exposed to high chloride environments and retains a 50% higher embodied carbon value. It is important to consider the choice of stainless steel for resistance to chloride; this is summarised by the Steel Tank Institute where the grade of stainless steel has been indexed to chloride resistance (PREN value) and a relative cost ratio, comparing type relative to 316L and 304L grades.

New ways to make steel

New manufacturing processes are emerging where steel may be produced using molten oxide electrolysis that offers a low carbon alternative to conventional high energy usage method providing decarbonisation of this element of reinforced concrete. At the time of writing, it is being reported that the Swedish company, Hybrit, is shipping its first batch of “green steel” made without using coal. It is made with a hydrogen-based production process.

Fibre reinforced polymer (FRP)

Fibre reinforced polymer or composite reinforcement is a relatively new alternative to steel reinforcement. Traditionally reinforcement has taken the form of steel rebar or mesh, however, this builds in a number of issues for reinforced concrete. Namely, corrosion of the steel by carbonation and/or chlorides, which results in expensive renovation to the structure at some point in the future.

FRP reinforcement may provide a solution to this problem. There are two common fibres used, glass (GFRP) and basalt (BFRP). FRP reinforcement is lightweight and has a high ultimate strength. They also have similar disadvantages such as a low elastic modulus, a relatively brittle failure and the fire performance needs to be appropriate for the context.

Whilst they can be produced as straight and bent bar, bending is only currently available from certain manufacturers and this is only achievable before curing is complete in the factory, although development is currently being undertaken to produce a bar which can be bent post-production on site. The thermal expansion coefficient of basalt is similar to that of concrete which gives the advantage of similar deformations, while for steel reinforcement debonding is common due to the expansion of the reinforcement.

An Environmental Product Declaration (EPD) produced by Milieu Relevante Product Informatie[12] indicates that similar embodied carbon weight for weight for BFRP and steel. However, as BFRP is a quarter of the weight of steel and with increased tensile strength, smaller diameter bars can be used in many applications. This means that the embodied carbon for BFRP reinforcement can be significantly less than steel for the same application. It is important to note the specific conditions of the application, such as load conditions and temperature. Long-term static loads at elevated temperature may induce creep, whereas transient loads at temperate conditions may be acceptable.

The requirement to reduce embodied carbon in reinforced concrete for UK Government contracts has resulted in testing of precast elements using BFRP and alkali activated concrete.

Strength characteristics of basalt FRP bars are given in **Table 1**.

Table 1 TZUS Technical Approval[13]

Properties	Steel Rebar	Basalt FRP
Tensile strength	500 MPa	1250MPa
Youngs Modulus	200 GPa	50 GPa (min)
Elongation	0.8% (<8mm) 2% (>8mm)	1.6%

Generally, BFRP has a tensile strength twice that of steel, the density of basalt FRP is 2g/cm^3 whereas steel is around 8g/cm^3 making FRP reinforcement some four times lighter than steel.

FRP is also non-magnetic and dielectric making it ideal for use where stray electrical currents can be problematic.

Both GFRP and BFRP can be produced as bar and wire mesh. To achieve the stated characteristics of both materials it is important that the fibre content and configuration is taken into consideration as this is what gives the material its high tensile strength. Fibre content should be at least 80% and the strength of the bars is improved by ensuring fibres are parallel and each fibre is coated with resin.

Durability

FRP is corrosion resistant as they are non-metallic. It is unaffected by sulfates and has a high resistance to acids and alkalis.

Accelerated wet testing data for BFRP bars in concrete[14] has shown that they may retain 79.6% of their tensile strength over a period of 100 years.

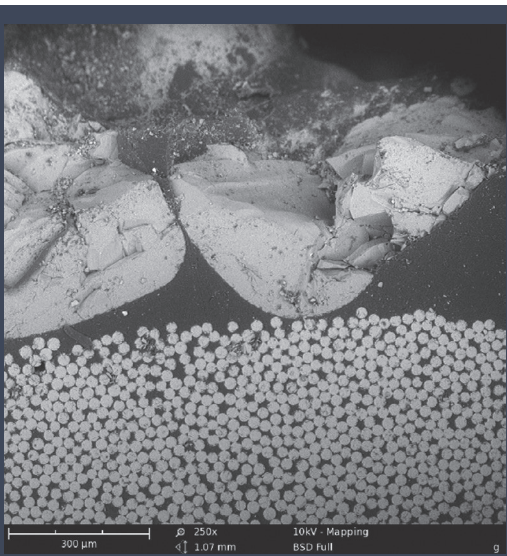


Figure 9 Shows the individual fibres with a full coating of resin – the larger elements are grains of sand which provide increased bond strength

Figure 10 Shows parallel fibres which can enhanced strength as opposed to a wound fibre

University of Miami (UoM) research[15] suggested that some 2000 billion litres of fresh water is used annually in the production of concrete, whereas it has been calculated[16] that global water availability is dominated by 97.5% seawater and only 2.5% freshwater. Using seawater for reinforced concrete would result in high risk of premature failure due to corrosion if steel were used[17].

An ecological approach to reduce the stress on freshwater supplies globally was conceptualised by UoM with Florida DOT. This was driven by the benefits of using the readily available supply of seawater and following the destructive effects from Hurricane Irma on marine structures in Florida, and the need to reconstruct economically. Demonstrator structures were designed and constructed. These used FRP in multiple forms as either carbon fibre (CFRP), BFRP and GFRP (known as Seabar™) within bridge deck and marine bulkhead reconstructions, in order to use reinforcement in combination with concrete mixed with seawater (Seacrete™), without the corrosion risk. Advantages of the lightweight nature of FRPs and no corrosion risk were balanced by limitations with the inability to bend FRP and the lack of ductility, but the demonstrator structures were constructed successfully.

Certification

Currently there is no BS or EN for FRP rebar although there is an EAD under development: *Carbon, glass, basalt and aramid FRP (fibre reinforced polymer) bars as reinforcement of structural elements*, which will be published in 2022, allowing for CE marking and a transfer to the new UKCA mark.

The fib task group 9.3 has produced a technical document, *FRP Reinforcement in concrete structures fib 40*, which gives guidance on design using FRP.

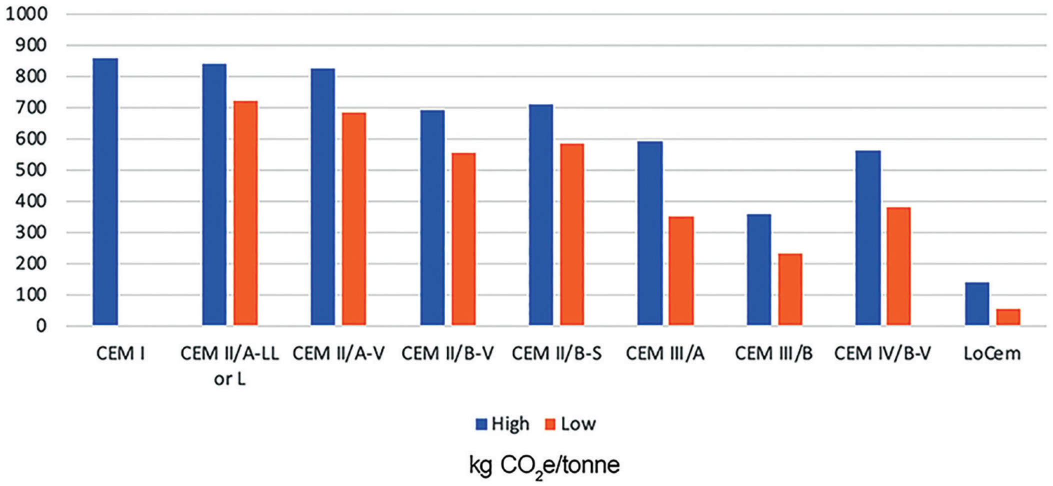
The American Concrete Institute has a design guide for structural concrete reinforced with FRP ACI 4401R[18].

ASTM has the D7957 *Standard specification for solid round glass fiber reinforced polymer bars for concrete reinforcement*[19].

Cements and concrete mix designs

The most disruptive design change would be to replace CEM I designed concrete with non-Portland binder alternatives. However, carbon reductions are also gained by increasing slag, fly ash and pozzolana constituents in the mix design of Portland concrete that occurs with CEM II, III and IV also improving resilience. Portland and non-Portland binders can compete for these feedstocks and designs should take into account the best outcome on performance, as binders such as AACMs become available in high volume.

Caution should be exercised when considering the impact on resilience in new concretes that depend on CO_2 sequestering (see **Chapter 2**) that on the face of it absorb CO_2 as a benefit but are at longer term risk in use as the structure absorbs water and corrosion initiates. Measures, however, can be taken to alleviate and control this risk (see the following sections). Repurposing of industrial wastes from fossil fuels, steel, mining and agriculture to blend as AACMs offer low carbon binders that significantly save on CO_2e (see **Figure 11**). The calculated carbon savings are affected by feedstock source and transportation, leading to a quoted range of CO_2e reduction values.



Note: MPA Fact Sheet 18[29], table 2 and C-Probe. For CEM the high and low values relate to the secondary main constituent content. For LoCem they reflect a range of raw material sources.

Figure 11 Benchmarking embodied carbon in LoCem (an AACM) used in ICCP systems

The specification of AACMs is the subject of BSI's PAS 8820:2016[9] that details the expected physical and mechanical characteristics. Compressive and flexural strengths are comparable to Portland cement mixes with resilience to external impacts often better, such as fire, chemical attack (especially sulfate and acids), and freeze-thaw effects.

Some AACMs use less water in the alkaline activator within the concrete mix design to initiate hardening with commonly used retarders and superplasticisers used to control open time and workability.

Aggregates

Recycled concrete aggregate (RCA) is the designation used in BS 8500-2[20] for repurposing crushed concrete. These can be used as aggregate in new concrete, particularly the coarse portion. When using the recycled concrete as aggregate, the following should be taken into consideration:

- Recycled concrete as aggregate will typically have higher absorption and lower specific gravity than natural aggregate and will produce Portland concrete with slightly higher drying shrinkage and creep. These differences become greater with increasing amounts of recycled fine aggregates.
- The chloride content of recycled aggregates is of concern if the material will be used in reinforced concrete. The alkali content and type of aggregate in the system is probably unknown, and if mixed with unsuitable materials, a risk of alkali-silica reaction (ASR) is possible. However, these issues can be addressed, the former by using proactive corrosion mitigation (see **Chapter 3**) and the latter using AACMs where polymerised aluminosilicates are formed on hardening that are normally resistant to alkali-silica reaction as the reaction has already taken place as part of the hardening process.
- When calculating carbon reductions, values should reflect transportation and handling of the materials.

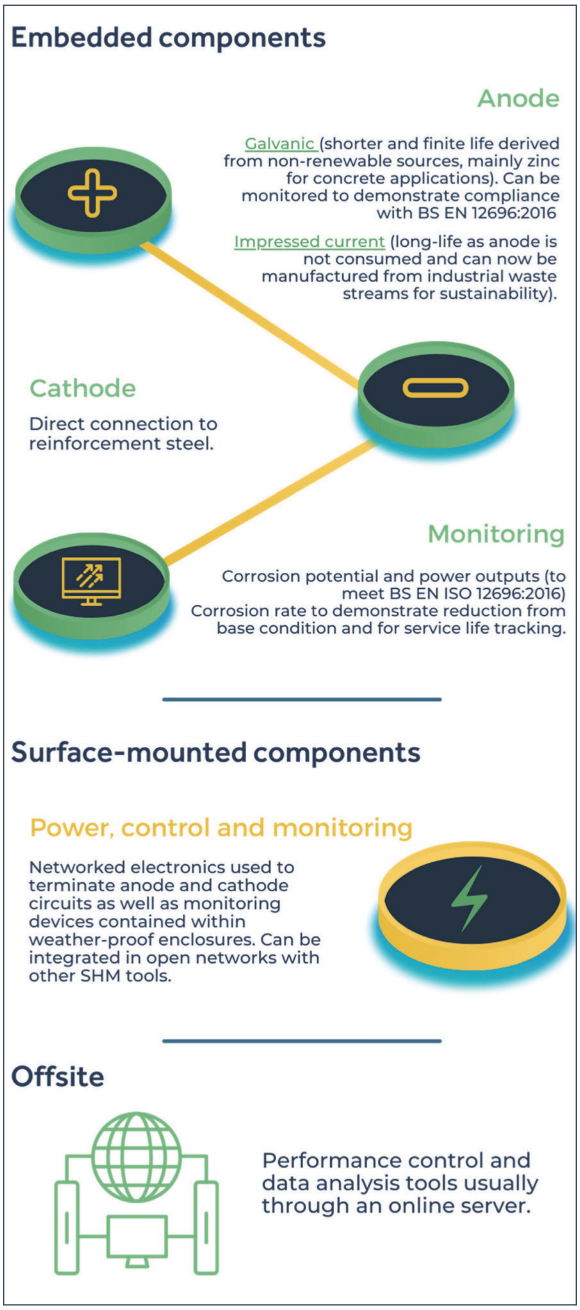


Figure 12 Components of a designed cathodic protection system

Another technology emerging (Carbon8 Aggregates) applies patented "accelerated carbonation technology" to solidify waste residues produced by the incineration of municipal waste. Carbon8 Aggregates' accelerated carbonation processes make these wastes cheaper to dispose of and produce aggregates that can then be used as construction materials. Carbon8 Aggregates claim to be the world's first carbon negative aggregate producer.

In a similar issue to RCAs, the chloride content may be higher than natural aggregates but can be managed in the same proactive manner as mentioned, which will be discussed further as follows.

Where the objective with CO_2 capture is to convert recycled concrete to new limestone aggregate, this offers complementary features to the low carbon design of structures.

Taken together, sustainability in precast structures can be achieved in steel, alternative reinforcements, low carbon cements, and aggregates used, with each contributing significantly to lowering the carbon impact of construction.

It is likely that steel will remain the dominant structural reinforcement material in construction, so measures to proactively prevent corrosion should be considered.

Designing-in proactive measures

Proactive corrosion protection, such as cathodic protection (CP) can be an effective way to protect embodied carbon for the built structure by preventing and controlling the incremental and accelerated environmental effects on the steel reinforcement. This avoids disruption to the concrete cover (see **Figure 13** for the key components used).

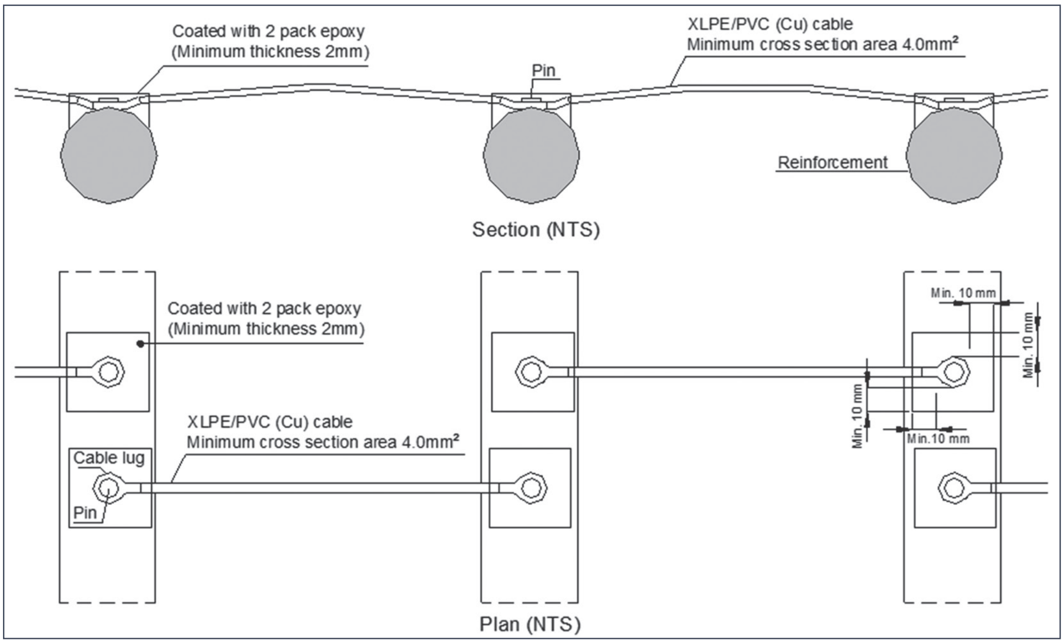


Figure 13 An example of a design incorporating continuity bonds (courtesy Mott MacDonald)

Cathodic protection is a well-established corrosion mitigation technique whereby either galvanic (GCP) or impressed current (ICCP) anodes are installed within the concrete cover to offer electrochemical control of steel corrosion to BS EN ISO 12696:2016[21].

GCP is commonly offered using zinc components connected directly to the steel with stainless steel wires twisted around the steel reinforcement. Zinc, being the baser metal in the galvanic series compared to steel, will corrode in preference to the steel. The disadvantage of this is that protection is only provided for the consumption life of the zinc and replacement becomes necessary in the future.

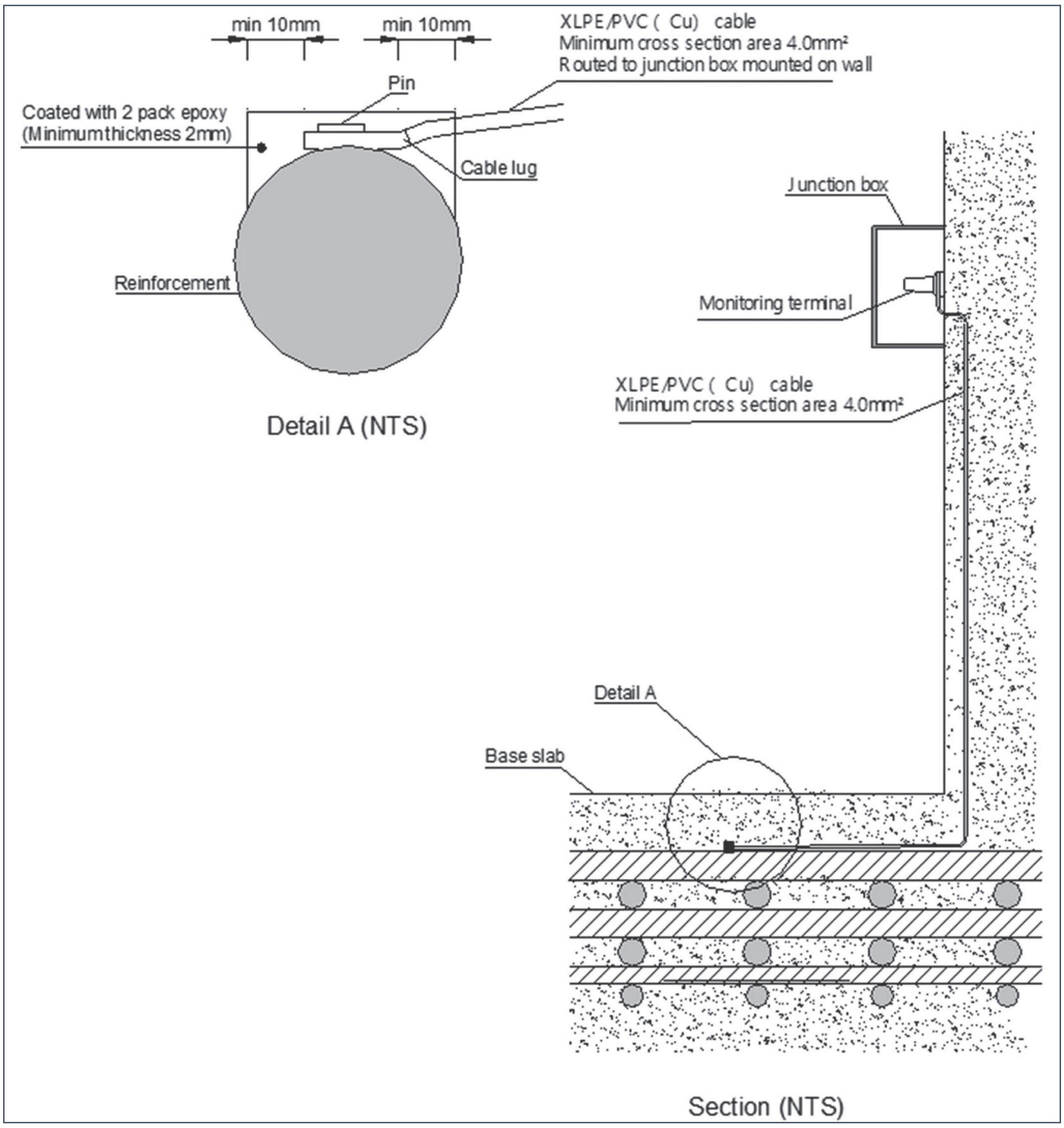


Figure 14 An example of a design incorporating circuitry to link cathodes in a future ICCP system (courtesy Mott MacDonald)

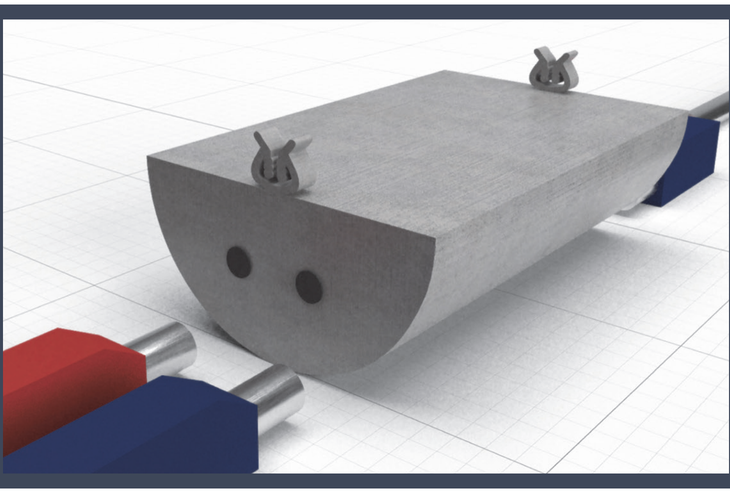


Figure 15 C-Probe's modular anode unit (patent pending) (MAU) enables easy incorporation of ICCP into precast concrete products and on-site concrete pours

The life expectancy is linked to the weight of zinc introduced to the structural element, so longer service lives of 60 or 120 years are difficult to achieve as the zinc weight cannot be accommodated within the structure. Moreover, from an environmental standpoint, zinc manufacturing is energy and carbon intensive, contributing 3.41kgCO_2e/ kg of zinc produced[22].

An example of designing-in features is increasingly taking place where electrical steel continuity bonds and cathode (steel) connections are installed at the construction stage, such that an ICCP system can be retrofitted by future installation of the anode system only. This minimises disturbance to the concrete cover and minimises time on site to complete the system. The decision to monitor early also makes sense as the data informs the decision of when to implement full ICCP before damage develops.

Innovations recently take this a step further for precast and cast in-situ constructions where factory-molded cementitious ICCP modular anode units (MAUs) can be connected directly to the reinforcement and interconnected with plug-and-play wiring, which is tested prior to concrete being poured and compliant with BS EN ISO 12696:2016[21].

This has the intent of providing simple to install ICCP from day one and futureproofing by control of corrosion condition of the steel in use for whole life protection.

These MAUs are also manufactured using low carbon conductive AACMs and, therefore, offer a low carbon option in component selection.

Summary

Emerging technologies offer the opportunity to design new reinforced concrete structures in the factory in all aspects of precast construction. Materials are available that are low or no carbon as well as becoming controllable remotely over their whole life to provide sustainable structural resilience.

These innovations offer significant opportunity for ESG compliance with a sustainable legacy.

Monitoring performance of these new structures informs stakeholders with data that resilience in use is being achieved and tracked (see **Chapter 4**). The availability of these data with accessible reporting offers owners clarity on asset value, safety and due diligence evidence for an asset sale.

Measuring and controlling whole life performance

Stephen Davis, Structural Healthcare Limited

4

Introduction

Assessment of a structure's continuing ability to function in its intended purpose has been carried out using a variety of methods from visual inspections for defects through simple stand-alone analogue sensors to digital systems that can be remotely accessed from tablets and smart phones.

With the advancement of technology over the past few decades, the assessment process has developed into complete structural health monitoring (SHM) systems that can produce data from different types of sensors and devices to a centralised database. These data can then be used to provide comprehensive information about structural condition, material properties, defects, service life and integrity for effective asset management, whole life costing and safety.

Existing structures continue to suffer the effects of ageing and environmental impact with time, making the cost of maintaining and repairing an ongoing concern. Structural health monitoring may alleviate these concerns by replacing regular scheduled maintenance with as-needed maintenance or in the case of corrosion, the introduction of proactive control methods, saving both future monetary cost and environmental impact of continuing unnecessary and unscheduled disruptive maintenance and repair.

For new structures, including structural health monitoring sensors and systems, as well as remote, proactive corrosion control measures, from the design stage is likely to greatly reduce the life cycle costs, disruption and environmental impact, along with increased safety and resilience throughout the extended life of the structure.

Structural health monitoring

A typical SHM system would consist of:

- Sensors (usually embedded or surface mounted).
- Data acquisition devices with on-site data storage.
- Data transfer devices and software, and off-site storage system.
- Data management and presentation for interpretation and analysis.

Sensors used within SHM systems can provide a wide variety of measurements including strain, load, force and displacement, as well a range of corrosion related measurements. Historically, embedded sensors used for assessing corrosion measured just the steel potential but newer sensors, such as corrosion rate, resistivity, and chloride depth, have been developed to inform on the condition of both the steel and concrete cover.

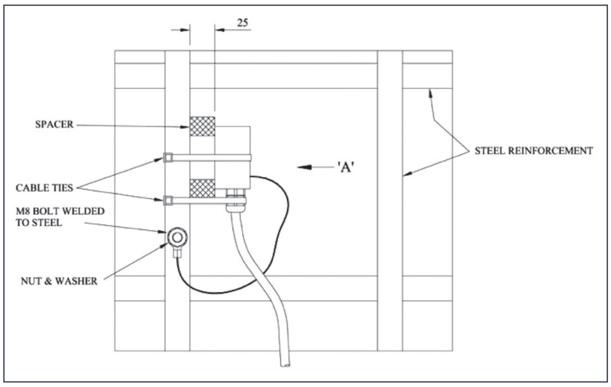


Figure 16 Corrosion rate probe detail (courtesy C-Probe)

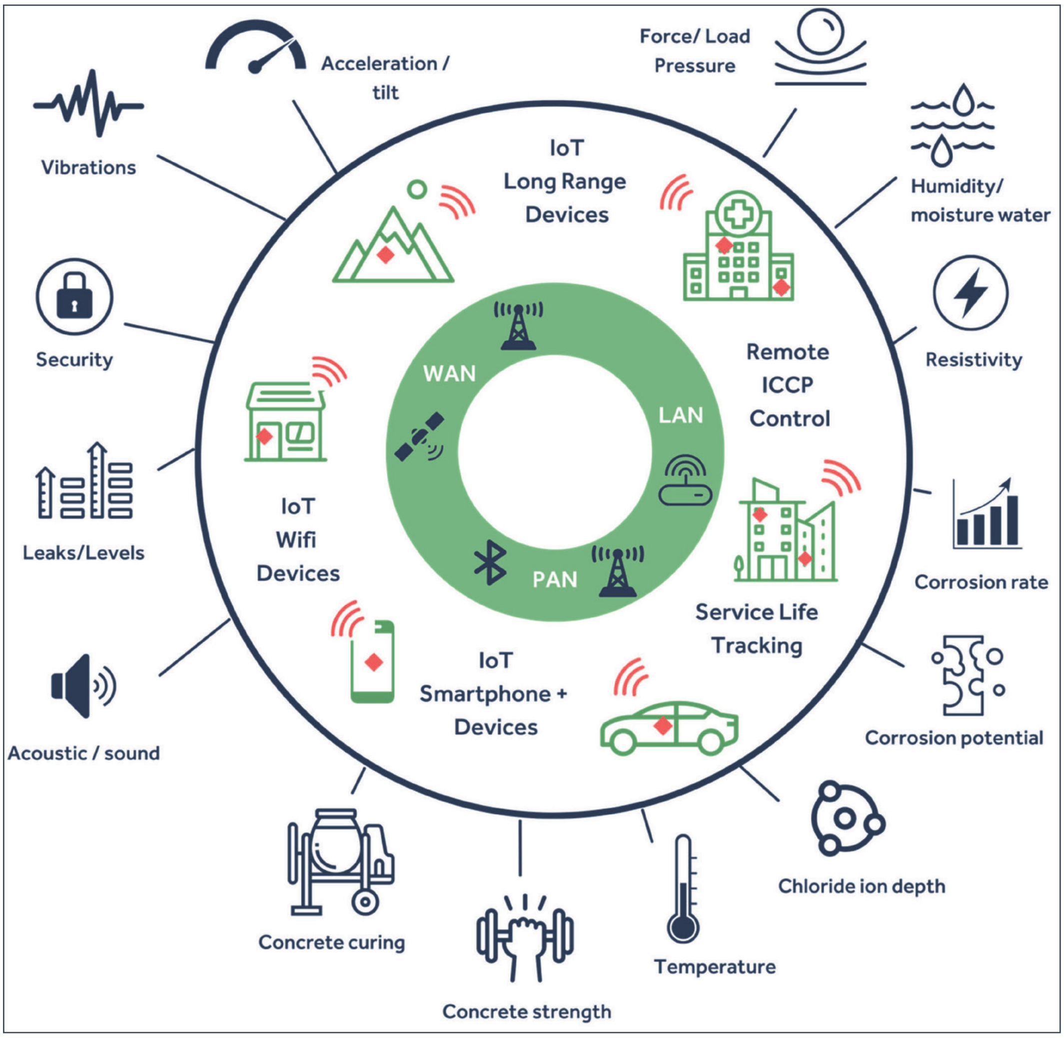


Figure 17 A variety of devices can be built into a structure from new to inform use and resilience over time, accessed from anywhere; the system may monitor and control a portfolio of assets (courtesy C Probe)

These corrosion sensors can be used by retrofitting into existing structures and attached prior to placing the concrete in new structures. This provides ongoing performance data either as an early detection system or in conjunction with proactive corrosion control techniques to assess the performance and effectiveness of those techniques, such as ICCP to the international standard (BS EN ISO 12696:2016[21]).

Structural information can also be included in a structure's whole life design to inform and detect issues such as load, movement, stress/strain and impact.

Sensor technology for structural health monitoring continues to advance and the following provides a brief review to the most widely used SHM sensors:

- Fibre optic sensors benefit from being small and lightweight with good immunity to temperature, EMI, RFI and corrosion. They are primarily used for stress/strain and temperature sensing on structures.
- Load cells utilise an electrical signal produced by a transducer where the signal is directly proportional to the force being measured. Common types of load cells are hydraulic, pneumatic, strain gauge and capacitive. The most common of these are strain gauges that measure changes in electrical resistance when under stress or strain. This resistance is linear and proportional to the stress or strain applied to the cell and is simple to calibrate for accurate measurement.
- Accelerometers are electromechanical devices that measure acceleration forces. They are primarily installed on structures to assess vibration and seismic activity.
- Acoustic sensors have been used to detect the failure of post-tensioned tendons in a variety of structures.

In general, and because of the amount of data collected, sensors are connected to networked electronic data acquisition devices, which either store data in onboard memory or transmit the data to a dedicated data storage device. In addition to acquiring these data, the devices may carry out analysis of the data locally for compliance with preset conditions that may trigger alarms or automated control decisions if relevant.

Depending on the system and the sensors being used, the data can be stored on-site and transmitted to a centralised off-site data storage system, such as a server and SQL database, on a regular basis, or continuously transmitted to the off-site data storage system.

Monitoring systems can produce large amounts of raw data and it is important to be able to present these data in simple to read formats for data assessment. There are multiple commercially available software packages that can be installed on PCs or servers that are local or remote to the monitoring system or, increasingly, can be cloud based. These will analyse and display the data as a dashboard summary in various formats, such as graphs or numerical tables, and can be based on real-time data or historic recorded data.

Given that structural monitoring has been available for many years, it is inevitable that there will be existing systems installed on structures that may not be networked, have no remote access or be proprietary to a particular company. These legacy systems can be replaced with more modern systems but advances in network interfaces, gateways and human-machine interface (HMI) software allow for these systems to be upgraded with relatively simple and cost-effective add-ons.

Presentation of data takes advantage of online tools that can show values and trended graphs equipped with alarming to assess against specification performance.

Increasingly, owners and operators of portfolios of structures are implementing systems to manage a range of assets.

For ICCP, control and monitoring online services exist that have over 20 years of development and use. This provides remote control of installed systems and performance assessment to BS EN ISO 12696:2016[21] as well as tracking of service life from corrosion rate data from embedded probes[2].

Networks and protocols

SHM system devices are installed on a local network distributed around the structure and then on to a wider area network for offsite data transmission. Both the local and wider networks can consist of a cabled network, such as twisted pair, power line or fibre optic, and/or a wireless network such as wi-fi or LPWAN (low power wide area network).

The choice between the types of networks often depends on the structure and existing services available at the structure. Consideration should be given to the following items:

- **Installation:** Wireless networks tend to be easier to install but a structure may have an existing wired network in place that would negate the need for new cabling by repurposing to include the new services.
- **Performance:** Wired networks generally perform better, mainly due to being less susceptible to interference. The performance of wireless networks depends on the operating environment, such as signal range, building features and the number of connected devices, although technology advancements such as 801.11ax are increasing their capabilities.
- **Security:** Wired networks tend to be more secure by the fact that access to a physical cable connection is required. Both network types can be secured with advanced authentication.

Advancements in technology have increased the options available for wireless networks with LPWANs now being widely used. Generally, LPWANs are either cellular or non-cellular.

- **Cellular:** Utilises the same networks as those used for mobile phones and operates within the licensed frequency bands. It is available with a range of data transmission speeds, with 5G currently being the fastest, although access to 5G networks is limited as the infrastructure for it is not in place and continues to be rolled out at the time of writing. Devices require a SIM card or eSIM to connect to the cellular network and proximity to a cellular mast affects data transmission performance.
- **Non-cellular:** There are a number of options available which all operate in the unlicensed frequency bands, such as LoRa and Weightless SIG.

The devices on the networks may interact with each other, controllers and computers and the way in which these devices communicate across the network is called the protocol (a set of rules to be followed to allow communication between devices).

Protocols can be either open or proprietary and many of the available SHM system devices use protocols initially developed for building automation systems (BAS). Examples of such open network protocols are Modbus, BACnet and LonWorks.

Open network architecture has the benefit of being available to a multitude of control and monitoring units (or nodes) that can be bound to the network to provide versatile functionality and competitiveness. This is known as interoperability. An example of this could be a bridge having photocell sensors for activating lighting, cameras for traffic, web security monitoring and a SHM system with corrosion rate and stress/strain monitoring, all installed on the same network and monitored from a single remote PC or tablet.

It is possible to design not only with ease of construction of modular precast units in mind but with what information or control is desired for its whole life of each element or the structure in its entirety.

The buildup of multiple databases of information from structures can, in time, see structures exposed to the same or different environments learning optimised resilience from other structures of similar construction and exposure conditions to inform on performance in use.

Measuring the costs and benefits of using sustainable resilience technologies

Nigel Fraser, Buildoffsite

5

The recently published UK Government's Construction Playbook[5] highlights the need to concentrate on value rather than just cost. It focuses upon three cross-cutting priorities that help define value:

- health, safety and wellbeing
- building safety
- building back greener.

Sustainability and resilience in the creation of precast products are significant to all of these.

There is a need to integrate new products and materials into controlled operating procedures in factories and produce more in safer factory environments whilst doing less on site.

Chapter 3 on designing for sustainable resilience highlights numerous ways in which buildings and civil infrastructure may be made both safer and greener.

In the Construction Playbook[5], there is consistent emphasis on whole life costs and whole life carbon.

Historically, the cost of construction has tended to dominate decision making. Each project is generally assessed on its own merits and product innovators have little information on which to assess the rate at which economies of scale can be delivered through multiple projects. When it comes to the price of new, low carbon materials, there may be a "carbon premium". This is the case with alternative concretes at the time of writing. However, this is being reduced as more demand and competition emerges.

The thinking behind the Construction Playbook[5] and other changes in society are making a difference. Whole life considerations of cost and carbon are coming to the fore. This will significantly change the market.

Whole life costing methodologies and guidance have been available for some time. The international standard for service life planning and life-cycle costing, BS ISO 15686-5:2017[23], has been adopted by the UK. The Royal Institute of Chartered Surveyors' (RICS) professional guidance[24] on its application is available online.

Similarly, there is guidance for calculating whole life carbon from the RICS[25] (also available online). This refers to no less than 12 UK and international standards that have been issued on this subject. The RICS guidance is understood to be in the process of further development at the time of writing this report.

Critical to assessing whole life carbon is the realistic evaluation of refurbishment emissions. The RICS guide defines this as:

"a planned alteration or improvement to the physical characteristics of the building in order for it to cater for the desired future function identified and quantified at the outset. This would typically involve a predetermined change of use at a point during the service life of the project, as well as a siseable amount of works to several parts of the building".

This is in addition to "replacement works" which are scheduled for windows, doors, boilers etc.

Whilst buildings and infrastructure are designed for long lives, experience has demonstrated numerous contexts where significant refurbishment can be predicted if the normal standards are used for designs. The causes are described in **Chapter 2**. Everyday examples can be seen in the form of so-called concrete "cancer" to varying degrees in many locations (with spalling concrete and cracks in precast façades and reconstituted stone).

Some environments are more prone to these than others, which determines the rate of onset and development of the problem, with marine environments and heavily used road bridges treated with de-icing salt over the winter being some of the most severe.

The approaches to whole life cost and whole life carbon require realistic assumptions to be made about the timing and extent of restoration interventions as addressed in a "fabric first" approach in BS PAS 2035[26] and 2038[27].

In the case of whole life cost, these are typically assessed in discounted cash flow (DCF) or internal rate of return (IRR) calculations. Such calculations for the installation and maintenance of impressed current cathodic protection, monitoring and control systems need to take into account realistic maintenance requirements throughout the design life. Increasingly the business interruption and societal costs will need to be factored in, not only for carbon dioxide implications but also for the impact on users of facilities arising from suspensions or degradations of service during maintenance periods. These can be significant for car parks, shopping centres, road and rail viaducts, and bridges.

The whole life carbon cost of projects is now also very significant and the Construction Playbook[5] requires it to be evaluated for UK Government-funded projects. The UK Government's guidance values carbon in 2022 at 245 £/tCO_2e (rising to 252 in 2023 and 378 by 2050) when assessing energy use and greenhouse gas emissions[28].

This trend is not exclusive to the UK. In the USA, Government policy requires investments to be evaluated in terms of the social cost of carbon (SCC). In February 2021 it set the SCC at $51 per tonne (using a discount rate of 3%). The EU's carbon credits are trading at around €50 per tonne at the time of writing.

Conclusion

There is a strong financial case for assessing the benefits of incorporating structural healthcare monitoring and control systems in infrastructure, with the trends to look holistically at whole life costs and carbon increasing this.

A well-designed asset could be protected well beyond current operational life assumptions[4].

Furthermore, with the introduction of factory installed ICCP systems, the up-front installation costs could be expected to be reduced further. Automated production of anodes and their robotic placement into precast products should continue this trend. Initial costs have a significant impact on the IRR calculation so this will drive up the IRR rates and make the use of ICCP from conception of a facility even more attractive and help avoid adding to the massive global backlog of infrastructure repairs that has developed.

Clearly, such calculations would be very specific to each project.

With respect to whole life carbon, the RICS guide[25] highlights the need for longer term thinking:

"…early consideration of likely future climate change impacts and the development of appropriate adaptation strategies will promote the resilience of built assets".

In the past, calculating embodied carbon in construction has been challenging. There are now practical tools available for doing so and a compelling need to do it. The manufacture of traditional Portland cement and concrete is a major source of carbon emissions, so society needs to make the most of that carbon investment, and start to use alternatives to drive down carbon premiums of new materials through using them. This would provide a basis for progressing down the cost curve.

This all has implications for end clients, specifiers, procurers and manufacturers today.

Regulators could:

- Incentivise low-carbon design and procurement on a life cycle basis.
- Modernise standards and codes to enable and support sustainable construction and innovation.

Clients could consider:

- Putting a value on reducing total embodied and in use carbon.
- Paying a carbon premium in the short term.
- Aligning targets and decision making for capex (capital cost) and opex (revenue cost) focused parts of the organisation.
- The benefits of protecting structures for longer life and less refurbishment, including the impact of taking assets out of service for refurbishment, IE value resilience.
- The benefits of having current information on the structural health of an asset, for example enabling early, low operational impact interventions on assets, such as critical transport systems, or for due diligence use at the time of a sale.

Specifiers/designers could:

- Incorporate whole life assessments into projects, for both cost and carbon.
- Consider use of low carbon concretes and alternative binders.
- Consider corrosion risks more in designs and mitigate them from conception to optimise the whole life cost and carbon and reduce disruption of future asset use.
- Design for efficiency and adaptability, rather than premature demolition.

Procurers could:

- Incorporate whole life cost and carbon assessments into selection criteria.
- Record the basis for a design (e.g. whole life cost/carbon) to avoid inappropriate value engineering that removes longer term benefits for short term gains in this context.
- Consider risk reduction strategies where newer materials are used (such as including structural healthcare monitoring and control).
- Understand the client value of whole life cost and carbon related design decisions.
- Negotiate warranties that are robust, meaningful and sustainable.
- Ensure that project handover includes any whole life requirements (such as ongoing facilities management requirements to support warranties and long-term structural performance).

Manufacturers could:

- Bring to market a wider range of innovative low-carbon materials solutions, validated for durability and sustainability performance.
- Assess alternative concrete mixes.
- Consider offering integrated long term structural protection system components at the time of manufacture. This is much lower cost than retrofitting them and should help win work that is procured on a whole life or whole carbon basis.
- Consider the benefits of having structural healthcare protection embedded in products so that their performance may be warrantied with the assurance that they can be monitored and optimised for very long-life use.

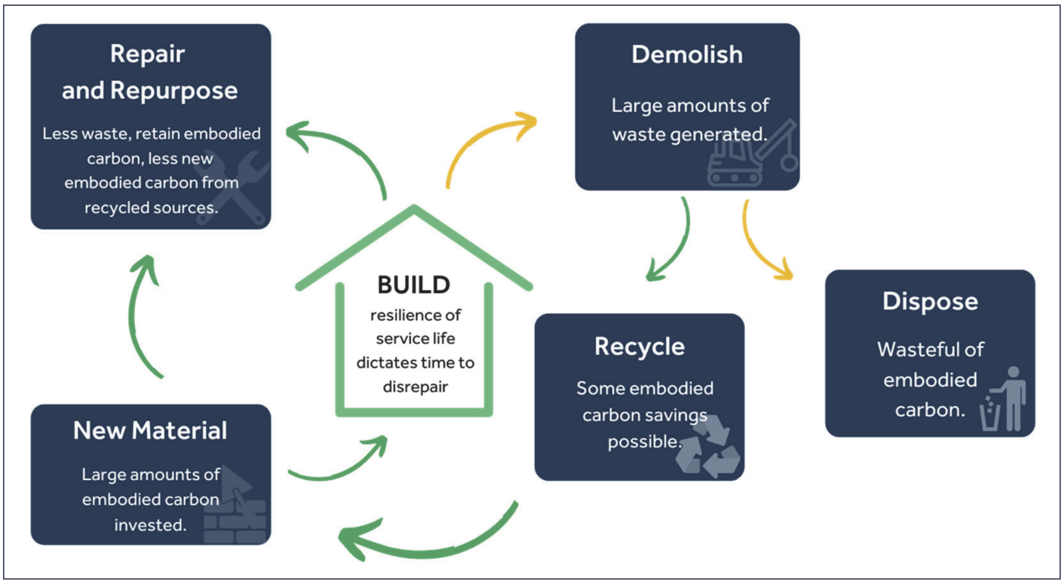


Figure 18 Embodied carbon over the whole life of a structure is influenced by the choices made as its environment impacts on it (courtesy Mott MacDonald)

Figure 19 indicates the increasing certainty associated with different degrees of monitoring and control from designing for later protection/future proofing (for example, electrical continuity of rebar/lifting points, installing galvanic anodes, installing ICCP components) through to installing complete systems from day one, including power supplies, network interfaces, monitoring and control services, and options of when to "power up" the system.

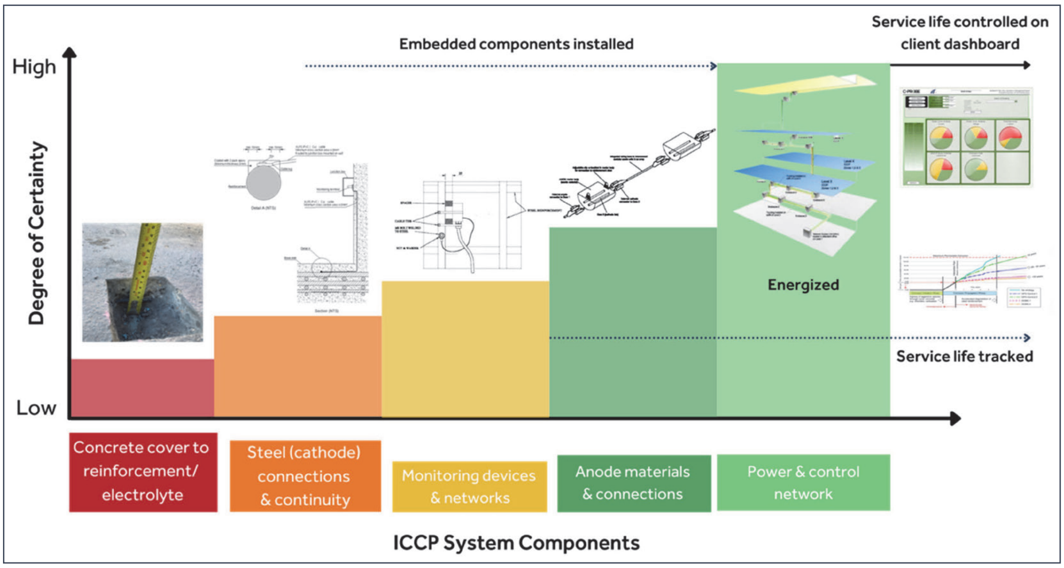


Figure 19 Levels of corrosion protection and control. Incorporating ICCP components into new constructions increases confidence that corrosion is controlled for the whole life of the structure

Conclusions

6

The world has a huge backlog of repairs that are due to a lack of whole life resilience of designs in the past. Climate change, in the form of global warming, is going to amplify the rate of deterioration of assets unless we design things differently going forward. Reinforced concrete is and will remain a fantastically versatile material for construction. We need to exploit it in different ways with planned preventative maintenance in mind.

From a market perspective, clients are increasingly setting carbon and efficiency targets that are driving value through reducing whole life cost and carbon.

The good news is that there are technologies emerging and available to improve the resilience of assets and reduce the embodied carbon in their design, and that a group of these are particularly relevant to the precast concrete sector, which is capable of delivering the efficiency gains needed.

This report explains how to deliver assets that will perform well and predictably into the future, through design for sustainable resilience.

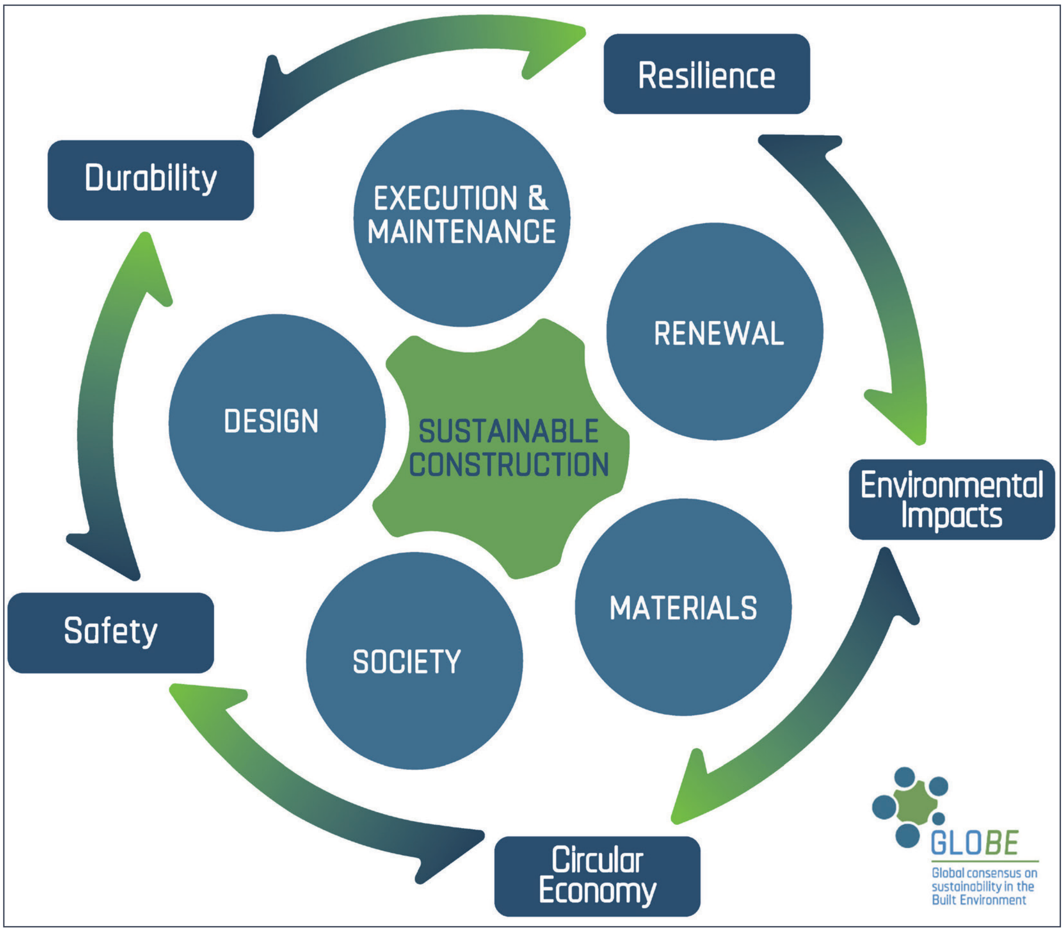


Figure 20 All aspects of sustainable construction interconnect to achieve and impact resilience (courtesy RILEM – Globe Consensus Support, https://www.rilem.net/globe)

Some thoughts on ...

Decarbonisation of corrosion protection

Governments are challenging industries to reduce greenhouse gas (GHG) emissions in pursuit of Net Zero Carbon[5], including the corrosion and protection industry. This means addressing the carbon intensity of source materials whilst still offering long-term resilience to all structures that use steel.

The corrosion and protection industry has its own challenges towards decarbonisation given the sector's primary focus on maintaining pipelines and marine facilities for their income and growth, with sporadic use by the wider construction sector. To date this has used technologies that are largely non-renewable.

Examples of this are seen in cathodic protection (CP) with the use of:

- Sacrificial anodes that, once they corrode, cannot be recycled and, therefore, lose their embodied carbon forever, after a finite service life, typically 10 to 15 years.
- Impressed current (ICCP) anodes that commonly use rare earth metals to form dimensionally stable anode oxides on titanium substrates that, in turn, are embedded (for concrete) so cannot be economically reused or recycled.

ICCP anodes do have longevity in use, typically 100 years, as they do not corrode. Their use is reported to be the best option to preserve embodied carbon in reinforced concrete structures[30].

Competition with other industries for such precious metals and the impact on the environment in their extraction are also likely to come under increasing scrutiny. This could lead to resistance to their application and drive their cost up over time.

As the construction sector embraces resilience management of reinforced concrete structures then the focus should start to swing towards the sustainable construction sector, ideally using more sustainable products[31].

This report highlights how innovative approaches to design can be applied to new build precast structures, adopting proven technology from the restoration and heritage sectors, whilst helping the corrosion protection industry contribute significantly to the circular economy, protecting investments in embodied carbon in traditional concrete and introducing low carbon elements. Helping the corrosion protection industry decarbonise in the process.

Graeme Jones, C-Probe Group

The UK Government's Building Regulations Advisory Committee's full definition of the "golden thread" of safety information

A

Summary

The golden thread is both the information that allows you to understand a building and the steps needed to keep both the building and people safe, now and in the future.

Full definition

1 The golden thread will hold the information that those responsible for the building require to:
   - a show that the building was compliant with applicable building regulations during its construction and provide evidence of meeting the requirements of the new building control route throughout the design and construction and refurbishment of a building
   - b identify, understand, manage and mitigate building safety risks in order to prevent or reduce the severity of the consequences of fire spread or structural collapse throughout the life cycle of a building

2 The information stored in the golden thread will be reviewed and managed so that the information retained, at all times, achieves these purposes.

3 The golden thread covers both the information and documents, and the information management processes (or steps) used to support building safety.

4 The golden thread information should be stored as structured digital information. It will be stored, managed, maintained and retained in line with the golden thread principles[32]. The government will specify digital standards which will provide guidance on how the principles can be met.

5 The golden thread information management approach will apply through design, construction, occupation, refurbishment and ongoing management of buildings. It supports the wider changes in the regime to promote a culture of building safety.

6 Building safety should be taken to include the fire and structural safety of a building and the safety of all the people in or in the vicinity of a building (including emergency responders).

7 Many people will need to access the golden thread to update and share golden thread information throughout a building's lifecycle, including but not limited to building managers, architects, contractors and many others. Information from the golden thread will also need to be shared by the accountable person with other relevant people including residents and emergency responders.

Case study: preventative corrosion protection, Woodhouse Inn Viaduct

B

In 2001 work was undertaken to design, install and commission an impressed current cathodic protection (ICCP) system as a proactive measure to prevent corrosion from forming on complex steel reinforcement within deep half-joints (see cross-sectional detail) at the Woodhouse Inn Viaduct near Worksop.

This viaduct carried the A57 arterial road towards Sheffield, and the client wished to avoid future disruption and to limit costs associated with closure and repair. After around 20 years the first signs of disrepair were showing on the underside nib of the joints but were small-scale at the time, so it was decided to prevent this from worsening by installing an ICCP system.

Anodes were drilled into the spaces between steel bars to protect all steel within 1m of the nib of the half-joint for its full length.

Monitoring devices were installed to prove compliance with ICCP standards for performance (now BS EN ISO 12696:2016[21]).

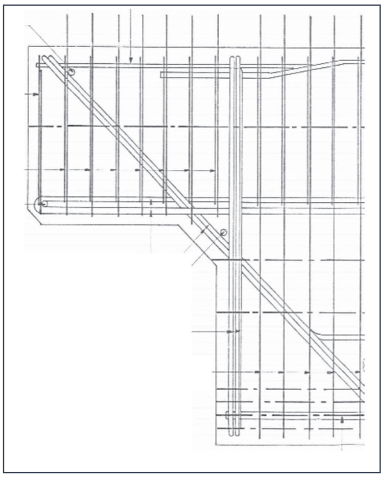


Figure 21 Cross-sectional detail of steel reinforcement arrangement within the half-joint

Figure 22 General view of viaduct with ICCP installed to four half-joints

Figure 23 Close-up view of installed ICCP to the underside of a half-joint showing control electronics enclosure and junction boxes

Controlled in 12-zones (three per half-joint) the system has performed well for over 20 years, managed and controlled online, remotely.

The performance of this retrofitted system has been successful with no concrete repairs necessary for the past 21 years.

Footnote

For context within this report, today this viaduct would very likely be built offsite in precast elements. This would provide the ideal moment to cast anodes into the precast units in the factory prior to the concrete being placed to ensure precise anode locations, high quality of connections and placement of monitoring devices whilst avoiding the disruption caused by erecting scaffolding and retrofitting ICCP components.

Installing from day one of a structure's life provides assurance of the service life and avoidance of the need and cost of future repair.

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About 70% of global structural degradation in industrialised countries is reportedly due to corrosion. It is estimated that globally there are US$2.5 trillion of repairs to be carried out on infrastructure and buildings due to this issue. The surprisingly high (if largely hidden) cost of corrosion represents about 3.4% of global GDP. This is huge, but it is potentially avoidable in the future.

This report aims to help construction clients, architects, engineers, main contractors and precast manufacturers reduce the impact of corrosion in future. It does this by signposting methods for combatting the root causes of corrosion using sustainable materials and methods that, when combined, deliver enhanced resilience and reduced whole-life cost and carbon for a structure.

With increases in carbon dioxide in the atmosphere and average temperatures, along with more frequent, extreme weather events, society can expect the impact of corrosion to grow even larger – unless industry does things differently. This report suggests how to design more resilient structures, using precast concrete, and protecting investments in embodied carbon.

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