ASSESSMENT OF REINFORCED CONCRETE HALF-JOINT STRUCTURES: DEALING WITH DETERIORATION

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ABSTRACT

In the US and UK the existing infrastructure is aging and the safety is sometimes questioned. Of all bridges in the US, constructed with reinforced concrete (RC), around 10% are classified as structurally deficient or functionally obsolete.

After the collapse of the de la Concorde Overpass (Quebec, Canada), the shear resistance of half-joints has come under intense scrutiny. A half-joint is a particular type of RC structure. The advantages include a level running surface along the bridge deck and support spans, and precast beams that can be easily lifted into place during construction. However, a major disadvantage are the problems associated with leakage through the joint.

When assessing the remaining bearing capacity of half-joint structures, the deterioration is often disregarded as current code provisions do not provide guidance to take strength loss into consideration. Above that, available design rules and guidelines differ significantly. In cases where assessors do consider the deterioration, it is unclear to which extent.

This paper aims to provide guidance on how deterioration processes can influence the mechanical and structural behaviour thereby facilitating a more accurate assessment of half-joint structures.

Keywords: Assessment, Corrosion, Deterioration, Half-Joint, Reinforcement

INTRODUCTION

In the UK, the existing infrastructure is aging and the safety of tunnels, bridges, dams, etc. is sometimes questioned. The road network managed by the UK Highways Agency (HA) alone is valued at around £85 billion[1] and the entire transport network includes approximately 150.000 bridges[2]. Many bridges in the UK are constructed using reinforced concrete (RC) or prestressed concrete (PC). Concrete is a common construction material in other countries as well, such as the US and Canada. Of the over 535.000 bridges in the US, around 19% have been classified as either structurally deficient or functionally obsolete (non-compliance with functionality or geometry requirements). For reinforced concrete bridges approx. 10% are considered structurally deficient[3].

A half-joint (sometimes also referred to as dapped end) is a particular type of RC structure (Figure 1) that was introduced into bridge decks as a means of simplifying design and construction operations. It is a support detail where an L-shaped ledge supports an inverted ledge of a drop-in span. The advantages of this structural form include a level running surface along the bridge deck and the support spans, and precast beams can be easily lifted into place and supported during construction.

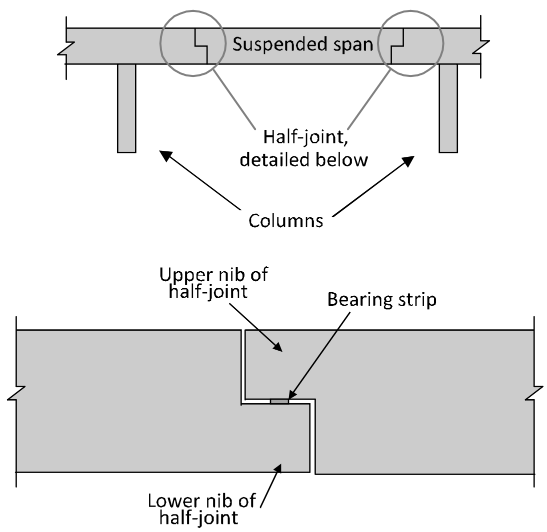

Figure 1: Typical half-joint geometry (based on [1])

However, a major disadvantage are the problems associated with leakage through the joint. For example, chloride rich seepage can cause concrete deterioration and corrosion of the reinforcement. Loss of part of the reinforcement bar cross-section due to corrosion can induce higher stresses in certain regions of the structural member and significantly reduce the safety margins[5]. TS Interim Amendment No. 20[5] states: ‘Half-joints are a particular concern because they are not easily accessible for inspection or maintenance and they are mostly located over or under live traffic lanes.’

After the collapse of the de la Concorde Overpass, over Quebec AutoRoute 19 in Laval (Canada), the shear resistance of half-joints has come under intense scrutiny. Five people were killed and six others injured as a result of the collapse. A Commission of Inquiry[6] conducted a thorough investigation concluded that the bridge was sufficient to carry the applied loads and generally complied with design guidance at the time of construction, although not with current guidelines and standards. However, the concrete freeze-thaw resistance was deficient and the detailing did not comply with best practice. Those detailing vulnerabilities may have been exacerbated during construction when some reinforcing bars were misplaced. Above that, repair interventions, during which regions of concrete were removed and replaced, could have had a negative impact as well.

This incident clearly shows that the load capacity of half-joint structures can be influenced to a significant extent by improper execution during the construction of a bridge, deterioration processes, repair works, etc.

ASSESSING REINFORCED CONCRETE HALF-JOINTS

New half-joint structures are typically modelled using strut-and-tie methods. Analytical approaches (e.g. Finite Element Calculations) are sometimes used for new construction as well, however these assume that structures are detailed properly.

When assessing the load bearing capacity of existing half-joint structures, deterioration and repair works are often disregarded as current code provisions or guidelines do not provide guidance to allow for any strength loss due to these factors. Furthermore, available design rules and guidelines have changed over the last decades[7] and there are significant differences between the design approaches. In cases where assessors do consider the deterioration, it is unclear to which extent.

With respect to assessments, strut-and-tie methods are often used[8] but can be overly conservative leading to unnecessary assessment failures. A structure with noncompliant details may still be serviceable, but there is a distinct lack of validated tools to accurately predict the residual capacity.

In the past, a number of experimental studies on half-joint beams have been conducted[9,10] but those have typically focussed on new construction. Older structures with non-compliant details represent an additional challenge. The two main shear failure planes in a half-joint structure are a full slab failure and a failure at the re-entrant corner (Figure 2). But there are complex interactions between them and, above that, the modes are sensitive to small changes in the detailing and/or strength reductions due to concrete deterioration.

A first step in the development of better assessment techniques for reinforced concrete half-joint structures, is to determine the effect of deterioration processes on the mechanical properties of RC structures. This aspect will be the focus of the current work.

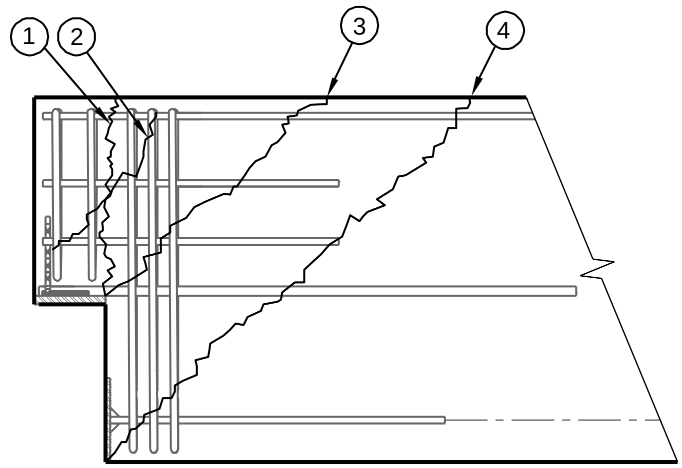

Figure 2: Potential failure modes in half-joint connections (based on [2])

INFLUENCE OF DETERIORATION PROCESSES

Until a few decades ago, it was assumed that reinforced concrete structures were maintenance-free and had an almost unlimited life time. Unfortunately, over the last 30 to 40 years this assumption has shown to be wrong. Severe problems including reinforcement corrosion, chemical deterioration of the cement matrix in aggressive environments and destructive chemical reactions between the concrete constituents have led to costly interventions and/or reduced service lives.

The durability of a material is determined by the speed at which the structure of the material is changing, in other words by the speed at which the material is being degraded[12]. This degradation is the result of physical, physiochemical or chemical processes.
With respect to reinforced concrete, the common deterioration processes can be classified into two distinct groups:

- Direct deterioration of the concrete due to internal or external causes
- Indirect deterioration of the concrete due to the deterioration of reinforcement located inside the concrete

This classification suggests that some substances can be aggressive towards the reinforcement but not towards the concrete itself. As long as these substances do not reach the level of the reinforcement, the half-joint will not degrade.

The main focus of the research into deterioration processes in concrete has been, and still is, on the durability and the reduction of the remaining service life[13]. Less attention is given to the impact of deterioration mechanisms on the structural behaviour. As the aim of this study is the assessment of existing half-joint structures, the discussion below will focus primarily on the impact of deterioration processes on the mechanical properties and overall structural behaviour of concrete elements.

DIRECT DETERIORATION PROCESSES

Carbonation

Carbonation is often referred to as an indirect deterioration process, however the chemical reactions corresponding to carbonation can alter the properties of the concrete itself and in this sense is classified as a direct process. It is one of the most common types of deterioration and is frequently detected during half-joint inspections. The extent of carbonation, however, can differ significantly based on the local exposure conditions, concrete conditions, concrete composition, etc.

Carbonation is a reaction of carbon dioxide in the environment with the calcium hydroxide in the cement paste[14]. The reaction produces calcium carbonate and water, and lowers the pH of the concrete. Several factors influence the speed and extent of carbonation in concrete structures[15] including the material properties (W/C-ratio, cement quantity and type, etc.), environment (relative humidity, temperature, pressure, etc.) and construction (vibration, curing, etc.).

The number of studies focussing on the changes in physico-mechanical properties of carbonated concrete are limited. By testing prism, cylinder and cube specimens of four different concrete compositions, Jerga[16] looked into the influence of carbonation on strength, density and the deformation properties. The changes in these properties due to carbonation were proportional to the cement content and were significant. With respect to the compressive strength, higher values of f_c were measured for carbonated concrete. The authors attribute this increase to the formation of water due to carbonation which leads to an enhanced hydration of the cement. An increase in compressive strength due to carbonation has also been reported by Rigo da Silva et al.[17] (22% to 78%) and Aguilera et al.[18]. As the strength increases with carbonation, the stress-strain curve becomes steeper, leading to a more brittle behaviour and increased modulus of elasticity[16]. The density was found to increase by 40 kg/m^3 (concrete with W/C-ratio of 0.8) up to 85 kg/m^3 (concrete with W/C-ratio of 0.47) after 100 days. After 100 days the increases in density were small[16].

Xiao et al.[15] studied large scale beams and columns under accelerated carbonation. They conclude that the load bearing capacity of concrete columns and beams is increased after carbonation of the concrete cover, but the deformation capacity is decreased (increase of modulus of elasticity) and a more brittle failure is observed. The increase in ultimate flexural capacity was approx. 7%.

It should be noted that the re-alkalisation of carbonated concrete (a possible rehabilitation technique) leads to a deposition of material in the pore structure and hence densification. This leads to a further increase in compressive strength, flexural strength and modulus of elasticity[19].

Overall it can be stated that the direct effect of carbonation on strength and Young modulus is an increase in both. Depending on the source (and so the concrete composition and other parameters), this increase ranges from a few up to more than 50% in the carbonated zones.

Chloride Attack

As with carbonation, the influence of chloride ingress is mostly through the indirect deterioration of the concrete. It is rather unclear if the diffusion of chloride ions into concrete has a direct effect as well. In half-joints, problems with chloride ingress are mostly found on the inner corners of the L-shaped ledge due to leakage through the joint. Chloride rich seepage stagnates on the bearing seat of the dapped end, causing the chlorides to migrate into the concrete.

Chloride transport in concrete is a rather complicated process[20]. It involves ion diffusion, capillary suction and convective flow with water, accompanied by physical and chemical binding. Other mechanisms such as absorption, permeability and wicking action may also contribute to chloride transport. Chloride ions can be present in the concrete due to being deliberately included in the mixture in the fresh state (to enhance the hydration process) or through the introduction of chlorides from an external environment[21]. Although the deliberate inclusion in the mix is discouraged in current standards (in the UK their use has been prohibited since 1976), existing half-joint bridges constructed in the late 60's and early 70's sometimes had chlorides mixed into the concrete. Chlorides can also enter the structure from an external source. Amongst these sources are seawater in marine environments and de-icing salts used in the winter on roads and bridges[20].

Barberon et al.[22] studied the interaction between chloride and cement-paste materials by means of nuclear magnetic resonance (NMR). They noticed that exposure of concrete to a NaCl solution leads to a rehydration of the residual cement. While not explicitly tested, this suggests Cl^--ions increase the concrete strength to a small extent.

A study performed by Türkmen[23] however contradicts this finding. By comparing strength results obtained on standard cylinders stored in lime-saturated water for 400 days and specimens stored in a 5% NaCl solution, they detected strength reductions due to NaCl of 13 to 15% for pure Portland cement concretes with a W/C-ratio ranging from 0.35 to 0.45. For concretes with 10% replacement of cement by silica fume (SF) similar results were obtained, while in case of a 10% SF mix combined with 40% blast furnace slag (BFS) replacement the reduction increased to 24 to 30%. It has to be emphasized that, in this study, the specimens were exposed to a 5% NaCl solution for over a year. This content is much higher than that regularly found in actual structures which typically reach chloride contents of up to 1% on bridges and parking lots in marine environments[24].

Despite these contradictory results, the majority of researchers[20, 25] still believe that, in normal circumstances, chloride itself does not result directly in any damage to the concrete. It can however induce corrosion of the reinforcing steel. Technical report No. 54 of the Concrete Society[14], agrees with this, and states that chlorides have little effect on the concrete itself (though large quantities may cause some surface dampness). The most significant consequence of chlorides in concrete is to increase the risk of the corrosion of the reinforcement.

Cracking

Cracks in concrete can be caused by a wide range of different causes. The ones discussed in this section are related to direct impacts on the concrete. Even before loading or any environmental effects, micro-cracks exist at the cement paste – aggregate interfaces. These are mostly formed due to drying and thermal shrinkage mismatches of aggregate particles and the matrix[26]. Over time these cracks will grow in length and number due to loading and external effects.

Different types of cracks occur at different times in the life time of a (reinforced) concrete structure e.g. Figure 3. Although many cracks are not structural and are considered to be aesthetic, they can influence the durability. Examples of non-structural cracks are plastic shrinkage, crazing and drying cracks[14]. As reinforced concrete is designed on the assumption that the concrete has no significant tensile strength and the reinforcement carries the tensile forces, members subjected to bending, shear and torsion will always show cracking to some degree. Load-induced cracks or cracks due to structural design inadequacies can have an impact on the load capacity. A further category of structural cracks in existing concrete structures are those induced by deterioration processes (e.g. ASR) and repair works.

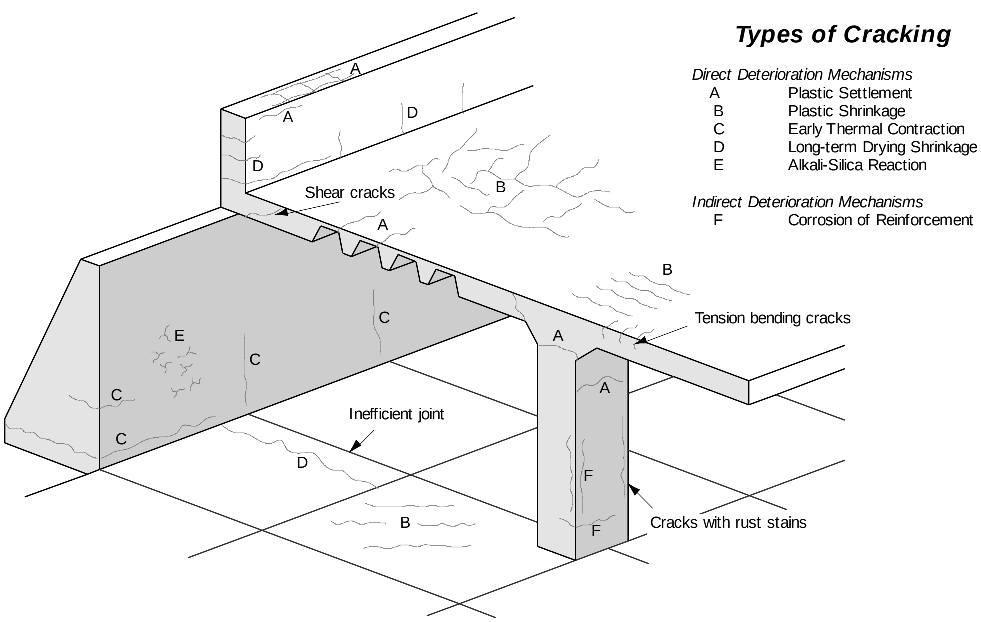

Figure 3: Examples of intrinsic cracks in hypothetical structure (based on [3])

Cracks in concrete do not have smooth surfaces and so the crack width is variable along the length. The maximum allowable widths under service loads are given in codes and depend on what is considered to be aesthetically acceptable, durable and watertight (if required).

However, some cracks will be wider than the maximum specified in codes, nevertheless this should not necessarily cause concern unless the wider cracks are at critical locations. ACI 224.1R[28] points specifically to the importance of a proper design and detailing of re-entrant corners as these provide locations for stress concentrations and therefore the initiation of cracks.
An overview of different crack origins and their appearance is given in Table 1.

Table 1: Overview of different crack origins and patterns (based on [4] and [5])

Origin	Formation (time after casting)	Appearance	Width
Plastic settlement	First hours	Along rebars or cross-sectional changes	Large
Plastic shrinkage	First hours	Random pattern, corners of plates	2 to 4 mm
Early thermal contraction	First days	Large cracks forming natural joints	f(A)
Drying shrinkage	Several months to years	Similar to tension and bending cracks	Small
ASR	Several years	Random pattern	Large
Load-induced	Several months to years	Depending on load condition	Small*
Displacement / settlement	Several months to years	Depending on extend of displacement	Large
Impact	Unknown	Unknown, depends on cause of impact	Large

* Highly dependent on proper design of the structure. In case of improper design, crack widths can become large.

The extent to which cracking will have an influence on the structural response of a reinforced half-joint is highly dependent on the crack widths, the number of cracks and the location of the crack.

Other Deterioration Processes

There is a variety of other deterioration processes that can have a significant influence on the structural integrity of reinforced concrete elements. These processes can either be internally initiated, or can be caused by an environmental attack on the surface of the concrete inducing migration / diffusion into the RC element.

One of the most striking examples of an internally initiated deterioration process, that can highly affect the mechanical properties of concrete, is Alkali-Silica-Reaction.

Some aggregates exhibit the ability to initiate expansive reactions under certain environmental conditions. This interaction is caused by a reaction of the aggregates in the concrete and the alkalis in the cement. Mostly silica-based aggregates are vulnerable, although cases of reactions with carbonate-based aggregates have also been reported. For silica-based aggregates the associated deterioration processes are referred to as Alkali-Silica-Reaction (ASR).

The changes detected in concrete due to ASR are:

- Expansion of the concrete

- Formation of cracks at the surface
- Spalling of concrete
- Secretion of alkali-silica gel

As the reaction products are extracting water, local stress concentrations are built up leading to swelling and eventually cracking. This crack formation has a strong influence on the mechanical and structural behaviour of ASR affected concrete members.

Ahmed et al.[30] performed research into the impact of ASR on the compressive strength, tensile strength and the modulus of elasticity. Results of three different concretes were compared: one reference mix without reactive aggregates, one with solely reactive aggregates and one with a mix of reactive and non-reactive aggregates. With respect to the compressive strength, a reduction in strength was observed in specimens with reactive aggregates. The reduction varied between 7.5% and 12.4% at 28 days, and 12.7% and 59.4% after one year (depending on the amount of reactive aggregates). On average the strength reduction was 22.5%. Clark[31] and Clayton et al.[32] found similar reductions of about 25% and 23.8%. In a few cases the compressive strength increased after the initial decrease, but did not reach the strength of the reference concrete. This can be attributed to the continued hydration and filling of the cracks with ASR-gel. The recorded drops in tensile strengths were higher than the reductions in compressive strength. After one year reductions of up to 60.0% in tensile splitting strength and 86.0% in flexural strength were reported. The reduction in direct tensile strength was 48.8% after 3 months and increased to 82.1% after one year. The reductions in modulus of elasticity were as high as 95.3%.

For reactive aggregate concrete, Giacco et al.[33] report almost no strength increase over time and a significant reduction in modulus of elasticity and Poisson’s ratio. For concrete with a less reactive coarse aggregate, a strength increase was detected but the strength gain was at a slower pace than the reference mixture (without reactive aggregates) resulting in lower compressive strength results at all ages. The elastic properties of concrete with reactive aggregates are also highly affected.

Huang et al.[34] studied the influence of hydrochloric acid and state that H-Cl corrosion leads to a flexural and compressive strength loss and affects the elastic modulus. By testing 360-days old specimens, that have been submersed in an H-Cl solution for 24h prior to testing, a clear influence of the H-Cl concentration and concrete strength grade on the strength degradation was measured. Higher initial concrete strength lead to higher strength reductions due to acid attack. A reduction of approx. 16% in flexural strength was noticed for C25 after submersion in a 20% H-Cl solution, while the reduction was as much as 35% for C55 concrete. Reductions in the dynamic modulus of elasticity varied between 15% and 40%.

Other processes such as thaumasite formation, sulphates, freeze-thaw damage, etc. also have a significant influence on the mechanical properties of half-joint structures and reinforced concrete in general. These deterioration mechanisms are either rare in a UK environment, are rather uncommon in bridge environments or are deterioration mechanisms that were initiated by an impropriate design of the concrete composition. Therefore these processes will not be considered further in this paper.

INDIRECT DETERIORATION PROCESSES

Indirect deterioration processes are mechanisms that do not directly have an impact on the concrete properties. However they attack components within the concrete which eventually will lead to the deterioration of the concrete itself. The most common type of indirect deterioration is reinforcement corrosion.

Corrosion of the Reinforcement Bars

Bond between reinforcement and concrete is essential in the force transfer between the two materials and the composite action of a reinforced concrete element[35]. In design this force transfer is often simplified as a shear stress over the surface of the bar. Initially, the bond strength comes from weak chemical bonds between the reinforcing bars and the surrounding concrete. This resistance is broken down at very low stress levels after which a small slip is noted and the bond transfer is provided by friction (plain rebars) and through mechanical interlock between the ribs of the rebar and the surrounding concrete (ribbed bars). However, corrosion can influence the force transfer to a great extent.

Most research into the corrosion of reinforcement in concrete is aimed at the causes and mechanisms of corrosion, and the durability of repair materials. Much less attention is given to the residual strength of deteriorated structures, although this is a major concern for those responsible for the assessment and maintenance of half-joints[35]. This paper focusses on the available information on the changes in bond characteristics induced by corrosion and the consequences of that reduction on the residual loading capacity of RC elements. Further details about other aspects related to bond can be found elsewhere e.g. [36].

In freshly cast concrete, the alkaline environment created by the hydrating cement results in the formation of a passivating layer on the surface of the reinforcing bar. This passivating layer (a stable oxide layer) prevents the rebar from corroding and is formed due to the large amount of calcium hydroxide resulting in a pH of about 12.5[14]. However, over time, this layer can be broken down due to environmental influences. The most common processes leading to depassivation are[35]:

- ***Carbonation***
  The reaction of carbon dioxide in the environment with calcium hydroxide in the cement paste. This reaction produces calcium carbonate and lowers the pH to about 9. At this value the protective oxide layer breaks down and corrosion of the reinforcing bar becomes possible[14].

- ***Penetration of chlorides***
  Chlorides do not reduce the background pH, but inhibit the mechanism by which the protective oxide layer is maintained[14].

- ***Sulphide ion attack***
  This type of corrosion is less common and mostly found in sewers, tanks and equipment treating waste water that contains dissolved sulphide. The biological activity of the anaerobic bacteria results in the formation of sulphide which is released to the atmosphere as hydrogen sulphide acid. The acid attacks unprotected surfaces of iron, steel and copper[37].

- ***Stray DC electrical currents***
  The origin of stray currents can be natural (e.g. variation in the earth's magnetic field) or man-made from extra-high-voltage power lines, DC tram or railway systems or adjoining cathodic protection systems. The corrosion in this case is initiated by the flow of external current from the environment[38].

Depassivation does not automatically lead to corrosion of the reinforcing bars. In addition to a depassivated environment, oxygen and water (moisture) have to be available to initiate the corrosion process. The ferrous hydroxide $Fe(OH)_2$ formed during the corrosion reaction has a volume which is about 3.5 times the volume of the original Fe molecule, leading to severe problems when reinforcement is embedded in concrete. Corrosion affects bond in several ways[35]:

- An increase in bar diameter due to the expansive nature of the corrosion reaction initially increases the frictional component of bond. Over time, due to the formation of further corrosion products, the radial stresses increase and induce longitudinal cracking in the concrete which leads to a reduction in the resistance to the hoop forces generated by bond action.
- The friction at the interface of the rebar and concrete is affected by the corrosion products. These products provide a weak and friable material layer which will partially reduce the bond strength.
- The ribs of the rebars may be reduced in height due to corrosion. This effect is insignificant at early stages but can become more significant at advanced stages of the corrosion process.
- The layer of corrosion products formed by oxidation of the steel may force the concrete away from the bar. The effective bearing area of the ribs is reduced.

Fib bulletin 10 summarizes these schematically in a flow diagram (Figure 4).

In many research projects the corrosion process is accelerated. Bond tests are often performed on bars which were corroded by exposure to a chloride salt solution and acceleration by electrical polarisation. In this technique a positive electrical potential is applied to the bars to make the reinforcement anodic and encourage dissolution of Fe^{2+}-ions. During the tests, the specimens are submersed in or sprayed with a salt solution. Submersion of the specimens restricts the availability of oxygen which influences the corrosion process and the expansive force development. In this way unrepresentative test results can be obtained when compared to field conditions where wetting and drying cycles are recorded.

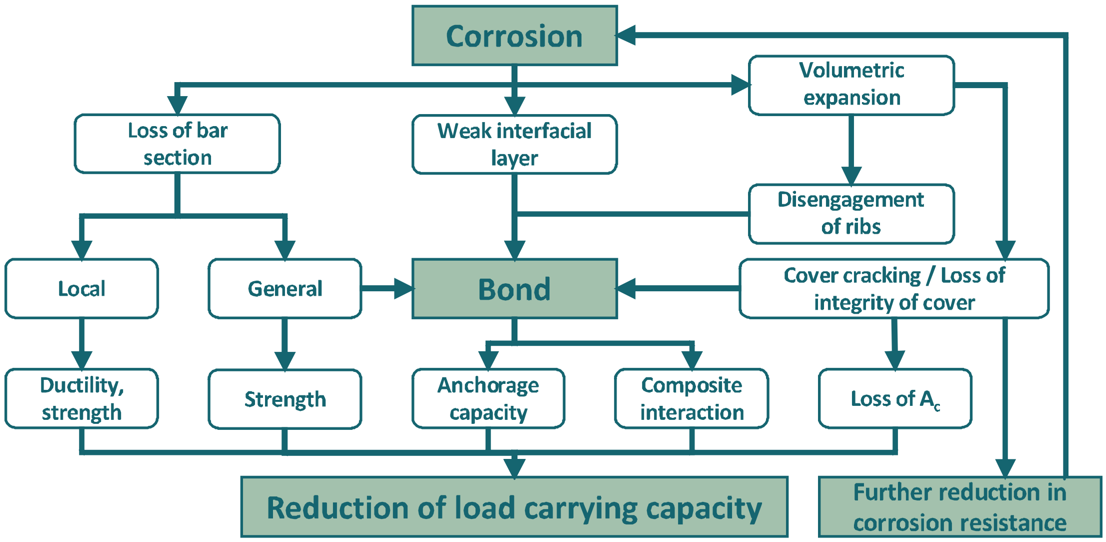

Figure 4: Effects of corrosion on the residual load carrying capacity (based on [6])

As soon as the concrete cracks (due to the expansive nature of the corrosion products formed), the bond strength reduces significantly. This reduction can be higher than 50%. Fib bulletin 10 on Bond in Concrete[35] summarises results by researchers all over the world. The measured bond strengths vary significantly and values between 0% (complete loss of bond) and 110% (a small gain in bond strength) have been observed. Any strength gain is mostly noticed at very low levels of corrosion where the corrosion products have not yet induced cracking, and provide a kind of extra confinement to the rebar by filling the gaps between the ribs and the surrounding concrete (e.g. gaps due to entrapped air underneath the ribs of the bar caused during vibration).

No clear pattern of the key parameters that influence the strength loss due to corrosion emerges from these studies, however, in most cases the reduction in bond strength exceeds the reduction in tensile strength of the rebar due to a loss of section. This means that it is much more likely the bar will lose its bond to the surrounding concrete before reaching the yield strength of the steel.

Based on a statistical analysis of gathered test results, fib bulletin 10 proposes an empirical expression for the characteristic bond strength f_b as a function of the bar radius reduction x (in mm) and the ratio ρ_{tr} of the transverse reinforcement area at the anchorage length (taking into account the reduction in diameter of these bars due to corrosion) to the area of the longitudinal reinforcement:

- In cases, where $\rho_{tr} > 0.25$

$$f_b = 4.75 - 4.64x \tag{1}$$

- In cases, where $\rho_{tr} < 0.25$

$$f_b = 10.04 + \left(-6.62 + 1.98\left(\rho_{tr}/0.25\right)\right)\left(1.14 + x\right) \tag{2}$$

These equations are only applicable to situations where cracking due to corrosion has occurred since the initial gain in bond strength at very low levels of corrosion is not reflected in the expressions.

External pressure significantly enhances the bond. In anchorage zones above supports this external pressure provides a confinement to the bars, in the case of a half-joint similar pressures would exist at the bearing pads. During assessments and loading tests, on elements before demolishment, it is noted that the rebars in these zones still have some anchorage capacity even though the stirrups can show significant corrosion or can be completely broken. Based on tests performed on beams designed to fail at the anchorage zone, the following expression has been derived for the characteristic residual bond strength f_b in anchorage zones with an external pressure p (in MPa).

$$f_b = \frac{(4.75 - 4.64x)}{(1 - 0.08p)} \tag{3}$$

This expression has been found to be independent of the amount of stirrups and the level of stirrup corrosion[35].

Equations 1 to 3 are derived from a rather limited set of data and are purely empirical. A better understanding of the mechanism(s) through which bond is affected by corrosion is necessary to develop more effective models and reliable assessments. Furthermore most test data relates to ribbed bars while in practice a lot of older bridges are constructed with smooth plain rebars. The aim of a test programme currently being conducted by the authors is to provide more information on these aspects and will lead to clearer guidance on the assessment of half-joints with corroded rebars.

CONCLUSIONS

A half-joint is a particular type of RC structure that has a number of advantages. However, major disadvantages are potential of leakage through the joint and the lack of access for inspection. Loss of part of the rebar section through corrosion can induce higher stresses in certain regions of the structural member and reduce the safety margins.

The assessment of existing structures is not straight forward as there are no clear guidelines or methods to consider the full impact of deterioration. Deterioration processes can act in a direct (e.g. carbonation and chloride ingress) or indirect way (e.g. reinforcement corrosion) to alter the mechanical and structural behaviour of the half-joint.

Based on research performed to quantify the effect of deterioration processes, the following conclusions can be drawn:

- *Carbonation:*
  The direct effect of carbonation is an increase in strength of the concrete of up to 50%. However it should be emphasised that corrosion induced by carbonation can lead to severe cracking causing a significant strength loss. If a beneficial concrete strength increase due to carbonation is taken into account it should be done with care and only in regions where there is no corrosion.

- *Chloride ingress:*
  The effect of chloride ingress on the mechanical properties of concrete is limited. As is the case for carbonation, chloride ingress can cause severe reinforcement corrosion which leads to a reduction in the loading capacity. However the presence of chlorides in the concrete as such does not influence concrete strength and elasticity to a significant level for common levels of chloride content.

- *Cracking:*
  The extent of cracking can be significantly different from one structure to another. Most cracking observed during assessments are non-structural cracks which will not lead to significant reductions in the load capacity. However, they may enhance durability processes which will cause problems over time. Cracks should be taken into consideration when performing assessments of half-joint structures, especially if they occur at critical sections. The extent to which they influence the load capacity, however, will very largely with the case specific crack pattern.

- *Corrosion:*
  Corrosion can cause significant reductions in the load bearing capacity of reinforced concrete half-joints. In addition the formation of a weak interface zone between the reinforcing bar and the concrete, and a reduction in the bar diameter, the expansive nature of the corrosion process induces cracking. These cracks can be as significant as a loss of parts of the concrete cross section. Specific guidance is available in terms of the reduction of bond strength due to corrosion. However more research in this area is needed (e.g. the bond reduction in cases of severe cracking and spalling, bond of smooth corroded bars, etc.) to provide proper guidance on how to take corrosion into account during the assessment of reinforced concrete half-joints.

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