Galvanized Steel Reinforcement in Concrete: An Overview

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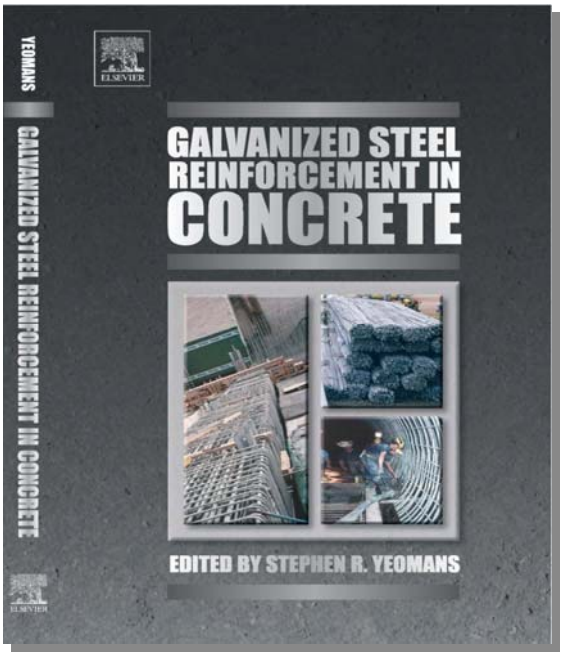
Editorial Note

This paper presents an overview of the characteristics and use of galvanized reinforcement in concrete construction. It is provided to supplement the presentations in the Workshop – ***More Durable Concrete Structures using Hot Dip Galvanized Reinforcing Steel*** supported by the International Zinc Association, the United Nations Common Fund for Commodities and the International Lead Zinc Study Group.

The information presented here is extracted from the recently published book ***Galvanized Steel Reinforcement in Concrete***, SR Yeomans (Editor), Elsevier, 2004. In preparing this overview, it was decided not to provide extensive referencing other than to individual chapters in the book. Rather, this paper is a summary of key aspects of the science and technology, and engineering, surrounding the use of galvanized reinforcement in reinforced concrete construction. Readers should refer to the book for extended detail of the topics considered in brief here and also for full referencing.



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1. Introduction

The long-term performance of reinforced concrete is usually assessed against two main criteria, serviceability and durability. Serviceability relates to structural integrity, the ability of the element to sustain loads throughout its life and perform its intended function. Durability refers to the ability of the concrete to resist changes in its microstructure and properties, particularly where such changes may adversely affect the serviceability of the element. Perhaps the most obvious consequence of a lack of durability in reinforced concrete is the corrosion of the reinforcement steel.

Steel embedded in concrete is protected from corrosion due to the passivation of the surface of the metal. This protective film forms in the highly alkaline environment of hydrated cement (> pH 12.5), and the steel will not corrode so long as the passive film remains in tact. For long-term corrosion protection, the concrete mass must limit the transport of species such as water, chloride ions, oxygen, carbon dioxide and other gases through the concrete to the depth of the reinforcement. The presence of threshold levels of these species, usually carried into the concrete in solution in water, either changes the nature of the concrete or alters the condition of the embedded steel. In either case, corrosion of the steel can then initiate.

Chloride ions present in concentrations above the threshold level depassivates the steel even if the pH of the adjacent concrete remains high. On the other hand, carbon dioxide and other gases in aqueous solution react with the alkali-rich pore water and lower the pH of concrete below the minimum passivation level. This process, known as carbonation, specifically refers to the neutralization of the lime-rich pore solution by the slightly acidic gases dissolved in water. The availability of oxygen for cathodic reduction is also an essential component of the corrosion process.

Should corrosion of the reinforcement occur significant damage to the concrete mass soon follows, as shown schematically in Figure 1. The corrosion products formed are expansive (2-10 times larger) and precipitate at the bar-concrete interface. This causes a swelling pressure of sufficient magnitude (3-4 MPa) to crack the concrete in tension, the cracks usually running from the bar to the nearest outer surface. Once cracking has occurred, rust staining of the surface usually follows with subsequent delamination of the mass or spalling of pieces of concrete from the surface. By this stage, the structure would be seriously distressed, and repair would be necessary to extend its life.

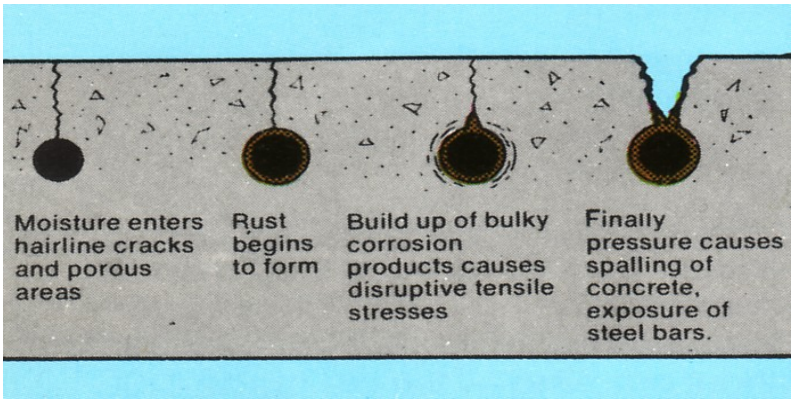


Figure 1. The progress of corrosion-induced damage in concrete.

Worldwide, the costs associated with such remedial work are massive and are expected to increase in the future at an alarming rate. Estimates of these costs vary widely. For example, as early as 1977 in the USA, the cost of major repair and replacement of damaged bridge decks was about $US23b. By the late 1980s, the UK Department of Transport estimated repair costs of some £616m for motorway bridges in England and Wales. Over the same period in the USA, annual costs associated with bridge deck repairs due to deicing salts alone was in the range $US50-200m, plus an additional $US100m for substructures and $US50-100m on multi-level parking garages.

2. Corrosion Prevention in Reinforced Concrete (refer Chapter 1)

The most cost effective way to minimize the risk of corrosion in reinforced concrete is to ensure that the cover to the reinforcement is of adequate thickness and that the concrete itself is dense and impermeable. The primary function of the concrete cover is to protect the reinforcing steel and it can only do so if the structure and the mix has been properly designed and appropriate materials chosen to suit the expected exposure conditions, the reinforcement has been accurately located in the formwork so as to achieve the required cover, and the mix has been well placed, compacted and cured.

Despite this knowledge, it is unfortunate that the deterioration of concrete due to corrosion is not uncommon. This may be the result of poor design or the use of concrete of inadequate quality in aggressive conditions. Equally however, it may be due to simple deficiencies in the concrete such as insufficient cover to the reinforcement, porosity and cracking as a result of poor site practices (workmanship) in placing concrete even in mild-to-medium exposure conditions.

To mitigate these effects, a number of approaches are available including:

- the use of membrane-type coatings applied to the surface of concrete;
- the impregnation of concrete with materials intended to reduce its permeability;
- the addition of corrosion inhibitors to concrete;
- the use of corrosion resisting reinforcement;
- cathodic protection of the reinforcement; and/or
- the application of coatings to the reinforcement itself.

Over a considerable period of time, the coating of the reinforcement has been widely accepted as an economical and convenient means of corrosion protection beyond that afforded by the cover concrete in many types of concrete construction. The coating material, which may be metallic or non-metallic, or perhaps a combination of both (i.e. duplex coatings), provides barrier-type protection to the steel by isolating it from the local environment. Some examples include organic coatings such as paints and fusion bonded powders, and noble metal coatings on steel such as tin, chromium, copper and stainless steel. On the other hand, active metal coatings on steel such as zinc, cadmium and aluminium, provide not only simple barrier protection but also additional cathodic protection in that the coating acts as a sacrificial anode in the event that the underlying steel is exposed. Of all the coating systems available, the two most common are hot dip galvanizing (HDG) and fusion bond epoxy coatings (FBECR).

As a general principle, if coated reinforcement is chosen as a corrosion protection system this should not be at the expense of using the best quality concrete available and appropriate to the intended application. If this is achieved, and providing due care is taken in the specification of the concrete materials and the mix design as well as attention to good workmanship and supervision of the concreting practice, the coating of reinforcement offers a number of advantages over black steel including:

- an increased time to the initiation of corrosion of the steel and a reduced risk of cracking, rust staining and spalling of the concrete;
- an increase in the service life of the concrete structure or component;
- a reduction in the frequency and extent of repairs to the concrete;
- greater tolerance of both the natural variability of the concrete and the presence of inferior quality or poorly placed concrete; and
- corrosion protection of the steel prior to it being embedded in concrete.

For metal coated reinforcement, hot dip galvanized (i.e. zinc-coated) bar is by far the most common. Its first regular use was in the 1930s in the USA. Since this time, and especially over about the last 25-30 years, its use in a wide variety of types of concrete construction and exposure conditions in many countries has been widely documented. In support of this there is also a published record of very large body of laboratory-based research and field studies of the characteristics and performance of zinc-coated steel products in concrete construction, some more than 30 years old Acceptance of the use of galvanized reinforcement is also reflected in the number of national and international standards for the use of zinc coated (i.e. galvanized) reinforcement published in recent years, and the existence of many Codes and Specifications relating to galvanized reinforcement published by Federal/State bodies, especially in North America.

3. Galvanizing of Reinforcing Steel (refer Chapter 4)

Zinc can be applied to the surface of steel in a variety of ways but for structural steelwork (generally >5 mm thick) hot dipping is the preferred and most widely used method. This involves immersing cleaned steel in a bath of molten zinc at about 470°C during which a metallurgical reaction occurs between the steel and the zinc. The layout of a typical hot dip galvanizing facility is shown in Figure 2.

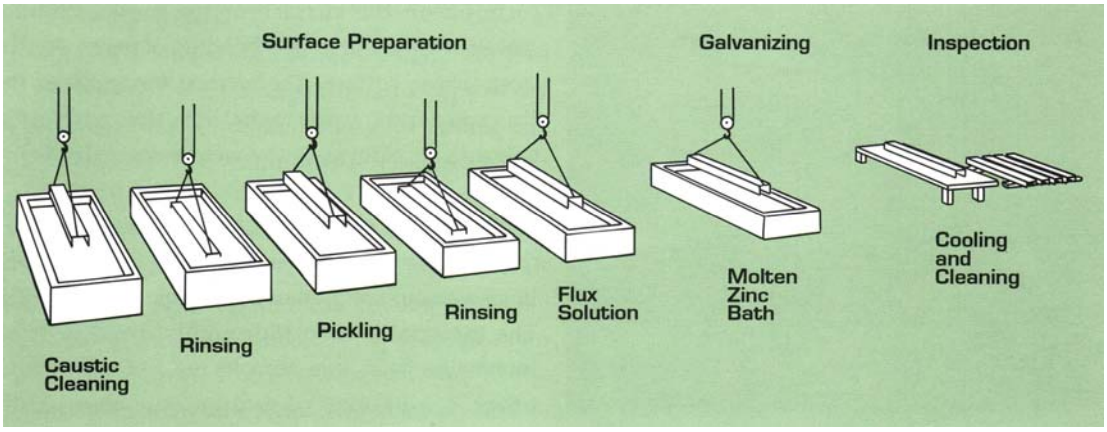


Figure 2. Schematic of hot-dip galvanizing process.

3.1 Coating morphology

The reaction between steel and molten zinc produces a coating on the steel made up of a series of iron-zinc alloy layers (gamma, delta and zeta) which grow from the steel/zinc interface with a layer of essentially pure zinc (eta) at the outer surface. What distinguishes galvanizing from other types of coatings is that the coating is metallurgically bonded to the steel; it actually becomes an integral part of the steel, in stark contrast to the situation with paints and epoxy coatings which simply attach to the steel surface by physical bonding. The alloy layers in the coating are harder than the base steel resulting in a coating that is not only firmly adhered to the steel but is tough and hard and can resist abrasion and fairly heavy handling. It also allows the galvanized article to be handled, transported and fabricated in much the same way as ordinary steel. A typical (so-called bright) galvanized coating structure is shown in Figure 3.

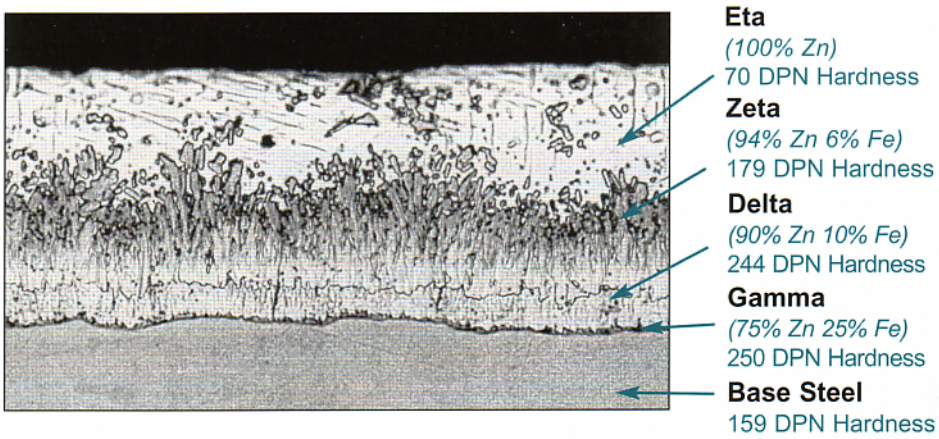


Figure 3. Photomicrograph of hot-dip galvanized coating showing detail of the alloy layers and their hardness

A unique feature of galvanizing, since it is a total immersion process, is that all areas of the product are coated including those that are hidden or hard to reach such as recesses and internal surfaces. Galvanizing also naturally produces coatings that are at least as thick at corners and edges, and sometimes thicker, as on other parts of the product, as shown in Figure 4.

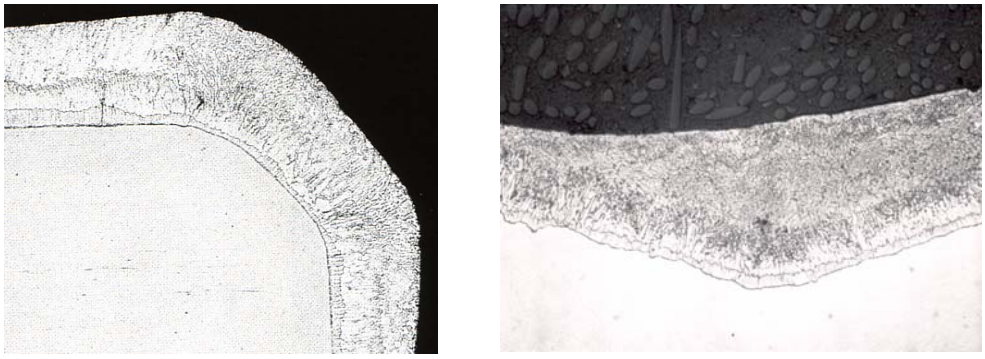


Figure 4. Corner protection and extra coating thickness at recesses in hot-dip galvanized coatings.

Due to the vectorial nature of the growth of the alloys, the coating does not thin out on edges and corners as do paint or spray applied coatings. Since coating damage is most likely to occur at these regions during handling, transportation and fabrication, the extra thickness affords additional protection where it is most needed.

Galvanized coatings do not necessarily contain all of the alloy layers shown above. Depending on the steel chemistry and the processing conditions, the coating may contain only one or two of the layers. For example, the microstructure of the coating on silicon-containing steel shown in Figure 5 consists almost entirely of enlarged zeta crystals, due to the reactive nature of the steel. Also, the zeta crystals have grown to the surface of the coating and have consumed the outer pure zinc layer. This coating would have a dull gray surface appearance. The effect of the silicon content of the steel on the thickness of the galvanized coating, known as the Sandelin Effect, is shown in Figure 6.

Similarly, when galvanized steels are heated (annealed) above about 430-450°C, the growth of the zeta phase is accelerated which can result in the complete disappearance of the eta layer at the surface. This effect is utilized in the manufacture of galvannealed products where improved painting, weldability and forming of steel sheet and strip products are obtained by converting the coating fully to an iron-zinc alloy. Although galvanized coatings may have a variety of microstructures, essentially no change occurs in the corrosion resistance of the coating. As previously noted, the extent of corrosion protection is a function of coating thickness, not coating structure. As such, the service life of bright, shiny coatings is similar to those with a dull gray appearance.

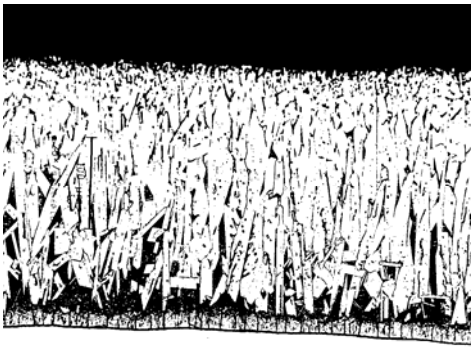


Figure 5. Galvanized coating on silicon-containing (reactive) steel.

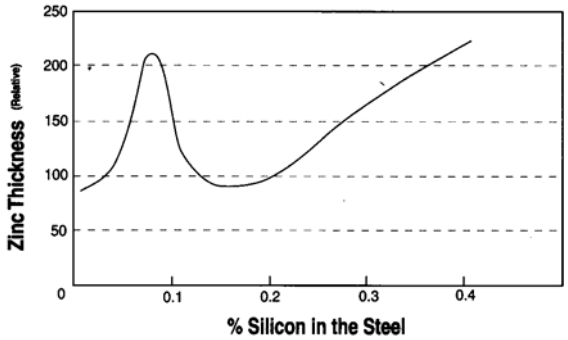


Figure 6. Effect of silicon content of steel on zinc coating thickness.

3.2 Service life

The anticipated service life of zinc coatings of varying thickness in a variety of atmospheric exposure conditions is shown in Figure 7. It is to be noted that this data, relating to conditions where the surface is fully exposed, shows that the corrosion rate of zinc tends to be quite linear over time. This is due to the fact that corrosion of the coating in the atmosphere is usually generalized and the coating can be refreshed by water action to remove the corrosion products. It is not expected that galvanized steel in concrete will behave in the same way since corrosion in the somewhat 'fixed' environment of concrete is more localized and the corrosion products so formed are restricted in their movement away from the surface, so tending to stifle the process.

The service life reported in Figure 7 also relates to the time to 5% rusting over the entire surface, not the time for complete removal of the whole coating mass. Note that 1mil = 25.4 microns coating thickness equivalent to a coating mass of 0.58 oz/ft^2 or approximately 182 g/m^2.

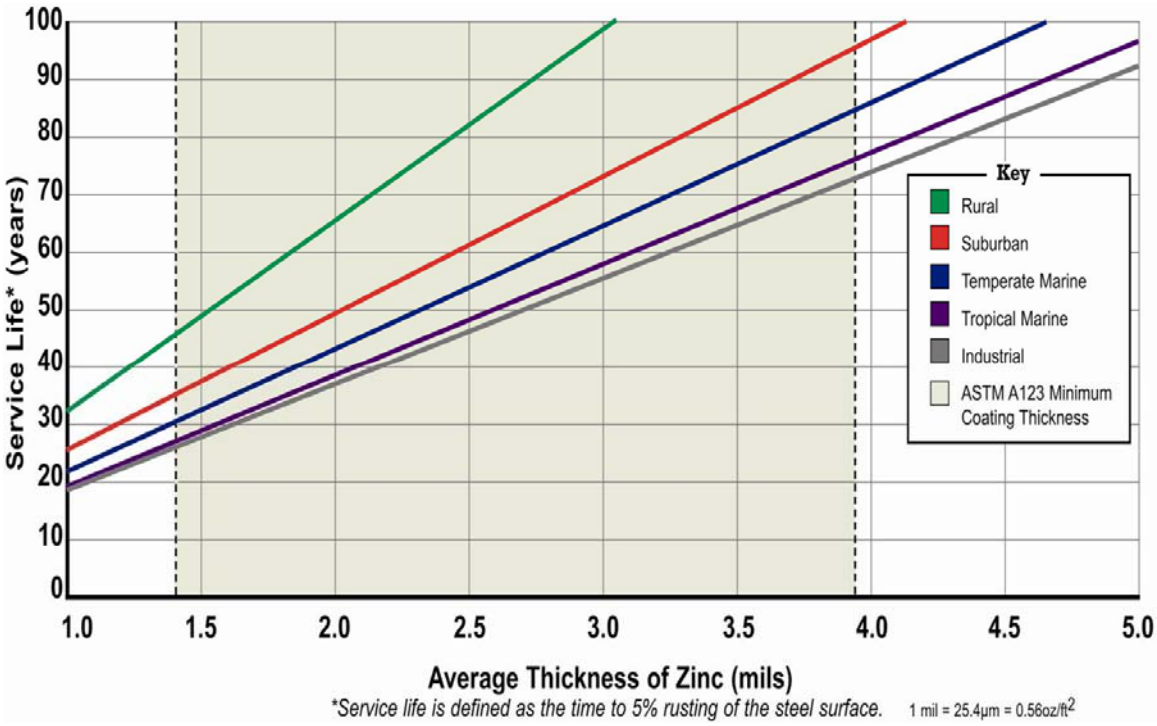


Figure 7. Service life chart for hot-dip galvanized coatings.

3.3 Fabrication of Galvanized Products

The fabrication of reinforcing bar and other components (stirrups, ties, etc) should ideally be done prior to galvanizing. Post-fabrication galvanizing provides coating protection to all edges and joints and takes full advantage of the corrosion protection afforded by the zinc coating. It also avoids unnecessary damage to the coating and minimizes the exposure of unprotected edges. Though damage to the coating can be repaired by applying zinc-rich paints or zinc solders, the repair is never as good as the original coating, nor will it last as long. There are, of course, many situations in which galvanized reinforcing products need to be fabricated in the field. In these situations, some damage to the coating must be expected but with due care the severity of this damage can be reduced.

When processing reinforcing bar, it is generally most convenient and economical to galvanize straight lengths of reinforcing bar with all fabrication being done after galvanizing. During fabrication of galvanized bar, the tendency for cracking and flaking of the galvanized coating in the area of the bend increases with bar diameter and severity and rate of bend. Damage to the coating can be minimized by using large bend diameters and appropriately sized mandrels and formers. On the whole, the methods used for the handling, fabrication and transportation of galvanized reinforcement are

similar to those used for traditional steel reinforcement and no special requirements or techniques need be considered.

As an alternative to fabricating straight bars after galvanizing, prefabricated bars bent to special configurations or complete cage sections (e.g., spiral column reinforcement or formed mesh) can be galvanized. This offers the distinct advantage that little or no damage to the coating will occur as may be the case with normal fabrication practices. Examples of a variety of steel products commonly used in reinforced concrete construction are shown in Figure 8.

Figure 8. A variety of galvanized steel products for use in concrete.

3.3.1 Bending galvanized steel

Products that have been (batch) galvanized exhibit different bending characteristics than sheet galvanized products mainly due to differences in the coating thickness and the coating structure on each product. Sheet galvanized products have a much thinner coating than batch galvanized products, and the coating is either entirely pure zinc or totally alloyed as in galvannealed coatings. Both these types of coating have excellent bending properties; the pure zinc coating stretches during forming operations, while galvannealed coatings develop small cracks to relieve the bending stresses.

As previously indicated, the coating structure on batch galvanized products such as reinforcement is typically a combination of alloy layers and pure zinc. During bending,

the outer pure zinc layer is stretched, while the alloy layers relieve the stresses generated by cracking. Flaking of the coating can occur if the bending is too severe and, as a general rule, products that have an excessively thick coating (> 250 microns) should not be bent.

Bending prior to galvanizing

Good fabrication practices state that when bending steel bar prior to galvanizing, a minimum 3d bend diameter should be used, where d is the bar diameter. Bending to this size minimizes the damaging effects of cold working of the microstructure of the steel that could result in strain age embrittlement during galvanizing. Hot rolled bar with a yield stress of about 250 MPa, or higher strength reinforcing bar (400-500 MPa) strengthened by either quench and temper processing or micro-alloying and a small amount of cold working, and which is bent prior to galvanizing, remains ductile after bending thereby allowing limited straightening and re-bending.

Bending prior to galvanizing will result in a superior product since damage to the coating due to cutting and forming operations is totally avoided. This also applies to the galvanizing of pre-fabricated and welded reinforcing elements such as column reinforcement and pre-cast panel reinforcement. For practical reasons, bending is normally undertaken after galvanizing. The transportation and processing of bundles of straight bars is easier and more economical, and is preferred by most galvanizers. Special handling of bent pieces (stirrups, ties, hooks etc) is not required.

Bending after galvanizing

For practical reasons, bending is normally undertaken after galvanizing. The transportation and processing of bundles of straight bars is easier and more economical, and is preferred by most galvanizers. Special handling of bent pieces (stirrups, ties, hooks etc) that may involve unbundling, tagging and rebundling, is not required. Pre-bent pieces cannot thus be misplaced during handling and storage, and scheduling delays are reduced.

Although the bendability of most galvanized bar is only marginally altered from that of uncoated bar, to minimize cracking of the galvanized coating the following minimum bend diameters (for 90° bends) are generally recommended:

- up to 16 mm bar diameter - 5d bend; and
- greater than 16 mm bar diameter - 8d bend.

Any forming operation, including bending, may cause some cracking and flaking of the galvanized coating. This is particularly so if bend diameters less than the recommended minima are used, and if re-bending or straightening of bent bars is required. Any damage to the coating should be repaired as recommended in most galvanizing standards. The use of heat for bending or re-bending galvanized reinforcing bar should be avoided due to the possibility of the zinc coating causing liquid metal embrittlement.

3.3.2 Welding of galvanized steel

Galvanized reinforcement (as with other galvanized products) may be satisfactorily welded by all common welding techniques. Though welding can be accomplished by welding through the galvanized coating, the preferred method is to remove the zinc coating in the region of the weld, generally by grinding or grit blasting, and directly weld the exposed base metal. In general, anything that can be welded before galvanizing can be welded after galvanizing, though some minor changes to the welding technique need to be incorporated to insure full weld penetration. These changes are primarily intended to allow the galvanized coating to burn off at the front of the weld pool. In areas where the coating has been removed to facilitate welding, and where the heat of welding has damaged the remaining coating, repairs should also be undertaken.

3.3.3 Repair of galvanized coatings

Galvanized coatings that have been damaged during fabrication or welding can be repaired in a number of ways as described below (refer also ASTM A780):

Zinc-based solders
Common solder (zinc-tin-lead, zinc-cadmium, zinc-tin-copper alloys) is applied in stick or powder form to a prepared and preheated surface. Surface preparation can be by wire brushing, light grinding or mild blast cleaning and the surface must be free of grease and solid matter. A paste or liquid flux is applied as the surface is heated (generally by gas flame) to about 300°C. Caution must be taken while heating to prevent oxidising the exposed steel or damaging the surrounding galvanized coating. The molten solder is spread with a knife or spatula; then wiped clean. Solders are not suited to the touch-up of large areas, and the resultant coating is inherently quite thin.

Zinc-rich paint
The use of a zinc-rich paint (either organic or inorganic) is the most rapid and convenient means of repair (see Figure 9). Zinc dust paints contain between 65-69% zinc by weight or greater than 92% metallic zinc in the dry film. Inorganic paints are particularly useful for repair and touch-up that may spread over undamaged galvanized areas. The paint is applied by brush or spray over a surface that has been prepared to a near-white finish. Thorough surface preparation is important for good adhesion. A total film thickness of 100 µm is usually specified for optimum performance and thickness measurements are taken to ensure that the required coating is applied.

Figure 9. Showing touch-up repair of the cut ends of galvanized rebar using an inorganic zinc-rich paint.

Zinc metallizing
Sprayed zinc (or metallizing) should be applied to a surface that has been cleaned to a white metal finish. The zinc used, in the form of zinc wire or zinc powder, is normally 99.5% pure though zinc-aluminium alloys can also be used. The sprayed coating should be applied as soon as possible after surface preparation (certainly within four hours) and before visible deterioration of the surface has occurred. Adhesion of the zinc spray to the base metal is by mechanical means and is dependent on the quality of the surface preparation and extent of cleaning. The coating is normally applied to a thickness equivalent to that of the undamaged coating and measurements should be taken to ensure the required coating has been applied.

3.4 Galvanizing Standards

The regulation of the hot dip galvanizing of steel reinforcing bars is handled in different ways around the world. Some countries treat steel reinforcing bars in the same way as any another steel products and so the hot dip galvanizing of reinforcement falls under a general galvanizing standard. In others, dedicated Standards relating solely to reinforcing steel have been published. A summary is in Table 1.

Table 1. Standards for hot dip galvanizing of reinforcing bar.

	Designation	Title
General Galvanizing Standards		
Australia / New Zealand	AS/NZS 4680	After-Fabrication Hot Dip Galvanizing
Canada	CAN/CSA G164	Hot dip galvanizing of irregularly shaped articles
South Africa	SABS/ISO 1461	Hot dip galvanized coatings on fabricated iron and steel articles
Sweden	SS-EN ISO 1461	Hot dip galvanized coatings on fabricated iron and steel articles
United Kingdom	BS EN ISO1461	Hot dip galvanized coatings on fabricated iron and steel articles
International Standards Organization	ISO 1461	Hot dip galvanized coatings on fabricated iron and steel articles
Reinforcing Steel Standards		
United States	ASTM A767	Zinc-coated (galvanized) steel bars for concrete reinforcement
United Kingdom	BS ISO 14657	Zinc coated steel for the reinforcement of concrete
France	NF A35-025	Hot-dip galvanized bars and coils for reinforced concrete
Italy	UNI 10622	Zinc-coated (galvanized) steel bars and wire rods for concrete reinforcement
India	IS 12594	Hot-dip coatings on structural steel bars for concrete reinforcement specifications
International Standards Organization	ISO 14657	Zinc-coated steel for the reinforcement of concrete

In all these general galvanizing standards an average minimum thickness (or mass) of the coating is specified depending on the type and thickness of the base material. For structural sections heavier than 5-6 mm thick, which would include reinforcement and most other reinforcing products, a minimum average coating thickness in the range 600-

610 g/m^2 is specified, which equates to a coating thickness of 85-87 µm. Similar requirements are in ISO 14657 for bar greater than 6 mm in diameter.

3.5 Field Handling Techniques

As a general guide, galvanized reinforcement can generally be transported and handled in the same way using the same methods as are used for conventional black steel. It also does not require any special precautions to protect the coating against superficial damage during transport and field handling. In Table 2, a summary is given of field handling techniques that may be used with galvanized reinforcement. While not meant to be fully inclusive, it is presented as an industry guide to best practice (refer American Galvanizers Association). Other issues in field handling may arise from time-to time and these should be assessed in light of these broad recommendations.

Table 2. Summary of field handling techniques.

Operation	Recommendation
Material receipt and inspection	• visually inspect for damage, and • check for secure tie-downs on transport.
Unloading and job site handling	• no special handling or care necessary, • lift bundles at multiple pick-up points, or • use a spreader bar with additional nylon straps to prevent sag and bar-to-bar abrasion in longer bundles.
Storage	• block material and store on a slant to allow for water drainage and air flow.
Placement	• no special care necessary.
Bar supports and tie wire	• bar supports, spacers and reinforcement supports should all be hot-dip galvanized, • 16.5 gauge or heavier galvanized tie wire should be used, or • other acceptable materials for these parts are plastic or non-conductive coated steel.
Splicing and coupling details	• a bar-lock coupler is recommended, either galvanized or stainless, • for welded splices all welds must be touched up as recommended, and • use appropriate protective masks and suitable ventilation when welding.
Field cutting	• field cutting should be avoided, and • repair of cut ends shall be done using touch-up procedures (refer ASTM A780).
Final inspection and repair	• touch-up of cut and burned ends should be done following recommended procedures (refer ASTM A780).
Concrete pour	• no special handling or care necessary.

4. Design of Galvanized Reinforced Concrete (refer Chapter 2)

Experience over many decades of successful use has demonstrated that the design and construction of galvanized reinforced concrete is, to all extents and purposes, essentially the same as that used for conventional steel reinforced concrete. As noted above, no special precautions need to be taken in the fabrication and handling of galvanized bar,

other than that appropriate bend radii need to be used and touch-up of cut ends and areas of damage to the coating is recommended. Similarly, there are no special requirements for the design of galvanized reinforced concrete above and beyond that which apply to conventional reinforced concrete. In particular, splice and lap lengths are the same as for black steel bar, as are bond and load transfer considerations.

In effect, best practice when utilising galvanized reinforcement is to use appropriately designed and placed concrete as would normally be used in general reinforced concrete construction. There are, of course, some issues that require consideration and a summary of these is given in the following sections.

4.1 Cracking of the galvanized coating

One of the major concerns of engineers in using galvanized bars in reinforced concrete is the cracking of the zinc layer when bending and the consequent loss of adhesion of the coating to the substrate steel. To ally concerns over this, it is to be noted that bend and re-bend tests carried out according to BS449-1988 on galvanized reinforcing bars produced by thermo-mechanical treatment showed that all bars with diameters in the range 8-40 mm diameter performed satisfactorily. Parallel assessment of the adhesion characteristics of these bars indicated that while some cracking of the galvanized layer occurred on all bar diameters, the 40 mm diameter bars showing most cracking, the adhesion rating steadily improved as the bar diameter reduced.

Fracture at tight bends (of the order of 2d) in galvanized high tensile bars has been observed, though noting that it is possible such bars may have cracked prior to dipping. A minimum radius of as little as 3d was found to avoid such failures. Cold worked deformed high tensile bars have generally low ductility – generally around 40-70% of that of a corresponding hot rolled bar. Such bars, and particularly those of large diameter, may crack during bending and care should be taken to avoid this. If cold worked deformed high tensile bars are to be galvanized, precautions need to be taken to avoid the possible risk of hydrogen embrittlement arising from galvanizing operations.

Many bend tests have shown that the extent of cracking and the width of cracks in the zinc coating are influenced by the bend radii, the diameter of the bars, the angle of bend, and the thickness of the coating. In general, the smaller the bend radius, the larger are the cracks; and the thicker the coating the greater the intensity of cracking. Cracking in the coating will invariably occur at right angles to the length of the bar and if the cracking causes local de-bonding between the coating and base steel, the durability of the coating may be compromised. In practice therefore it is safer to galvanize bars after bending, and this should be considered especially where stirrups are concerned.

The corrosion susceptibility of bent galvanized bars with cracked coatings has been investigated over two years in 100% RH. These bars showed no corrosion products at the cracks produced by bending. There was also evidence that zinc oxide corrosion products had blocked the cracks in the coating thereby preventing localised corrosion of the base steel. Companion black steel bars showed considerable local corrosion and loose rust. Experience has demonstrated that the zinc coating has good resistance to abrasion and impact during storage and testing has shown that transportation of

galvanized bars, and normal concreting operations, will not damage the coating. Further, galvanized steels will not corrode when exposed to moist and warm air.

4.2 Mechanical properties of steel bars

Extensive verification testing over many years has demonstrated that galvanizing does not adversely affect the static tensile properties (yield and ultimate strength, and elongation) of typical constructional grade steels providing the steel has not been excessively cold worked, say by bending and re-bending. Such steels include low strength reinforcing bar at about 250 MPa yield strength.

With the introduction of higher strength reinforcing steels, there is some evidence that the early style cold-twisted high strength bars at about 410 MPa, and which had been subsequently bent during fabrication, may be embrittled by galvanizing. This problem was however effectively eliminated by the 1970s with the introduction of thermo-mechanically treated steels and micro-alloyed steels for high strength bars (minimum yield of 400 MPa) as replacements for cold-twisted reinforcing steel. More recently, higher strength reinforcement to 500 MPa yield has been introduced and extensive testing has again verified that the mechanical properties of this material are not adversely affected by galvanizing. A summary is given in Table 3.

Table 3. Summary of reinforcing steel types.

Type of Steel	Considerations for Galvanizing
Low strength grades - 250 MPa yield strength	• no effect on mechanical properties provided the bar has not been excessively cold worked during fabrication.
Cold-twisted steels (Grade 410C) - 410 MPa minimum yield	• double cold-worked material (i.e. to strengthen during manufacture plus fabrication by bending) may be embrittled by galvanizing; and so • requires expensive stress relief heat treatment.
Thermo-mechanically treated or micro-alloyed grades (Grade 410Y) - 410 MPa minimum yield	• can be satisfactorily galvanized without need for any special requirements; and • no significant effect on strength or ductility.
New generation high strength bars (Grade 500N) - 500 MPa minimum yield	• superior mechanical properties are retained after hot-dip galvanizing; and • testing actually showed a slight improvement in yield and ultimate stress and also ductility.

Pure zinc has low fatigue strength, and so the fatigue strength of zinc-coated bars is affected more than their static properties. This may therefore be of some concern for structures designed to withstand earthquake forces, and the possibility of failures of highly stressed bars under such conditions should be taken into consideration in design.

There are only limited results available on the fatigue strength of galvanized bars. Fatigue tests reported in Germany showed that fatigue cracks start in the zinc layer, and that multiple cracking occurs side by side which eventually penetrate the zinc-iron alloy layer and finally continue into the steel. A reduction in fatigue strength of about 15% - from about 290 MPa to 250 MPa - was observed. Tests from Finland, on the other hand, show that the fatigue strength of certain structural steels may be reduced by as

much as 25% as a result of hot-dip galvanizing and that the reduction is independent of the silicon content of steel or the thickness of the zinc layer.

By contrast however, fatigue tests on galvanized bars extracted from cracked reinforced concrete beams subjected to repeated bending in chloride solution over an 18 month period indicated that their fatigue strengths were similar to those of uncoated bars without exposure to the corrosion process. In essence, such testing can be taken to confirm that the fatigue strength of galvanized reinforcement in beams and similar concrete elements remains unaffected by exposure to corrosive environments.

4.3 Bond and slip characteristics (refer Chapter 8)

The bond between concrete and the reinforcement is essential for developing the full capacity of the reinforcement and is the most important property contributing to the successful functioning of a reinforced concrete system. The stresses which develop in the surrounding concrete are complex and are affected by many factors including:

- the strength of the concrete;
- the diameter of the bar;
- the existence (or not) of bar surface deformations (so-called ribs);
- the geometry of the ribs themselves;
- the presence or absence of confining reinforcement;
- the cover to reinforcement; and
- the position of the bars in the member.

The principal single contributor to bond strength is whether the bars are ribbed. If the bars are smooth, the main contributions to bond strength come from the chemical adhesion and the friction resistance occurring between the bar and the concrete. If, however, the bars are ribbed, two additional sources of bond strength become more significant. These are the bearing capacity of the concrete between the lugs and the shear strength of the concrete cylindrical surface located between the lugs.

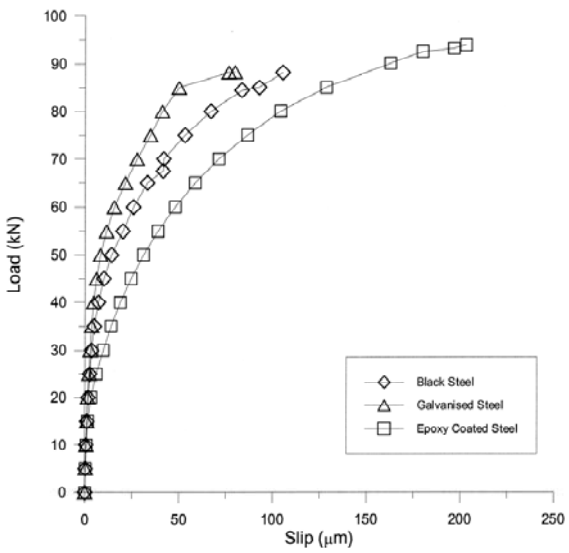
In the use of galvanized reinforcement the principle issues relating to bond and slip behaviour concern whether there is any significant difference in behaviour compared to conventional black steel bars, what is the effect, if any, of the presence of the zinc coating, and are there any special considerations to be taken into account in design.

A significant amount of research has been undertaken addressing this range of issues. Some observations/outcomes from this research are as follows:

- the time to develop full bond strength for galvanized bars may , in some circumstances, be longer than that for black steel though this effect is usually overcome prior to 28 days curing;
- galvanized smooth bars have superior bond strength to equivalent black steel bars, though in some cases not as good as pitted and rusty steel bars, thereby indicating the sensitivity of the bond strength to the roughness of the surface;
- there was no significant difference in the ultimate bond capacity of ribbed black steel or galvanized steel bars; and

- in beam tests, at ultimate load there was no significant difference in the free-end slip of galvanized bars and black bars. At intermediate loads there was a noticeable reduction in slip for galvanized bars compared to black steel bars as shown in Figure 10.

Figure 10. Load-slip data for black, galvanized and epoxy coated ribbed bars.



What is clear is that the bond of galvanized bar is no less than that of equivalent black steel bar; in fact it may be higher than that of black steel. Multiple comparative studies undertaken at the University of California (Figure 11) clearly shows this effect. Despite the clarity of these results there are however a number of questions that do arise when galvanized reinforcement is to be used. These principally relate to the effect that hydrogen evolution, as a result of the reaction between zinc and wet cement, may have on the bond capacity, and the use of chromates to overcome this perceived problem.

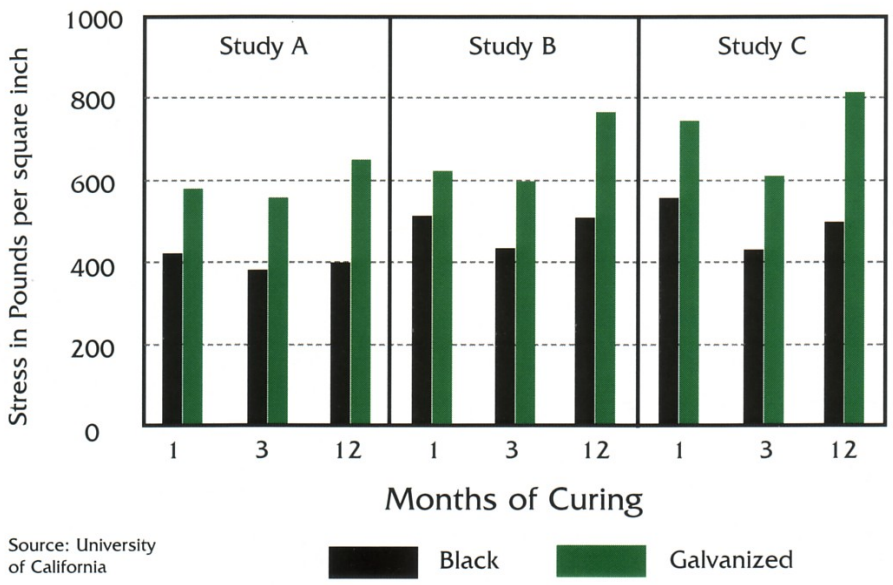


Figure 11. Comparing the bond strength of black and galvanized bars.

4.3.1 The phenomenon of hydrogen evolution

When galvanized steel comes in contact with wet cement (i.e. freshly placed concrete), a chemical reaction occurs resulting in the formation of crystals of calcium hyrdoxyzincate which precipitate on and ultimately passivate the zinc surface. This reaction is accompanied by the evolution of hydrogen gas. As this reaction proceeds, the hydrogen accumulates into small bubbles which slowly move upwards (due to buoyancy effects) and away from the zinc-concrete interface. Because of the short time frame for this reaction, which may not last for more than about one hour and which effectively ceases once the cement starts to harden, only quite small quantities of hydrogen are produced.

In mass concrete with significant quantities of coarse aggregate and entrained air, the hydrogen bubbles are well distributed in the concrete surrounding the bar and can barely be separately identified. In light weight concretes with low volume fractions of coarse aggregate, such as may be used in precasting, it is possible for the bubbles to accumulate somewhat and rise though the concrete cover. This may, in some unique circumstances, result in variations in the texture of the concrete at the surface of the precast panel which may be aesthetically undesirable.

While the evolution of hydrogen is theoretically possible, the practical effects of this are often over-emphasized. In particular, concerns are often expressed that the evolution of hydrogen will reduce the bond strength of galvanized bars in concrete. This matter has been the topic of extensive research which has almost universally demonstrated that there was no reduction in bond strength for galvanized bars compared to equivalent black steel. A key aspect of this research was that the hydrogen evolution from galvanized steel immersed in Portland cement paste occurs on surfaces where iron and zinc are in contact but not on a pure zinc surface. This suggested that it is the zinc-iron alloy layers near the surface of the coating which initiated the formation of hydrogen. As such, the evolution of hydrogen is not expected to be significant if the outer layer of the coating is predominantly pure zinc, which is the situation usually found with hot-dip galvanizing of non-reactive steels. Thus, to prevent hydrogen formation, it is necessary to maintain the presence of a pure zinc layer for at least the first hour of fresh concrete being in contact with galvanized steel. Bright galvanized coatings typically have such a structure and so the likelihood of a significant amount of hydrogen being evolved from the surface is quite low.

It is to be noted that hydrogen evolution from the coating surface can effectively be eliminated if the coating is passivated by another means. This can be achieved by treatment of the freshly galvanized steel with a variety of chemicals, the most common of which are chromate salts.

4.3.2 The role of Calcium Hydroxyzincate

The calcium hydroxyzincate that forms on the coating surface by the reaction between zinc and wet cement is known to positively contribute to the bond between the reinforcement and the surrounding concrete. Detailed microscopic examination has shown that this particular hydration product acts as a physical anchorage between the coating and the surrounding concrete thereby strengthening the level of adhesion of the

bar. This effect is qualitatively confirmed in the observation that Portland cement mortar droppings adhere strongly to zinc and when fully hardened become very difficult to remove without damaging the metal. Equally, it is well-known how difficult it is to remove hardened concrete from galvanized bars, a process that occurs easily with black steel bars.

There is now ample evidence that the adhesion between the zinc and cement paste is relatively stronger than that between the steel and the paste. What could reasonably be inferred from this is that the strength of the adhesion gained from the formation of calcium hydroxyzincate on the galvanized surface may well compensate for any potential loss of bond due to the hydrogen evolution. This may well account for the widely reported comparability between black and galvanized bars as far as bond strength is concerned as previously discussed. Further, the extent of adhesion between galvanized steel and concrete, though not a large component of the overall bond strength, clearly contributes to bond and also accounts for the reduced slip of galvanized bars shown in Figure 9.

4.3.3 The practice of chromate treatment

The prevention of hydrogen generation on the surfaces of galvanized steel, by precluding the reaction between zinc-coated reinforcement and fresh Portland cement, can be achieved by the application of a dilute chromate solution to those surfaces. ASTM A767 includes such a requirement and ISO14657 states that "if specified by the purchaser, the galvanized coating shall be chromate treated".

So-called chromate passivation can be achieved by applying the solutions directly to the galvanized bars, most commonly by quenching the freshly galvanized bars into a solution containing 0.2% sodium dichromate in water (i.e. 2 kg per m^3 of water) or by quench chromating in a minimum of 0.2% chromic acid solution. The solution needs to be at a temperature of at least 32ºC, and the bar needs to be immersed for at least 20 seconds. If the bar is at ambient temperature (i.e. has naturally cooled after galvanizing), 0.5-1.0% concentration of sulphuric acid needs to be added to the solution to activate the bars. An alternative method is to add chromates to the concrete mix water in the form of sodium or potassium dichromate at a rate of 70 ppm, expressed as CrO_3 by mass of cement. This is equivalent to 104 g/tonne of cement of pure sodium dichromate dihydrate or 103 g/tonne of cement of pure potassium dichromate.

The advantage of the concrete mix-water addition approach is that it ensures that the galvanized product is passivated at the actual time it is cast into concrete. For bar that is quench passivated immediately after galvanizing and then fabricated, transported and stored on site, there can be no guarantee that the passive film remains on the surface at the time of casting. There is ample evidence available that shows that the chromate passivating film on the surface of zinc does deteriorate over time depending on the nature and severity of its exposure. It is also to be noted that, at a practical level, the use of chromates, either to the quench bath or the concrete mix water, is presently not well received. Apart from higher processing costs and general inconvenience, there are serious occupation health and safety issues, and also environmental concerns, with the

use of chromium salts. As such, the use of chromates in many parts of the world is being severely restricted and stringent environmental regulations have been put in place.

Research has also shown that the small quantities of chromates which occur in most cements are sufficient to passivate galvanized surfaces, provided an amount of at least 20 ppm is in the final concrete mixture. Indirectly, this effect has offered another route to passivation of galvanized bar, albeit not one that is controlled or necessarily reliable since the amount of naturally existing chromates in cement does vary widely (from less that 2-3 ppm to 500 ppm). Several countries have recently introduced regulations to limit the residual chromate level in cement to less that 2 ppm. In these circumstances, reliance on self-passivation via the residual chromates in cement should be discounted.

The effect of chromate passivation on the bond of galvanized bars has been widely investigated. The results from these investigations vary widely, some showing a significant benefit from chromate treatment, others no benefit or even a reduction compared to non-chromate treated bars. One possible explanation for this variation is that zinc does have a slight retardation effect on the hardening of concrete and so pull-out tests conducted at a very early age (say seven days curing) may not have yet developed their full bond capacity and give erroneously low or misleading results. To account for this effect, it is recommended that all bond testing using galvanized bars not be conducted before 28 days curing, buy which time the properties at least match those of black steel bars.

Whether chromate treatment has a beneficial effect or not, the most common result from this type of testing confirms that the bond strength of non-chromate treated galvanized bar is consistently and significantly higher than that of equivalent black steel bars. It would appear that the superiority of the non-chromate-treated galvanized bars is attributed to the uninterrupted formation of calcium hydroxyzincate crystals growing perpendicular to the galvanized surface which act as a mechanical key into the surrounding concrete. Similarly, in long term studies (to ten years) of the bond of galvanized reinforcement in chloride contaminated concretes, it was found that there was no loss in the bond of galvanized steel after such long-term exposure to chlorides, and further there was no significant effect of chromate addition compared to non-treated galvanized bars. This work also indicated that the generation of hydrogen bubbles (in the absence of chromate treatment) did not have a significant effect on bond strength.

In other work comparing black, galvanized and epoxy coated plain bars, there was no statistically significant difference in the ultimate bond stress of plain black steel bars and galvanized bars while the epoxy coated bars were some 26% less. Further, the addition of chromates in the mixing water (35-150 ppm by weight of cement) significantly increased the bond strength of galvanized bars with the largest increase (about 38%) for additions of 35 ppm (see Figure 12). In related work comparing plain black bars and galvanized bars either untreated or treated with solutions of sodium dichromate, the galvanized bars were 50% superior in bond strength than plain black bars, and the sodium dichromate treatment to the bar prior to casting did not result in any significant difference when compared with untreated galvanized bars.

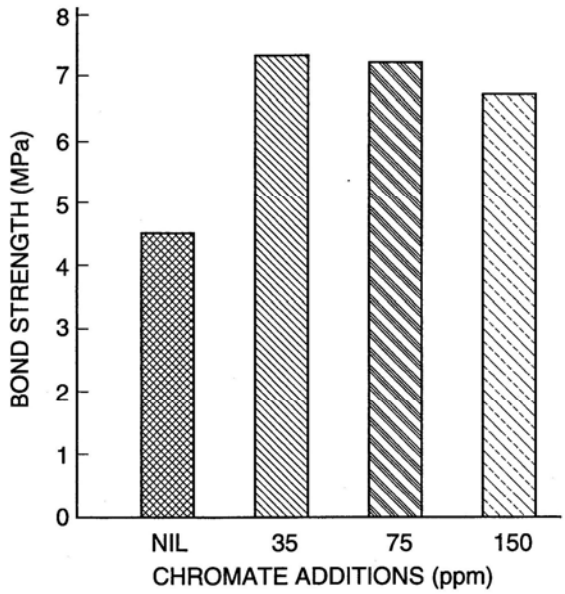


Figure 12. The effect of chromate additions to concrete mix water on the bond strength of galvanized bars.

What this mix of evidence points to is that, in the first instance, the galvanizing of steel reinforcing bar has no adverse effect on bond strength and, if anything, would result in an improvement of bond. Further, the practice of chromating the reinforcement, whether by applying it directly to the steel surfaces or to the concrete mixing water, is not at all necessary. This is because chromating does not reduce the bond capacity and, if anything, likely increases it further. Since the bond of galvanized bar is normally superior to that of black steel bar, and the presence of minor amounts of hydrogen has no noticeable effect, the additional benefit obtained from chromating is unnecessary.

It is to be noted as well that abandoning this practice would also conform to health and environmental requirements in many countries as well as making the handling and use of galvanized steel much safer, easier and possibly cheaper. To some extent, the approach adopted in ISO 14657, by allowing an option for chromate passivation, recognises these trends in the recent research indicating that chromate passivation is not really necessary.

5. The Electrochemical Nature of Galvanized Steel (refer Chapter 5)

Steel in concrete is protected against corrosion by a passivation mechanism. The reason for this passivation is the high alkalinity of the concrete pore-water solution, the pH of which in hydrated concrete is greater than 12.5. During the first short period after mixing, the solution filling the pores of concrete is over-saturated in $Ca(OH)_2$. Later, equilibrium with other species is reached such as NaOH, KOH and $CaSO_4.2H_2O$. The pH value of this aqueous solution varies from 12 to 14 as a function of the alkali content of the cement and the degree of hydration. One particular feature of these alkaline solutions, which is relevant for the behaviour of zinc, is that the concentration of Ca^{2+} ions decreases when the pH increases. The importance of this is that the presence of Ca^{+2} is needed for the passivation of zinc in alkaline solutions.

5.1 Formation of the passive film

Under the highly alkaline conditions of concrete a microscopic oxide layer is formed on the steel surface of the reinforcement, the so-called passive film. This passive film impedes the dissolution of the iron and so the corrosion of steel reinforcement is severely limited, even in the presence of moisture and humidity. In the case of zinc, the situation is different to steel since zinc is an amphoteric metal. This means that the zinc is stable over a wide range of pH, from approximately 6 to 12.5, but below and above these values the corrosion rate increases exponentially as shown in Figure 13.

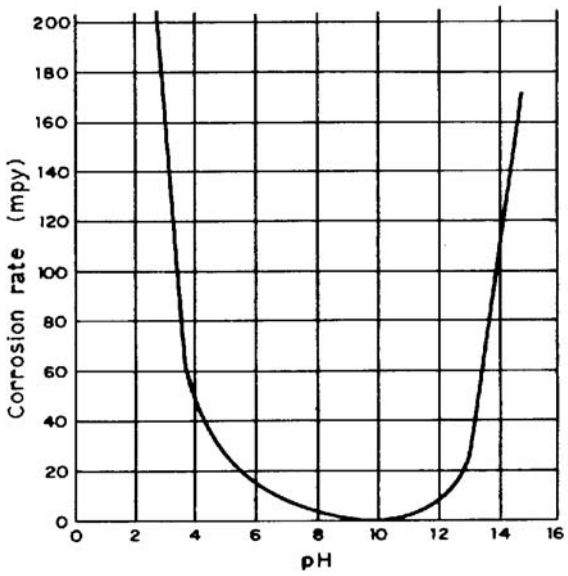


Figure 13. The corrosion rate of zinc as a function of the pH of the environment

The behaviour of zinc in both weak and strong alkaline solutions has been widely studied. Some important conclusions from this wide-ranging work are that:

- below a certain OH^- content, the first anodic product is $Zn(OH)_2$, while above pH 12.9 the main product is the soluble zincate ion (ZnO_2^{2-});
- in a pH interval between 12 and 13.2 ± 0.1 the galvanized coating corrodes at an acceptably low rate;
- at pH below 12 localized corrosion takes place while above pH 13.2 total dissolution of the coating occurs with no passivation;
- a threshold for the onset of hydrogen evolution is at pH 12.8 ± 0.1; and
- the corrosion product that causes the passivation of zinc in calcium-rich alkaline solutions is calcium hydroxyzincate (CaHZn).

A two-stage mechanism for the formation of CaHZn has been given as:

$$Zn + 2H_2O \leftrightarrow Zn(OH)_2 + H_2$$

then

$$2Zn(OH)_2 + 2H_2O + Ca(OH)_2 \rightarrow Ca(Zn(OH)_3)_2.2H_2O$$

In was also noted that ZnO and ε-$Zn(OH)_2$ formed during the corrosion process.

As noted, it was found that galvanized steel become passivated at a pH value below 13.2 ± 0.1. In this circumstance, the passivating film was calcium hydroxyzincate, but it was also observed that its morphology varied with the pH of the solution in which it formed. The existence of the previously mentioned insoluble corrosion products ZnO and ε-$Zn(OH)_2$ was also identified, although no passivating properties were observed with the ZnO product. It is to be noted that once the passive film of calcium hydroxyzincate is formed, its stability is not altered even if the pH increases to a value of 13.6 ± 0.1.

Regarding the morphology of the passivating layer, analysis of the corrosion products of galvanized steel in calcium-rich alkaline solutions shows that when the pH is around 12.6, the surface is totally covered after two or three days mainly by CaHZn crystals as shown in Figure 14. Its appearance is that of a very compact carpet of crystals. As the pH increases so does the CaHZn crystal size to the point that the crystals cannot completely cover the surface and, under these conditions, complete passivation of the surface is not possible and dissolution continues at a high corrosion rate.

At even higher pH values (above 13.5), the crystals of CaHZn become quite coarse and they grow as isolated crystals (Figure 15). The reason for this is that at pH values above 13.2, the concentration of Ca^{2+} ions in solution is depleted. At these high pH values, because the formation of the passive layer of CaHZn crystals is impeded, the dissolution of the zinc is not retarded and as a result the galvanized coating may completely dissolve in a short period of time.

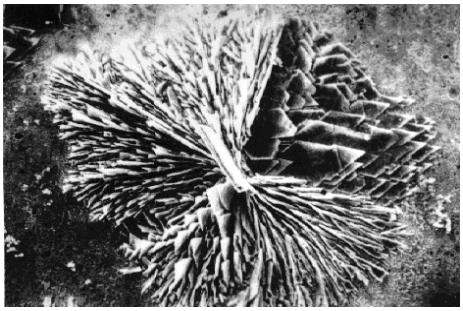


Figure 14. CaHZn crystals after 24 h in $Ca(OH)_2$ solution of pH 12.6.

Figure 15. CaHZn crystals after 10 days in $Ca(OH)_2$ + KOH solution of pH 13.24.

5.2 The evolution of hydrogen

Simultaneous with the processes of passivation of galvanized steel in concrete, hydrogen evolution occurs along the bar surface. The initial reaction between the zinc and the alkaline media is quite vigorous. However, it steadily decreases with time due to the continued formation of the surface layer of CaHZn which eventually becomes continuous on the surface with the hardening of the cement paste.

Electrochemical studies have revealed that while the generation of hydrogen is common, the total duration of the reaction depends primarily on two factors:

- the chromium content of the cement which varies considerably in different cement types and may completely suppress the hydrogen evolution; and
- the alkali content of the cement and therefore the pH of the pore solution.

As discussed above, the main consequence of the hydrogen gas evolution is the formation of bubbles at the bar/concrete interface which is thought responsible for some loss in bond of galvanized reinforcement when no chromium additions are made to the concrete or when separate chromate passivation of the bars is not performed. However, this decrease in contact zone at the interface is only transitory, as the formation of the CaHZn crystals progressively fills these gaps, and so this effect is of minor significance.

5.3 Influence of alkali content

The component of cement that most influences the behaviour of zinc in alkaline media is the alkali content (Na^+ and K^+). These alkali ions are incorporated into the cement in different proportions as a function of the raw materials and fuels used for cement manufacture. They are usually present in the form of alkaline sulphates.

Different cements can produce different pore solutions due to the presence of alkali ions which are the most soluble components and thus responsible for the final pH of the pore solution. What has been found is that the corrosion rate of galvanized reinforcement embedded in mortars made with various cement types usually increases with increasing pH values of the cements, indicating a pH threshold for zinc in concrete pore solutions between pH 12.8 and 13.2 ± 0.1. Above this pH limit, the corrosion rate developed is quite high with a risk of dissolution of the galvanized coating.

This relationship between the cement alkali content and the corrosion rate may explain the observed different behaviours and life of galvanized coatings in concrete. The type of cement in contact with the galvanizing is very important because it allows the formation of a compact passive CaHZn layer. This may also explain some of the variable behaviour with galvanized reinforcement when the cement type has not been taken into account.

What is clear is that the layer of passivating corrosion products develops during the first hours after mixing, when the pH value of the pore concrete solution is lower than 12.8 ± 01. If the pH is between about 12.8 and 13.2, the passivating layer develops slowly and the galvanized coating may continue to dissolve until full passivation is reached. At higher pH, the passive layer is not developed and the galvanized coating may continuously dissolve. Fortunately however pH values greater than 13.2 do not develop in concrete pore solutions during the first hours after mixing if sulphate is used as a setting regulator or enough alkaline sulphates are present. While sulphate ions are present in the pore solution, the pH value does not increase beyond 13.2. Only when the sulphates disappear from the solution, due to the formation of sulphoaluminates, does the pH rises a maximum value which is a function of the total alkali content. This usually happens several hours or days after mixing by which time the passivating CaHZn layer has all but completely formed and, as a result, the increase in pH is not harmful to the galvanized coating.

5.4 Influence of the galvanized coating structure

As previously discussed, the alloy layer structure of the galvanized coating depends on the composition of the base steel, and also on the temperature and composition of the hot dip bath as well as the time in the galvanizing bath. What is well known is that the presence of different microstructures has a significant effect on the stability of the galvanized coating in contact with alkaline solutions. This is primarily because it is the outer pure zinc layer (η) which provides the most effective passivation, while the underlying Fe-Zn layers are less stable particularly so in the presence of chlorides which selectively attack them inducing progressive disintegration of the coating.

The nature of the attack on the galvanized coating during passivation is by dissolution of the external pure zinc layer in conventional galvanized coatings, while for annealed galvanized coatings the Fe-Zn alloy layers disintegrate by selective attack in which the zinc is used to develop the CaHZn film. From observations of this type it has been deduced that galvanized coatings should have sufficient reserve of the pure zinc layer (thicker than around 10 μm) to enable the development of a perfect, and so passivating film of calcium hydroxyzincate.

6. Behaviour of Galvanized Steel in Concrete (refer Chapters 1, 4, 5)

As previously noted, there are two main circumstances that need to be separately discussed when considering the behaviour of galvanized reinforcement in concrete. These are first, the effect of carbonation and second, the effect of the chloride ion.

6.1 Carbonated concrete

The carbonation or neutralization of the cover concrete is one of the principal reasons for reinforcement corrosion. The pH of the aqueous phase changes from highly alkaline to values around neutrality (pH 7). By reference to Figure 12, it is clear that at or near neutral pH the rate of corrosion of zinc is very low and so it would be expected that the galvanized coating would perform well.

Extensive research and field observation has shown that carbonation does not significantly increase the corrosion rate of galvanized bars in concrete, and in some cases it is even reduced. The general observation is that galvanized steel does not corrode in carbonated concrete.

In studies where the corrosion rate of galvanized reinforcement embedded in carbonated and uncarbonated mortars is measured with changes in relative humidity, it is observed that before the concrete is carbonated the galvanized steel shows high corrosion rates due to the coating being consumed in forming the protective layer of CaHZn. However, the rate of corrosion decreases significantly with the onset of carbonation and with reducing RH. Once the concrete is carbonated, it is possible for the galvanized coating to depassivate with a consequent rise in the corrosion rate. What is observed in these circumstances however is that after short time a sharp decrease in the corrosion rate occurs. This has been attributed to the formation of a new passivated layer, likely due to the precipitation of zinc carbonates on the surface.

6.2 The presence of chlorides

Chlorides are the more aggressive ions for reinforced concrete and are the most frequent cause of reinforcement distress. The chlorides are present in the concrete from two sources: first, from the mixing as part of the raw materials (water, aggregates or as an admixture); and second if they penetrate from marine environments or from the use of deicing salts. In both cases the attack produced on the reinforcement is localized resulting in a reduction of the cross section of the reinforcement.

For black steel, corrosion initiates when a threshold value of the chloride ion (Cl^-) in the pore solution is reached. This threshold concentration depends, among other factors, on the pH and increases as the pH increases. The American Concrete Institute has published recommended limits for chloride in concrete in contact with black steel as shown in Table 4.

Table 4. ACI recommended limits for chlorides in concrete.

Type of exposure	Chloride limit
Prestressed concrete	0.06
Conventional RC – moist environment and exposed to external chlorides	0.10
Conventional RC – moist environment but not exposed to external chlorides	0.15
Above ground building where concrete will stay permanently dry	No limit

ACI Committee 20, Guide to Durable Concrete, Chapter IV, 1994.
Limit expressed as percentage by weight of cement.

It is to be noted that these values are not necessarily the chloride threshold; rather they are a conservative recommended limit. In most specifications an actual chloride content of less than 0.2% of the cement content (or 0.6 kg/m3 of concrete) for a low corrosion risk is recommended. This value is more often reported as the chloride threshold.

In contrast, there is not a universal agreement on the resistance to chloride attack of galvanized reinforcement. What seems clear however is that while zinc is also attacked by chlorides, a somewhat higher chloride threshold is needed. Figure 16 shows a comparison of the range of potential and chloride ion concentrations in $Ca(OH)_2$ saturated solution at which zinc shows stability of the passive state or pitting corrosion; in effect these are the potential and chloride ion concentration at which film breakdown and anodic dissolution occur. From this data, it can be deduced that zinc becomes susceptible to pitting attack in $Ca(OH)_2$ solutions polluted with chlorides at chloride ion concentrations of approximately 0.45 M, while steel corrodes when the chloride ion concentration exceeds 0.08 M. This represents a 5-6 times higher threshold for zinc over black steel in such solutions which partly simulate concrete pore water.

These values do vary in the actual environment of concrete. What has been observed in a range of research and the results from field studies, is that the chloride threshold for galvanized bars is at least 2-2.5 times higher than that for black steel, to as much as 8-10 times higher.

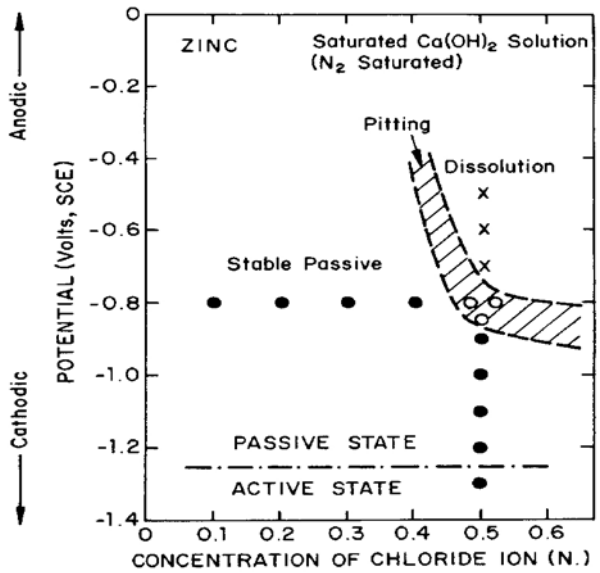


Figure 16. Corrosion of zinc in the presence of chlorides.

What is also clear is that the behaviour depends on the origin of the chlorides and the state of the galvanized surface.

6.2.1 Chloride ions added during mixing

The addition of chloride in the mixing water produces changes in the pH of the pore solution; for example, $CaCl_2$ produces a decrease of the pH but NaCl does not alter it significantly. When calcium chloride is added to mortar, the initial corrosion rates can be smaller than without admixtures although alternative periods of activation and passivation occur before reaching complete passivation. For NaCl, data for pure zinc bars shows higher corrosion rates than with $CaCl_2$, at least in the initial stages of corrosion, which is attributed to the higher pH produced by NaCl additions. At a later time however, the state of passivity seems more perfect with NaCl than with $CaCl_2$.

The galvanized microstructure also has an important influence in that the absence of the external zinc layer produces much higher corrosion rates while the alloy layers are less resistant to chloride attack than the pure zinc. In consequence, the most resistant galvanized coatings are those with a thicker external layer of pure zinc. When plain zinc bars are used, low corrosion rates are measured while galvannealed coatings are catastrophically destroyed when they are used in chloride-containing concrete. Thus the more resistant part of a galvanized coating is the pure zinc outer layer, and the weakest (or less resistant) is the underlying alloy layers.

6.2.2 Chloride ions penetrating from outside

The resistance of the galvanized reinforcement against chloride penetration depends on the compactness of the CaHZn layer and on the microstructure of the remaining coating. By the time the chlorides reach the reinforcement, the CaHZn layer should have already been formed. Therefore, if it is compact and continuous, and the remaining coating has

a thick enough pure zinc layer to resist pitting attack, the galvanized coating will resist chloride attack quite well. However, when instead of a thick pure zinc layer it is so thin that it is consumed in forming the CaHZn layer, when the chlorides reach the reinforcement they find below the CaHZn layer only the alloy layers that allow a much higher rate of attack.

If the amount of chlorides continues to increase, the threshold, although higher than for bare steel can ultimately be reached and the corrosion of the galvanized layers develops. This delay in the onset of corrosion with respect to the bare steel is known as the extension of the service life of the reinforcement provided by the galvanizing. This has variously been reported for galvanized bars to be in the range of 4-5 times longer that that for the corrosion of black steel in equivalent exposure conditions.

The issue of the extension of the life of galvanized coatings can be demonstrated by a simple calculation of the time to corrosion of black steel and galvanized steel in similar exposure conditions as per the following:

- for black steel, assume an upper threshold value of 0.4% Cl^- by mass of cement; and
- for galvanized steel, assume a lower threshold of 1.0% Cl^- based on conservative experimental and field data.

For the calculation, assume an equivalent exposure condition in a marine concrete:

- 0.35% chloride ion concentration at the concrete surface; with
- 30 mm cover to the reinforcement; and
- a diffusion coefficient D = 1.4 x 10-12 m2/s.

On this basis, Fick's Law predicts that for black steel corrosion of the reinforcement will initiate after 15 years, while for galvanized steel attack initiates after 44 years. This indicates a theoretical extension of life of 3 times for galvanized bar over black steel bar.

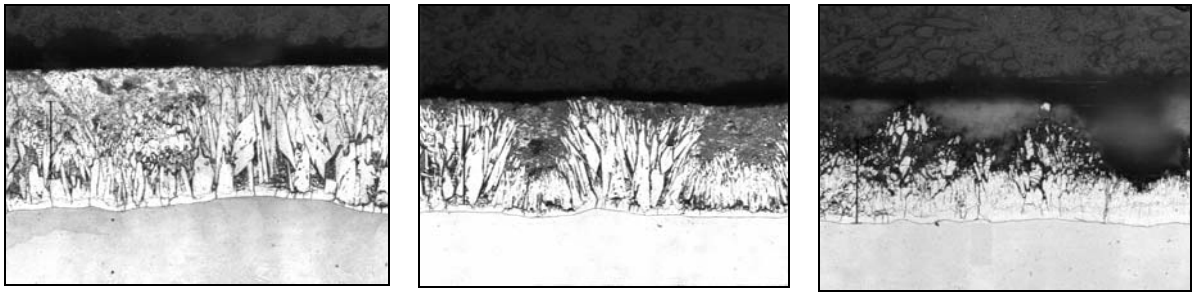
This result is clear confirmation of what is observed in a range of laboratory studies and also in the field. It is to be noted though, that in addition to the delayed corrosion onset, zinc corrosion products are not expansive in nature and therefore, during the time the galvanized coating is dissolving, the life of the structure is also effectively being extended. The corrosion products which have expansive character are those of the base steel leading to the rapid onset of cracking and spalling of the concrete mass once corrosion initiates. This is not the case of zinc corrosion products and, as such, the actual extension of life of galvanized steel is usually somewhat longer that the 3 times factor calculated above.

6.3 Behaviour of the coating and corrosion products

An understanding of the reaction mechanism of the zinc alloy coating when placed in concrete and the characteristics of the corrosion products so formed is fundamental to a full appreciation of the corrosion protection afforded by the galvanizing of reinforcement. Considerable work has been done over many years to investigate these effects including the reaction of the various coating alloy layers when in contact with wet cement, the nature of the corrosion products that form when zinc reacts with

cement, and the mixing of the corrosion products into the concrete matrix. What has been observed in extensive research in this area is that the dissolution of the galvanized coating differs depending on the state of the galvanized surface. If the coating exhibits a pure zinc layer, it dissolves uniformly at first and only later does localized attack occur in the alloyed layers.

This research has indicated that when the galvanized coating first comes in contact with wet cement and is initially passivated, about 10 µm of zinc is dissolved from the pure zinc (eta) layer of the coating. This effect is shown in Figure 17 for a galvanized steel with an initial coating thickness of 180 µm (Figure 17a) embedded in non-chloride contaminated concrete for a short period (Figure 17b). The average thickness of the coating remaining at this stage is 164 µm and the coating retains a smooth and bright surface. Studies of galvanized bars recovered from field structures indicate that the coating remains in this condition for extended periods of time provided the conditions in the concrete do not significantly change. In such circumstances, very little further metal loss will occur until the zinc is depassivated and active corrosion commences.



a) Freshly galvanized steel with 180 µm thick alloy layer coating.

b) Galvanized bar exposed to fresh concrete showing partial loss of outer pure zinc layer. Remaining coating ~164 µm thick.

c) Exposure to chloride-contaminated concrete showing loss of pure zinc layer with intrusions around alloy layers. Average coating thickness ~110 µm.

Figure17. Changes in the galvanized coating with exposure to concrete. (200x)

Once active corrosion of the zinc initiates, usually due to the accumulation of high levels of chloride at the depth of the reinforcement, continued dissolution of the eta alloy layer occurs followed by progressive dissolution of the underlying alloy layers as shown in Figure 17c. This form of attack results in the formation of deep tunnels and holes in the alloy layers, particularly around and through the delta phase which comprises the bulk of the coating.

Though the coating appears to be disintegrating at this stage, a dense layer of both the gamma and delta phases remains intact at the bar surface and this affords ongoing corrosion protection to the underlying steel. Once the coating is completely lost from small areas of the bar surface, the zinc continues to provide sacrificial protection over distances of up to about 8 mm (as revealed in one experiment). Some examples of this effect are shown in Figure 18.

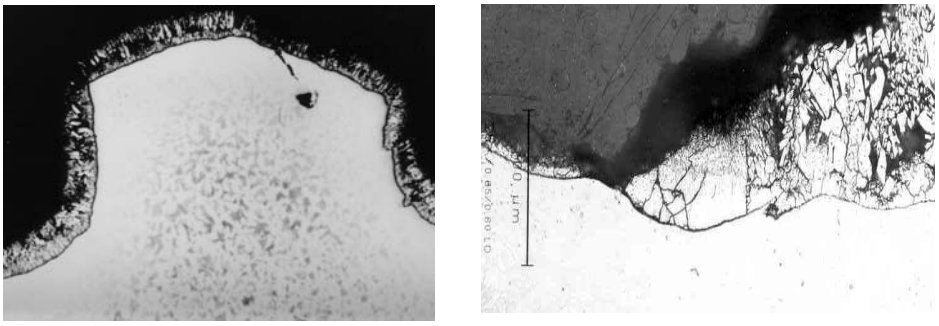
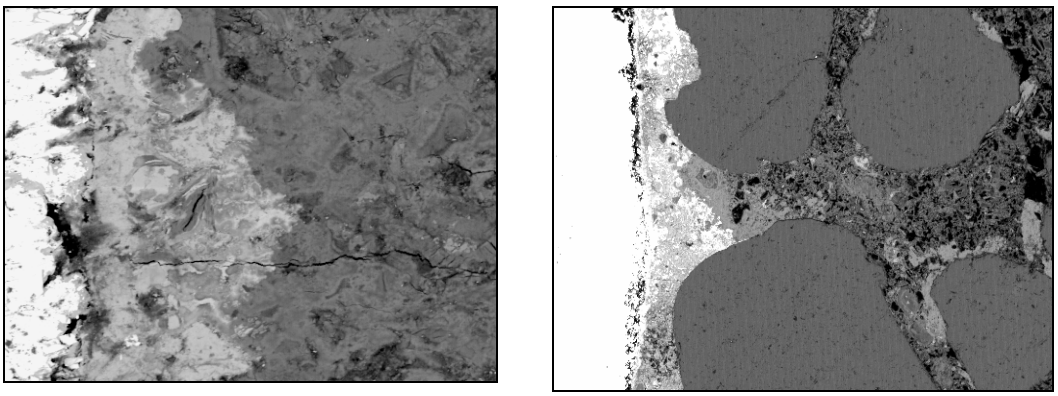


Figure18. Showing areas of exposed steel on embedded galvanized bar that have been cathodically protected by the adjacent zinc coating.

Considerable work has also been done to identify the nature of the corrosion products produced and the effect of these on the concrete mass. A number of minerals have been identified in the corrosion products, primarily zinc oxide and zinc hydroxide. A unique feature of these products is that they are friable (loose and powdery) minerals, are less voluminous than iron-rich corrosion products, and are able to migrate away from the bar and into the adjacent concrete matrix where they fill voids and microcracks. This is shown in Figure 19 in which the plume of zinc-rich corrosion products appears white against the gray calcium-rich cement matrix.

In contrast to the situation encountered when steel corrodes in concrete, the presence of the zinc corrosion products cause very little physical disruption to the surrounding matrix, thereby maintaining the integrity of the cover concrete. There is also evidence that the presence of these corrosion products and the filling of the pore space in the matrix may create a barrier in the matrix of reduced permeability which not only increases the adhesion of the matrix to the bar but may also reduce the transport of aggressive species such as chlorides through the matrix to the coating surface.



a) Showing partial dissolution of the galvanized coating (left) and plume of zinc-rich corrosion product (centre) migrating into cement matrix (1000x).

b) Migration of zinc-rich corrosion products away from the bar/matrix interface into the cement matrix. Large particles are sand. (100x)

Figure 19. SEM images of interfacial zone between bar and matrix showing the presence of zinc corrosion products (white plume).

7. Field Studies of Galvanized Reinforcement (refer Chapters 2, 6, 7)

Evidence from field applications, supported by a growing body of experimental data, has demonstrated that galvanizing extends the life of reinforcement in concrete and provides a safe-guard against premature cracking and rust staining of the concrete. The corrosion protection afforded by galvanizing is due to a combination of beneficial effects. Of primary importance is the substantially higher chloride threshold for zinc coated steel in concrete compared to conventional (black) steel. In addition, galvanized reinforcement is resistant to the effects of carbonation of the concrete mass. The net effect of the presence of the zinc coating is that it not only delays the initiation of the corrosion process, but it continues to provide barrier protection during that period when the coating is reacting (i.e. dissolving) but remains intact.

What has become clear from the considerable body of research undertaken is that the life of the galvanized coating, and thus the reliability of the corrosion protection it provides, depends on the morphology and thickness of the coating, the quality of the concrete in which it is placed, and the severity of the environment to which the concrete is exposed. In addition, in circumstances where the underlying steel is exposed, such as at breaks in the coating or at cut edges, the zinc sacrificially protects the steel thereby further extending the life of the reinforcement.

Considerable research has been done in the USA in particular to investigate the use of galvanized reinforcement for concrete bridge and highway construction exposed to high levels of accumulated chlorides due to the application of deicing salts or in marine exposure. In the case of top and bottom mat reinforcement for bridge decks for example, when both top and bottom mat bars were galvanized, very low corrosion current densities resulted compared to black steel, and the extent of corrosion on the galvanized bars was significantly less with no ferrous corrosion products (i.e. red rust) apparent. It has been shown that when galvanized bars were used in the top mat only with black steel bottom mats, significant corrosion of the zinc occurred though with very much less red rust corrosion compared to black bars in equivalent conditions.

Other work has indicated that for a 0.5 w/c (water/cement ratio) concrete, galvanized bars performed better than black bars, though in a 0.4 w/c concrete there was similar behaviour for both black and galvanized bars after 8 years cyclic exposure, and meaningful comparisons could not be made. It was also noted that the worst case corrosion occurred when top mat galvanized bars in high chloride concrete were coupled to black steel bars in relatively chloride-free concrete at the bottom of the slab; the best case was when galvanized bars were used in both the top and bottom mats.

Other data has also verified the enhanced field performance of galvanized reinforcement in both marine and bridge deck applications. Surveys of many structures at various ages of exposure with varying concrete quality (high w/c and low cover) and high-to-extreme chloride levels (up to 10 times recommended ACI levels) at the reinforcement, have consistently revealed that galvanized steel outperforms black steel where meaningful corrosion comparisons were able to be made. For example, in 1991 a survey a number of bridges in Iowa, Florida and Pennsylvania was undertaken to compare the

performance of galvanized and uncoated reinforcement in decks exposed year round to humid marine conditions or deicing salts in winter.

This survey complemented earlier surveys in 1974-6 and 1981 of many of the same bridges. After periods of up to 24 years exposure it was found that the galvanized bars had suffered only superficial corrosion in sound, uncracked concrete even when the chloride levels were high. Though the chloride levels had increased since the 1981 survey, no major change in the galvanized bars was detected and average thickness of zinc remaining on the reinforcement had not significantly changed since 1981 and was still well in excess of that required by ASTM A767 for new material.

In 2002, a follow-up study of the long-term performance of galvanized steel in concrete bridge decks in Pennsylvania was again undertaken. Earlier surveys over the period 1974-1999 (previously noted) had examined bridges in Florida, Iowa, Pennsylvania and Vermont. This survey was of the Athens and Tioga bridges in Pennsylvania, both galvanized reinforced and which had been previously examined in 1981 and 1991.

- ***Athens Bridge*** (age 28 years). The average chloride level was 0.41% (by weight of cement) which is more than 2.5 times higher than the ACI threshold value for black steel. In areas where the potential was low (about -700 mV), no signs of corrosion of the galvanized bars was evident. Metallographic examination revealed the majority of bars exceeded the minimum galvanized coating thickness required for new bars of about 84 microns.

- ***Tioga Bridge*** (age 27 years). The average chloride level was 0.40% (by weight of cement), again more than 2.5 times higher than the ACI threshold value. There were no signs of corrosion on any of the galvanized reinforcement, even from high potential areas. The thickness of zinc remaining on the bars greatly exceeded the minimum specified thickness of 84 microns.

The overall results from this survey confirmed the satisfactory performance of galvanized reinforcement in these bridge decks after long-term exposure to both calcium chloride used as an admixture at the time of casting, and roadway de-icing salts. The report concluded that the "galvanized reinforcing bars generally showed satisfactory resistance to corrosion" and visual inspection revealed "no signs of corrosion on any of the steel reinforcement" except in one area of the Athens bridge. Further, "cracking, delamination and spalling or evidence of active corrosion was not generally observed".

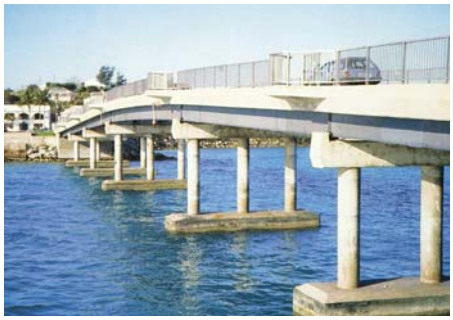
Similar data from Bermuda has also verified the long-term durability of galvanized reinforced concrete in marine environments. Commencing shortly after WW2, a number of docks, jetties and other infrastructure were constructed using a mix of galvanized and bare steel bars (see Figure 20). A survey undertaken in 1991 showed that the galvanizing was providing continuing corrosion protection to reinforcement at chloride levels well in excess of threshold levels for bare steel corrosion.

Follow-up examination confirmed these findings and revealed that the galvanized bars maintained a residual zinc coating thickness at a structure age of 42+ years well in

excess of the minimum requirement. Examination of concrete cores from these structures confirmed the previously mentioned observations that the zinc corrosion products had migrated a considerable distance (300-500 microns) beyond the surface of the coating and into the adjacent concrete matrix with no visible effect on the concrete mass. Field data of this type provides practical evidence of the migration effects of the zinc corrosion products shown laboratory experiments (refer Figure 19).

a) The islands of Bermuda showing the aggressive marine exposure conditions .

b) The Royal Bermuda Yacht Club (1968) with galvanized bar, and still in excellent condition.



c) The new Watford Bridge (1979), fully galvanized reinforced.

d) Tynes Bay waste-to-energy plant foundations with 100% galvanized reinforcement.

Figure 20. The Bermuda case study.

Studies such as these clearly indicate that galvanized bar, when properly used as the exclusive reinforcing material, can provide enhanced corrosion protection compared to black steel in equivalent concrete and exposure conditions. What is clear is that in good quality concrete that is well compacted, cured and of adequate cover, galvanized bar survives for extended periods of time and offers a cost-effective method of corrosion protection. In poor quality concrete however, particularly those with high w/c ratio and low cover to the reinforcement, galvanizing will delay the onset of chloride induced corrosion of the reinforcement, but this may be of limited benefit.

8. Economics of Galvanized Reinforcement (refer Chapters 1, 7, 9)

When the costs and consequences of corrosion damage to a reinforced concrete building are analyzed, the extra cost of galvanizing is seen as a small investment in corrosion protection. While the initial cost of galvanizing may add up to 50% to the cost of the reinforcement, depending on the country of origin and the availability and access to galvanizing plants within the country, the cost of using galvanized reinforcement as a percentage of total building cost is always significantly less than this. The overall cost depends, of course, on the nature and location of construction and the extent to which galvanized bar is used throughout the structure. For example, it is rarely necessary for the structural core or internal elements of large reinforced concrete structures such as high rise building, or the deeply embedded components of large abutments and foundations, to be galvanized.

General cost analysis for building construction reveals that the galvanizing of reinforcement increases the overall cost of reinforced concrete as-placed by about 6-10%. The actual value will vary depending on many factors including the type of bar and the galvanizing price, the amount of steel used per cubic meter of concrete poured, and the unit cost of the concrete mass. The concrete price is made up of several main components including the supply of the concrete, the formwork and steel supply and fixing costs. On average, the cost of the steel would not be more than about 25% of the total cost of the concrete as placed. Considering also that it is rarely necessary to galvanize all steel in the structure, and that the cost of the structural frame and skin of a building normally represents only about 25-30% of total building costs, the additional cost of galvanizing reduces to between 1.5-3.0% of total building cost. However, by galvanizing only certain vulnerable or critical elements, e.g. surface panels, the additional cost of galvanizing reduces further still, perhaps to as little as 0.5-1.0%.

These percentages, of course, relate only to total construction costs and when taken against total project costs or final selling prices the added cost of galvanizing becomes very small indeed, often less that 0.2%. This represents a very small fraction of the cost of repairs should unprotected reinforcement corrode. Similar costing analysis has been reported on a number of occasions.

9. Applications of Galvanized Reinforcement (refer Chapters 1, 7)

Galvanized steel bar and other fittings including bolts, ties, anchors, dowel bars and piping, have been widely used in a variety of reinforced concrete structures and elements. The rationale for this is based on the philosophy that the coating provides a safeguard against early or unexpected corrosion of the reinforcement. Should such damage occur costly repair and remediation of the structure may be necessitated in order to realise the full design life of the structure. This represents an ever-increasing economic burden and the redirection of scarce resources.

Particular circumstances where the galvanizing of reinforcement is likely to be a cost-effective and sound engineering decision include:

- light-weight precast cladding elements and architectural building features;
- surface exposed beams and columns and exposed slabs;

- prefabricated building units such as kitchen and bathroom modules and tilt-up construction;
- immersed or buried elements subject to ground water effects and tidal fluctuations;
- coastal and marine structures;
- transport infrastructure including bridge decks, roads and crash barriers; and
- high risk structures in aggressive environments.

Many examples exist around the world where galvanized reinforcement has been successfully used in a variety of types of reinforced concrete buildings, structures and general construction including:

- reinforced concrete bridge decks and pavements;
- cooling towers and chimneys;
- coal storage bunkers;
- tunnel linings and water storage tanks and facilities;
- docks, jetties and offshore platforms;
- marinas, floating pontoons and moorings,
- sea walls and coastal balustrades;
- paper mills, water and sewerage treatment works;
- processing facilities and chemical plants;
- highway fittings and crash barriers; and also
- lamp posts and power poles.

A number of reviews have been published over the years dealing with the use of galvanized reinforcing steel in many of these applications. Some general experiences with hot dip galvanized reinforcement, mainly from a European perspective, have also been published. In addition, a detailed listing of galvanized reinforced structures, extending to several thousand entries and including buildings, transport infrastructure and chemical and treatment plant, has been published by the American Galvanizers Association. More detailed reviews of the use of galvanized reinforcement specifically in highway bridge construction and off-shore constructions for the oil and gas industry in the Netherlands has recently been published.

Some prominent examples, many of which are well-known buildings and major structures from around the world, are listed in Table 5. Other examples in general construction, buildings, bridges and highways, and coastal and marine structures are shown in Figures 21-24.

Finally, it is noteworthy that in the State of the Art Report on Coating Protection for Reinforcement (Comite Euro-International du Beton, 1992) the benefits from the practical use of galvanized reinforcement were listed as follows:

- proper galvanizing procedures have no significant effect on the mechanical properties of the steel reinforcement;
- for best performance, galvanized reinforcement should be passivated by chromate treatment;
- zinc coating furnishes local cathodic protection to the steel, as long as the coating has not been consumed;

- galvanized reinforcement provides protection to the steel during storage and construction prior to placing the concrete;
- corrosion of galvanized steel in concrete is less intense and less extensive for a substantial period of time than that of black steel;
- galvanized steel in concrete tolerates higher chloride concentration than black steel before corrosion starts;

Table 5. Examples of prominent structures utilising galvanized reinforcing steel.

Sydney Opera House: 35 mm thick panels for cladding of sails and seawall units	Hydro-Electricity Commission, Hobart: clad with 950 galvanized precast panels
NZ Parliament House, Wellington: clad with precast fascia panels	Telecom Exhibition Exchange, Melbourne: clad with precast panels
Bank of Hawaii, Waikiki: thin decorative precast arches with galvanized bar	Intercontinental Hotel, Sydney: 1549 precast windows and fascia units
National Theatre, London: over 1000t of galvanized bar in exposed parapet walls	ANDOC North Sea Oil Rig: 2000t galvanized bar in roof of storage tank
Crocker Building, San Francisco: galvanized reinforced structural elements	Eastbourne Congress Theatre, UK: cladding panels and window mullions
Collegiate Buildings, University College, London: galvanized bar and mesh	University Sports Hall, Birmingham: 37 mm thick panels using galvanized bar
New Hall, Cambridge University: galvanized mesh in roof segments	Library Tower, Sydney: galvanized bar in external columns and panels
Staten Island Community College, New York: brilliant white precast panels	High Court and National Gallery, Canberra: galvanized bar in critical areas
New Parliament House, Canberra: 1800 galvanized cladding panels.	Barclays Bank, City of London: galvanized precast window surrounds
Offices, Westminster Bridge, London: galvanized reinforced white facing panels	National Tennis Centre, Melbourne: precast stadium support beams
Department of Housing and Urban Development, Washington, DC:	University of Wisconsin: precast panels and insitu concrete in numerous buildings
Financial Plaza of the Pacific, Honolulu: precast cladding panels	Levi Strauss Building:, California: precast panels
Wrigley Field Sports Arena, Illinois: precast panels in seating decks	Georgetown University Law Centre, Precast panels
Frontier Chemical Company, USA: galvanized reinforcing mat for floor slabs	US Coast Guard Barracks, Elizabeth City, NC: galvanized bar in 237 precast panels
Bridge deck and road construction in New York, New Jersey, Florida, Iowa, Michigan, Minnesota, Vermont, Pennsylvania, Connecticut, Massachusetts, Ontario and Quebec	John F Kennedy Parking Garage, Detroit: galvanized reinforcing steel to protect against subsurface rusting
IBM Data Processing Division HQ, White Plains, NY: hot dip galvanized reinforcement in precast façade panels	Football Hall of Fame Stadium, Canton, OH: galvanized reinforcing steel
Coke quenching towers, Dunkirk, France: galvanized structural reinforcement	Dome of the Mosque, Rome, Italy: galvanized reinforcement
Arkansas Civic Centre: galvanized reinforcement in slim external columns	Power station cooling water ducts, Spijk, Netherlands: fully galvanized reinforced
Offshore piers at Ominichi, Japan and Riva di Traiano, Rome, Italy: galvanized reinforced throughout	Toutry Viaduct, St Nazaire Bridge and Pont d'Ouche Viaduct, France: galvanized reinforcing bars

- galvanized reinforcement delays the onset of cracking, and spalling of concrete is less likely to occur or is delayed;
- the concrete can be used in more aggressive environments. Thus a standard design of concrete components can be retained for various exposure conditions by the use of galvanized steel in the most aggressive cases;
- lightweight and porous concretes can be used with the same cover as for normal concretes;
- greater compatibility is obtained with low alkali cement;
- poor workmanship resulting in variable concrete quality (poor compaction, high water/cement ratio), can easily be tolerated;
- accidentally reduced cover is less dangerous than with black steel;
- unexpected continuous contact between concrete and trapped water can be tolerated;
- repair of damaged structures can be delayed longer than with black steel;
- galvanized hardware is acceptable at the surface of the concrete, as it is for the joints between precast panels;
- the use of galvanized reinforcement ensures a clean appearance of the finished concrete with no trouble arising at cracks either from spalling or rust staining; and
- galvanized reinforcement is cleaner and easier to work with, and makes it possible to consider the use of thinner wires as welded fabrics.

The report goes on to say that "it is important to remember that even if these benefits are achieved, the use of galvanized reinforcement should not be considered as an alternative to the provisions of adequate cover of dense, impermeable concrete, unless special design criteria have to be met. Galvanizing of reinforcement is a complementary measure of corrosion protection - a kind of insurance against the inability of the concrete to isolate and protect the steel."

10. Concluding Comments

Over a very long period of time (in fact about 60 years), the galvanizing of steel reinforcement has been shown to provide a cost-effective and reliable means of corrosion protection to concrete in a variety of exposure conditions. Clearly, galvanizing is only one of a number of protection systems that can be used in reinforced concrete. However, the convenience of manufacture and supply of the product, the ease of handling, transportation and installation, and the fact that no special design requirements are needed, has meant that it has been accepted in many countries for a wide range of concrete construction.

The last 15-20 years in particular has seen extensive research and field investigations undertaken of the characteristics and behaviour of galvanized reinforcement. This considerable body of work has repeatedly highlighted the benefits of galvanizing in delaying the onset of corrosion in reinforced concrete and in reducing the risks of cracking and rust staining of the concrete mass. The higher chloride threshold for zinc compared to steel, and that zinc in concrete is virtually unaffected by carbonation,

provides galvanized reinforcement with an inherent corrosion resistance well beyond that of conventional steel bar. The very presence of the coating itself further extends the service life of galvanized bar because of the time delay during which dissolution of the coating occurs.

As with all corrosion protection systems, there is a cost associated with galvanizing. Though the cost of the reinforcement may increase by about 50% when galvanized, when considered against total building and construction costs, and the enormous potential costs associated with untimely repair of damaged concrete, the premium that is paid to galvanize reinforcement is very small indeed. Even if one cycle of local patch repairs over a large concrete structure can be avoided, the cost of the galvanizing would have been more than met. Primarily though, the reason for using any corrosion protection system is to extend the service life of the structure. Experience with galvanizing has shown this can be readily achieved in many types of reinforced concrete structures and elements in mild, moderate and severe exposure conditions.

Above all however, it is important to remember that when using galvanized reinforcement (as with any protection system for concrete), that the concrete is properly designed and placed and is appropriate for the type of element and the exposure conditions. Unless specific design requirements apply, such as reduced cover or ultra light-weight construction, the concrete should be designed and placed as though conventional steel reinforcement was to be used. In essence, the use of galvanizing should not be at the expense of this basic quality and integrity of the concrete. In this way, the galvanizing can be considered to provide protection against those circumstances that may lead to premature corrosion of conventional reinforcement and deterioration of the concrete mass.

11. Further Reading (www.galvanizedrebar.com)

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American Galvanizing Association, Hot-dip galvanizing for corrosion prevention: A guide to specifying and inspecting hot-dip galvanized reinforcing steel, AGA, Centennial, CO, USA, 2002, 20pp.

Bentur N, Diamond S and Berke NS, *Steel Corrosion in Concrete*, E & FN Spon, Chapman and Hall, London, 1997.

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Committee Euro-International du Beton, Coating Protection for Reinforcement: State of the Art Report, Thomas Telford Services Ltd, 1995, 51pp.

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International Zinc Association, Hot Dip Galvanized Reinforcing Steel – A Concrete Investment, IZA, Brussels, 2006, 16pp.

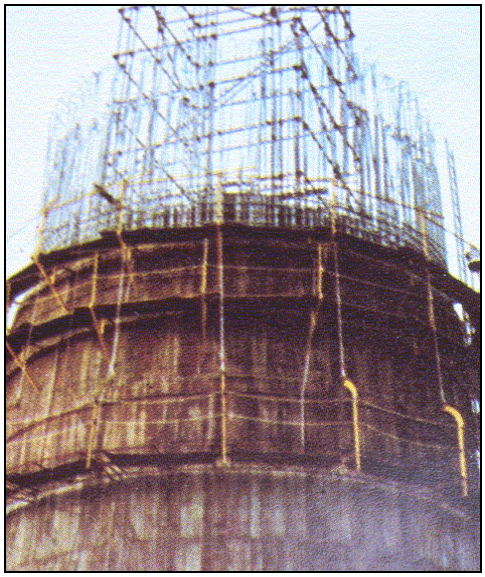
Yeomans SR (Editor), *Galvanized Reinforcing Steel in Concrete*, Elsevier UK, December 2004, ISBN 008044511X, 320pp.

Reinforced wall, Long Bay, NSW

Access hole steps

Steelworks - coke ovens storage

Rail tunnel, Melbourne



Slip formed chimney

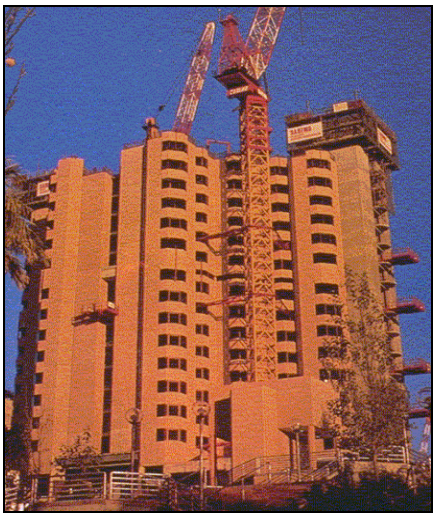
Sundial - Singleton, NSW

Figure 21. Galvanized reinforcement concrete in general construction.

Courthouse, Townsville, Queensland

Parliament House, Australia

100 William Street, Sydney

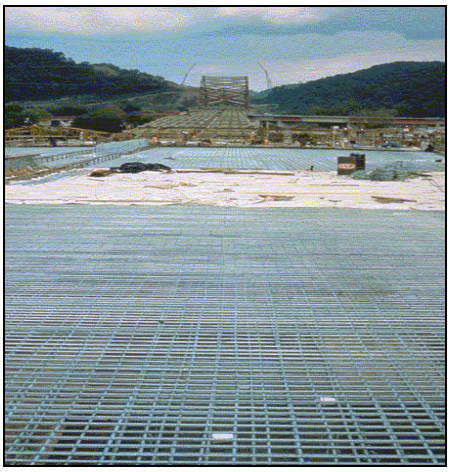


ASER Tower, Adelaide

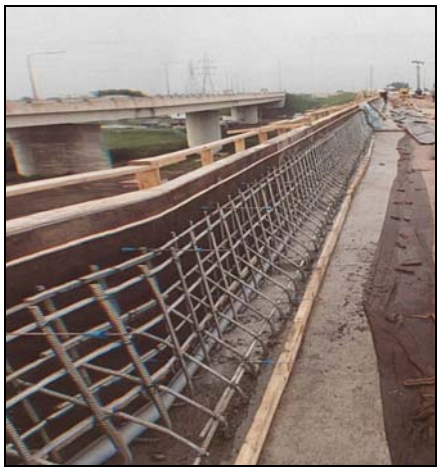
Precast window panels

Spandrel beams

Figure 22. Galvanized reinforcement concrete in buildings.



Bridge deck, USA



Safety barrier, Auto route

Road pavement, USA

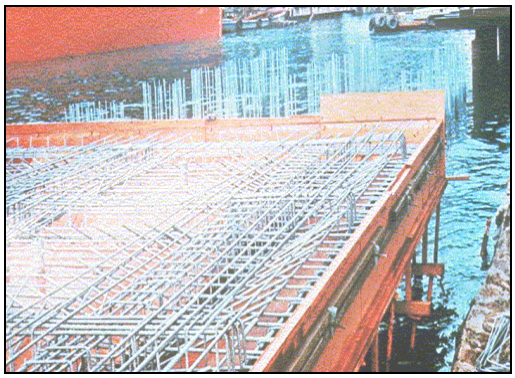
Elevated roadway – USA

Bridge construction – USA

Crash barrier, Canada

Figure 23. Galvanized reinforcement concrete in bridges and highways.

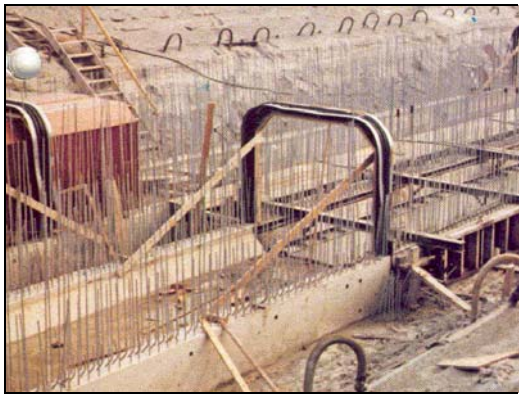
Floating marinas, Australia



Ominichi Pier, Japan

Sewerage outfall tunnels - Australia

ANDOC oil platform – North Sea



Seawater cooling channels - Holland

Seawall – Australia

Figure 24. Galvanized reinforcement concrete in coastal and marine environments.