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ASSOCIATION OF AUSTRALIA

Galvanized Reinforcement In Concrete Structures Questions and Answers

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In collaboration with the Galvanizers Association of Australia

Edition 2.0 | April 2018

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Cover page: Sydney Opera House

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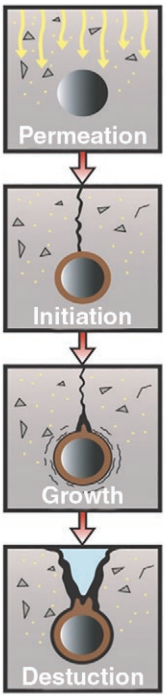
Introduction

Some issues with reinforced concrete

When steel is placed in concrete it is protected from corrosion due to the formation of a protective, so-called passive, film on the surface of the metal in the highly alkaline environment of hydrated cement (> pH 12.5). For long-term corrosion protection, the concrete cover must limit the transport of aggressive species such as chloride and other ions, oxygen, carbon dioxide and other gases through to the depth of the reinforcement. The effect of these is that they change the protective nature of the concrete and/or disrupt the passive film on the surface of the steel leading to the onset of corrosion. This situation in reinforced concrete construction is broadly identified as a lack of durability.

Once corrosion of the reinforcement commences, physical deterioration of the concrete mass soon follows. The reasons for this are that the various iron corrosion products formed are expansive (by a factor of up to 7 times) and their presence at the surface of the steel causes a swelling pressure sufficient to crack the concrete in tension. Once the cracks reach the external surface, a more direct entry path for the aggressive species is created and the corrosion process gathers momentum.

Corrosion of normal reinforcement



At this stage, rust staining of the surface is usually evident and, as more corrosion products are formed, pieces of concrete may spall from the surface. In this condition, issues of public safety become a concern – the problem of falling concrete – and eventually the structural integrity of the element may be impaired.

The prevention of reinforcement corrosion

Without question, the most cost-effective way to minimize the risk of corrosion in reinforced concrete is to ensure that the concrete is of appropriate quality for the intended application and that the depth of cover to the reinforcement is adequate. These are matters primarily related to the design and manufacture of the concrete itself and its placement on site including positioning of the reinforcement followed by proper compaction and curing of the fresh concrete. Though this is all well understood and, if followed, a long and trouble-free life of reinforced concrete construction can be achieved, it is unfortunate that the deterioration of concrete due to corrosion of embedded steel in the form of reinforcement, bolts, fittings, anchorages etc, is not uncommon.

What then can be done to minimize the risk of corrosion in the event that the concrete mass is not of sufficient durability? A number of options are available including the use of membranes on the surface of concrete, corrosion resisting reinforcement such as stainless steels, cathodic protection of the reinforcement, or coating of the reinforcement itself. The choice of any of these supplementary protective measures is based on both economic and technical considerations. Clearly issues such as availability of the product or system, initial and long-term costs, need for repair and maintenance, and its overall suitability for the intended application are all important.

As far as coatings are concerned, galvanizing is by far the most common. Its first regular use was in the 1930s in the USA. Since this time, and especially the last 25-30 years, its use in a wide variety of concrete construction and exposure conditions in many countries has been widely documented. There is also a published record of both laboratory-based research and field studies of the characteristics and performance of zinc-coated steel products in concrete construction. Acceptance of the use of galvanized reinforcement is also reflected in the significant number of national and international Standards for the use of zinc coated (i.e. galvanized) reinforcement published in recent years, as well as technical publications, codes of practice and specifications relating to galvanized reinforcement.

This document has been designed to concentrate on common questions and answers raised by designers and practitioners alike on the use of hot dip galvanized coatings on steel used in concrete.

Further technical detail can be obtained from the Galvanizers Association of Australia or from the literature and websites referred to at the end of this document.

Example of HDG reinforcement used in the construction of sewer pipes to prolong life and resist the effects of corrosion

Q1: What is the rationale for using galvanized reinforcement in concrete construction?

Galvanized steel reinforcement and other fittings including bolts, ties, anchors, dowel bars, and piping have been extensively used in a wide range of reinforced concrete structures and elements in many different exposure conditions. The rationale for this is simply that the zinc coating provides a safeguard against early or unexpected corrosion of the reinforcement. Should such damage occur, deterioration of the concrete mass will result and the structural integrity of the element may be compromised. The consequences of this are that repair and remediation of the structure, often at great expense, may be necessary not only to maintain the ongoing functional requirements but also to ensure that the design service life of the structure is achieved.

Repairs to reinforced concrete, should they be required, represent an ever-increasing economic burden on governments and other agencies and which redirects already scarce resources, both financial and material. Galvanizing, as a primary means of corrosion protection of steel, can significantly reduce the need and urgency for these repairs to reinforced concrete construction.

Q2: What are the important differences between galvanizing and other coatings for reinforcing steel?

Unlike painting and epoxy coating on steel which are solely barrier-type coatings, galvanizing provides both barrier and sacrificial protection to the underlying steel. In a barrier coating, once the coating is damaged and the underlying steel is exposed, corrosion commences. This often leads to so-called under-film or filiform corrosion in which corrosion proceeds under the adjacent coating resulting in the further de-adhesion of the coating and continuation of corrosion.

As a barrier, the galvanized coating on reinforcement isolates the steel from the cement matrix and corrosion of the underlying steel will only commence once the coating has been completely corroded away. Because the rate of corrosion of zinc in concrete is usually extremely slow, the loss of the coating in this way is a very long-term process and so corrosion of the steel is significantly delayed.

However, even if the coating has dissolved or been mechanically damaged such that the underlying steel is exposed, the remaining zinc on the adjacent surface becomes anodic and provides sacrificial cathodic protection to the bare steel. As such, the corrosion of the exposed steel is further delayed. The extent of coverage afforded by this reaction depends on many factors but primarily the conductivity of the surrounding environment, i.e. concrete in this case. Experimental data has shown that in sand-cement mortars with a water/cement ratio of about 0.4, exposed steel is protected by the presence of the zinc to a distance of about 8mm.

Q3: How long have galvanized steels been used in concrete?

The first reports on the use of zinc coated steel in concrete date to about 1908. Its first regular use as a reinforcing material was in the 1930s in the USA. One early example was in the construction of concrete water tanks where galvanized wire was used to pre-stress the tank wall. In the post-WWII period the use of galvanized rebar became more common and by the 1960s and early 1970s a considerable tonnage of steel reinforcement was being galvanized especially for use in bridge and highway construction across the snow-belt states of the USA and Canada. Its use diminished somewhat from the late-1970s when the FHWA temporarily classified galvanizing as an experimental system. After a period of extensive research this ruling was rescinded in 1983 thereby allowing the various States more flexibility in the selection of corrosion protection systems, again including galvanizing.

Since this time, and especially over about the last 25-30 years, there has been a steady world-wide use of galvanized reinforcement in a wide variety of types of concrete construction and exposure conditions. 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 and State bodies, especially in North America.

The first reports on the use of zinc coated steel in concrete date to about 1908. Its first regular use as a reinforcing material was in the 1930s in the USA

Q4: In designing of reinforced concrete are there different requirements when galvanized bar is to be used?

There are no special requirements for the design of galvanized reinforced concrete 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. Best practice when utilising galvanized reinforcement is to use appropriately designed and placed concrete as would normally be used in general reinforced concrete construction.

Q5: Can galvanized and black steel reinforcement be used together in concrete?

Because zinc is naturally protective to steel, galvanized reinforcement can be safely mixed with uncoated steel in concrete. However, if galvanized steel and black steel are to be connected in concrete, say for example between different mesh layers of an exposed panel or the upper section only of reinforcement in a pile foundation in the ground, the best option is to ensure that the point of connection between the two materials is well embedded and sufficiently deep such that there is no corrosion risk for either material, but especially so the steel.

If corrosion of the black steel were to initiate at the connection, the zinc on the adjacent bar will simply act to cathodically protect the black steel. Clearly, the protection afforded by the zinc will cause the zinc to slowly dissolve and this is, of course, not the preferred outcome. To an extent this could be seen as wasting the benefit obtained by using galvanized steel in the first instance. So, to be safe, minimise the connections between galvanized steel and black steel as far as possible but if this is necessary then keep the point of connection deeply embedded in sound concrete where the risk of corrosion of the steel is minimal.

Q6: What is the cost of galvanized reinforcement?

As a general guide, the cost of hot dip galvanizing typically adds about 50% to the cost of the reinforcement, however this figure does vary somewhat around the country and even in different parts of a State. Many factors influence the cost of galvanizing including the variable cost of zinc, the type, size and complexity of the items being galvanized, the current cost of labour, chemicals and power, and even transport costs. Advice on this can of course be obtained from your local galvanizer.

Q7: When specifying galvanizing, why is it necessary to specify hot dip galvanizing?

Zinc can be applied to steel in a number of ways including hot dipping, electroplating, spraying and mechanical alloying. Each method produces a specific type of coating which will vary in its structure, thickness and performance, especially its anticipated life in different exposure conditions. This is because the life of a galvanized coating is primarily determined by its thickness.

Hot dip galvanizing is the most common method of galvanizing and is that which should always be specified for the coating of structural steels including reinforcing bar. The coating produced by hot dipping, which is metallurgically bonded to the steel and generally more than 85 µm thick or 100 µm thick on reinforcing bar, is strongly adhered to the base steel, quite tough and damage resistant.

It is important to remember that the term galvanizing is often used to broadly mean *the coating of steel with zinc*. When used in isolation, it does not specifically identify the method of coating and so may be taken to allow coating by any of the available methods. This is the reason why it is important to be precise when specifying galvanizing to ensure that the requisite coating thickness and coating morphology will be obtained. Thus, for reinforcing steel as with most structural steel sections, hot dip galvanizing to AS/NZS 4680 should always be specified.

Q8: What types of steel reinforcement can be safely galvanized?

Nearly all types of reinforcing steels can be galvanized, including the newer high strength grades. Over the years, extensive testing has confirmed that galvanizing does not adversely affect the tensile mechanical properties of conventional reinforcing steels (around 250 MPa) providing such steels have not been excessively cold worked prior to galvanizing (e.g. by bending and re-bending).

There is some evidence that the earlier cold-twisted, high strength bars (around 400 MPa) which had been subsequently bent during fabrication may be embrittled by galvanizing. However, this problem was 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). These steels can be satisfactorily galvanized without need for any special requirements with no significant effect on their strength or ductility.

More recently, higher strength reinforcement to 500 MPa yield has been introduced and extensive testing has again verified that the superior mechanical properties of these steels are retained after hot dip galvanizing.

Example of HDG reinforcement used in the construction of sewer pipes to prolong life and resist the effects of corrosion

Q9: Does galvanizing adversely affect the structure and properties of reinforcing steel?

The microstructure and the mechanical properties of steels are primarily controlled by the temperatures to which they are heated during processing and the subsequent rate of cooling to ambient temperature. Cold working (i.e. rolling, forming or twisting) also significantly alters both the microstructure of steel and its mechanical properties. As a general rule, steels must be heated for a reasonable period of time above about 650°C for there to be any significant effect on either the microstructure or the mechanical properties of the steel concerned.

In hot dip galvanizing, the maximum temperature reached in the zinc bath is about 450°C. This temperature is not sufficiently high to cause any noticeable heat treatment effect in structural steels and exhaustive testing of all types of reinforcing steel has consistently shown this to be the case. Reinforcement that has been cold-worked (e.g. by twisting or bending) might soften very slightly during hot dipping but this has not been identified as being of any concern.

Similarly, high tensile steels with yield strengths approaching 1,000 MPa are regularly galvanized without any significant effect on their properties. One concern with these types of steels is embrittlement which may occur when they are exposed to heat and hydrogen, an effect known as hydrogen embrittlement. However, since even the highest strength reinforcing steels do not have yield strengths above about 750 MPa, the risk of hydrogen embrittlement is negligible.

As a general guide, if there is any concern about the effect of galvanizing on the properties of the steel concerned a simple retest of the steel after galvanizing can be performed.

Q10: Are any special techniques necessary when using galvanized reinforcement?

There are no special techniques necessary beyond that used for conventional concrete construction with black steel. Here are some general, good-practice guidelines to be followed.

On receipt of the material, visually inspect for damage and check for secure tie-downs on transport. In unloading and job site handling, there is no special handling or care necessary but bundles should be lifted at multiple pick-up points and spreader bars should be used with additional nylon straps to prevent sag and bar-to-bar abrasion in longer bundles.

When storing galvanized products, the material should be blocked and stored on a slant to allow for water drainage and air flow. When placing galvanized reinforcement in the formwork, no special care is necessary but bar supports, and spacers should all be hot-dip galvanized, though other plastic or non-conductive coated steel materials can be used. When splicing, a bar-lock coupler is recommended which can be either galvanized or stainless.

For welded splices, all welds should be touched up as recommended in appropriate Standards, for example using zinc rich paints. It is also recommended to use appropriate protective masks and suitable ventilation when welding. Field cutting of reinforcement should be avoided and cut ends should be repaired using an appropriate touch-up procedure. In the concrete pour itself, no special handling or care is necessary.

Q11: What is the cost premium to be paid in construction if galvanized reinforcement is specified?

While the initial cost of galvanizing may add up to 50% to the cost of the reinforcement, this cost premium as a percentage of total building cost is always significantly less. The overall cost for using galvanized reinforcement in concrete construction depends largely on the extent to which it is used throughout the structure. For example, it is rarely necessary for the structural core or internal elements of a high rise building or the deeply embedded components of large abutments and foundations, to be galvanized. In these situations, it may only be necessary to use galvanized reinforcement in surface exposed elements or where foundations and the like may be affected by aggressive or fluctuating groundwater.

In building construction, it is generally found that the cost of galvanizing increases the overall cost of concrete as-placed by about 6-10% depending on the size and type of bar used, the galvanizing price and the quantity of steel per cubic meter of concrete. On average, the cost of the reinforcement would not be more than about 25% of the total cost of the concrete as placed. Considering 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 costs. This premium reduces to as little as 0.5-1.0% if galvanizing is restricted to surface panels only. However, when taken against the total project cost or final selling price, the added cost of galvanizing becomes very small indeed, often not more than 0.1-0.2%.

When the costs and consequences of corrosion damage to a reinforced concrete building are analysed, this extra cost of galvanizing is often seen as a very small investment in achieving long-term corrosion protection.

Q12: Can a poorer quality concrete be used given the extra protection of galvanizing?

When using galvanized reinforcement, as is the case with any corrosion protection system in concrete, it is important that the concrete itself 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.

Commonwealth Bank, Brisbane

Q13: What Standards should be used when galvanizing reinforcing steels?

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 as with other typical or general steel products, so the galvanizing of reinforcement falls under a general galvanizing Standard. Elsewhere, dedicated Standards relating solely to reinforcing steel have been published. Some examples are:

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

Reinforcing Steel Standards

- **United States:** ASTM A767, Zinc-coated (galvanized) steel bars for concrete reinforcement
- **ISO:** ISO 14657, Zinc-coated steel for the reinforcement of concrete
- **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

Q14: What coating thickness should be specified when galvanizing reinforcing steel?

In all general galvanizing Standards, and also those specific to reinforcing steels, an average minimum thickness (or mass) of the coating is specified depending on the thickness of the base material.

As a general guide, a minimum average coating mass in the range 600-610 g/m^2, which equates to a coating thickness of 85-87 µm, is specified for sections greater than 5-6mm thick. This is a typical specified coating thickness for general galvanizing and should be followed for reinforcing steel and related products as well. For example, this value is nominated in both AS/NZS 4680 and ISO 14657 for bars greater than 6 mm in diameter. Note however that some Standards (e.g. ASTM A 767), include requirements for thicker coatings on heavier structural bars.

Q15: Zinc reacts in both acids and strong alkalis (i.e. is amphoteric). Can it be safely used in the highly alkaline environment of concrete?

Yes it can. When freshly galvanized reinforcing bar is embedded into wet concrete or cement paste, generally with a pH about 13.1, a tightly adhered layer of calcium hydroxyzincate salts forms on the bar surface which inhibits further attack on the coating due to its passivating effect. This reaction consumes about 10 µm of the original zinc coating at the surface of the coating.

This layer, known as a passivating film, isolates the zinc coating from the surrounding cement-rich matrix and once the concrete has hardened (which usually only takes a few hours) the reaction effectively ceases. The calcium hydroxyzincate layer is quite stable and remains intact on the bar surface as long as the passivating conditions at the bar surface are maintained.

Q16: Will concrete bond adequately to galvanized reinforcement?

There is a vast body of evidence showing that concrete tightly adheres to galvanized reinforcement. In fact, this adhesion is better than that achieved with uncoated steel. The basis of this is the formation of the protective surface layer of calcium hydroxyzincate. This layer is not only tightly adhered to the zinc surface it also interacts with the adjacent cement matrix effectively creating a bridge between the bar and the matrix. There is also evidence to show that the zinc corrosion products released from the surface of the coating in these circumstances migrate (or diffuse) into a narrow interfacial zone between the bar and the concrete resulting in strengthening and densification of this zone.

The result is that the galvanized bar has a high level of adhesion to the concrete which substantially increases the bond between the bar and the concrete. This situation is quite different to that found with black steel bars where there is in fact very little chemical adhesion between the bar and concrete. Similarly, with epoxy coated bars, there is no adhesion, per se, of the concrete to the coating with the result that such coated bars show a reduced bond capacity to both black steel bars and also galvanized bars.

Q17: What is the bond strength of galvanized bar in concrete?

The bond (or pull-out) strength of reinforcement in concrete is determined by a combination of the mechanical interlock between the concrete and the deformation ribs on the surface of the bar, adhesion between the bar and the concrete and frictional resistance along the surface of the bar as slip commences. With conventional deformed (i.e. ribbed) bar, mechanical interlock where the concrete bears against the raised rib pattern is the primary factor in determining the bond strength. However, the level of adhesion between the bar and the concrete does provides additional bond capacity.

Black steel reinforcement embedded in concrete exhibits only limited adhesion to concrete and so its pull-out strength is mainly determined by the geometry of the rib pattern. Galvanized reinforcement on the other hand is quite firmly adhered to concrete and, as a result, it usually displays a higher bond strength and reduced load-induced slip than equivalent black steel reinforcement.

Though these bond and slip improvements with galvanizing are realised in practice, this is not taken into account in the design of galvanized reinforced concrete and it is always assumed that the bond strength of galvanized reinforcement is no less than that of equivalent black steel reinforcement. That this may be somewhat higher than for black steel is purely taken as an added advantage. This approach simplifies the RC design process in that the same structural design considerations apply to galvanized reinforced concrete and conventional reinforced concrete. The same cannot be said however for epoxy coated reinforcement where the lack of adhesion and the low frictional effect necessitate greater embedment lengths of epoxy coated steel to achieve the same bond capacity as black steel.

Q18: Why is there sometimes a delay in the development of the full bond capacity of galvanized reinforcement?

When galvanized steel comes in contact with fresh concrete, the reactions which occur at the coating surface which ultimately leads to passivation produce small quantities of zinc-rich corrosion products which mix into the adjacent concrete. These zinc salts (e.g. ZnO) retard the hydration of cement and so slightly delay the strength development of the concrete in this region. The result is that the increase in the bond strength of galvanized reinforcement lags slightly behind that of uncoated steel. This effect only lasts for the first week or so of curing and by 28 days it is usual for the concrete to have developed both its normal 28 day compressive and bond strength. Beyond this time as curing continues, the galvanized reinforced concrete will develop the typical higher bond capacity and reduced slip characteristics over that of black steel.

This is the reason why the bond strength of galvanized reinforcement may occasionally be reported as less than that of equivalent black steel in early age testing (i.e. less than 28 days). Beyond 28 days, the reduction is no longer evident and galvanized reinforcement exhibits the improved bond characteristics noted. Thus be cautious and always check the curing period when comparative bond strength test is being undertaken with black and galvanized steel.

Q19: What is the effect of the carbonation of concrete on the behaviour of galvanized reinforcement?

Carbonation is a natural process in concrete and is the neutralization of the high alkalinity of the cover concrete due to reaction with slightly acidic rainwater or reaction with atmospheric carbon dioxide. Over an extended period of time, which is largely determined by the quality of the concrete, a carbonation front migrates into the concrete mass eventually reducing the pH to near neutral levels (pH 7). As the pH is reduced below about 11.5, black steel in concrete depassivates and corrosion initiates. This is one of the more common reasons for the corrosion of black steel reinforcement.

In contrast, galvanized steel can resist the carbonation-induced reduction in pH since zinc has a very low rate of corrosion across a wide range of pH. This would indicate that galvanized reinforcement should perform well in carbonated concrete, and this has been confirmed by extensive research and field observation. In effect, it can be safely stated that galvanized steel does not corrode in carbonated concrete.

"the use of galvanized reinforcement should not be considered as an alternative to the provisions of adequate cover of dense, impermeable concrete"

Q20: What is the chloride threshold for galvanized rebar in concrete?

Chlorides are the most frequent cause of reinforcement corrosion. The chlorides are present in the concrete from two sources: from mixing as part of the raw materials (water, aggregates or as an admixture); and from marine exposure or the use of de-icing salts. In both cases the attack on the reinforcement is localized in the form of pitting which results in a reduction of the cross section of the reinforcement. For black steel in concrete the chloride threshold 0.2% of the cement content (or 0.6 kg/m^3 of concrete) is recommended for a low corrosion risk.

For galvanized steel in concrete, there is no universal agreement on what the chloride threshold may be. What is clear however is that a significantly higher chloride threshold is needed to initiate attack on the zinc coating. For example, in simulated cement solutions, it has been shown that zinc is attacked at chloride concentrations some 5-6 times higher than that required for black steel while in concrete specimens the chloride threshold is reported to be at least 2-2.5 times higher than that for black steel, and likely somewhat higher than this. Some isolated field results suggest a threshold up to 8-10 times higher.

These high tolerance levels to chloride are a major contributor to the long-term durability of galvanized reinforcement in concrete exposed to aggressive chloride-containing environments.

Q21: Does the coating structure influence the corrosion rate of galvanized steel in concrete?

The structure of the galvanized coating has an important influence on the rate of corrosion. Experimental results clearly show that the presence of the external pure zinc layer has the greatest effect in resisting chloride-induced corrosion while the underlying alloy layers are less resistant to chloride attack. In consequence, the most resistant galvanized coatings are those with a thicker external layer of pure zinc.

It is also known that the resistance of the galvanized coating to chloride attack depends on the compactness of the passivating surface layer as well as the microstructure of the remaining coating. By the time chlorides reach the reinforcement during the life of the structure, the protective surface layer of calcium hydroxyzincate should have already formed. If this layer 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.

The floating pontoons at this marina at Sandringham, Victoria used galvanized reinforcement

Q22: What is the life extension achieved with galvanized reinforcement?

The delay in the onset of corrosion of galvanized steel compared to black steel is known as the extension of the service life. For galvanized reinforcement in concrete, this extension of life to the onset of corrosion has variously been reported to be some 4-5 times longer than that for the corrosion of black steel in equivalent exposure conditions.

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 follows. For black steel assume an upper threshold value of 0.4% Cl^- by mass of cement, while for galvanized steel assume a lower threshold of 1.0% Cl^- based on conservative experimental and field data. Also assume an equivalent exposure condition in a marine concrete with 0.35% chloride ion concentration at the concrete surface, a 30 mm cover to the reinforcement and a chloride diffusion coefficient D of 1.4×10^{-12} m^2/s.

By using *Fick's Law* it is shown 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. In practice however, the extension is normally much longer.

Q23: Do accelerated corrosion tests on galvanized reinforcement provide a reliable assessment of their actual performance in the field?

Accelerated corrosion tests are used to compare the corrosion performance of similar materials under specific test conditions but they do not reliably predict the service life of those materials in the natural real environment. The reason is simply that an artificial and accelerated environment cannot precisely mirror the complex conditions that govern the rate of corrosion in service. Moreover, an accelerated test may not allow sufficient time for materials to passivate as they would in natural exposure and the test conditions may artificially change the natural behaviour characteristics of the material in question. In the accelerated testing of reinforced concrete, it is often the case that specimens with reduced concrete covers and/or high water-to-cement ratios, and even pre- cracking, have been used to promote an early corrosion reaction. Clearly, such specimen conditions rarely represent the real life situation.

As a result, it is dangerous to draw too heavily on the results of the accelerated testing of isolated specimens. What may be possible however is to make general comparisons between specimens of (say) different reinforcement in concrete of similar geometry in identical exposure conditions. If accelerated testing results can be correlated with data from natural and long-term exposure, this will be the most reliable comparison to make and of the greatest benefit.

Lotus temple, Delhi

Q24: Is hydrogen embrittlement an issue when zinc coated products are exposed to wet concrete?

Even though some hydrogen may be liberated when galvanized steel is embedded in fresh concrete, this doesn't present any risk of hydrogen embrittlement in traditional reinforcement. However, heavily cold worked steels (e.g. cold-twisted bar and reinforcement that has been bent and re-bent) may be sensitised to hydrogen embrittlement during acid pickling in the galvanizing process, but this is not likely to be encountered with modern forms of reinforcement.

Cold working may also render the steel susceptible to an effect known as strain ageing at the temperature of the molten zinc bath. This does cause a reduction in ductility of the bar and because of this stain ageing is sometimes mistakenly attributed to hydrogen embrittlement. An understanding of the composition and metallurgy of the steel will assist in avoiding such difficulties.

Q25: Are any special considerations necessary when galvanized reinforcement is cast in black steel formwork in the manufacture of precast concrete?

In this situation, the black steel panel formwork becomes cathodic in contact with galvanized steel in fresh concrete. Bond-breakers or mould release agents commonly used with steel formwork do not function effectively when the steel is cathodic, so concrete sticks to the formwork. A chromate dip or wash which passivates the galvanized steel restores the effectiveness of the bond-breakers. Chromic oxide additions to the concrete (100 ppm based on the weight of the mixing water) have proved to be effective.

Q26: What is “white rust” and is this damaging to galvanized reinforcement?

Zinc is a relatively active metal and like other metals, such as aluminium, zinc relies on the formation initially of an oxide film (which later converts to a carbonate film) on its surface for its long-term durability. Once this film is formed, the rate of corrosion of zinc (i.e. galvanized) coatings is very slow, typically less than 2 microns loss in thickness per year in normal environments. When steel is freshly galvanized, there is no significant oxide film on its surface and in conditions where water is present and oxygen is deficient, such as between contacting surfaces where water can penetrate, water continues to react with the zinc over an extended period. The usual result is the formation of a heavy surface layer of zinc hydroxide, known as white rust.

Though not particularly damaging, and with very little effect on the corrosion resistance of the coating, it does detract from the appearance of the galvanizing. There is no evidence to suggest that small quantities of white rust on the surface of galvanized reinforcement have any effect on the adhesion of concrete to the bar or the long-term corrosion resistance provided by the coating.

To overcome this potential problem in general galvanizing, it is standard practice in hot dip galvanizing facilities to cool the work by quenching it in water containing a low concentration of sodium dichromate. Chromate quench passivation, as this is known, provides initial protection to the zinc and gives it time to develop its own protective oxide film. It is to be noted however that such treatment is only temporary as the chromate passivation film, which is slightly soluble in water, can be washed off the surface. Short-term exposure to rain water is not necessarily a problem, and wetting and drying cycles may in fact assist in forming the protective oxide film, but over time exposure to such conditions will certainly deplete the chromate film.

Q27: Why is the galvanized coating sometimes thick and dull grey in colour?

Galvanizing normally has a bright and shiny surface. This is due to layer of pure zinc which remains on the surface of the coating as the product is withdrawn from the galvanizing bath. Some steels, especially those containing elevated silicon levels, react differently when they are galvanized. Known as reactive steels, the galvanized coating appears dull and grey and may be quite thick in comparison to the usual bright coating on normal steels. The reason for this is the continued growth of the underlying alloy layers in the coating which results in the complete disappearance of the pure zinc surface layer.

There is essentially no difference in the long-term corrosion resistance of grey coatings compared to bright coatings since the extent of corrosion protection is a function of the coating thickness not the coating structure.

As far as galvanized reinforcement is concerned, there is no effect on either the corrosion resistance or bond capacity if a grey coating is present. The only issue may be that the extra thickness of the coating and the absence of the pure zinc layer may cause some slight flaking during fabrication, but again this is not of concern. It should also be remembered that if galvanizing produces a grey coating this cannot be blamed on the galvanizer for it is the nature of the steel and not the galvanizing process which is the cause.

Sydney Opera House

A multi-storey car park suffering from spalled concrete due to corrosion of the rebar

Q28: Are there special transport and site handling methods necessary for galvanized rebar?

There are no special handling or transport methods necessary when loading/unloading or job site handling of galvanized reinforcement. In essence, the same methods used to handle and transport black steel reinforcement can be used for galvanized products including the use of wire ropes, chains and slings. It is recommended however that when bundles of long lengths of galvanized reinforcement are to be lifted (the bundles being inherently flexible), a spreader bar with additional nylon straps should be used to prevent excessive sag and bar-to-bar abrasion which may slightly damage the surface of the coating.

Q29: Are there special on site storage requirements for galvanized rebar?

Galvanized reinforcement (as with other galvanized products) can be stored directly on the ground without risk of significant damage to the coating. This is because the coating is quite tough and abrasion resistant and is firmly adhered to the base steel. As with all reinforcing materials for use in concrete, and in particular black steel, it is sensible to protect the product should it be necessary to store it for extended periods (say more than a few weeks) and especially so if it is exposed to marine spray conditions. Limiting the build-up of chlorides on the surface is of course desirable. For galvanized steel, it is recommended that bundles of freshly galvanized products be blocked and stored on a slant to allow for water drainage and air flow in order to minimise the risk of white rust formation.

Q30: When fixing galvanized rebar what types of ties and spacers should be used?

There is little point and no cost benefit in using black steel tie wires or spacers when fixing galvanized reinforcement. The reason is that should black steel ties be used to secure galvanized reinforcement and corrosion initiates, the surrounding zinc coating on the bar will sacrificially dissolve in order to protect the uncoated steel tie. This is what the galvanized coating is expected to do in the event the underlying steel is exposed but clearly this is not the intended outcome where a decision has been made to use galvanized rebar in the first instance.

To avoid this situation, it is recommended that bar supports, spacers and reinforcement supports should all be hot dip galvanized and that 16.5 gauge or heavier galvanized tie wire should be used. Alternatively, solid plastic or non-conductive coated steel components may be used though care should be exercised to ensure that the non-conductive (i.e. plastic) coating is itself not damaged.

Q31: Can threaded splice couplers be used with galvanized reinforcing bar?

The concern sometimes expressed here is that the galvanizing may clog the threads of the coupling and, if it is removed, it may not be possible to satisfactorily protect these areas from corrosion. The fact is however that hot dip galvanized threaded fasteners have been widely used for many decades. Generally, all that is required is that the male threaded components of the fastener be treated in manufacture to expel excessive zinc from the threads. The female components are dipped prior to thread cutting and their threads are tapped slightly oversized, typically by about 0.4 mm. Though the female threaded components are uncoated they nevertheless remain protected by the adjacent zinc surfaces. Most proprietary reinforcing couplers have threads with a very slack fit enabling even the female components to be dipped without problems of fouling. To assist fixing and prevent galling, these threaded components should be coated with a lubricant prior to assembly.

Q32: Can galvanized reinforcement be welded?

Galvanized reinforcement (and other galvanized products) can be satisfactorily welded by all common welding techniques. Some changes in the welding procedures to those used for uncoated steels are necessary but these are simple and well established. These changes are primarily intended to allow the galvanized coating to burn off at the front of the weld pool and to ensure full weld penetration. 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. This will minimise the risk of entraining zinc in the weld pool which may lead to porosity and intergranular cracking if not controlled.

Care should be exercised when welding galvanized steel to ensure that there is adequate ventilation and exhausting of fumes that may be generated. Because of the relatively low melting point of zinc, it is easily vaporised and converted to white zinc oxide fume. Though this fume is not toxic, it can cause discomfort if it is inhaled. In general, anything that can be welded before galvanizing can be welded after galvanizing. Further advice on the welding of galvanized steels can be obtained from the GAA.

Q33: Is it necessary to repair damage to galvanized rebar?

In areas where the coating has been damaged such as by bending, cutting or welding, local repair of the coating should be undertaken. A number of alternate repair systems are available including zinc-based solders which are spread across the cleaned and preheated surface, zinc-rich paints which contain a high proportion (generally over 90%) of metallic zinc in the dry film, zinc metallizing in which molten zinc is sprayed onto the cleaned surface, and zinc-rich epoxy-based fillers.

Overall, the repair can be easily undertaken by any of these methods and the results, though not as good as the original coating will provide adequate corrosion protection to the previously damaged region. Whenever a repair is undertaken it is important to appropriately clean the exposed metal surface and adjacent region. Further advice on the repair of galvanized steels can be obtained from the GAA.

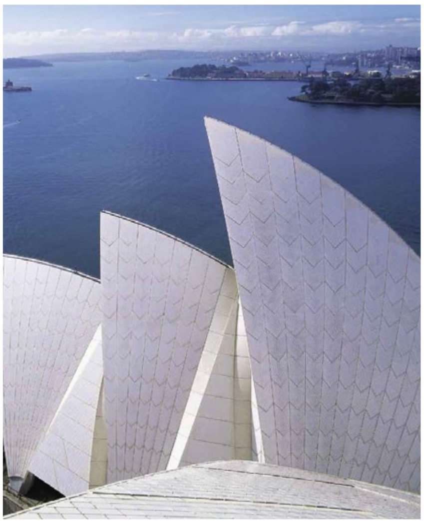
Parliament House, Canberra

Q34: What is best – galvanizing before or after fabrication?

While the majority of reinforcing steel is galvanized as straight lengths and then fabricated this often does require some repair of the coating at cut ends, bends and welds. Though coating repair can be easily and reliably completed, as is done with a wide range of galvanized products, there are advantages to be gained if galvanizing can be undertaken after all fabrication has been completed.

For example, if a sizeable reinforcing cage for a column, beam, foundation or a precast panel can be fabricated then galvanized, the coating will completely cover the bends, cuts and welds with no need for local repairs. In this case black steel tie wires can be safely used as will also be coated during the galvanizing process. The same principles apply to pre-fabricated stirrups and ties which are also regularly galvanized.

So the question of whether pre- or post-galvanizing is best depends on the circumstances. If it is possible to pre-fabricate and then galvanize this is a good option to follow. Note however that the ability to do this may well be dictated by the capacity of the galvanizing bath, especially so if large complicated pre-fabricated sections are to be coated. This is a matter that needs to be discussed with the galvanizer well in advance with appropriate planning.



Sydney Opera House

Q35: In what type of applications is galvanized reinforced concrete typically used?

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 and pulp mills, water and sewerage treatment works;
- processing facilities and chemical plants;
- power stations;
- waste water and sewerage treatment facilities;
- highway fittings and crash barriers, and also;
- lamp posts and power poles.

Q36: Is galvanized reinforcement suitable for use in light weight precast or tilt-up construction?

Galvanized reinforcement is ideally suited for use in all types of thin and light weight concrete construction. For example, it has been widely used in precast cladding panels and facades where the depth of cover to the reinforcement must be somewhat reduced over that used in normal concrete construction. Tilt-up panels is another good example and also ferro-cement construction in applications such as shelters, boats, pontoons and marine buoys where galvanized wire or mesh is often employed.

The reasons for this are straightforward. Where the cover is intentionally reduced and/or thin elements may crack, the corrosion protection afforded by the zinc coating ensures that the reinforcement does not prematurely corrode.

Q37: Why is galvanized reinforcement often used in large, prestige buildings?

Prestige buildings are usually important public buildings which are high-profile, perhaps iconic, and are highly visible and with extensive public access. They are often quite large and of complex construction, and usually built for a very long life. Some well-known examples are the National Theatre in London, the Sydney Opera House and the Australian Parliament House in Canberra.

A vitally important issue with such buildings, especially where large amounts of public funds have been expended, is that they maintain their pristine condition. The key to this is that cracking and rust staining of exposed concrete must not be allowed to occur and so very high quality materials and construction methods are usually employed. To this end, galvanizing of reinforcement in precast cladding panels, facades and exposed structural elements has been widely used to ensure a long, trouble-free life.

The bright white sails of the Sydney Opera House, located as it is on the foreshores of Sydney Harbour, is a perfect case in point: it would be 'catastrophic' if those sails were to be stained by rust streaming from the precast cladding panels.

Q38: What are the best sources of information on the use of galvanized reinforcement in concrete?

Many technical organizations and galvanizing associations across the world provide technical information on galvanizing in general and galvanized reinforcement in particular. Most of these have free-access web sites from which manuals, technical documents, specifications and local literature can be downloaded.

- **Galvanizers Association of Australia:** www.gaa.com.au
- **International Zinc Association:** www.galvanizedrebar.com
- **American Galvanizers Association:** www.galvanizeit.org
- **Galvanizing Association of New Zealand:** www.galvanizing.org.nz
- **Asia Pacific General Galvanizers Association:** www.galvanizingasia.com
- **Galvanizers Association UK:** www.hdg.org.uk

Q39: What are the practical benefits in using galvanized reinforcing steel in concrete?

This is best summarised by noting the benefits of the use of galvanized reinforcement published in the State of the Art Report on Coating Protection for Reinforcement (Comite Euro-International du Beton, 1992):

- proper galvanizing procedures have no significant effect on the mechanical properties of the steel reinforcement;
- 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;
- 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, and so 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;
- 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.

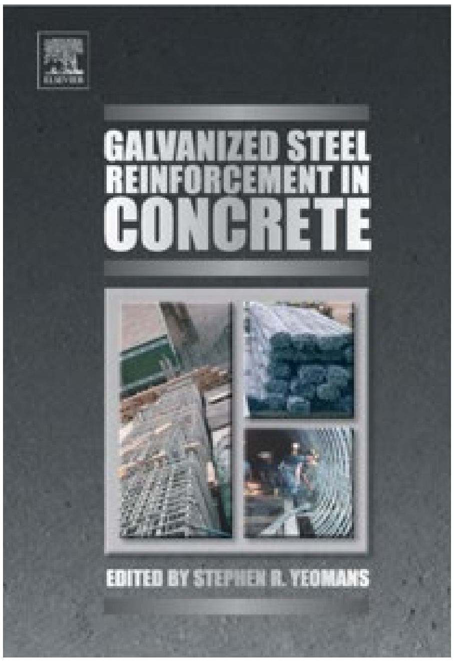
The report goes on to say that “it is important to remember that even if these benefits are achieved, the use of galvanized reinforcement should not be considered as an alternative to the provisions of adequate cover of dense, impermeable concrete, unless special design criteria have to be met. Galvanizing 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”.

Racking concrete

Q40: Is it advisable to communicate with the galvanizing company before specifying the galvanizing of reinforcement?

It is always advisable to be in contact with your local galvanizer at an early stage when any steelwork, including reinforcement, is to be galvanized. The galvanizer will readily provide advice on galvanizing capacity (bath size, etc.) scheduling, transport, packaging and handling. They will also assist with the design of items to be galvanized. This is an important preparatory consideration when complex built-up elements, such as prefabricated reinforcement cages for large columns and beams, are to be galvanized.

More information is available from the GAA at www.gaa.com.au or from the IZA at www.galvanizedrebar.com.



The bright white sails of the Sydney Opera House, located as it is on the foreshores of Sydney Harbour, is a perfect case in point: it would be 'catastrophic' if those sails were to be stained by rust streaming from the precast cladding panels.

Galvanized steel reinforcement in concrete

ISBN: 008044511X
Author/Editor: Yeomans, Stephen
Publisher: Elsevier Science
Website: www.elsevier.com
Pages: 350
Publication: December 2004
Price: USD 150.00

Key Features: Provides information vital to prolonging the life of buildings constructed from this versatile material. Gathers a disparate body of knowledge into concise and authoritative text.

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A multi-storey car park suffering from spalled concrete due to corrosion of the rebar

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