Galvanized Reinforcement: Recent Developments and New Opportunities

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Abstract

This paper discusses the traditional use of hot dipped galvanized reinforcement and the recent development of the continuous coating of reinforcement. The different process technologies and the effects of this on the thickness and morphology of the zinc coatings so produced are explained. The behaviour of zinc in the alkaline environment of concrete, the role of pure zinc in the passivation of the coating and its carbonation resistance and chloride tolerance also discussed. Approaches to the design of galvanized reinforced concrete including bond strength and slip are discussed as well as general fabrication practices. Recent applications of galvanized reinforcement in large construction and infrastructure are presented.

Results from a life-cycle cost and total present cost analysis of epoxy-coated, grade 316 stainless steel and hot dipped (batch) galvanized reinforcement in high chloride bridge deck exposure conditions are presented. In comparison, galvanized bar had the lowest life-cycle cost and total present cost. Galvanized steel also out-performs epoxy coated steel concerning time to deterioration of bridge decks, this difference increasing as the severity of chloride exposure increases. The service life of galvanized reinforced decks was 100 years in comparison to 55 years for epoxy coated reinforced decks and 100+ years for stainless bars.

1 Introduction

While the provision of good quality concrete based on sound design principles is fundamental to ensuring adequate durability of concrete and primary protection of the reinforcement, the galvanizing of reinforcement (i.e. coating with zinc) provides additional corrosion protection to embedded steel in the event of premature deterioration of the concrete mass. From its first reported use in the 1930s, galvanized reinforcement has been widely used, especially so over the last 40-50 years, in many types of concrete construction in a variety of exposure conditions.

The protection afforded to steel by the zinc coating is two-pronged; the coating itself provides barrier protection to the underlying steel and being more anodic than iron the zinc provides sacrificial cathodic protection of exposed steel in the event the coating is locally damaged. The characteristics and behaviour of galvanized reinforcement in simulated pore water solutions and in various mortars and concretes has been very widely investigated in a multitude of laboratory-based studies and also field examinations of existing structures.

An extensive record of this work has been published by ILZRO (1981) and CEB (1992) and more recently by Yeomans (2004). In broad terms, the results from these investigations have clearly demonstrated a number of key features of galvanized steel in concrete. These include the nature of the passivation reaction and the importance of the presence of pure zinc layer on the coating surface, the higher chloride tolerance of galvanized steel compared to black steel, and the resistance of galvanized steel to the carbonation of concrete. Other effects such as the morphology of the

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galvanized coating on its corrosion behaviour, the processes operating when the galvanized coating is corroding, and the resultant migration of zinc corrosion products into the adjacent cement matrix have also been widely studied. Some key aspects of this research are discussed in the following.

2 Hot Dip Galvanizing

Traditional hot dip galvanizing (HDG), often called 'batch galvanizing', involves immersing clean and pre-fluxed steel in a kettle of molten zinc at about 450°C. Once at the steel heats to the temperature of the zinc bath, a metallurgical reaction occurs resulting in the formation of a coating on the steel made up of a series of iron-zinc alloy layers (gamma, delta and zeta) that grow from the steel/zinc interface with a layer of essentially pure zinc (eta) at the outer surface. The alloy layer structure of a typical (so-called "bright") galvanized coating is shown in Fig. 1.

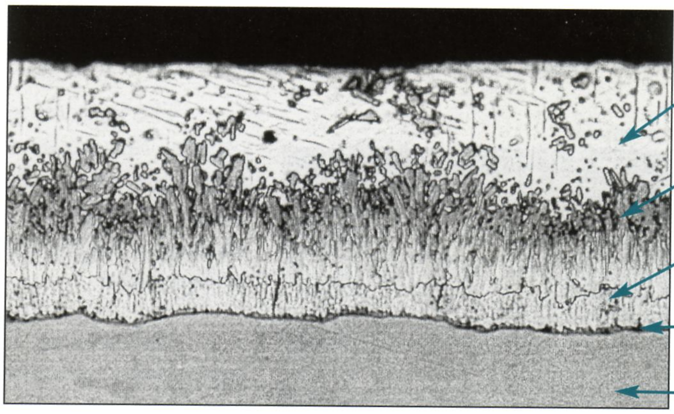

Figure 1. Typical coating structure of hot-dip galvanized steel.

In broad terms, the thickness of the HDG coating varies with the mass (i.e. thickness) of the steel being coated. The heavier the base steel the longer it resides in the zinc bath resulting in a thicker coating due to growth of the underlying alloy layers.

For steel greater than about 5 mm thick, national and international general galvanizing standards, as well as those for reinforcing steel (ISO14657, BS ISO14657, ASTM A767), nominate a minimum specified thickness of galvanized coatings of 85-87 microns equating to a coating mass of 600-610 g/m^2. In practice, typical coating thickness on HDG coated reinforcement is 110-120 microns though may be as much as 150-180 microns for larger bar sizes and prefabricated sections.

The distinguishing feature of galvanized coatings is that the coating is metallurgically bonded to the steel due to inter-alloying between the steel and the molten zinc. This results in a strongly adhered, tough and robust coating that can withstand the rigours of transportation, storage and placement as is the case for uncoated "black" steel bars.

A key feature of HDG coatings is that the outer eta layer, which is effectively pure zinc remaining on the surface of the product as it is withdrawn from the bath, is generally about 40-50 microns thick. As discussed below, it is the presence of this eta layer that controls much of the behaviour of zinc when in contact with wet cement.

3 Continuous galvanizing

A recent and developing technology is the continuous coating of galvanized reinforcement (CGR). As a simple and convenient in-line processes, continuous coating can process straight bar or coil-to-coil product directly into galvanized bar and offers not only an ease, speed and economy of production compared to traditional hot dip galvanizing, but is more energy efficient and with less environmental impact.

Continuous coating of reinforcement is a process similar to the widely used continuous coating of steel sheet and pipe products. In this, blast cleaned and preheated bar is fed through a molten zinc bath at speeds around 10 m/min such that the bar remains in the zinc bath for no more than 1-2 seconds. This has the effect of reducing the total time the bar is held at high temperature which including the preheating stage is not more than 4-5 seconds (Dallin, 2013). A schematic of this in-line process is shown in Fig. 2.

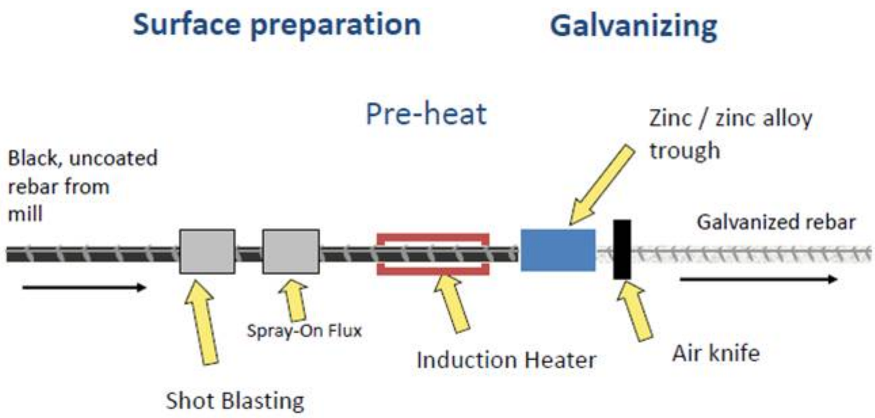

Figure 2. Typical layout of a continuous galvanizing line for reinforcement.

By adding a small amount of aluminum (0.2%) to the zinc bath, a coating typically 50-60 microns thick is produced which is almost entirely pure zinc with only a very thin layer (approximately 0.1 micron) of a ternary ($Fe_2Al_{5-x}Zn_x$) alloy at the zinc/steel interface. The speed of reaction and the addition of aluminium effectively retard the development of the underlying zinc-iron alloys layers typical of the hot-dip process where dwell times in the zinc bath and very much longer. The typical microstructure of continuously coated bar is in Fig. 3.

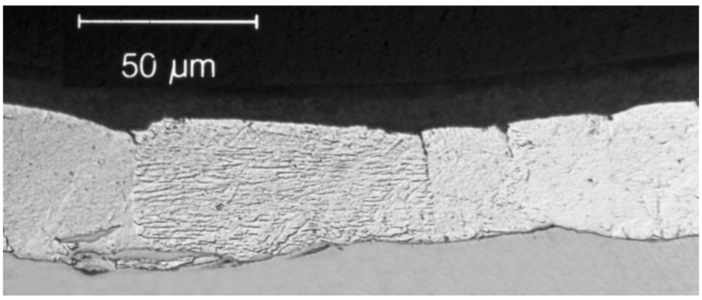

Figure 3. Coating structure of continuously galvanized reinforcement.

The absence of the underlying zinc-iron alloy layers, which detract somewhat from the formability of HDG bars, and that the coating is almost entirely pure zinc significantly improves the adhesion and formability of continuously coated galvanized bar. The CGR process thus results in a flexible and adherent galvanized coating. The coating can be bent, stretched, twisted or otherwise fabricated after galvanizing without cracking or flaking the coating, regardless of the total coating mass. Similarly, there is no zinc loss due to flaking during forming in the field and repair requirements are minimal.

Considering also that the passivation of zinc in concrete requires the presence of pure zinc on the coating surface (noting that about 10 microns of zinc is consumed during passivation), CGR affords ongoing corrosion resistance in concrete due to the large reserve of pure zinc in the coating. While HDG coatings with a pure zinc outer layer do have good corrosion performance, the zinc-iron alloy layers below have less corrosion resistance than pure zinc and do not contribute significantly to the corrosion performance.

CGR on the other hand, with a much thicker pure zinc coating (~ 50 microns) than the outer eta layer on many HDG coatings, provides ongoing corrosion protection in the event that corrosion commences over coatings with a thin or non-existent pure zinc top layer, thereby using less zinc without compromising corrosion protection.

While traditional hot-dip coating of reinforcement is common and can be undertaken as a batch process in general galvanizing baths, continuous coating requires the installation of dedicated in-line facilities. In general terms, CGR lines can be run as a low-volume, relatively simple operation coating one, two or three bars at a time or 6 to 8 bars simultaneously for higher volumes. Even at a lower production rate, a CGR line can run continuously for longer times (with minimal manpower) to increase thru-put and the line can easily be started on demand and shut down very quickly – the zinc reservoir is relatively small, easily heated and temperature controlled.

It is also conceivable to construct a line that has the capability to convert coat coiled black rebar into coiled CGR. Overall, continuous coating is much easier to control than batch galvanizing of bundles of bars. To the present time only a few CGR lines have yet been commissioned.

In Fujian Province SE China, Xiamen New Steel has been producing CGR since 2011 in the world's first continuous galvanizing rebar line. Output from this line has found applications in railway, highway and subway construction in China. For example, CGR have been used in the No.11 subway line – the fastest line in Shenzhen with a design speed of 120 km/h. CGR is also being used in the construction of the important G7 Expressway linking Beijing to Urumqi in Xinjiang Province. In other applications, the excellent coating formability of CGR has been used for cable hooks in railway roadbed cable troughs and power wells on the railway line from Beijing to the coastal city of Fuzhou. In Dubai, a pilot CGR plant has been commissioned by Super Galvanizing with the intention of coating specialist high strength reinforcement.

In the US, AZZ Incorporated has recently repurposed one of its plants from standard galvanizing to a continuous coating line by using existing technology applied to rebar. This facility in Oklahoma is currently owned by Commercial Metals Company and is the only CGR-producing facility in the United States. As noted, continuous galvanizing offers major benefits in terms of cost and quality. Compared with hot-dipping, the CGR process is a single step process using half as much zinc thereby reducing the weight of the coating[2]. The opportunities that have been identified are in highway concrete construction, including concrete bridge beams, jersey barriers, parapets, continuous concrete pavements and dowels. Another potential end market is general construction, such as balconies, pilings, seawalls and boat docks (American Metal Market, 2017).

As the demand for CGR increases it is expected that further lines will be commissioned to supply the world market. In moving forward, the development of national and international standards specifically for CGR is vitally important. Historically, ISO 14657 has covered the thickness range

[2] Zinc accounts for 4% of the weight of continuous galvanized rebar compared to about 8% of hot-dipped rebar.

for continuous galvanized coatings (i.e. to about 70 microns) and this has been used as appoint of reference.

To formalize this for continuously coated reinforcement, the American Society for Testing and Materials recently published a process specification for continuous hot-dip galvanized steel bars for concrete reinforcement manufactured in cut lengths or coils (ASTM A1094M, 2016). This specification identifies the process as the uninterrupted passage of long lengths of steel products through a molten bath of zinc or zinc alloy and that to control alloy formation and promote adhesion with the base steel, the molten metal coating would normally contain 0.05-0.2% aluminium. It notes that immediately after passing through the zinc bath, an air or steam wiping system is to be used to remove excess coating from the bars. The average thickness of the coating is specified as not less than 50 microns, equivalent to a coating mass of 360 g/m^2. The specification also gives guidance for the transportation, storage and construction site practices for continuously galvanized bars.

4 Behaviour of zinc in concrete

4.1 Passivation

Zinc reacts in both strong acids and strong bases but is relatively stable over the pH range from about 6 to 12.5. In the alkaline environment of fresh concrete, the main product to form on the zinc surface above pH 12.9 is the soluble zincate ion (ZnO_2^{2-}) with the effect that the galvanized coating corrodes at a relatively low rate and will passivate. Above pH 13.2, dissolution of the coating occurs with no passivation (Macais & Andrade, 1987a,b).

The corrosion product that leads to the passivation of zinc in calcium-rich alkaline solutions is calcium hydroxyzincate (CaHZn), the morphology of which varies with the pH of the contact solution. For example, at a pH around 12.6 the zinc surface is totally covered with a dense and compact layer of CaHZn crystals. However, as the pH increases the individual size and distribution of the CaHZn crystals also increases to a point where they cannot completely cover the surface.

When galvanized coatings come in contact with wet cement, about 10 microns of the outer layer of pure zinc is consumed during passivation. This progresses through the initial setting time (~ 1-2 hours) though once the concrete starts to harden the reaction at the surface diminishes as the passive film forms and blankets the zinc surface. Once the passive film has formed it will remain intact even if the pH increases to about 13.6.

4.2 Effect of carbonation

The carbonation of concrete, due to a reaction between the alkaline products in concrete and weak atmospheric acidic water results in a progressive lowering of the pH of the cover concrete. As the carbonation front progresses deeper into the concrete over time, corrosion of black steel commences when the alkalinity at the depth of the bar reaches pH 11.5. This is, of course, a significant durability consideration for conventional reinforced concrete construction.

Galvanized reinforcement is however immune to this effect due to the increasing corrosion resistance of zinc as the pH of the cover concrete is reduced even below pH 11.5. As such, galvanized reinforcement is not significantly affected by the carbonation of concrete and in some circumstances carbonation may actually reduce the rate of corrosion (Andrade and Alonso, 2004).

4.3 Effect of chlorides

Chlorides, which find their way into concrete by either being added through the mix materials or by migration from the marine environment, brackish water or de-icing salts, are a common cause of corrosion of steel reinforcement in concrete. A threshold concentration of chlorides, which is pH dependent, is required to initiate corrosion. The chlorides disrupt the passive film on steel even at high pH and prevent it from re-forming resulting in highly localised pitting attack. For black steel, a chloride content of less than 0.2% by mass of cement is recommended for a low corrosion risk (ACI, 1994) while a chloride threshold of 0.4% by mass of cement is often cited.

While there is some divergence of opinion on a precise chloride threshold for galvanized steel in concrete, a conservative value of 1% chlorides by mass of cement is often used, thus 2.5 times higher than that for black steel (Yeomans, 1994). This value is derived from numerous laboratory and field studies that clearly indicate that a significantly higher chloride threshold, some 2-2.5 times higher, is needed to initiate corrosion compared to black steel (Yeomans, 2004).

Recent work by Darwin et al (2007, 2009) showed that galvanized reinforcement exhibited a chloride corrosion initiation over black steel up to 3 to 4 times higher though on average 1.6 times higher. Presuel-Morento and Rourke (2009) reported chloride levels of about 2% by weight of cement for the onset of attack galvanized bars and which significantly extended the service life over black steel. In studies of galvanized reinforcement in concretes exposed in the Mexican Caribbean, Maldonado (2009) indicated that galvanized reinforcement can resist chloride levels 2.6–3 times higher than black steel and that the time to initiation for galvanized steel was twice that for black steel reinforcement.

In other work, Srimahajariyaphong and Niltawach (2011) recorded chloride levels as high as 0.38% by weight of concrete (about 2.3% by weight of cement) on galvanized bars with no signs of corrosion. Further, Bertolini (2013) reported a threshold 1.5 to 2 times that for black steel in chloride contaminated concrete, while Sanchez (2014) cited a 2 times threshold from laboratory and field studies, and Hegyi (2015) indicated a chloride threshold for galvanized bars 3.1 times that of black steel in concrete admixed with $CaCl_2$.

As the above indicates, there is variation in the chloride threshold for the initiation of corrosion on galvanized steel in concrete. While measuring a chloride threshold is quite straightforward in aqueous solutions simulating concrete pore water, the conditions in concrete are, of course, quite different and variable. Also, differences in the structure of the alloy layers of the galvanized coating and especially the presence of the pure zinc outer layer, is known to affect corrosion initiation and thus the measured chloride levels. Thus it is not unexpected that these differences in the chloride threshold are reported. Despite this, it is apparent the chloride threshold for galvanized steel is several times that for black steel and a factor of 2 to 2.5 times (as noted above) is not unreasonable.

4.4 Coating behaviour

Other important issues concern the behaviour of the zinc coating when in contact with concrete, in particular how the coating dissolves and what happens to the corrosion products so formed. As previously noted, when the galvanized coating first comes in contact with wet cement, about 10 microns of zinc is dissolved from the pure zinc outer layer of the coating during passivation. What has been widely observed in field structures is that the remainder of the galvanized coating (generally 100 microns or more) remains in its original 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 from the coating until active corrosion commences, usually due to the accumulation of threshold levels of chloride at the depth of the reinforcement (Yeomans 1998, 2004).

Once this occurs, dissolution of the remaining free zinc occurs in and around in the alloy layers, particularly so the delta phase, which comprises the bulk of a bright galvanized coating (Yeomans, 1998). Though the coating thickness is partially reduced by this loss, a dense layer of both the gamma and delta phases remains at the bar surface and this affords ongoing protection to the underlying steel.

4.5 Zinc corrosion products

When black steel corrodes in concrete, the corrosion products so formed are significantly more voluminous than iron (a factor of 2-10 times) and precipitate immediately at the bar/concrete interface. This causes the buildup of tensile stress around the bar leading to cracking of the cover concrete and ultimately spalling.

This effect does not occur with galvanized reinforcement since the zinc minerals formed, primarily zinc oxide and zinc hydroxide, are friable and less voluminous than ferrous corrosion products and migrate away into the adjacent concrete matrix where they fill voids and micro-cracks (Yeomans, 1998). This effect is shown in Fig. 4 where the plume of zinc-rich corrosion products that have migrating away from the coating surface (at left) appears white against the grey calcium-rich cement matrix.

The key issue here is that, in contrast to the situation when black steel corrodes in concrete, 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 filling of the pore space in the interfacial zone creates a barrier in the matrix of reduced permeability that not only increases the adhesion of the matrix to the bar but also reduces the transport of chlorides through the matrix to the coating surface.

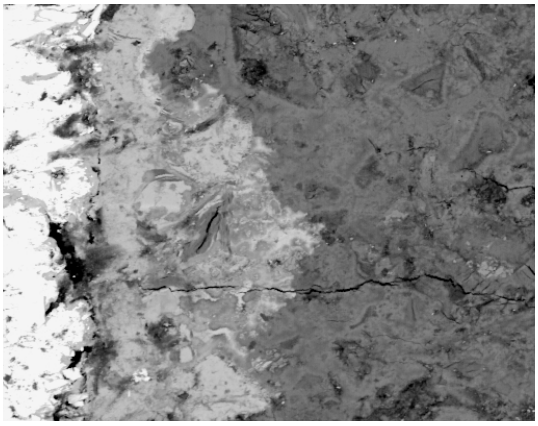

Figure 4. *Migration of zinc corrosion products into the adjacent cement matrix*. (1000x)

5 Field studies

Evidence from numerous field applications has demonstrated that galvanizing extends the life of reinforcement in concrete and provides a safeguard against premature cracking and rust staining of the concrete. Considerable research has been done in the USA, especially in relation to bridge deck installations, which has been extensively reviewed by ILZRO (1981), Yeomans (2004a) and Presuel-Morento and Rourke (2009) and Presuel-Morento (2013).

In one long-term survey dating from the early-1970s, bridge decks in Iowa, Florida and Pennsylvania were examined to compare the performance of galvanized and black reinforcement exposed to humid marine conditions or deicing salts (Stejkal, 1992). After periods up to 24 years the galvanized bars had suffered only superficial corrosion in sound, uncracked concrete even when the chloride levels were high, and the average thickness of zinc remaining on the bars remained above the minimum 84 micron requirement of ASTM A767.

Two bridges in Pennsylvania were also examined in 2002 (Olson, 2002) - the Athens bridge (28 years) and the Tioga bridge (27 years). For both bridges, the average chloride level was 2.5 times higher than the threshold value for black steel. There were no signs of corrosion on any of the galvanized bars and the remaining thickness of zinc exceeded the minimum specified thickness of 84 microns.

Similar data from Bermuda has also verified the long-term durability of galvanized reinforced concrete in marine environments (Allen, 2004). Commencing shortly after WW2 and continuing to date, a range of docks, jetties and other large infrastructure were constructed using a mix of galvanized and black steel bars. An early survey 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.

A further examination in the early 2000s of structures at least 42 years old confirmed these findings and revealed that the galvanized bars retained zinc coatings well in excess of the minimum thickness requirement of ASTM A767. In cores taken at this time, zinc corrosion products had migrated some 300-500 microns into the adjacent concrete matrix with no visible effect on the concrete mass, this providing field confirmation of laboratory findings of the migration of zinc corrosion products away from the bar interface (Yeomans, 1998).

An example of the continued reliance on the use of galvanized reinforcement in Bermuda is the Tynes Bay Waste-to-Energy Facility. Completed in 1994 at a cost of $US70m, this facility was part of a $US300m capital works program undertaken by the Bermuda Government over an eight year period to 1997 for which all reinforcement was specified to be galvanized. The scale of the foundations for this massive facility, in which several thousand tons of hot dip galvanized reinforcement was used, is shown in Fig 5. Detail of one of the heavily galvanized reinforced ground beams is in Fig 6.

Figure 5. Foundations for the Tynes Bay Waste-to Energy Facility, Bermuda.

Figure 6. Heavily galvanized reinforced insitu beams for Tynes Bay.

6 Design and fabrication

6.1 Steel properties

Extensive testing has demonstrated that galvanizing does not adversely affect the strength and ductility of traditional reinforcing steels (250 MPa yield) providing the steel has not been excessively cold worked by bending and re-bending (AGA, 2011). Where reinforcement has in earlier years been cold twisted to raise its yield strength to about 410 MPa (this is no longer practiced), there is some evidence that such steels may be embrittled by galvanizing (Porter, 1991).

The introduction of thermo-mechanically treated and micro-alloyed steels for high strength bars (minimum yield of 400 MPa), the likelihood of embrittlement has been largely eliminated expect perhaps where bars have been bent and re-bent. 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. The effect of galvanizing on various grades of reinforcing steel is given in Table 1.

Table 1. Effect of hot dip galvanizing on grades of reinforcing steel.

Type of Steel	Considerations for Galvanizing
Low strength grades - 250 MPa yield strength	• no effect on properties provided the bar has not been excessively cold worked during fabrication.
Cold-twisted steels - 410 MPa minimum yield	• heavily cold-worked material subsequently fabricated by bending may be embrittled and would require stress relief heat treatment.
Thermo-mechanically treated or micro-alloyed grades - 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 - 500 MPa minimum yield	• superior mechanical properties are retained after hot-dip galvanizing; and • slight improvement in yield and ultimate stress and also ductility due to minor stress relief.

6.2 Design of galvanized reinforced concrete

The design and construction of galvanized reinforced concrete is, to all intents and purposes, the same as that used for conventional steel reinforced concrete. Splice and lap lengths are the same as for black steel bar as are bond and load transfer considerations. In effect, best practice for galvanized reinforcement concrete is to use appropriately designed and placed concrete as applies in general reinforced concrete construction (Swamy, 2004).

A significant amount of research has been undertaken concerning the bond capacity of galvanized reinforcement and this has been thoroughly reviewed by Kayali (2004). Research by Kayali and Yeomans (1995) showed that both the ultimate load capacity and mean critical load at a slip of 0.01 and 0.02 mm of galvanized reinforced beams was not statistically different (after 28 days curing) to that of black steel reinforced beams. Further work using ASTM beam end test samples confirmed that there was no adverse effect on bond capacity with galvanized steel and also identified the very strong adhesion between concrete and the galvanized coating, something that is almost lacking between black steel and concrete (Kayali and Yeomans, 2000).[3]

Further work by Hamad and Mike (2005) utilising concrete beam specimens in 28 MPa concrete found that the use of galvanized bars (compared with equivalent black steel) has negligible effect on the bond strength of reinforcement in this concrete. Also, Maldonado et al (2010) found that the average bond strength of black steel and galvanized steel bars in concretes with w/c of 0.4 and 0.5 was very similar with less than a 2% difference over the 28 day curing period which is within normal statistical variation).

6.3 Fabrication and construction

Due to the robust nature of galvanized coatings there are no special transportation and handling requirements for reinforcement other than the use of appropriate bend radii to minimize cracking of the coating. Usual placement recommendations are that galvanized or plastic coated tie wires be used for fixing, and cut ends and areas of damage to the coating should be protected with a zinc rich paint or zinc solder.

There are also no special precautions or work practices needed in the placement of the reinforcement or in the pouring, compaction and finishing of the concrete. All practices are in effect the same as for black steel reinforcement (Langill & Dugan, 2004; AGA, 2011).

7 Applications of galvanized reinforcement

Over a period of some 50-60 years, hot dip galvanized reinforcement and fittings including bolts, ties, anchors, dowels etc have been successfully used in a range of reinforced concrete construction in many different environmental exposure conditions. The majority of such product is pre-galvanized straight lengths of reinforcing bars and associated stirrups and ties. There is also a significant use of galvanized mesh, especially in lightweight and pre-cast concrete construction.

With pre-fabricated reinforcement cages and column reinforcement, galvanizing after bending, cutting and welding provides total protection to the entire reinforcement structure thereby eliminating the need for touch-up of cut ends, bends and welds.

A detailed review of the world-wide application of galvanized reinforcement and other galvanized steel inserts in concrete construction has been compiled by Yeomans (2004). The American Galvanizers Association (AGA, undated) has also complied and extensive listing of several thousand galvanized reinforced structures covering, inter alia, buildings, bridges and other transport infrastructure, marine structures, chemical and processing plants, power generation, and water treatment facilities.

In broad terms, the common uses of galvanized reinforcements, fittings and inserts have been in precast cladding and tilt-up elements, exposed building beams and columns, modular building units, and immersed or buried elements such as deep foundations, piles and tunnel linings. It has also been used in a range of coastal and marine structures such as bridge abutments, beams and columns, sea walls, floating marinas, pontoons, docks, jetties and offshore platforms.

In transport infrastructure it has been widely used in bridge decks, road pavements, crash barriers and parking structures. It has also found wide use in chemical and petro-chemical processing, power generation, pulp and paper mills, and water and sewerage treatment works.

Significantly, galvanized reinforcement has also been used in expensive and prestige construction where very long life and the maintenance of appearance is vitally important, such as the Sydney

[3] It is important to note that due to the inhibiting effect of zinc on the early set of concrete, the time to develop full bond strength for galvanized bars may initially be longer than that for black steel though this effect is usually overcome by 28 days curing.

Opera House, NZ and Australian Parliament buildings and the National Theatre London. Some examples of large and comparatively recent infrastructure applications follow.

In Singapore, 1200 t of galvanized reinforcement was used in the top 6 m of 3200 foundation piles for the Changi Water Treatment facility – one of the largest such facilities in the world. Located immediately adjacent to the coast, the facility is subject to a tidal salt water table that is highly corrosive. Treated effluent is discharged into the Straits of Singapore some 5 km offshore via twin galvanized reinforced slip-formed concrete pipes laid in a dredged trench on the seabed. A total of 1300 pipes were manufactured on site using some 10 000t of galvanized bar. Potential corrosion effects of both the effluent and seawater and the 100 year design life prompted the use of galvanized reinforcement (Figs. 7, 8).

Figure 7. Galvanized reinforced foundation piles - Changi Water Treatment facility.

Figure 8. Prefabricated galvanized reinforced pipe cages for slip forming.

In the construction of the ANDOC North Sea Oil platform, 2 000t of galvanized reinforcement was placed in the roof of the seabed oil storage caissons. The primary concern was the temperature difference between the seawater at 5ºC and crude oil which is cooled from 75 to 35ºC. The temperature difference across the surfaces of the caisson may propagate crack leading to corrosion of unprotected reinforcement. Galvanizing was used to counter this risk.

Floating precast concrete marina components are galvanized reinforced. In one installation in tropical North Queensland, after more than 20 years operation all floating cells were removed and inspected as part of a redesign of the marina layout. Though a number of black steel elements around the marina needed to be replaced, all of the galvanized reinforced cells were in such good condition that all were relocated in the new layout.

In Sydney, galvanized reinforcement was used in the linings for three deep water ocean outfalls for treated effluent. The tunnels which were bored through cliffs and laid in seabed trenches to about 3 km offshore, were lined with precast and in situ concrete incorporating galvanized reinforcement for long-term corrosion protection (Fig. 9).

In Taiwan, 4 6000t of galvanized reinforcement was used in the construction of the foundations of the National Museum of Marine Biology and Aquarium. A further 3 680t was used in the construction of the sea water and other facilities around this coastal site (Fig. 10).

In Chile, galvanized reinforcement was used in the sea water reticulation systems for a coal fired thermal power station at Coronel Port. Also at Coronel, galvanized reinforcement was use in the concrete deck of the Artisanal fishing pier expansion project. Similarly, in Spain, galvanized reinforcement was used extensively in the construction of a marina at the Port of Torrevieja and in precast seawall sections in the new seaport dock in Denia, Alicante (Figs 11, 12).

In Okinawa where prevailing winds carry salt-laden moisture across most of the island, galvanized reinforcement has been used for many years is used in public works projects and also in residential housing. As one example, 415 t of galvanized reinforcement was used in the foundation of fish breeding tanks for the Okinawa Marine Research Institute.

Figure 9. Sydney ocean outfall tunnels for treated effluent.

Figure 10. Foundations for National Museum of Marine Biology and Aquarium, Taiwan.

Figure 11. Denia Port, Alicante, Spain

Figure 12. Precast galvanized reinforced sections for Denia Port.

A very recent large infrastructure application is the construction of the 3.1 mile twin span New NY Bridge crossing the Hudson River. Designed for a life of 100 years and beyond and due for completion later this year, about 30 000t of hot dip galvanized reinforcement is being used in the construction of all critical elements of this new bridge. Some 60 regularly spaced reinforced concrete piers support the approach spans that extend into the river from the two shores until they reach the cable-stayed main span of the bridge.

The eight towers at the main span will be 419 ft high. Galvanized reinforced concrete forms the bridge's critical structures, including the main span towers, approach span, piers, abutments and deck panels. Some 6 000 of galvanized reinforced pre-cast road deck panels will rest on previously installed steel girder assemblies. Protecting this immense concrete structure against corrosive attack from the brackish waters of the Hudson River and salt laden spray was the basis of the decision to use galvanized reinforcement throughout (Figs 13-16).

Figure 13. Galvanized reinforcement in approach spans of the new New York Bridge

Figure 14. Installing galvanized reinforcement in the main span towers.

Figure 15. Galvanized reinforced precast bridge deck panels - New York Bridge

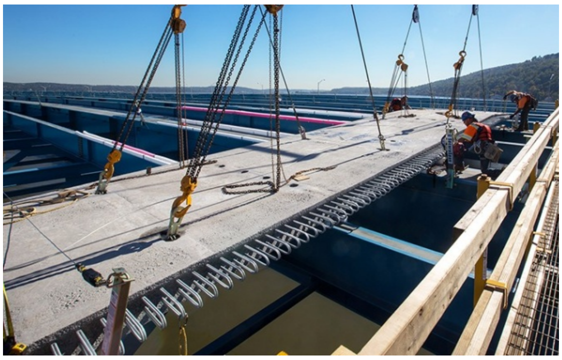

Figure 16. Placing precast deck panels over installed steel beams.

8 Service life performance

A recent investigation for the American Galvanizers Association compared the life-cycle cost and total present cost analysis of epoxy-coated, Grade 316 stainless steel and hot dip (i.e. batch) galvanized reinforcement in high chloride bridge deck exposure conditions (IZA, 2017).

Three climatic zones for Virginia bridge decks were examined; Northern with high de-icing salt loads due to population characteristics (4369 kg/lane km), Southern Mountain with typical salt loads (688 kg/lane km), and Tidewater at lower loads (255kg/lane km). For each zone, surface chloride contents and diffusion rates into the concrete were calculated in order to determine the effects on the service life of epoxy-coated, batch galvanized, and 316 stainless steel rebar.

For epoxy-coated bars, critical chloride thresholds are the same as that for black rebar and the corrosion protection afforded is limited to the extent of the so-called propagation period. For black steel this is five years while for epoxy-coated bar it is ten years, the short extension being due to the barrier effect of the fusion bonded coating.

The protection period for galvanized bar was concluded to be 4 to 5 times that of black bar. With galvanizing, the propagation period is less than that of black bar because the corrosion of the zinc coating, when this does occur in the higher-chloride environment that has accumulated over time due to the higher chloride threshold of zinc, and accordingly is taken as two years. Therefore the sum of the protection and propagation periods for galvanized rebar was taken as 22 years.

For stainless steel bar, a propagation life of 15 years was used. What was also apparent was that epoxy-coated bar requires much more frequent patching than galvanized bar and the bridge requires replacement after 54 years, compared with over 100 years for the galvanized bar bridge.

Based on the distribution of values for each of these parameters a Monte Carlo probability analysis based on Fick's Second Law of Diffusion was undertaken. The results of this analysis are reported as the percentage of the deck area that required patching after an indicated number of years, with patch areas of 2, 4, 8 and 12% being reported where 12% patch area is assumed to be equal to the effective service life of the bridge. The sum of the corrosion initiation plus the corrosion propagation times in each case is reported as the time to deck deterioration.

In the Northern climatic zone with the highest salt load, the service life for epoxy coated bar and galvanized bar at 12% damage are 55 and 108 years respectively. The equivalent service life of solid stainless steel in this same most sever exposure is far in excess of 100 years. In contrast, at the 2% damage level, for epoxy coated bars corrosion initiation occurs at 1 year and first deck patching would occur at 11 years. An additional 10% patch would be required between 11 and 55 years, at which time the deck would need to be overlaid. For galvanized bar at the 2% damage level, first patching would be needed at 23 years at 2% deterioration and an additional 6% patching would be required to reach the 75 year period.

A cost analysis of these circumstances indicated that the epoxy-coated rebar requires much more frequent patching than galvanized rebar and the bridge requires replacement after 54 years, compared with over 100 years for the galvanized rebar bridge. The galvanized steel had the lowest total present costs and life cycle costs, regardless of the amount of damage initially present in the bridge deck or the severity of the climatic zones examined. The difference between epoxy-coated rebar and galvanized rebar increased as the level of chloride exposure increases and this trend was expected to be maintained to higher chloride levels as might be expected with heavier salt-dosing rates.

In the most severe conditions, the present cost of epoxy-coated bar exceeds that of stainless steel bar, though while the galvanized steel bar has a lower Fig. than stainless steel the expectation is that with higher chloride levels the galvanized steel total present costs and life-cycle costs would eventually approach that of stainless steel, while the epoxy-coated rebar total costs and life cycle costs would be far in excess of stainless steel.

In circumstances of a bridge deck with low permeable concrete, design cover depth of 2.5 inches and chloride surface concentrations, hot-dipped galvanized reinforcing steel had the lowest life cycle cost for all combinations of deck cracking and environmental climate zones. Solid stainless is the most costly alternative based on life cycle costs, but provides a maintenance free condition for service lives of greater than 75 years. The use of epoxy coated reinforcement would require more maintenance over a 75 year service life compared to galvanized reinforcement.

In summary, this detailed study has indicated that when comparing epoxy coated, galvanized and solid stainless steel in chloride exposed bridge decks, galvanized steel has the lowest life cycle cost and total present cost. Galvanized steel performs better than epoxy coated steel and the difference between epoxy and galvanized increases as the chloride exposure increases, this trend expected to hold to the higher chloride levels typical of heavier salt-dosing rates. Further, the service life of galvanized decks is shown to be 100 years in comparison to epoxy coated decks life of 55 years and solid stainless steel of 100+ years. Not unexpectedly, stainless steel is more favourable in conditions of increased bridge deck surface cracking and chloride exposure.

9 Conclusions

Galvanizing is a widely used corrosion protection method for steel reinforcement in concrete. In concrete, the zinc and zinc alloy coating provides both barrier protection and also sacrificial protection to the base steel. Hot dipping produces a tough and adherent coating a minimum of 85 microns thick, though typically 100-150 microns thick, that is metallurgically bound to the base steel. The coating comprises a series of zinc-iron alloy layers with a thin layer of pure zinc at the outer surface.

About 10 microns of the pure zinc outer layer is consumed as the coating passivates in the high alkalinity of concrete and this protection is maintained as the pH of the concrete is lowered due to the effects of carbonation. Zinc also has a significantly higher chloride tolerance than black steel and a factor of 2.5 times is normally accepted. This provides galvanized steel with a higher resistance to chloride ingress which, combined with its resistance to carbonation effects, provides for a significant life extension over black steel reinforcement.

While hot dip galvanizing of bundles of reinforcement is the usual coating method, the recent development of continuous galvanizing of straight lengths of bar or coil presents new opportunities for on-demand, quick and economical coating of reinforcement. The speed of this reaction results in a coating about 50 microns thick that is essentially pure zinc. This coating has great formability compared to traditional hot dipped coatings and being pure zinc it provides a significant reserve of zinc should re-passivation be necessary.

Though continuous coating of steel products is a well-established technology, applying this to reinforcement is a quite recent and to date only a limited number of facilities worldwide provide this service. However, new investment in continuous coating lines and increasing demand for continuously coated reinforcement will see an expansion of this versatile product.

Life cycle analysis of epoxy coated, galvanized and solid stainless steel reinforcement in high chloride exposure bridge decks in the US has shown that galvanized steel has the lowest life cycle cost and lowest total present cost. Galvanized steel performs better than epoxy coated and the difference between epoxy and galvanized increases as the chloride exposure increases. The service life of galvanized decks is 100 years in comparison to epoxy coated deck life of 55 years and solid stainless steel of 100+ years.

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