Galvanized Steel as a Sustainable Material-Technology and Failure Analysis

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Abstract

The building industry is responsible for 40% of global CO2 emissions and 36% of global energy consumption. Therefore, it is not surprising that the industry is motivated to embrace more environment-friendly procedures and turning to more environment-friendly materials and manufacturing processes. Driven by ever-stricter environmental norms and regulations, as well as rising costs, galvanizing is considered as an affordable, again, an environment-friendly and ‘green’ corrosion protection method. In order to prevent corrosion and produce a tough, long-lasting surface, clean steel is coated with a layer of molten zinc during the hot-dip galvanizing process. It has the extra benefit of completely covering the steel, making it more durable than conventional coatings that just adhere chemically or mechanically. As a result, it is not only very efficient but also very environment-friendly. A single, one-time treatment will completely coat a product's interior and exterior, giving it a coating that can shield steel and keep it from needing maintenance for more than 70 years. In this paper, galvanizing will be introduced as an efficient, affordable, and environment-friendly anti-corrosion method. Technical issues related to the process are presented and challenges associated with galvanizing are addressed. The experimental part includes measuring the zinc coating layer using optical microscopy. Failure cases related to galvanized structures which include bridges, bolts, and fire affected monopole are discussed, root causes were analyzed, and recommendations are provided.

Keywords: Corrosion; Galvanized steel; Failure analysis; Sustainability

1 Introduction

Corrosion is a natural phenomenon and has a great impact on society. Its impact includes economic, security, energy, health, safety, and environment (Maeda, 1996; Krylova, 2001; Moodley, 2019; Romero et al., 2006). In 2002, the US federal highway Administration (FHWA) released its study on the direct cost associated with metallic corrosion, which was estimated at $276 billion that is approximately 3.1 of the nation’s Gross Domestic Product (GDP) (Sharma et al., 2014). Corrosion and weathering resistance are key characteristics that affect the strength and longevity of building structures, especially those composed of metal. Corrosion can occur in buildings and structures with exposed metal and concrete (Sherrawi et al., 2018).

Climate change may have a significant impact on the damage risks of concrete infrastructure and, as a result their durability and sustainability. In many cases, the scale of the change in risk should not be overlooked. Wang et al. (2012) studied the impact of climate change on the corrosivity of concrete infrastructure in Australia using a mathematical simulation model. The authors concluded that some measures, such as new materials and structures, can be adopted. Cover design, mixing, coating, and cathodic protection were recommended to protect the existing structures. The material of choice for all engineers, designers, architects, and fabricators is structural steel. Affordability, ductility, and tremendous strength make steel the perfect material for building and construction. A wide range of steel parts and structures used in infrastructure, construction, and other fields are all long-term protected by general galvanized steel.

Galvanizing is a process of coating steel structures with zinc in order to prevent corrosion. The most popular method is hot dip galvanizing (HDG) in which a steel part is soaked in a molten zinc bath. The galvanizing layer acts as a barrier that keeps corrosive substances like Cl^- ions from reaching the matrix steel. The build-up of zinc anti-corrosion products from this would increase the ability of the galvanizing layer for protection. Additionally, the galvanizing layer serves as a sacrificial anode, corroding zinc rather than steel more favourably (Carpio et al., 2010; Adetunji, 2010; Shibli, 2015). Using galvanized steel dramatically lengthens wind turbine service life while reducing costly maintenance and downtime caused by corrosion. Additionally, galvanizing has long been used to protect steel transmission towers, which serve as the backbone of many of the world's power grids.

HDG has limitations, such as a relatively insufficient level of protection to withstand the harsher environmental conditions (Maaß & Peißker, 2011; Maeda, 1996; Krylova, 2001; Moodley, 2019; Romero et al., 2006). McDonald studied the effect of using galvanized bars in concrete and how corrosion behaviour of the coated bars is different from other anti-corrosion protection. The author concluded that by adopting advanced methods in concrete marine structure, long design life can be achieved (McDonald, 2011). Joseph et al. (2021) investigated the corrosion resistance of galvanized steel roofing sheets in acidic and rainwater environments. They concluded that the corrosion rate was lower in the rainwater environment comparing to the acidic environment. Way et al. recommended different practices to ensure adequate durability of galvanized steel structures used as steel framing in residential buildings. Their recommendations include maintaining the building envelop, avoiding direct contact with moisture, and preventing any direct contact between the galvanized structure and any aggressive or moist material (Way et al., 2009).

In addition to other design aspects such as having concrete structure with adequate thickness to protect the rebar, HDG forms a coating that isolates the steel bars from the surrounding concrete (Sharma et al., 2014; Hegyi et al., 2015; Yeomans, 2018). Ortlon performed a comparative study on the corrosivity of reinforced concrete with unprotected steel and hot-dipped galvanized steel. The authors concluded that hot-dipped galvanized steel bars show better corrosion resistance when tested using four different concrete compositions (Ortlon & Tutikian, 2017).

The collapse of bridges has made corrosion-related infrastructure failures most obvious on a global scale. There has been a history of corroded bridge failures, frequently resulting in fatalities (Lee et al, 2013; Zhang et al, 2022; Deng et al, 2016). When considering the entire life cycle of a bridge, both weathering steel and HDGS with a coating thickness of at least 200 μm provide significant advantages over conventional coating techniques. Suzumura and Nakamura (2004) investigated the environmental factors that affect corrosion behaviour of galvanized steel wires used in bridges. They concluded that the corrosion is related to the wire position inside the tension cables. Similar to other researchers, the authors found that corrosivity of the steel wires increases with the increase of sodium chloride content and temperature. Morgado and Brito (2015) studied the failure causes of pre-stressed steel cables of a suspension bridge that collapsed during use. They concluded that the predominant failure cause was stress corrosion cracking (SCC).

2 Experimental Work and Analysis

2.1 Visual Examination

Failed components were initially examined visually in *as-received* condition. In some cases, failed parts were cleaned with acetone and ultrasound cleaner. Fracture surface initially examined either visually and/or using a stereo microscope.

2.2 Metallography and Microstructural Analysis

Samples cut from the failed components were prepared for metallographic investigation by hot mounting, grinding, polishing, and etching. The grinding step was performed using silicon carbide emery paper starting with 240, 320, 400, 600, and 1000 grit. Polishing was performed using alumina suspension solution with particle sizes of 9, 6, 3, and 1 µm. An optical microscope (OM) equipped with image analyzer software and magnification power up to 1000x was used for optical microscopy analysis.

2.3 Hardness and Microhardness testing

Rockwell hardness scale HRB and HRC were used for hardness measurements. In some cases, small samples, and microstructural features in the range of a micro scale were tested using Vickers (Hv) microhardness machine equipped with a 136° pyramidal diamond indenter and a load of 10 kg.

2.4 Chemical Analysis and Scanning Electron Microscopy (SEM)

Chemical analysis of sections cut from the failed components were analyzed using a Spectro test spectrometer equipped with ultraviolet spark probe under argon gas. SEM examination was conducted using Tescan field emission scanning electron microscope (FESEM) equipped with energy dispersive spectroscopy (EDS) analysis for microanalysis.

3 Failure Cases

3.1 Case 1 - Fire-damaged Monopole

In this failure case, galvanized steel samples removed from a fire-damaged monopole were analyzed for the extent of damage. The HRB hardness, as well as the expected ultimate tensile strength (UTS) and yield strength (YS) were calculated based on the Vickers hardness values. It is found that these values closely correspond to the values obtained from the mill certificate. The result of one of the samples is shown in Table 2. The galvanized layer thickness measurements were performed as shown in Figure 1. The thickness of the sample was in the range between 188µm and 277 µm with an average of 208 µm which was in the specification range.

Table 1: Mechanical properties of the monopole material

Property	ID Hardness	MID Hardness	OD Hardness	Average Hardness Hv10	Average Hardness HRB	Estimated UTS (MPa)	Estimated YS (MPa)
Values	222	219	225	222	97.1	721	576

The microstructure analysis of the samples revealed a typical pearlitic structure in a banding form. Some other samples show evidence of spheroidization of pearlite, and others show evidence of carbides dispersed to the grain boundaries. Alterations of the microstructure due to heat would be evident in loss of the elongated pearlite banding generated during rolling operations. At elevated temperatures, the pearlite begins to spheroidize, or decompose into iron carbide particles that diffuse to the grain boundaries as shown in Figure 2. The strength of the steel is typically lower due to spheroidization, but ductility is typically increased. Spheroidization only becomes a problem when large amounts of carbides are deposited along the grain boundaries, resulting in embrittlement and potential cracking. This is a problem commonly seen in furnace heating tubes that are exposed to elevated temperatures for thousands of hours (Yang & Liu, 2016; Nasiri & Mirzadeh, 2019]. Hence, even the worst heat-affected samples showed adequate hardness values and strengths to remain in service, as the minimum strength required is 300 MPa is.

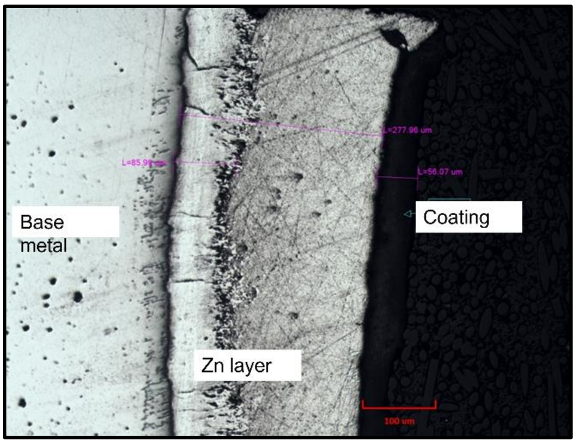


Fig. 1: Zinc layer thickness

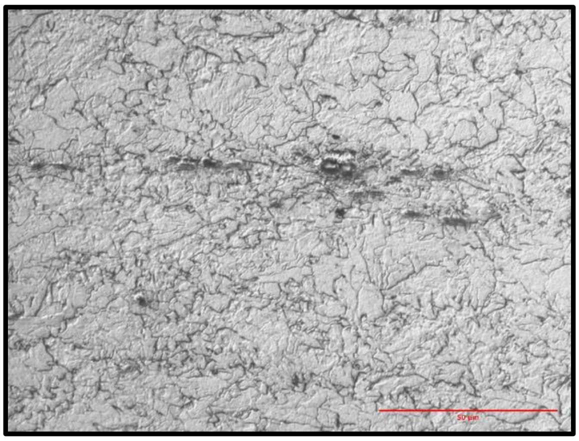


Fig. 2: Grain boundary carbide precipitates

3.2 Case 2-Corrosion Evaluation of Wrapping Wires of Mackay Bridge

This case involves corrosion evaluation of galvanized wrapping wires used to protect the tension wire cables in a Mackay bridge. Visual inspection shows clearly that the wrapping wires suffered corrosion. Figure 3 shows the sections, after cutting, with noticeable evidence of more corrosion at 6:00 o'clock than 12:00 o'clock positions. Figure 4 shows the galvanized cables and the wrapping wires used for protection as installed. The wrapping wires were zinc coated and painted orange. There are 61 cables inside the wrapping wires and wooden plates were placed inside the wrapping cables for separation. In addition to the wrapping wires, the cables show sign of corrosion, which is mostly associated with 6:00 o'clock position, evidence of localized corrosion was seen as shown in Figure 5 and Figure 6 respectively.

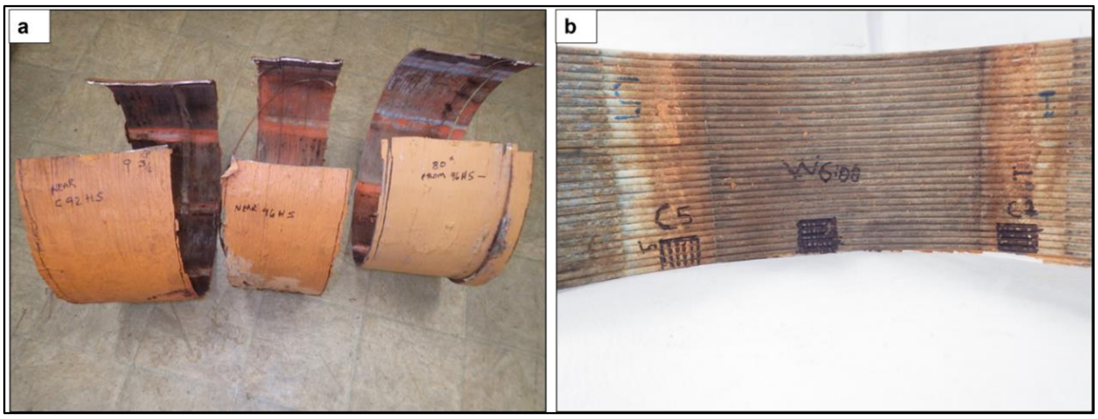


Fig. 3: Wrapping wires. **(a)** Sections cut; **(b)** wrapping wires show signs of corrosion

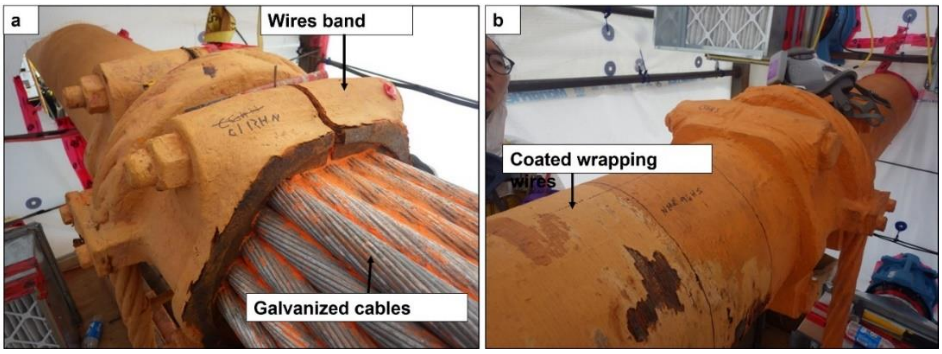
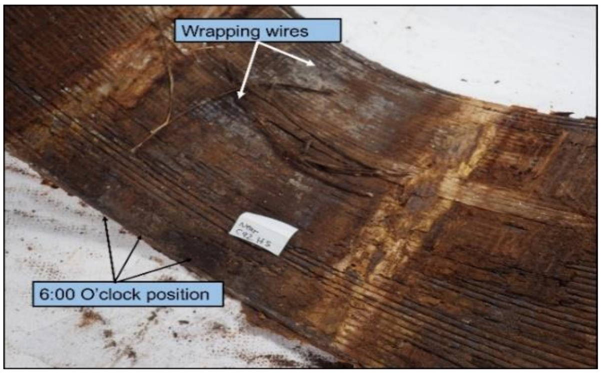


Fig. 4: Close up picture shows **(a)** exposed galvanized wires, **(b)** wrapping wires

The samples' locations were chosen to represent different positions such as 6:00, 4:00, and 12:00 o'clock. Each sample consists of 5 wires mounted together. Zinc layer thickness measurement was performed at the OD and ID on each wire. Five readings were taken at each side (OD & ID) which makes 50 measurements on each sample. The results show that the zinc layer thickness is higher on the outside (OD) than inside (OD). This is apparently due to the effect of paint on the outer side of the wrapping wires. Figure 7a shows optical micrograph of unaffected galvanized layer. However, some samples show complete deterioration of the galvanized layer and signs of pitting corrosion as shown in Figure 7b.



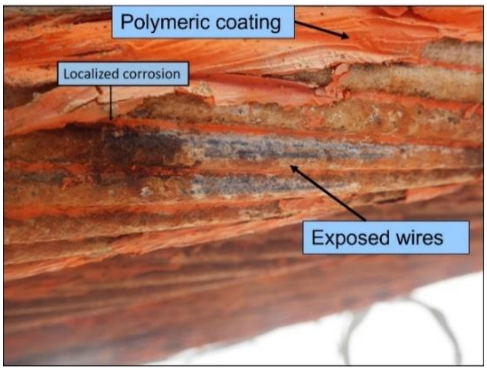


Fig. 5: Wires at 6:00 o'clock position

Fig. 6: Exposed wires show corrosion

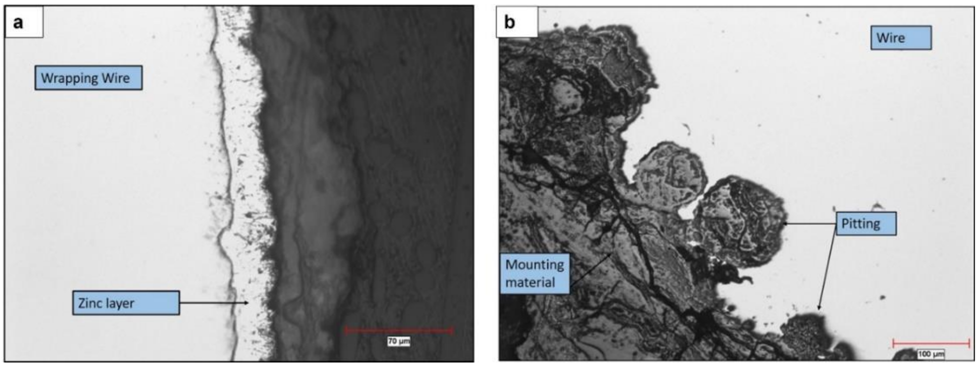


Fig. 7: Optical micrograph of, **(a)** zinc layer **(b)** corrosion pits formed on the wrapping wire

In general, bridge wires and cables are affected by atmosphere that contains acid rain, moisture, and dissolved gases. The exposure of the bridge wires to the de–icing salt and splash are considered as factors affecting corrosion. The main factor that contributes to corrosion of the wires is water entering the wrapping wires/cables and reacting with the cables. Water may enter the wires either as a liquid or as a vapour which may condense when the temperature drops. There was clear evidence that the wrapping wires did not provide enough protection to the cables and permitted water to penetrate. The damage primarily starts due to the deterioration and depletion of the zinc coating layer which should prevent the wires from direct contact with the environment. The deterioration of the zinc layer is mainly due to contact with water which may contain dissolved carbon dioxide and sulfur dioxide. In conclusion, the wrapping wires will help to protect the cable wires as far as they can prevent water and humidity from getting into contact with the cable wires. Dehumidification is an option to minimize corrosion of the wrapping wires.

3.3 Case 3-High-strength galvanized bolt failure

This case represented galvanized bolts that fractured within very short time. The bolt in *as received* condition is shown in Figure 8. The bolt is classified as DG 10.9. Chemical composition analysis performed shows that the bolt is made from AISI 4140 alloy steel as shown in Table 2.

Table 2: Chemical analysis of the bolt material

Element (wt %)	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Fe
Failed bolt	0.401	0.271	0.733	0.012	<0.002	1.108	0.190	0.102	0.122	97.0

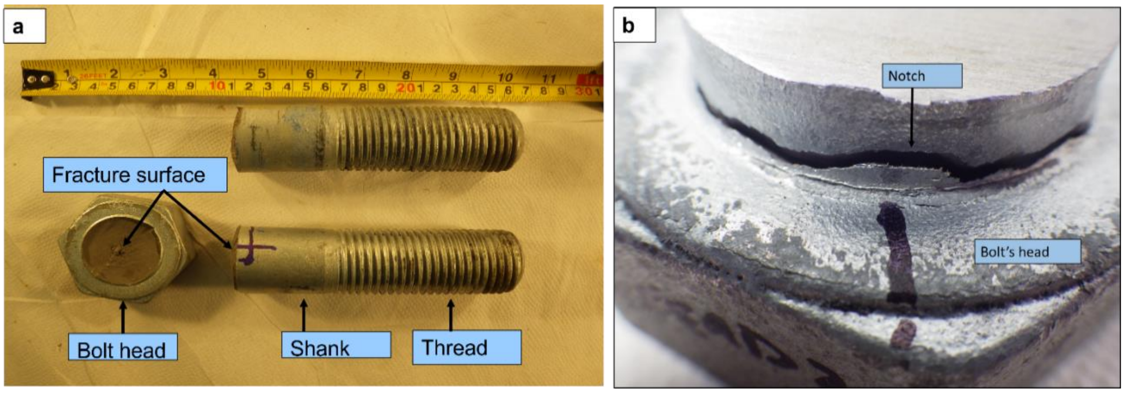


Fig. 8: Bolt as received **(a)** bolt parts, **(b)** fracture position and appearance

Microstructural analysis performed on the bolt material in its polished and etched condition did not show any abnormality in terms of inclusions, banded structure, or defects. The flow pattern observed from the macrographs suggest that bolts were manufactured by forging. Fracture surface examination shows a dis-coloured crescent-like zone that initiated at the edge of the bolt head and reached ~2 mm thickness in its center. To identify the nature of the crescent-like zone, the fracture surface examined under the SEM and EDS was used for the chemical analysis.

Figure 9 and Table 3 show the fracture surface and the EDS analysis, respectively. The result shows clearly that the crescent-like zone is rich in zinc (~50% by weight) and much thicker than the normal galvanized layer. This finding suggest that the crack happened during the galvanizing stage which consequentially allowed zinc to diffuse inside the crack. The crack eventually propagated and reached its critical length and the bolt failed. HDG cracks have been reported by many researchers (Elboujdaini et al., 2004; Elboujdaini et al., 1995; Carpio et al., 2010); one or more factors may contribute to HDG cracks. According to literature, local strain, hydrogen embrittlement, liquid metal embrittlement, etc. can act individually or together as a cause of cracking and failure (Mraz & Lesay, 2009).

It is reported that the cracking susceptibility during HDG increases with hardness and hence, a critical hardness threshold was proposed. Mraz proposed 34 HRC as a criterion for HDG cracking to start, the hardness measurement on the bolt material shows 39 HRC. This would suggest that the bolt material is very susceptible to HDG cracking. Furthermore, ASTM F568M-02 standards does not recommend this type of steel (10.9) to hot dip galvanized due to its high strength and its high susceptibility for cracking during the galvanization process. In this case, other galvanizing options need to be considered such as thermal metal spry or painting.

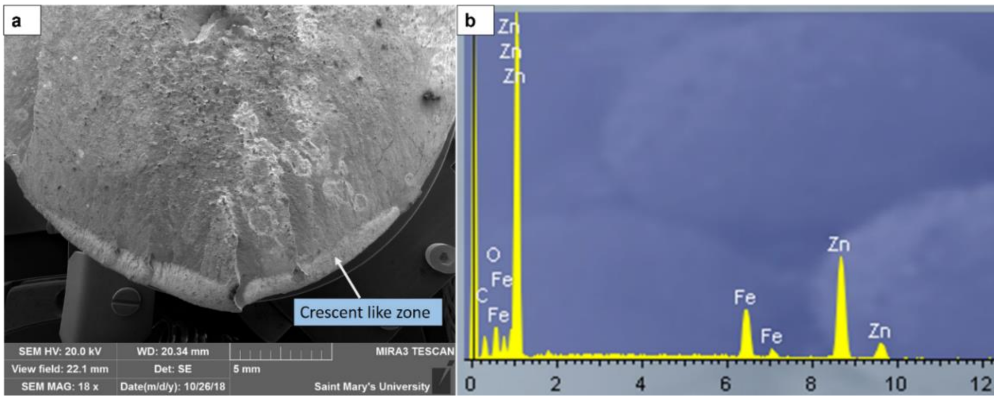


Fig. 9: SEM of the fracture surface, **(a)** Crescent-like zone **(b)** EDS shows presence of zinc

Table 3: EDS spectrum acquired from the crescent-like zone

Element	**O**	**Al**	**Cr**	**Mn**	**Fe**	**Zn**
Weight %	16.26	----	----	----	5.28	51.4

4 Conclusion

1 Galvanizing provides the most constant, effective, and affordable corrosion protection method for steel structures.

2 Galvanized steel can provide a sustainable solution for the construction industry as it needs less maintenance, last longer than other types of paints, and reduces time for maintenance.

3 Failure and root cause analysis provides information that can help to extend the life of infrastructure, reduce failure, and improve the sustainability.

References

Al-Sherrawi, et al. (2018). Corrosion as a Source of Destruction in Construction

Adetunji, O. R. (2010). Optimizing hot-dip galvanizing operations of steel sheets for better quality, *Journal of Natural Sciences Engineering and Technology*, *9*(2), 99-105

Carpio, et al. (2010). Stress corrosion cracking of structural steels immersed in hot-dip galvanizing baths, *Engineering Failure Analysis*, *17*(1), 19-27.

De Kayser Ortolan, V. & Tutikian, B. F. (2017). Comparative assessment of corrosion of concrete reinforced with unprotected steel and hot-dip galvanized steel, Revista de la Construcción. *Journal of Construction*, *16*(2), 238-248.

Deng, L., Wang, W. & Yu, Y. (2016). State-of-the-art review on the causes and mechanisms of bridge collapse, *Journal of Performance of Constructed Facilities*, *30*(2), 04015005.

Elboujdaini, M., Tyson, W.R., and Goodwin, F. (2004). Experiments on Delayed Failure during Galvanizing of Flame-Cut Structural Steels, 103-109.

Elboudjaini, M et al. (1995). "ZM-396: (Control of Cracking during Galvanised Structurals: Final Report Phase 2, 3 and 4b).

Moodley, K. (2019). (Advances in corrosion inhibition materials and technologies: A review. *Advanced Materials*

Letters, *10*(4), 231-247.

Hegyi, A., Păstrav, M., & Rus, M. (2015). Environmental And Economic Aspects Of Anticorrosion Protection By Hot-Dip Galvanized Method Rebars In Concrete, *Journal of Applied Engineering Sciences*, *18*(1).

Joseph, O. O., Dirisu, J. O., & Odedeji, A. E. (2021). Corrosion resistance of galvanized roofing sheets in acidic and rainwater environments, Heliyon, *7*(12), e08647.

Krylova, I. (2001). Painting by electrodeposition on the eve of the 21st century. *Progress in Organic Coatings*, *42*(3-4), 119-131.

Lee, et al. (2013). A study of US bridge failures: 1980-2012, Buffalo, NY: MCEER.

Maeda, S. (1996). Surface chemistry of galvanized steel sheets relevant to adhesion performance. *Progress in Organic Coatings*, *28*(4), 227-238.

Maaß, P. & Peißker, P. (Eds.). (2011). Handbook of hot-dip galvanization. John Wiley & Sons.

McDonald, D. B. (2011). Corrosion Protection for Concrete Structures in Marine Environments, In *Coastal Engineering Practice* (2011) (pp. 78-88).

Morgado, T. L. M. & e Brito, A. S. (2015). A failure analysis study of a prestressed steel cable of a suspension bridge, *Case Studies in Construction Materials*, *3*, 40-47.

Mraz, L. & Lesay, J. (2009). Problems with Reliability and Safety of Hot Dip Galvanized Steel structures, *Soldagem & inspecao* 14.2: 184-190.

Nasiri, Z. & Mirzadeh, H. (2019). Spheroidization heat treatment and inter-critical annealing of low carbon steel, *Journal of Mining and Metallurgy B*: Metallurgy, 55(3), 405-411.

Romero, et al. (2006). Behavior of Galvanized Steel in Tropical Marine Environments, *Materials Performance*, *45*(2), 24.

Sharma, R., Goodwin, F. E. & Dallin, G. W. (2014). Continuous Galvanized Rebar for Corrosion Control in RCC structures.

Shibli, S. M. A., Meena, B. N. & Remya, R. (2015). A review of recent approaches in the field of hot dip zinc galvanizing process, *Surface and Coatings Technology*, *262*, 210-215.

Suzumura, K. & Nakamura, S. I. (2004). Environmental factors affecting corrosion of galvanized steel wires, *Journal of Materials in Civil Engineering*, *16*(1), 1-7.

Wang, X., Stewart, M. G. & Nguyen, M. (2012). (Impact of climate change on corrosion and damage to concrete infrastructure in Australia), *Climatic Change*, *110*(3), 941-957.

Way, et al. (2009). Durability of Light Steel Framing in Residential Building.

Yeomans, S. R. (2018). Galvanized Steel Reinforcement: Recent Developments and New Opportunities, *Proceedings of 5th International Federation for Structural Concrete*, Melbourne, Australia.

Yang, C. C. & Liu, C. L. (2016). Optimization in Spheroidized Annealing of Two AISI 1022 Low Carbon Steels Used in Bolt Industry.

Zhang, et al. (2022). Causes and Statistical Characteristics of Bridge Failures: A Review, *Journal of Traffic and Transportation Engineering* (English Edition).

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