

# Corrosion Protection of Steel Structures

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## Introduction

As pointed out in Chapter 2, the responsibility of a professional structural engineer in the 21st century is not confined to the usual considerations of economy, safety, and aesthetics alone. The present-day design consideration include the long-term environmental impact and also the life-cycle cost. Hence more importance is given in current design codes to the durability of structures. It has to be recognized that the neglect of durability considerations has resulted in the degradation of several types of structures in almost all cities of India irrespective of whether they are made of reinforced concrete, prestressed concrete, or structural steel. Many engineers believe that structural steel alone is not durable because of the problem of corrosion. As discussed in Chapter 2, durability and corrosion are considered as a serviceability limit state criteria. In this chapter we will discuss some methods that are used to prevent corrosion. The choice of the method depends on the severity of environment, the importance of structure, and the cost involved (the initial and the life-cycle cost).

A durable steel structure may be defined as the one that performs satisfactorily the intended function(s) in the working environment under the anticipated exposure conditions during its service life, without any deterioration of the cross-sectional area and loss of strength due to corrosion. Thus the material used, the detailing, fabrication, erection, and surface protection measures should all address the corrosion reduction and durability requirements. Before discussing the various methods that are available to prevent corrosion, let us discuss the mechanism of corrosion.

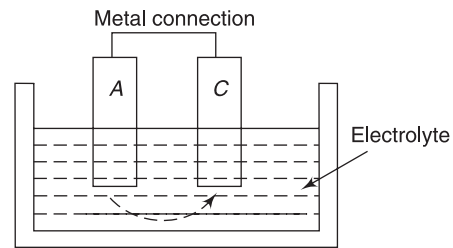
## 15.1 Corrosion of Steel

Iron is thermodynamically stable in its oxide form. Iron oxide is refined to obtain steel, which is thermodynamically unstable. Its tendency to corrode, and thereby to return to the stable state, is a fault of nature which cannot be changed. Iron and steel, the most commonly used metals, corrode in many media including most

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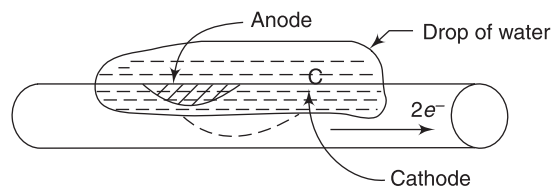
outdoor atmospheres. As discussed in Chapter 1, the final products of steel are produced by rolling, drawing, or forging. During hot rolling and forging the steel surface is oxidized by air and a scale is produced, called *mill scale*. In the air, the presence of mill scale on steel may reduce the corrosion rate over comparatively short periods, but over longer periods the rate tends to rise. In water, severe pitting of steel may occur if large amounts of mill scale are present on the surface of steel sections.

Corrosion processes are usually electrochemical in nature, having the essential features of a battery shown in Fig. 15.1, consisting of an *anode* and a *cathode* immersed in a solution of *electrolyte* (ASMI 1987). As shown in the figure, when two bodies of different electric potentials are connected electrically in the presence of an electrolyte, the anodic body provides electrons to the cathode. In this process the anode gets destroyed.



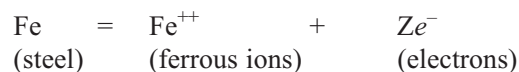
**Fig. 15.1** Corrosion mechanism in a battery

Steel covered with mill scale can suffer severe attacks at small interruptions in the scale when exposed to humid atmosphere or water containing salt. The mill scale acts as the cathode, and the exposed steel at the discontinuity acts as the anode. In the presence of water and oxygen, which act as the electrolyte, a miniature battery is formed on the surface. In this case, the attack is more severe since the anode is small compared to the cathode. The effect is concentrated at the small anode and the attack can produce serious pitting at the breaks in the scale (Gaylord et al. 1992). Ferrous ions travel into the solution from the anodic areas (see Fig. 15.2). The electrons (shown as  $e^-$  in the figure) that are released from the anode, move to the cathode, combine with water and oxygen present in the atmosphere to form hydroxyl ions. The reactions that occur are the following.

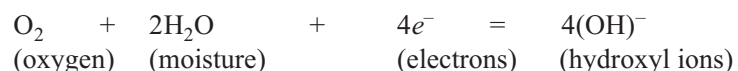


**Fig. 15.2** Corrosion mechanism in steel members

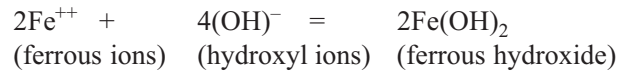
At the anode



At the cathode



The ferrous ions react with the hydroxyl ions:



The ferrous hydroxide then oxidizes to hydrated ferrous oxide ( $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ )—otherwise known as rust (which is brownish red in colour). Now, there will be a difference between the electrical potentials of the cathodic surface that is covered by rust (oxide film) and the non-corroded surface and, hence, the non-corroded anode will corrode, forming rust on its surface. This type of cyclic reactions will result in the formation of numerous miniature batteries and subsequent corrosion of the entire surface. Pollutants in the air, e.g., sulphur dioxide from the industrial atmosphere and salt from the marine atmosphere, increase the electrical conductivity of water and accelerate the corrosion reaction. From the above description, it may be clear that the elimination of water, oxygen, or the electrical conductivity reduces the rate of corrosion ([www.corrosion-doctors.org](http://www.corrosion-doctors.org)). Most of the corrosion-resistant systems try to eliminate any one or all the three elements in order to contain corrosion.

Rust builds up as a deposit on the surface and may eventually flake off. The coating of rust does not inhibit corrosion, except in special steels, and corrosion progresses beneath the rust and forms conical pits, thus reducing the thickness of the metal. The conical pits can act as stress raisers, i.e., the location of high local stresses, and in places subject to cyclic loads (e.g., cranes and bridges) may become the initiating points of fatigue cracks or brittle fracture.

### 15.1.1 Types of Corrosion

The types of corrosion encountered in structural steel elements may be classified into the following:

- Uniform corrosion
- Pitting corrosion
- Crevice corrosion
- Galvanic corrosion
- Fretting corrosion
- Stress corrosion
- Intergranular corrosion
- Bacterial corrosion
- Erosion corrosion
- Corrosion fatigue
- Hydrogen embrittlement

We will briefly discuss these types of corrosion in this section.

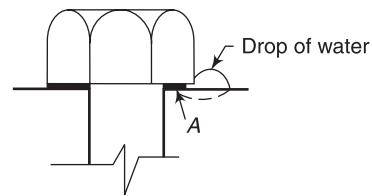
**Uniform corrosion** *Uniform corrosion* is characterized by a corrosive attack proceeding evenly over the entire surface area or a large fraction of the total area. A general thinning of the section takes place until failure. On the basis of tonnage wasted, this is the most important form of corrosion. However, uniform corrosion is relatively easily measured and predicted, making disastrous failures relatively

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rare. It is undesirable from an appearance standpoint and can be controlled by the use of coatings, paints, or cathodic protection. The breakdown of protective coating systems on structures often leads to this form of corrosion. In some cases, uniform corrosion can add colour and appeal to the surface (e.g., the patina created by naturally tarnishing copper roofs and the rust hues produced on weathering steel).

**Pitting corrosion** *Pitting corrosion* is a localized form of corrosion resulting in cavities in the surface of steel. It is more dangerous than uniform corrosion since it is more difficult to detect, predict, and design against. Corrosion products (rust) often cover the pits. As already mentioned, in addition to the loss of thickness, corrosion pits act as stress risers and may initiate fatigue and stress corrosion cracking. One pit in a large system may be sufficient enough to produce a catastrophic failure of the entire system. An example of such a failure was the failure of a gasoline line running over a sewer line, which killed 215 people, in Guadalajara, Mexico ([www.corrosion-doctors.org](http://www.corrosion-doctors.org)). This form of corrosion can be avoided by eliminating the presence of water by proper detailing and allowing free flow of air to dry the surface.

**Crevice corrosion** *Crevice corrosion* is a localized form of corrosion, usually associated with stagnant water in crevices (shielded areas) such as those formed under gaskets, washers, insulation material, fastener heads (see Fig. 15.3), threads, lap joints, and clamps. The oxygen content of the trapped water in a crevice reduces (than that of the water exposed to air) and hence the crevice becomes anodic with respect to the surrounding metal. This initiates corrosion inside the crevice. Proper detailing can eliminate this form of corrosion.



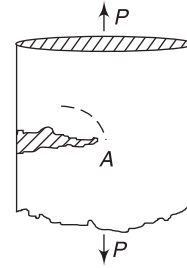
**Fig. 15.3** Crevice corrosion

**Galvanic corrosion** *Galvanic corrosion* (also called bimetallic corrosion or dissimilar metal corrosion or sometimes wrongly as electrolysis) refers to the corrosion damage induced when two (or more) dissimilar metals (e.g., iron and aluminium) are coupled in a corrosive electrolyte. Luigi Galvani invented this type of corrosion in the eighteenth century and this led to the invention of the battery by Alessandro Volta in 1800. Galvanic corrosion occurs because metals in general can be arranged in terms of their electric potential into a table called the *galvanic series*. The farther the metal in the galvanic series, the greater will be the tendency for the less noble material to corrode. A good example is the corrosion of steel screws in stainless steel members and steel bolts in aluminium members. Galvanic corrosion is common and can be destructive (a notable example is the galvanic corrosion of the Statue of Liberty, USA). Designing to avoid any contact between dissimilar metals can solve problems due to this type of corrosion.

It is interesting to note that Sir Humphrey Davy and Michael Faraday used the principle of galvanic corrosion in the early nineteenth century to develop cathodic protection of metals such as zinc, magnesium, and aluminium (see Section 15.2.6).

**Fretting corrosion** *Fretting corrosion* refers to the corrosion damage that occurs at the interface of two highly loaded surfaces that are not designed to move (rub) against each other. The most common type of fretting is caused by vibration. The protective film on the metal surface is removed by the rubbing action and exposes the bare metal surface to the corrosive action of the atmosphere. The exposed area becomes active compared with the rest of the protected metal surface. This kind of corrosion is found in machinery, bolted assemblies, and ball or roller bearings.

**Stress corrosion** *Stress corrosion cracking* is the cracking induced by the combined influence of tensile stress and a corrosive environment (see Fig. 15.4). The required tensile stresses may be in the form of directly applied stresses or in the form of residual stresses. Residual stresses are introduced by cold deformation and forming, welding, heat treatment, machining, and grinding. Stress corrosion cracking is a catastrophic form of corrosion, as the detection of such fine cracks is difficult to predict. A disastrous failure may occur unexpectedly, with minimal overall material loss.



**Fig. 15.4** Stress corrosion cracking

Stress corrosion cracking may lead to failure depending on the crack size, stress level, and temperature (corresponding to the conditions of brittle fracture). A typical example of this type of failure was the failure of the Silver Bridge across the Ohio River in USA in 1967, which resulted in the loss of 40 lives (Gaylord et al. 1992). This structure had eye bars with large pin connections, which were not accessible for inspection. A very small crack in one of the eye bars caused a fracture, resulting in the subsequent failure of other eye bars due to overload and subsequent complete collapse of the bridge.

**Intergranular corrosion** The microstructure of metals and alloys is made up of grains, separated by grain boundaries. *Intergranular corrosion* is a localized attack along the grain boundaries or immediately adjacent to grain boundaries. A classic example is the sensitization of stainless steel or weld decay. Reheating a welded component during multi-pass welding is a common cause of this problem. *Chloride stress corrosion* is a type of intergranular corrosion and occurs in austenitic stainless steel under tensile stress in the presence of oxygen, chloride ions, and high temperature. It starts with chromium carbide deposits along the grain boundaries which leave the metal open to corrosion. Maintaining a low chloride ion and oxygen content in the environment and the use of low carbon steel control this form of corrosion. The failure of a suspended ceiling over a swimming pool in Ulster, Switzerland, in 1985, resulted from this type of corrosion. The chlorine in the air above the pool produced corrosion of the stainless steel hangers supporting the suspended ceiling (Gaylord et al. 1992).

**Bacterial corrosion** *Bacterial corrosion* is due to the result of the microbiological activity and occurs in metal in contact with water or soil. Such corrosion is most common in pipelines, buried structures, and splash zones of offshore structures.

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**Erosion corrosion** *Erosion corrosion* is the acceleration in the rate of the corrosion attack in a metal due to the relative motion of a corrosive fluid and the metal surface. The increasing turbulence caused by pitting in the internal surfaces of a tube can result in rapidly increasing erosion rates and eventually to a leak. Erosion corrosion can also be aggravated by faulty workmanship—burrs left at the cut tube ends cause turbulence in the water flow, resulting in erosion corrosion. A combination of erosion and corrosion leads to high pitting rates.

**Corrosion fatigue** *Corrosion fatigue* is the result of the combined action of an alternating stress and a corrosive environment. The introduction of a corrosive environment often reduces the normal fatigue limit of a ferrous alloy, thereby creating a finite life regardless of the stress level. No metal is immune from some reduction in its resistance to cyclic stressing if the metal is in a corrosive environment. The control of corrosion fatigue is accomplished by either lowering the cyclic stress or by corrosion-protection methods.

**Hydrogen embrittlement** This type of deterioration involves the ingress of hydrogen into a component, which reduces the ductility and load-bearing capacity of the metal, which causes cracking and catastrophic brittle failures at stresses well below the yield stresses. An example of *hydrogen embrittlement* is the cracking of weldments or hardened steels when exposed to conditions which inject hydrogen into the component. Hydrogen embrittlement does not affect all metallic materials equally and is not a permanent condition. High-strength steels, titanium, and aluminium alloys are vulnerable to hydrogen embrittlement. Hydrogen embrittlement can be avoided by controlling the amount of the residual hydrogen in steel and restricting the amount of in situ hydrogen introduced during the service life of the structural part. Though hydrogen embrittlement is included in the discussion about corrosion, it is not really a corrosion phenomenon.

### 15.1.1.1 Loss due to corrosion

Unless rust-preventing measures are taken, structures made of steel will gradually deteriorate in strength and other properties and the service life of the structure will be shortened. The result of the surveys conducted in selected countries on the annual loss due to corrosion (see Table 15.1) shows that the figures are staggering.

**Table 15.1** Survey of annual loss due to corrosion

Country	Survey year	Loss amount	% of GNP
Japan	1974	2,550,930 million yen	1.8
USA	2001	276 billion US dollars	3.2
UK	1970	1,365 million pounds	3.5
West Germany	1968-69	19,000 million Deutche marks	3.5
Australia	1973	470 million Australian dollars	1.5

*Source:* Steel today and tomorrow 1989

However, with suitable corrosion-control methods, the rate of corrosion can be made very slow or practically nil, giving steel structures a long lease of life.

Table 15.2 shows the average annual loss in the thickness of untreated steel in the temperate zone.

**Table 15.2** Corrosion due to environment

Environment	Average corrosion losses (mm/year)
Rural and mountainous with clean air	0.01–0.03
Urban and moderately industrial	0.03–0.06
Sea side and industrial	0.06–0.12
Chemical/Industrial	0.12–0.3

The relationship between the thickness of the rust layer and the loss in the thickness of steel is given by (Matsushima 1997)

$$t_{rt} = \rho_r S_{r1} t_{r1} / (100 \rho_s) \quad (15.1)$$

where  $t_{rt}$  is the loss in the thickness of steel (mm),  $\rho_r$  is the apparent specific gravity of rust,  $\rho_s$  is the specific gravity of steel (7850 kg/m<sup>3</sup>),  $t_{r1}$  is the thickness of the rust layer (mm), and  $S_{r1}$  is the Fe content of the rust layer (%).

It has to be borne in mind that the thickness of the rust layer will be substantially greater (about three to four times) than the thickness lost in the original steel.

### 15.1.2 Rate of Corrosion

The *rate of corrosion* depends on the following parameters:

- Type of metal alloy
- Humidity (in humid areas—where humidity is greater than 70%—or where air is saturated with industrial effluents, the corrosion rate of low carbon steel is nearly 100 times as great as in the dry location)
- Rainfall
- Temperature variations
- Atmospheric pollution
- Condensation of moisture
- Chemical fumes
- pH value
- Oxygen content
- Dissolved gasses (in the case of structures submerged in water or soil)

As already discussed, the local corrosion rates are also influenced by contact with other metals (due to galvanic corrosion). The code classifies the general environment in which steel structures are exposed into five levels of severity as shown in Table 15.3.

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**Table 15.3** Environmental exposure conditions as per IS: 800

Environmental classifications	Exposure conditions
Mild	Surfaces normally protected against exposure to weather or aggressive conditions as in the interior of buildings, except when located in coastal areas
Moderate	Structural steel surfaces exposed to (a) condensation and rain (b) water continuously (c) non-aggressive soil/groundwater (d) coastal areas but in the interior of buildings
Severe	Structural steel surfaces exposed to (a) severe frequent rain (b) alternate wetting and drying (c) severe condensation (d) sea water (completely immersed) (e) saturated salt air in coastal areas
Very severe	Structural steel surfaces exposed to (a) sea water spray (b) corrosive fumes (c) aggressive subsoil or ground water
Extreme	Structural steel surfaces exposed to (a) tidal zones and splash zones in the sea (b) aggressive liquid or solid chemicals

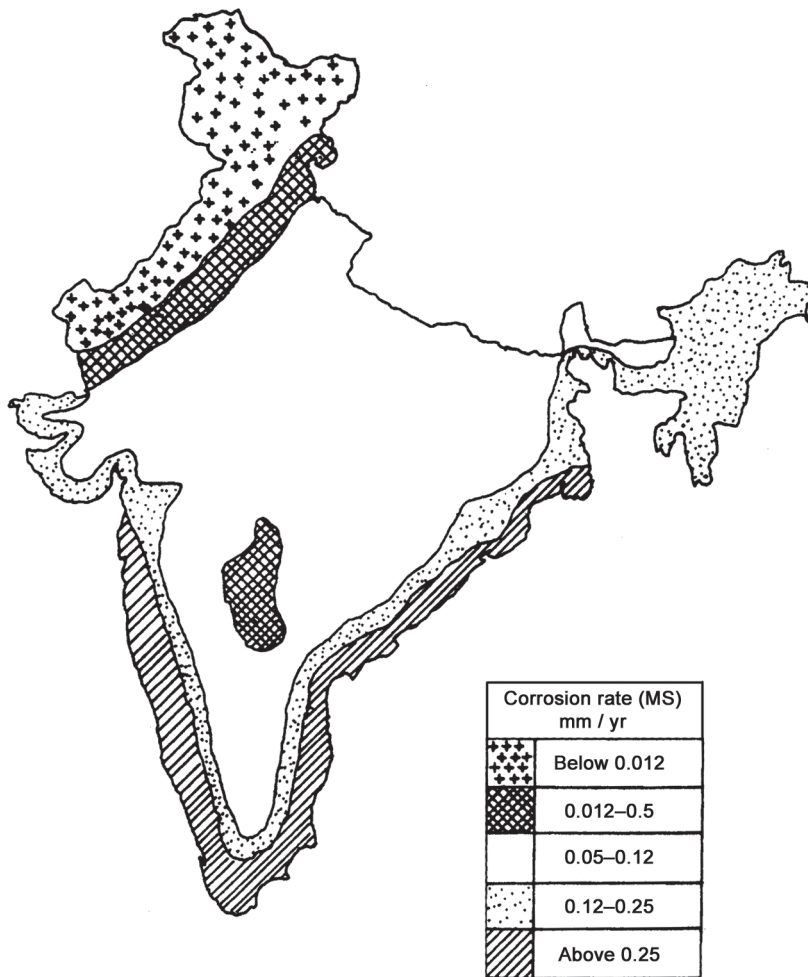
Figure 15.5 shows the corrosion map of India—showing zones of corrosion. This explains why the iron pillar installed near the Qutub Minar (see Fig. 15.6) is showing almost zero corrosion, whereas the speed of corrosion of structures in chemical and industrial areas is very rapid and hence need special attention.

Structural steel in a mild environment and in the interiors of shops, schools, residences, hospitals, airport terminals, hostels, etc., will not corrode noticeably during the expected 50–60 years life of the structure. In these situations no protective coating is required and the painting is done for decorative and aesthetic purposes only. Only when the steelwork is exposed to moisture conditions such as those existing in kitchens, bathrooms, or swimming pools, they may require a protective coating and attention is needed in the detailing of structural work. Some industrial buildings, dairies, laundries, breweries, etc. need protective coatings of sufficient thickness. Structures exposed to high humidity and corrosive atmosphere, such as chemical plants, steel bridges, structures near coastal areas, and offshore structures, need better surface preparation and sufficient thickness of paint coating.

### 15.2 Corrosion-protection Methods

Many different methods have been used to protect steel against rust. The most obvious approach is to apply a protective coating to steel, thereby sealing off its





**Fig. 15.5** Corrosion map of India

surface from a corrosive environment. Painting, zinc coating, and coating with various oils are examples of this method which have long been practised. More recently, thermal spraying of other metals, organic paints, and lining with rubber or porcelain enamel/plastic film lamination have come into use as protective coatings for steel.

Another approach to corrosion protection is the use of steel that is not readily susceptible to rust. Adding certain elements to steel during its production can modify the inherent properties of steel so that a protective film forms on its surface. This approach has produced stainless steel, first developed in the 1910s, and atmospheric-corrosion-resistant steel, which appeared in the 1930s. Electric protection is used where a high corrosion resistance is essential or for structures such as steel piles that cannot be repaired.

A good corrosion-protection system must take into account not only the effectiveness of protection but also the technical ease of fabrication, reliability,



**Fig. 15.6** Iron pillar near the Qutub Minar, constructed in the 4th century B.C. by King Chandragupta II

maintenance, and overall economy. Among these factors, *maintenance* often receives too little attention at the time of construction. Maintenance and its impact on the overall economy are among the most important factors in corrosion protection. No matter how effective a corrosion-protection system might be at the start, its effectiveness is reduced at a later date due to chemical or mechanical damage, or both. Organic coatings age, sacrificial anodes for cathodic protection is consumed, and corrosion-resistant steels are not entirely immune to corrosion. Inspection and maintenance are necessary at proper intervals, and they are usually the most difficult and costly part of corrosion protection.

Considering, for example, the maintenance of an offshore marine structure, inspecting the coatings in the splash zone, removing damaged coats, conditioning the steel surface, and applying new coats under open-sea conditions are not easy. This point should be considered from the beginning. It is important to note that no coating is completely impermeable. It is also interesting to note that there is a correlation between the cost of a particular protection system and the degree of

protection offered by it. Hence the selection of a particular system is largely based on economics.

The effectiveness of many corrosion-protection systems is affected by the surface preparation of the steel. Hence we shall discuss the methods of surface preparation briefly in the following section.

### 15.2.1 Surface Preparation

Table 15.4 gives the various factors and their percentage contribution to the durability of paint coatings. It is seen that *surface preparation* is the most important factor that affects the durability of paint coats.

**Table 15.4** Effect of various factors on the durability of paint coatings

Factors	Contribution (%)
Surface preparation	49.5
Number of coats	19.1
Quality of paint	4.9
Others	26.5

The various surface preparation methods which are used to clean the surface free of dirt, mill scale, and other impurities and improve the adhesion of paints include (IS: 1477-2000) the following.

- Hand scraping by means of a wire brush (economical but removes only 30% of the rust and scale).
- Mechanical cleaning using power-driven tools (fast and effective and cleans up to 55% of rust and scale).
- Flame cleaning (effective in removing mill scale, using differential thermal expansion caused by oxy-acetylene flame).
- Sand blasting/grit blasting/shot blasting: Sand blasting is the common method adopted for structural applications, though some states in India disallow this method citing environmental reasons. This method uses the abrasive action of sand/grit (using angular particles)/iron shots (using spherical particles), which are projected at a high speed on the steel surface, using compressed air or an impeller.
- Solvent cleaning (cleaning with a petroleum solvent such as turpentine).
- Trichloroethylene cleaning.
- Alkaline cleaning.
- Oil or water emulsion cleaning.
- Steam cleaning (steam at high velocity and high temperature is projected at the surface of steel).
- High pressure water washing (water under high pressure, usually 8.3 to 34 MPa, is used to clean the steel surface).
- Chemical cleaning called *pickling* (steel is immersed in a bath having very light sulphuric/hydrochloric or phosphoric acid to remove the rust). This method is opted for when hot-dip galvanizing is used.

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The choice of the solvent in cleaning depends on the type of the surface. After the solvent or alkali or acid cleaning, the surface must be cleaned to make it free from the cleaner.

We will now discuss the various corrosion-protection methods (see also IS: 9172-1979).

### 15.2.2 Painting

*Paints* basically consist of a *pigment*, a *binder* (or medium), and a *solvent* (or thinner). After the paint has been applied as a wet film, the solvent evaporates leaving the binder and the pigment on the surface. The pigment comprises fine solid particles which give the paint film colour and hardness, and inhibit corrosion by impeding the chemical or electrical processes. The binder is a resin or oil which binds the pigment particles together and provides a tough, flexible adhesive film. The solvent reduces the viscosity of the binder to allow even application. The characteristics of common types of paints are given in Table 15.5, which can be used as a rough guide.

**Table 15.5** Main generic types of paint and their properties (Dowling et al. 1988)

Paint type	Cost	Tolerance of poor surface preparation <sup>1</sup>	Chemical resistance	Solvent resistance <sup>2</sup>	Overcoat-ability after ageing <sup>3</sup>	Comments
Bituminous	Low	Good	Moderate	Poor	Good, with coating of some type	Limited to black and dark colours, thermoplastic
Oil based	Low	Good	Poor	Poor	Good	
Alkyd, epoxyes-ter, etc.	Low/medium	Moderate	Poor	Poor/moderate	Good	Good decorative properties
Chlorinated rubber	Medium	Poor	Good	Poor	Good	High-build films remain soft and are susceptible to 'sticking' during transport
Vinyl	High	Poor	Good	Poor	Good	
Epoxy	Medium/high	Very poor	Very good	Good	Poor	Susceptible to 'chalking' in UV light
Urethane	High	Very poor	Very good	Good	Poor	Better decorative properties than epoxyes
Inorganic silicate	High	Very poor	Moderate	Good	Moderate	May require special surface preparation

<sup>1</sup>Tolerance of poor surface: types rated 'poor' or 'very poor' should only be used on blast-cleaned surfaces.

<sup>2</sup>Solvent resistance: types rated 'poor' or 'very poor' should not generally be overcoated with any other type.

<sup>3</sup>Overcoating after ageing: types rated 'poor' or 'very poor' require suitable preparation of the aged surface if it is to be overcoated after an extended period.

Specifying paint coating system must take into account the following:

- Service life of the coating
- Ease of painting
- Place of coating in the total sequence of fabrication and erection steps
- Severity of exposure to corrosion of various members
- Ease of repairing
- Maintenance cost

Methods of painting include brush painting, spray painting, and airless spray painting (IS 1477 : 2000, Part II). It has been estimated that the initial painting cost of steel bridges is around 10% of the total construction cost. Repainting is a very significant item in the maintenance cost during the total life of a steel bridge. If the bridge is repainted 10 times (every five years during a total life span of 50 years), the repainting cost will be equal to the construction cost of the bridge—or possibly even greater!

The application of paint can effectively prevent corrosion in two ways: by sealing off the steel surface from the corrosive environment, or by the chemical action of the corrosion-inhibiting pigment contained in the paint.

The sealing properties of paints are due to the *vehicle* used. With the development of plastics, vehicles are now available in a great variety, from the solvent and water types to the chemical-reaction type and the powder type. Alkyd resin, melamine resin, urethane and other resins, phthalic resin, epoxy resin, chlorinated rubber, and other vehicles have been developed in rapid succession (see Table 15.5). Epoxy paints have found a particularly wide use in the corrosion protection of bridges and ships because of their outstanding durability, mechanical strength, and resistance to oil and chemicals. They also adhere well to the surface and can be applied in heavy coats. All paints may be subject to degradation by chemicals and by the UV radiation in the sunlight. They are also permeable to moisture and oxygen to some extent. Increasing the thickness of a paint coating increases the life of the structure.

High-performance *anti-corrosion paints* in which the vehicle is blended with zinc, micaceous iron oxide, and other highly corrosion-resistant pigments are also widely used. Guidelines for a range of corrosion-protection systems for structural frameworks for different environmental conditions as given in *Steel Construction Guide Book* (The Kozai Club 1983) and ECCS Technical notes (1998) are shown in Table 15.6. The types of paint, their thickness in micrometers, and their frequency as recommended by the code for different environmental conditions are given in Table 15.7.

One coat of red oxide is normally applied before the material leaves the fabrication shop and another coat of it is applied immediately after erection at site to prevent corrosion. A zinc- or aluminium-based primary coat is applied first, which serves as the foundation to the subsequent finishing coats. Some paints are toxic in nature and hence some precautions have to be taken while applying them; some of these paints should not be sprayed/applied in confined spaces or used on materials that will be subsequently welded or flame cut. The film thickness of a single coat of paint is about 0.035 mm for oil paint, about 0.025 mm for most synthetic resin paints, and about 0.015 mm for vinyl resin paint.

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**Table 15.6** Paint coating systems

Coating system	General coating system			Heavy-duty coating system	
	Corrosivity	Mild	Intermediate	Severe	
Surface preparation of the steel section	Blasting	Blasting	Blasting	Blasting	Blasting
Shop primer	Red lead/Red oxide	Red lead/Red oxide	Zinc chromate/Zinc-rich	Inorganic Zinc-rich primer	Inorganic Zinc-rich primer
Primer/Undercoat (1st coat)	Lead-pigmented primer	Lead-pigmented primer	Chlorinated rubber	High-build zinc-rich paint	High-build zinc-rich paint (mist-coat) <sup>1</sup>
Primer/Undercoat (2nd coat)	Lead-pigmented primer	Lead-pigmented primer	Chlorinated rubber	High-build epoxy	High-build epoxy
Primer/Undercoat (3rd coat)	—	—	—	High-build epoxy	High-build epoxy
Intermediate coat	Long-oil phthalic	Phenol/MIO	Chlorinated rubber	Polyurethane	Epoxy
Finish coat	Long-oil phthalic	Chlorinated rubber	Chlorinated rubber	Polyurethane	Fluorinated resin
Total coating thickness ( $\mu\text{m}$ )	130	190	155	255	250

<sup>1</sup>Not included in the coating thickness.

Source: ECCS, Technical Notes 90 and 88, 1998

**Table 15.7** Corrosion-protection treatment in external environment as per IS: 800

Coating System	Shop-applied treatments					
	1	2	3	4	5	6
Surface preparation	Blast clean	Blast clean	Blast clean	Blast clean	Grit blast	Blast clean
Prefabrication primer	Zinc phosphate epoxy, 20 $\mu\text{m}$	2 pack zinc-rich epoxy, 20 $\mu\text{m}$	—	2 pack zinc-rich epoxy, 20 $\mu\text{m}$	—	Ethyl zinc silicate, 20 $\mu\text{m}$
Post fabrication primer	High-build zinc phosphate modified alkyd, 60 $\mu\text{m}$	2 pack zinc-rich epoxy, 20 $\mu\text{m}$	Hot-dip galvanize, 85 $\mu\text{m}$	2 pack zinc-rich epoxy, 25 $\mu\text{m}$	Sprayed zinc or sprayed aluminium	Ethyl zinc silicate, 60 $\mu\text{m}$
Intermediate coat	—	High-build zinc phosphate, 25 $\mu\text{m}$	—	2 pack epoxy micaceous iron oxide	Sealer	Chlorinated rubber alkyd, 35 $\mu\text{m}$
Top coat	—	—	—	2 pack epoxy micaceous iron oxide, 85 $\mu\text{m}$	Sealer	—

(contd)

(contd)

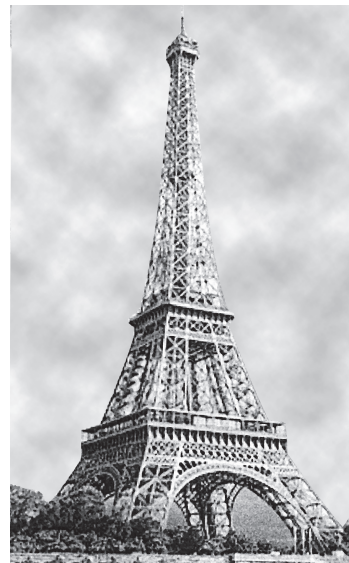
Site-applied treatments						
1. Surface preparation	As necessary	As necessary	No site treatment	As necessary	No site treatment	As necessary
2. Primer	Touch in	Touch in	—	—	—	Touch in
3. Intermediate coat		Modified alkyd	—	Touch in	—	High-build micaceous
	micaceous iron oxide, 50 $\mu\text{m}$				iron oxide, chlorinated rubber, 75 $\mu\text{m}$	
4. Top coat	High-build alkyd finish, 60 $\mu\text{m}$	Modified alkyd micaceous iron oxide, 50 $\mu\text{m}$	—	High-build chlorinated rubber	—	High-build micaceous iron oxide, chlorinated rubber, 75 $\mu\text{m}$
Expected life in years						
Normal inland	12	18	20	$\pm 20$	$\pm 20$	20+
Polluted inland <sup>1</sup>	10	15	12	$\pm 18$	$\pm 15-20$	20+
Normal coastal	10	12	20	$\pm 20$	$\pm 20$	20+
Polluted coastal	8	10	10	$\pm 15$	$\pm 15-20$	20+

<sup>1</sup>For a desired life of 12 years in a polluted inland environment, coating system 3 to be selected and so on.

Paint should be applied in dry weather and at temperatures between  $+0.5^{\circ}\text{C}$  and  $+50^{\circ}\text{C}$ . The total *thickness of paint* on a steel surface (primer plus finishing coats) should be as given below. For interior unclad steelwork

(with ordinary humidity conditions)	130 $\mu\text{m}$
In industrial atmosphere	160 $\mu\text{m}$
In aggressive atmosphere	220 $\mu\text{m}$
In marine atmosphere	260 $\mu\text{m}$

The 300-m-high Eiffel tower in Paris (see Fig. 15.7) required 7300 tons of steel for its construction. The tower still looks much as it was on its completion in 1889, thanks to the proper painting at regular intervals for corrosion protection.



**Fig. 15.7** Eiffel tower

### 15.2.3 Lining and Coating

*Linings* are used to protect the internal surfaces of tanks and pipes in chemical plants from corrosion. Coating in general protects the external surfaces of pipelines, plant piping, bridge cables, foundation piles, and structures. Depending on the surface to be protected and the corrosive nature of the material contacting the surface, appropriate lining and coating materials are chosen from among rubber, enamel, glass, concrete, and other inorganic or resin materials.

One method of lining is to bond to the surface a lining material of film, sheet, or tape form. A paste-like lining material is applied to the surface with a trowel. Lining material in the powder form is either flame-sprayed or electro-statically sprayed onto the surface. The method of application is determined by the size and shape of the structure to be lined.

In many cases, the line pipe is mill-coated and lined. Lining of joints can be provided at the construction site with ease, since lining materials are available in so many forms, such as film, tape, sheet, and tube.

For offshore structures intended for service in the splash zone, which is most corrosive, various combinations of concrete coating, high-build type resin coating, and other methods are selected to suit the specified conditions of the installation site.

### 15.2.4 Hot-dip Galvanizing and Zinc Flame Spraying

In *hot-dip galvanizing* the structural members are immersed in a molten bath of coating metal at a temperature of about 450°C. This method is employed for such metallic coatings as zinc, aluminium, and tin which melt at lower temperatures than does iron (IS 4759 : 1996). Hot-dip aluminizing is only used for light sheet material for high-temperature use (e.g., motor car exhausts). Lead also is coated onto steel sheets in this manner, with the addition of small amounts of tin. The item to be galvanized is first degreased and cleaned by pickling to enhance the adhesion properties. In general, hot-dip galvanizing provides a relatively heavy coating (minimum 86  $\mu\text{m}$  thickness or 610  $\text{g}/\text{m}^2$ ) with high efficiency. One drawback is that the size of the structural member that can be galvanized is restricted by the size of the plating tank. Another drawback is the need for a large amount of energy. Because of the high temperature involved, it is important to ensure that any enclosed members, such as tubes, are vented to avoid the risk of explosion from vaporization of the trapped moisture (Dowling et al. 1988). The zinc/iron alloy layer is harder than the underlying steel and hence is resistant to the impact damage. In addition, this alloy layer gives perfect adhesion and total impermeability to moisture. Hot-dip galvanizing is employed for transmission towers, guardrails, bridges, etc. Galvanized members are often painted before use. For a given service environment, the useful life of a hot-dip galvanized structure is directly related to the thickness of the zinc coating: the thicker the coating, the longer the useful life.

*Zinc flame spraying* is generally used as a treatment for the base metal for coating. Unlike plating, this method puts no restriction on the size of the structure to be



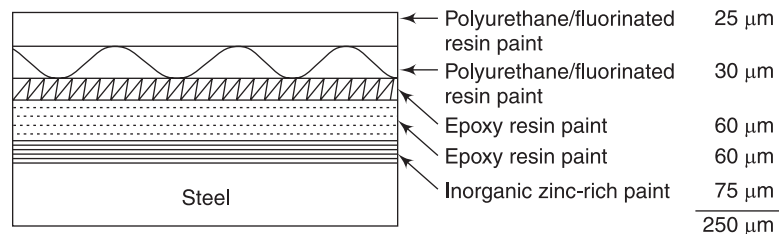
treated and can be used for on-site treatments. But it does have the drawback of requiring severe blasting of the surface to be treated. In industrial and marine atmospheres, aluminium coatings provide better corrosion protection than zinc coatings. A combination of metal-sprayed coatings and paintings achieve superior protection and is used for long-span bridges.

### 15.2.5 Heavy-duty Coating Systems

The paint system most commonly used for bridges presently is that consisting of corrosion-preventive oil paint/long-oil phthalic acid resin paint, about  $130\mu\text{m}$  thick coating, which may be good only for three to four years in corrosive coastal areas. The epoxy resin zinc-rich paint/chlorinated rubber paint system is slightly better, but does not suffice the present need in severe environments.

The use of thick, good quality paint coating systems with a repainting interval of more than 10 years in severe atmospheres started some 25 years ago. Since then the systems have been improved and are now commonly used for major bridges located at marine sites. They are called heavy-duty coating systems.

Construction of large, long-span bridges has been active in Japan since 1960s because they have large economic and social effects. Most of them are located over straits or in bay areas. Representative examples are those of the Honshu-Shikoku bridge project that links the mainland (Honshu) with the south-western island of Shikoku with three routes that incorporate 17 bridges, the longest one (Akashi Kaikyo bridge) having a centre span of 1990 m (completed in 1998). The durability of paint coating systems is of critical importance for such large, long-span bridges because of the high corrosivity owing to the environmental factors and the difficult accessibility for repainting. Based on an extensive study carried out over 20 years, a paint system consisting of high-build zinc-rich paint, high-build epoxy (two coats) and polyurethane (two coats), and having a thickness of  $250\mu\text{m}$  was specified for the first painting (1978) of this project. A system with high-build zinc-rich paint/high-build epoxy (two coats)/epoxy/fluorinated resin system, and having a thickness of  $250\mu\text{m}$  is also specified as per Matsushima (1997) (see Fig. 15.8).



**Fig. 15.8** Different layers of heavy-duty coating system

The prime coat of zinc-rich paint is pigmented with a high concentration of zinc dust, which, in contact with the steel surface, cathodically protects the latter in the same manner as galvanized coating. Zinc metal spraying is sometimes specified

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instead of zinc-rich paints. The intermediate coats, such as epoxy resin, function as a primer or protecting barrier, preventing intrusions of water, oxygen, and detrimental ions. Otherwise the prime coats would deteriorate too soon due to the rapid consumption of the zinc they contain. The intermediate coats also function as a layer to secure good adhesions of the primer and the finish coat. The finish coats, such as urethane, have good weathering resistance and protect the coats underneath from the detrimental action of sunshine (ultraviolet light) and water. More recent systems specify fluorinated resins as the finish coat for a longer service life.

A typical fabrication procedure for heavy-duty coating systems includes shot blasting of the steel plates followed by an immediate application of a shop primer, fabrication of steel plates into blocks, shot-blasting of the blocks, and application of high-build zinc-rich primer. The shop primer provides temporary protection during the fabrication of the blocks. To ensure good adhesion between coats, each overcoat must be applied within a certain time limit—10 days to 6 months, depending on the type of paint—after complete curing of the previous coat, which may require one to two days. The surface of the previous coat must be clean—free of dirt and chlorides (less than 50 mg/m<sup>2</sup>).

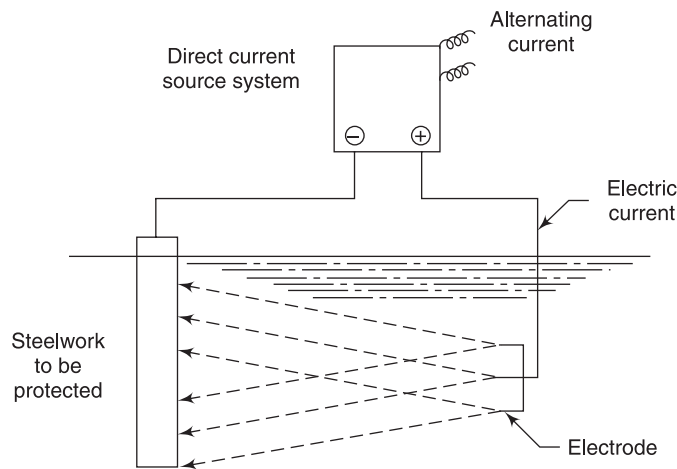
Most major bridges in marine areas are painted as per the above specifications for sections exposed to a severe environment. For example, Rainbow Bridge (centre span 570 m, total length 798 m) completed in 1993 to link the Tokyo teleport town in Tokyo bay within the heart of Tokyo is coated with a high-build zinc-rich/high-build epoxy/epoxy–MIO/fluorinated resin (two coats) system, 240 µm thick.

In general, such heavy-duty corrosion-protection methods are more economical than the use of corrosion-resistant metals. In addition, heavy-duty methods spell comparative ease of maintenance. Because of these advantages, heavy-duty methods are adopted for an increasing number of structures.

### 15.2.6 Cathodic Protection

As discussed earlier, when moisture is present, a steel surface behaves somewhat like a battery—anode and cathode exist on the steel surface. This creates voltage differences that cause tiny currents to flow from anode to cathode and the circuit is completed through the moisture on the metal surface. The electrochemical reaction between iron and oxygen then results in the corrosion of the steel surface. In *cathodic protection*, the flow of current is reversed, making the whole steel surface a cathode. This can be achieved in two ways: the impressed current method and the galvanic anode method (Kozai Club 1983).

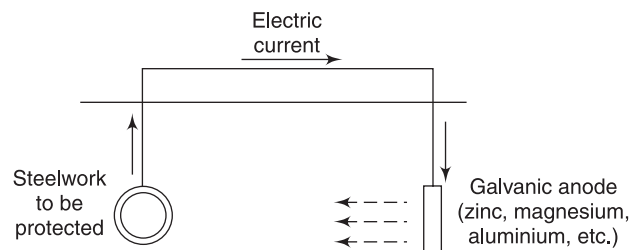
**Impressed current method** In this approach, shown in Fig. 15.9, a low-voltage direct current is applied to the steel structure from a rectifier. The positive terminal of the rectifier is connected to an electrode (the anode) installed underwater or underground, and the negative terminal is connected to the steel structure to be protected.



**Fig. 15.9** Impressed current method

The electric current density can be controlled according to the rate of corrosion. Also, electrodes do not need frequent replacement. However, periodic inspection and operating electric power are needed. The impressed current method is thus well suited to large piers that require semi-permanent protection.

**Galvanic anode method** If the steel structure is connected to electrodes made of metals that are lower in electric potential than iron, such as zinc, aluminium, magnesium or their alloys, a galvanic cell is formed in which the steel structure itself becomes the cathode. Thus the structure is protected while the anode gets gradually corroded. This approach is shown in Fig. 15.10. This *method* is simpler than the impressed current method and involves a lower initial cost and requires very little maintenance.



**Fig. 15.10** Galvanic anode method

### 15.3 Atmospheric-Corrosion-Resistant Steels

In this section we will discuss two types of steels, viz., weathering steel and stainless steel, which are increasingly being employed in important structures. These steels are produced by changing the chemical composition of mild steel and are considered as corrosion resistant.

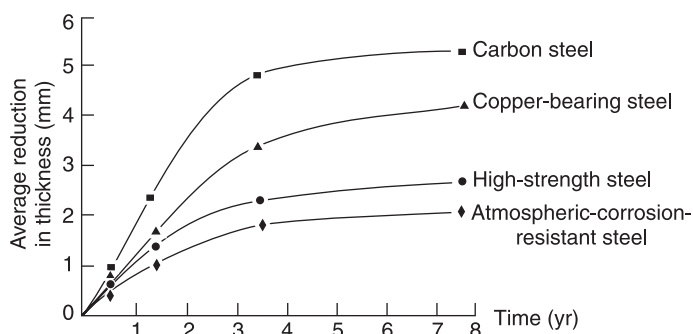
### 15.3.1 Weathering Steels

The corrosion resistance of steel may be improved by adding copper as an alloy element. However, copper-alloyed carbon steel is very expensive and hence not used extensively. Stainless steels are high-alloyed steels and are discussed in the following section. Atmospheric-corrosion-resistant steels are high-strength low-alloy steels that typically contain a combination of alloying elements such as copper, phosphorus, chromium, and nickel in small amounts (up to 3%). Originally developed by United States Steel Corporation, these steels are called *weathering steels* and popularly known as Cor-Ten (Salmon & Johnson 1996). Cor-Ten matches with WR-Fe 480A of IS: 11587-1986. A comparison of the chemical composition of weathering steel with other steels is given in Table 15.8. The reason for its low susceptibility to rusting is the same as that for stainless steel, since the base metal is protected against the corrosive environment by an oxide film, which is formed on its surface in the initial years of use. However, the mechanism by which the stable rust layer forms has not yet been fully studied. Generally, the formation of a stable rust layer requires repeated cycles of wetting by rain and drying by sunshine and wind. Rust is produced on steel by the oxidizing reaction of iron. But the protective film is formed in a different manner from that of stainless steel. In the early stage of exposure, weathering steel begins to rust in the same way as ordinary carbon steel. But later, after being subjected to repeated cycles of drying and wetting in the air, the initial layer of red rust transforms itself into a dark brown film wherever it contacts the steel surface. Within a few years, it becomes a stabilized, extremely fine-textured rust film [which has the composition  $\text{FeOOH}$  ( $\text{FeO}_3\text{H}_2\text{O}$ )] that covers the entire surface (Matsushima 1997). This film effectively prevents water and oxygen from reaching the steel beneath and thus halts the corrosion reaction almost entirely. Further rusting is thereby prevented. An added advantage is that sulphuric acid in the atmosphere, which stimulates the corrosion of ordinary steels, actually promotes the formation of the stable protective film in atmospheric-corrosion-resistant steels. A comparison of the reduction in the thickness for various steels is given in Fig. 15.11. The reduction in the thickness in 50 years would be less than 0.3 mm in many atmospheres.

**Table 15.8** Comparison of chemical composition of various types of steel

Type of steel	Chemical composition (%)							
	C	Si	Mn	P	S	Cu	Ni	Cr
Carbon steel	0.16	0.009	0.57	0.010	0.010	0.11	0.025	0.036
Copper-containing steel	0.13	0.152	0.55	0.071	0.011	0.39	0.025	0.035
Atmospheric-corrosion-resistant steel (Type 1) <sup>1</sup>	0.11	0.467	0.30	0.119	0.021	0.39	0.410	0.640
Atmospheric-corrosion-resistant steel (Type 2) <sup>1</sup>	0.10	0.458	0.37	0.103	0.021	0.29	0.280	0.760

<sup>1</sup>Mo, Nb, Ti, V, and Zr are also added (0.15% maximum in total)



**Fig. 15.11** Comparison of weather resistance of steels (*Steel Today and Tomorrow* 1989)

First introduced in 1958 in Illinois, USA, corrosion-resistant steels have already found application in buildings, bridges, and storage tanks, and their use continues to grow. Because of their superior resistance to atmospheric corrosion, they are painted (paint life is far longer than that of carbon steel) or coated with accelerants that hasten the formation of the protective film. The extra cost of such steel over ordinary mild steel is about 20% and its use is amply justified in view of the heavy cost of repeated painting. Though it was first produced in Japan in the 1960s, it was used in bridges only during 1970s. Now about 20% of the steel bridges in Japan use weathering steel, accounting for about 50,000 tons of weathering steel used annually.

Recently, Balasubramanian and his associates at the Indian Institute of Technology, Kanpur, have developed a novel phosphorus-containing iron which would be corrosion resistant, ductile, and long lasting (*Times of India* 2005).

**Limitations of weathering steels** Weathering steels perform properly when the concentration of chlorides in the atmosphere or the accumulation of sulphuric acid from burned fuels is not excessive, and when water pools after rainfall do not remain for a long time. Significant amounts of deposited chlorides and continuous wet conditions hinder the formation of the protective rust film (Khanna 1999).

The safe limit of the chloride concentration in the atmosphere is about 0.05 mg of NaCl/m<sup>2</sup>/day as determined by the wet-gauge method. Most sites 1 to 5 km or further from the sea coast or polluted industrial area satisfy this criterion, although in some areas where there is a strong prevailing wind from the sea, the critical distance inland from the sea coast may reach a maximum of 20 km. Also, weathering steels have no advantage over ordinary steels if buried in soil or totally immersed in water. In areas where a prolonged contact with water is unavoidable, such as the interior of box girders, weathering steels need to be painted.

It may take several years for the protective rust films to develop fully. It is necessary to clean the steel surface for more uniform and smoother formation of the protective rust films. During the initial period, the corrosion rate is higher than that in the subsequent, well-protected period of service, and the run-off of rainwater may colour the neighbouring concrete brown. Also, particles or flakes of rust may spall off during this period.

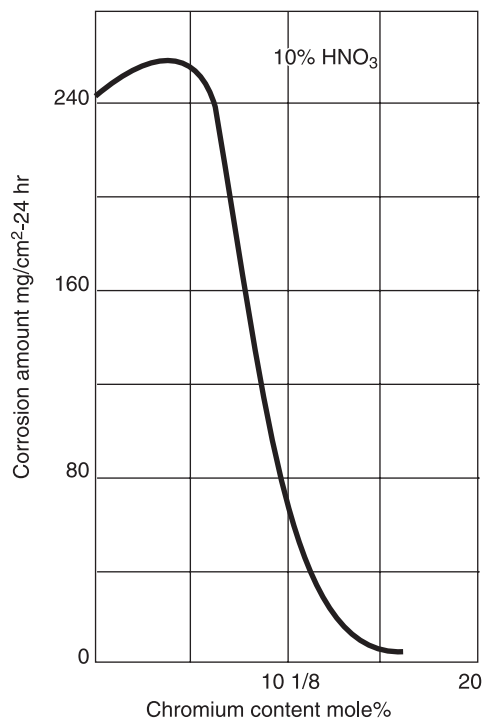
## 15.22 Design of Steel Structures

The fabrication and erection of weathering steel require care. Scale and discolouration from welding should be removed and unsightly gouges, scratches and dents should be avoided (Khanna 1999).

### 15.3.2 Stainless Steels

In terms of chemical composition, stainless steels are broadly classified into high-Cr stainless steels, which contain chromium, and Ni-Cr stainless steels, which contain both chromium and nickel (Nagoya 1998; Subramanian & Sampath 2002). Representative grades are 13% Cr stainless, 18% Cr stainless, and 18% Cr and 8% Ni stainless steels.

The general concept behind stainless steel is that a stabilized passive chromium-rich oxide film (3  $\mu\text{m}$  thick) forms on its surface, preventing further penetration by the corrosive atmosphere. The forming of such a film on the steel surface is called *passivation*. When chromium is added to steel in amounts of 11%–13% or more, the fine textured passive film that forms provides significant resistance against rusting (see Fig. 15.12). This film is ultra-thin, of the order of 10–30Å. Its composition can be expressed as  $\text{Cr}_2\text{O}_3\cdot\text{NH}_2\text{O}$ . Unlike steel, which has a crystalline structure, the oxide film is amorphous, like glass, and is thought to be a uniform and chemically stable film. When it is marred, the film is immediately repaired by the action of Cr ions. But once the protective film has been destroyed under certain circumstances



**Fig. 15.12** Graph showing the relation between chromium content and corrosion (Nagoya 1998)

(especially in coastal areas, where sea salt particles are deposited on the surface, damage this passive film, and eventually lead to small pitting), stainless steels become susceptible to rusting. Thus it cannot be said that stainless steels never rust. Nonetheless, they are highly resistant to rusting. Steel manufacturers have recently stepped up their development efforts in this field, with emphasis on new technology that speeds up the formation of the passive film. The addition of such elements as molybdenum, copper, titanium, and niobium, for example, makes the film form more quickly. Tests conducted in Japan show that the maximum depth of pitting corrosion is only 0.2 mm even after 40 years for type SUS 304 steel (produced in Japan). Designability is another advantage offered by the use of stainless steel. A variety of stainless steel sheets having attractive colours and patterns have been introduced. Figure 15.13 shows the Osaka Dome in Japan, which is covered with stainless steel sheets, and Fig. 1.40 shows a double-layer grid in India using stainless steel tubular members.

The recent developments in the field of stainless steel include (Nagoya 1998; Subramanian 2000) the following.

1. Superior weather-resistant stainless steel for use at waterfronts (ferritic steels SUS444 of 19% Cr-2% Mo type). The roof of the Japan Sea Base pavilion is of a new high-alloy steel (30 Cr-2 Mo type) having weather resistance comparable to that of titanium. Compared to SUS 304 (18% Cr-8% Ni steel), this stainless steel not only has a higher localized corrosion resistance in a chloride environment but also avoids stress corrosion cracking entirely in a hot water environment.
2. Metal coated stainless steels. In these either aluminium or zinc is coated onto the surface of stainless steel.



**Fig. 15.13** Osaka Dome built in Japan in 1997 (*Courtesy: Steel Today and Tomorrow*)

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3. Pre-painted stainless steel in which silicon polyesters and acrylics are painted on the surface of stainless steel. Recently fluorocarbon resins have also been introduced. Various transparent painting systems, which do not destroy the decorativeness of stainless steel, have also been developed recently.

More details about stainless steel are given in Section 1.15.

## 15.4 Corrosion Allowance

The concept of protection by *corrosion allowance* can be applied to projects involving steel piles, steel sheet piles, offshore structures, and other steel structures placed underground or underwater.

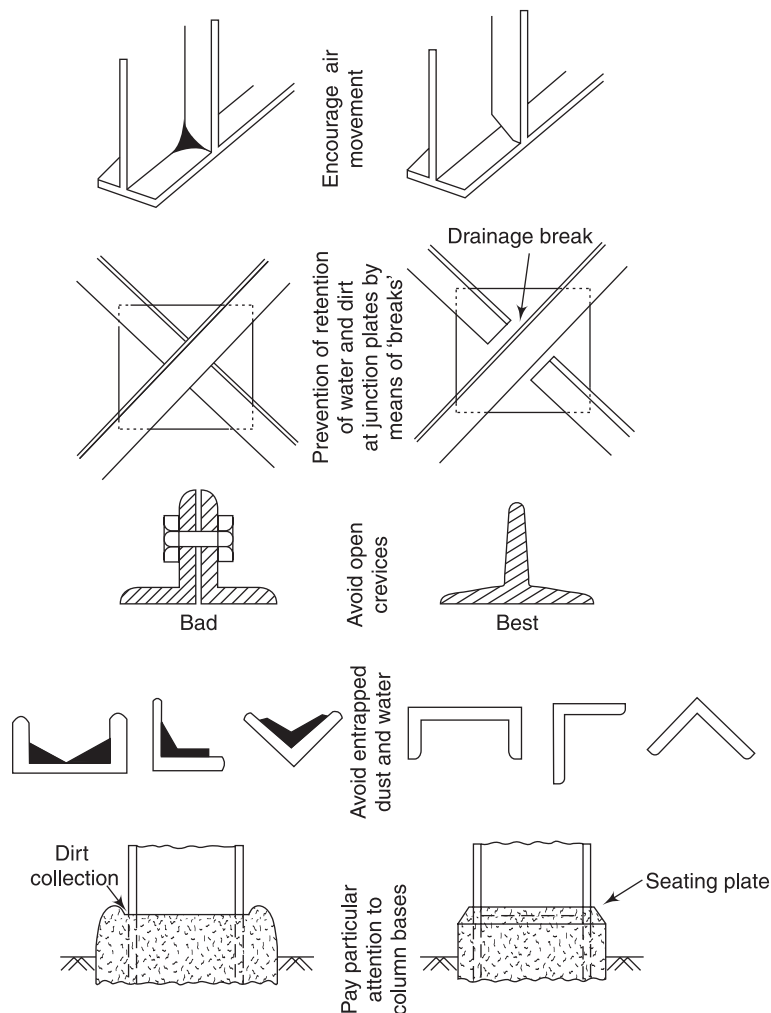
In the design of a steel pipe pile, for example, a wall thickness is calculated for each section of the pile that ensures safety with respect to compression, tension, bending, shear, and other stresses which may arise in service. Then an extra wall thickness is added, equal to the expected loss in the thickness due to corrosion during the intended service life of the pile. When the corrosion allowance approach is used, a clear knowledge of the rate of corrosion of underground and sub-sea steel installations is necessary. In Japan it has been found that the rate of corrosion averaged a mere 0.024 mm per year. This shows that a pile, if given a corrosion allowance of 2 mm in the wall thickness, has a life expectancy of 80 years.

## 15.5 Detailing to Reduce Corrosion

It is also important that the detailing of steel structures should be done in a way that enhances durability. Some of the points to be considered are (see Fig. 15.14) as follows.

1. The detailing should avoid water or dirt entrapment or accumulation in corrosion points, such as sharp and re-entrant corners, cavities, welded rough surfaces, to avoid corrosion due to accumulation of dust and moisture.
2. Discontinuous weld points, spot welds, and tubular edge welds are also trouble spots of corrosion. All such points should be cleaned and filled or smoothed with tar-paint to protect from corrosion.
3. Detailing should provide suitable drainage breaks or holes wherever possible so that water does not accumulate.
4. Detailing should encourage free air movement such that the surfaces are dried rapidly.
5. Detailing should avoid crevices as far as possible.
6. Suitable access to all the components of the steel structure (especially the joints in a bridge) should be provided for periodic inspection and maintenance.
7. Detailing should avoid contact with different materials to prevent galvanic corrosion.
8. When friction grip bolts are used, protective treatment should not be applied to the faying surfaces.





**Fig. 15.14** Detailing to avoid water entrapment (ECCS 1998)

## 15.6 Encasing in Concrete

Traditionally steel members are encased in concrete to prevent corrosion [see Fig. 1.46(a) and (c)]. Encasing steel in concrete provides an alkaline environment due to the hydration of cement (the  $pH$  value of concrete is of the order of 12.5–13.5). This results in the formation of a protective film of iron oxide on the surface of steel components. This passive protection is broken when the  $pH$  value of the regions adjoining the steel falls below about 9. This can occur due to the following:

- Water diffusion through the pores of concrete (carrying with it  $SO_2$  and  $CO_2$  gases from the air in the form of weak acids)
- Carbonation (reaction of carbon dioxide in the atmosphere with the alkalis in the cement paste)
- Ingress of soluble chlorides—the extent of penetration depends on the permeability and thickness of concrete

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The resulting corrosion of steel and the increase in pressure result in spalling of concrete. It has to be noted that the members that are encased in concrete should neither be painted nor oiled. Encasing steel members in concrete increases the dead load of the structure and results in increased foundation costs. Moreover, the steel members are not visible for inspection or repair; hence concrete encasing is not suggested now-a-days as a corrosion-protection method.

### **Summary**

The durability of structures is given more emphasis in recent times. Durability and corrosion are considered as serviceability limit states criteria. A durable steel structure may be defined as the one that performs satisfactorily the intended function(s) in the working environment under the anticipated exposure condition(s) during its service life, without any deterioration of the cross-sectional area and loss of strength due to corrosion.

Corrosion of steel is an electrochemical process which will not occur unless water and oxygen are both present on the steel surface. There are several types of corrosion. The results of surveys conducted in several countries show that the annual loss due to corrosion amounts to several million dollars. However, with suitable corrosion control methods, the rate of corrosion can be made vary slow or practically nil.

The rate of corrosion depends mainly on the degree of atmospheric pollution and the duration of wetness of the steel surface. Local corrosion rates are also influenced by contact with other metals. IS: 800 classifies environment into five different categories: mild, moderate, severe, very severe, and extreme. Each class of environment requires a different kind of corrosion protection. It is seen that the corrosion rate inside buildings is insignificant, since the steel members inside the buildings do not come into contact with moisture.

The most common type of corrosion protection is to apply a protective coating to steel, thereby sealing off its surface from a corrosive environment. However, the performance of such coatings depends largely on the correct surface preparation before coating. The blast cleaning process, in which abrasive particles are projected at a high speed onto the steel surface, produces a clean and rough surface that improves the adhesion of coatings. Shot blasting is preferred for most paint coatings, whereas grid blasting is used for sprayed metal coatings. Chemical cleaning may be opted for when hot-dip galvanizing is used.

Many generic types of paints are available and guidelines to use these paints in different environments are given. While specifying paint coatings, one should take into account the severity of exposure, ease of painting, sequence of fabrication and erection, ease of repairing, and maintenance cost. Linings are used to protect the internal surfaces of tanks and pipes in chemical plants and external surfaces of pipes, bridge cables, and foundation piles.

Hot-dip galvanizing, in which the steel members are dipped into a bath of molten zinc or aluminium kept at about 450°C, is the cheapest and most common method

of metal coating. Metal spraying uses a special spray gun to throw molten zinc or aluminium coating onto a clean, grit-blasted surface. No alloying takes place in metal spraying. Metal spraying may be provided with a sealing treatment to give maximum corrosion resistance. However, the cost of sprayed coatings is high due to the required surface preparation.

Heavy-duty coating systems with thicknesses up to 250  $\mu\text{m}$  have been used in steel bridges located in severe environments. Cathodic protection in the form of the impressed current method and the galvanic anode method is used in structures where a high corrosion resistance is essential or in structures that cannot be easily repaired. Low-alloy steels with alloying elements such as copper, phosphorus, chromium and nickel, called weathering steels and stainless steels, containing chromium and nickel have been used extensively in the recent past. Though the initial cost of these steels is high, the life cycle cost analysis has proved them to be economical in the long run. Though concrete encasement provides an alkaline environment that protects the steel member, it increases the dead weight and hence is not used extensively as a corrosion protection system.

Since longer periods of wetness result in greater corrosion, it is important to design and detail the structures in such a way that they shed the water rather than retain it. Wherever necessary, drainage holes of appropriate sizes and at appropriate locations should be provided to ensure that all the water is drained from the member and there is a free flow of air to promote rapid drying.

More details about the corrosion protection of steel structures may be found in Pimple et al. (2002), Samanta (2003a), Chaudhari and Samanta (2003), and Samanta (2003b).

## Review Questions

1. Explain the process of corrosion.
2. What are the three things that must be eliminated in order to prevent corrosion?
3. Does rust formation prevent corrosion?
4. What are the different types of corrosion?
5. Write short notes on the following:
  - a. Uniform corrosion
  - b. Pitting corrosion
  - c. Crevice corrosion
  - d. Galvanic corrosion
  - e. Stress corrosion
  - f. Corrosion fatigue
  - g. Intergranular corrosion
6. What is hydrogen embrittlement?
7. The thickness of the rust layer will be
  - a. Equal to the thickness lost in the original steel
  - b. Less than the thickness lost in the original steel
  - c. Double the thickness lost in the original steel
  - d. Four times the thickness lost in the original steel

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8. What are the factors that influence the rate of corrosion?
9. Match the following:
  - a. Severe environment
  - b. Extreme environment
  - c. Moderate environment
  - d. Mild environment
  - a. interior of building
  - b. structures under water
  - c. structures in coastal area
  - d. structure in chemical factory
10. What are the factors to be considered while selecting a corrosion-protection system?
11. Match the following:
  - a. Structures in remote areas
  - b. Members inside building
  - c. Industrial building
  - d. Bridges
  - e. Steel piles
  - a. heavy-duty coating system
  - b. cathodic protection
  - c. oil-based painting
  - d. chlorinated rubber painting
  - e. hot-dip galvanizing
12. List the various corrosion-protection methods.
13. What are the different surface preparation methods?
14. What type of surface preparation is used for hot-dip galvanizing?
15. What is the use of surface preparation?
16. What are the factors to be considered while specifying a paint coating system?
17. What are the main components of a paint coating system?
18. List some of the available types of paints.
19. What is the thickness of paint to be applied for interior members in mild environment and members in industrial environment?
20. Where are linings used and what are the materials used for lining?
21. Write short notes on the following:
  - a. Hot-dip galvanizing
  - b. Zinc flame spraying
  - c. Heavy-duty coating system
  - d. Cathodic protection
  - e. Weathering steel
  - f. Stainless steel
22. What is the difference between weathering steel and stainless steel?
23. What are the limitations of weathering steel?
24. What is meant by corrosion allowance?
25. Why concrete encasing is not preferred as a corrosion-protection method?
26. What are the points to be considered while designing and detailing steel structures in order to reduce corrosion and enhance durability?