The structural form of ocean structures is unique and expensive by design, installation, commissioning, and operability. Legislation calls for periodic certification of offshore structures. Alternatively, one could rely on the structures to be so well designed and built so that no serious failure develops during his or her working life. Unfortunately, weather conditions and marine growth become more severe than initially predicted values. Wave and current loads have been underestimated in few design cases. Fatigue and corrosion are still debatable subjects. All the above factors result in heavy penalty on the existing weight. Otherwise, this could save a large sum of material costs and ease out the installation procedures. Feedback of actual conditions of structures during their working life would be helpful to do the design successfully. Moreover, marine environment is corrosive in nature, which can cause serious degradation of material and strength of the structural members.

Material for construction should be carefully chosen so that the service life of ocean structures is guaranteed. Repair of ocean structures is a multicomplex phenomenon not because of its limited accessibility for repair but also due to its undesirable intervention of the structure for repair and rehabilitation. In this chapter, different types of structural materials that are useful for construction, repair, and rehabilitation are discussed. Recent advancements with respect to repair of concrete structures are also presented.

### 3.1 INTRODUCTION

Different types of materials are used in the construction of ocean structures. They are used for a variety of purposes: construction, repair, rehabilitation, corrosion protection, and so on. There are different groups such as (1) ferrous and nonferrous and (2) nonmetals, namely, fiberglass, concrete, wood, and glass. In addition, use of composites is on the increasing side in the recent times due to salient advantages they possess in the marine environment. However, concrete can never be ignored as one of the primary materials for the construction of ocean structures. Further, metals can be ferrous and nonferrous: mild steel, copper, aluminum, and brass. Moreover, fiber-reinforced plastics are also used in specific segments of construction of ocean structures. Plastics of thermosetting and thermoplastic resin types, acrylic polythene, and polyvinyl chloride also have their wide applications in the construction of marine structures. Selection of materials for the marine environment is a complex task as no single material characteristic shall rank the suitability of material for offshore applications, in particular. Though it is agreed upon that the
basic knowledge of structural characteristics of materials helps an offshore engineer to select appropriate materials for offshore applications, various categorizations of materials having similar structural properties make this task more complicated. Further, a continuous feedback loop of understanding the special requirements of material properties based on the failure in offshore platforms demands a clear understanding of fundamental properties of materials that are commonly addressed by all international codes; advanced properties to make a particular material suitable for offshore applications necessitates advanced learning of those required material properties, making it an unique domain of material research. Figure 3.1 shows the collage of materials for offshore structures. It also shows different types of materials that are available in the market; suitability of these materials to offshore applications categorizes them accordingly. This process of classification of materials can be more precisely addressed after understanding their fundamental properties that make them suitable; later their advanced properties to assess their suitability under particular environmental and loading conditions become important.

Offshore structures are exposed to different environmental loads, and their combinations guide the suitability of materials for the marine environment. For example, wind, waves, ocean currents coupled with thermal gradient, and ice are a few types of environmental loads. In addition, the marine environment also exerts on materials other forces due to chemical, fatigue, stress and corrosion effects, and biofouling effects. Hence, these materials must have properties that ensure survivability (1) in case of any accidents (collision) and (2) in case of excessive loads.

**FIGURE 3.1** Materials for marine applications.
during hurricanes; note also that underwater structures have to withstand hydrostatic pressure. Adding to their complexity, structures are also exposed to earthquakes, hurricanes, scouring, and typhoons. Earlier, the major application of materials was only for surface ships; now newly developed ocean systems require materials with special characteristics. Offshore drilling and production platforms, surface buoys, instrument platforms, submarine vehicles, and so on, are the examples of such newly developed ocean systems. As materials are subjected to different types of loads, they require specific properties to sustain these loads and their combinations.

3.2 SELECTION OF MATERIALS

There exists a close relationship between the selection of materials and the type of offshore structures. Various specifications/codes/regulatory agencies guide in the selection process of materials for the marine environment. Referring to the set of recommendations made by the American Bureau of Shipping with respect to the use of materials for surface ships, material selection based on such recommendations is only desirable but not mandatory as it may limit the selection of materials. Under the given wide choice of materials that are available, selection of materials for a specific application becomes very important. Apart from strength, environmental issues related to their recycling characteristics, sustainability, renewable property, and toxic and nontoxic nature are a few important areas of interest to offshore engineering professionals. In the recent times, use of geomembranes and geotextiles for slope stabilization of coastal embankments has also been seen in the literature. As the marine environment has high complexities that influence the performance of materials under the given environmental conditions, the choice of appropriate materials for ocean structures becomes an important engineering decision.

During the selection of materials for ocean structures, the following factors are normally accounted for: (1) physical and chemical properties of materials, (2) cost, (3) fabrication facilities, and (4) maintenance cost. Chosen materials should avoid catastrophic failure. Besides meeting the design requirements, they should withstand hazards (including those arise during operations). During selection, a few material (physical) characteristics are important. Yield strength becomes the first consideration, whereas Young’s modulus and ductility follow it. Poisson’s ratio is also important as structures are under multiaxis loading. Due to the dynamic nature of environmental loads, fatigue performance and fracture resistance also become equally important. Note that the physical characteristics are presented in the literature based on the data taken from standard specimens. Structure loading in the actual environment differs markedly from those of any tests conducted in controlled laboratory conditions. This warrants change in allowable stress levels for various ocean conditions. This is taken care in design in terms of material allowance, either by increasing the thickness of the members or by using an appropriate factor of safety. Apart from the cost of materials and their availability in the desired cross section and size, it is vital to understand their fundamental characteristics and performance under different environmental conditions to make such an important decision.
3.3 FUNDAMENTAL PROPERTIES

Mechanical properties are generally considered important indices for studying the behavior of metals under loads. For example, strength, hardness, toughness, elasticity, plasticity, brittleness, ductility, and malleability are useful to characterize their behavior under different types of loads. These properties are generally described in terms of the types of forces or stress that the metal must withstand as well as how these forces are resisted. In addition to their homogeneity and isotropic characteristics, their functional degradation in the corrosive environment also needs to be investigated before the choice of material is made. Unlike land-based structures where strength may be one of the most important criteria (in most of the cases, it is the only design criterion), performance-based design of offshore structures makes the material choice inadvertent. Mechanical properties of materials are used as measurements to estimate their behavior under loads. Though it is well known in the literature, it is still advantageous to review it in this section. This will help one to understand the special properties that are required by a material to qualify for offshore applications. Some of the important properties are strength, hardness, elasticity, plasticity, brittleness, ductility, and malleability. These properties are described in terms of the types of forces or stress that the material has to withstand and how are they resisted. Followed by this, the types of forces/stress that are common in offshore structures subjected to environmental loads will become important. Common types of stress are compression, tension, shear, torsion, impact, or a combination of these stresses, such as fatigue. Compression stresses are developed within the material when forces compress or crush the material. For example, a column that supports an overhead beam is in compression, and the internal stresses that develop within the column are compression. Tension (or tensile) stresses develop when a material is subjected to a pulling load; for example, using a wire rope to lift a load or using it as a guy wire to anchor the structure to seabed results in axial tension. “Tensile strength” is defined as the resistance to longitudinal stresses or pull. Shear stresses occur within a material when external forces are applied along parallel lines in opposite directions. Shear forces can separate materials by sliding them apart.

A basic question comes to mind when selecting materials for offshore applications—Under which type of load should one classify the maximum strength? Some materials are equally strong in compression, tension, and shear. However, many materials show marked differences; for example, cured concrete has a maximum strength of 14 MPa in compression but only 3 MPa in tension. Carbon steel has a maximum strength of 386 MPa in tension and compression but maximum shear strength of only 290 MPa; therefore, when dealing with maximum strength, it is always necessary to state the type of loading. Fatigue is induced in members (material) that are stressed repeatedly. Usually, it fails at a critical section at a magnitude of load, which is considerably below its maximum strength in tension, compression, or shear. For example, a thin steel rod can be broken by hand by bending it back and forth several times in the same place; however, if the same force is applied in a steady motion (not bent back and forth), the rod cannot be broken. Tendency of a material to fail under reversal of (nature of) forces at the same point is known as fatigue. Strength is the property that enables a material to resist deformation under load. Ultimate strength of
the material is the maximum strength a material can withstand, where tensile strength is a measurement of the resistance to being pulled apart when placed under tensile load. “Fatigue strength” is the ability of materials to resist stresses that are reversal or cyclic in nature and is expressed by the magnitude of an alternating stress for a specified number of cycles. Impact strength is the ability of a metal to resist suddenly applied loads. Hardness is the property of a material to resist permanent indentation. Because there are several methods of measuring hardness, it is always specified in terms of the particular test that is used to measure this property. For example, Rockwell, Vickers, or Brinell are some of the methods of testing hardness. Of these tests, Rockwell hardness is the one most frequently used. The basic principle used in the Rockwell test is that a hard material can penetrate a softer one; the amount of penetration is measured and compared to scale. For ferrous metals, which are usually harder than nonferrous metals, a diamond tip is used and the hardness is indicated by a Rockwell “C” number. For nonferrous metals, which are softer, a metal ball is used and the hardness is indicated by a Rockwell “B” number. Toughness is the property that enables a material to withstand shock and to be deformed without rupturing. This is considered to be a combination of strength and plasticity. Elasticity is the ability of a material to return to its original shape on removal of load. Theoretically, elastic limit of a material is the limit to which a material can be loaded and still recover its original shape after the load is removed. However, plasticity is the ability to deform permanently without breaking or rupturing. This property is in converse to that of strength. By careful alloying of metals, combination of plasticity and strength is used to manufacture large structural members that are commonly used in marine construction. Brittleness is the opposite of the property of plasticity. A brittle metal is the one that breaks or shatters before it deforms. Although cast iron and glass are good examples of brittle materials, brittle metals possess higher compressive strength in comparison with their tensile strength. Under the braces of performance-based design of structures, ductility plays an important role, which enables the member to stretch, bend, or twist without cracking or breaking. Malleability is the property that enables a material to deform by compressive forces without developing defects. A malleable material is one that can be stamped, hammered, forged, pressed, or rolled into thin sheets.

Compressive or tensile stresses are commonly generated on structural members in addition to bending, shear, and torsion; impact forces are occasional. Interestingly, the behavior of members and the capacity of material to safely disburse the combination of stresses are the most critical aspects in the design. The combination of various forces results in a complex behavior of the material. One classic example could be dynamic tether tension variations that can arise in tethers of tension leg platform (TLP), which can result in fatigue failure. Ductile materials such as steel are a favorite choice and widely used in offshore construction. The ductile behavior of steel is well understood from the stress–strain curve plotted under uniaxial stress; a typical curve is shown in Figure 3.2. Most ductile metals other than steel do not have a well-defined yield point. For these materials, the yield strength is typically determined by the “offset yield method.” A line is drawn parallel to the initial slope, from 0.2% of the maximum strain value. The point of intersection of this line with the stress–strain curve determines the yield point as shown in the figure. This is also called
0.2% proof stress. The ratio of the maximum strain to that at yield is called “ductility ratio,” which is an important engineering property in the design of offshore structures. This will govern the rotation capacity of plastic hinges, assumed to be formed at critical sections in the plastic analysis. Interestingly, the strength ratio, which is the ratio of ultimate strength to yield strength, is also important for design. However, the ductility ratio governs the decision of choice of materials for offshore structures as large ductility ratio is an index of energy absorption. In case of brittle materials such as concrete or ceramics, a well-designated yield point is not seen. Figure 3.3 shows a typical stress–strain curve for brittle materials. In such cases, rupture and ultimate strength are the same for these members. Area underneath the stress–strain curve with respect to the abscissa is an index of toughness of the material.

3.4 Effects of the Marine Environment on Materials

Earlier, the major application of materials is only with surface ships. New offshore structures, such as offshore drilling and production platforms, surface buoys, instrument platforms, and submarine vehicles that are developed in the past, require materials
with special characteristics. Large deformation induced in the design concept such as TLPs demands high ductility in tether materials. Articulated towers demand more fatigue resistance in the materials used for articulated joints. Offshore structures are exposed to a combination of a variety of environmental loads, as discussed in Chapter 2. The material strength degrades under the effects caused by the environmental loads. Few of them are chemical, fatigue, stress concentration, corrosion effects, and biofouling effects. It is desired that materials must have properties, which ensure survivability in case of any accidents (collision). In case of excessive loads during hurricanes, they should be able to withstand high hydrostatic pressure. Given different combinations of forces acting on the members of the offshore structures, it is imperative to understand the important characteristics that materials should possess to be qualified for construction of ocean structures. There exists a close relationship between the selection of material and the type of ocean structure. Various specifications suggested by codes and other regulatory agencies are only desirable general recommendations but not a requirement as they may impose a serious limitation on the suitability of materials for the marine environment. Materials must have properties that ensure survivability in the marine environment. They should be able to perform their intended function under special conditions: collision or impact, excessive loading that occurs during hurricanes, and special kinds of environmental forces. In addition, materials should withstand a severe hydrostatic pressure. All the above special conditions make the choice of the materials to a highly limited situation. As the algorithm of selection of materials for ocean structures grows complex in nature, one needs to understand the factors based on which materials can be chosen for such special applications. Apart from understanding the list of special properties of materials that are required to sustain the combination of different environmental loads in the critical marine environment, it is important to know about those specific properties, which are demanded from the materials if they have got to qualify for ocean structures. Factors that become vital for selection of materials include the physical and chemical properties of the materials, the cost and availability in large quantity, and the availability of fabrication facilities for the chosen shape, size, and geometry. Materials chosen for marine construction should be easy to fabricate and transport to the offshore site, which is one of the major constraints in material selection. It is also important to note the expected maintenance must be looked upon as the survivability of these kinds of structural systems in the complex ocean environment is very important. Hence, selection of materials is closely governed by the advice or recommendations given by various international codes. These codes indicate a variety of engineering properties that guide the selection for various applications.

Materials should be chosen not to initiate any catastrophic failure; this means that failure, if at all occurs, even at a lower probability, should not be sudden or immediate, or it may lead to loss of assets that are invested on offshore platforms. There can be hazards that arise from operational errors because oil production process is complex. It involves a lot of electromechanical and electrical equipment, which need to be synchronized in a specific format to perform drilling and exploration successfully. Under such a complex operation, materials selected for construction of the platform and other accessories such as pipe lines and rigs should be capable of withstanding the unforeseen hazards besides meeting the design requirements.
3.5 DESIGN CONSIDERATIONS

While selecting a material for marine applications, the following material (physical) characteristics are important in the order of priority as follows: (1) yield strength, (2) modulus of elasticity, (3) Poisson’s ratio, (4) fatigue performance, and (5) fracture resistance. In addition, the above material properties are only indicative. For example, if the material has a yield value of 250 MPa, it is only an indicative value for a standard specimen. However, in reality, this value may vary depending on the nature of loading and other conditions. Therefore, it is important to understand that there is a significant difference between the material properties under standard test conditions and those in the marine environment. It therefore warrants a change in allowable stress levels for the marine environment and is taken care of through “material allowance.” For example, an increase in thickness is seen as allowance in the design to take care of uncertainties that are caused by change in the conditions in the ocean environment. Alternatively, one can also use partial safety factor for materials to account for such uncertainties.

3.6 STEEL CLASSIFICATION

Steel is a common material used for marine construction. It is also one of the widely used materials in ocean structures. It is classified in several ways to make it suitable for particular set of applications in the ocean environment; in fact, classification enables us to identify their areas of application. Steel is classified based on its composition, manufacturing methods, finishing methods, microstructure, strength, heat treatment, and the product form. Based on the composition, it is classified as carbon, low alloy, or stainless steel. Based on the manufacturing methods, it is classified as electric furnace or open hearth process. Based on the finishing methods, it is classified either as hot rolling or as cold rolling. Based on the microstructure, it is classified as ferritic, pearlitic, or martensitic. Based on the strength required, different codes classify them in many ways. Based on heat treatment carried out on steel to achieve desired characteristics, it is classified as annealing, quenching, and tempering. Based on the product form, it is classified as bars, plates, sheets, strips, tubes, and other desired shapes named after the shape of the cross section as L, Tee, and so on.

Classification of steel based on strength is intrinsic in the design codes. Depending on the component of the member and type of load combinations, codes classify them according to their yield strength. Looking at the further level of classification based on carbon content, steel is classified as low, medium, high, and ultrahigh carbon steel. Low carbon steel contains less than (or equal to) 0.3% of carbon and does not contain other elements such as chromium, cobalt, and nickel. Medium carbon steel has a percentage of carbon varying from 0.3 to 0.6, whereas high carbon steel has a content varying from 0.6% to 1%. Ultrahigh carbon steel has about 1.25%–2% of carbon content. Carbon content influences the strength of steel; low carbon steel is also referred to as low-strength steel whose yield strength is less than 415 MPa. This type of steel is widely recommended for the hull structure of platforms, fittings, tanks, instrument ancillaries, and buoys. Medium-strength steel has a medium percentage of carbon whose yield strength is about 1035 MPa. It is widely used for fabricating
icebreakers and buoys for arctic regions. High-strength steel has a yield strength greater than 1035 MPa. For example, maraging steel has a yield strength in the range of 1–2 GPa. This type of steel is relatively ductile and manufactured by heat treatment to improve its specific properties such as ductility. The major standards that are used for offshore construction are prEN 10225, BS 7191, and Material Data Sheets of NORSOK, which is Norwegian standard, applicable primarily in European countries. American Petroleum Institute (API) standards are primarily used in American and Asian regions, although there is no bar of using any specific standard on any part of the world. It is important to note that most of the classification of steel and its applications, as recommended by various codes, corresponds to each other. For example, NORSOK refers to prEN 10225, which itself is based on BS 7191.

3.7 GROUPS OF STEEL

Steel is grouped according to the strength level and welding characteristics. Group I refers to steel with a specified minimum yield strength (SMYS) of 280 MPa or less and carbon equivalent of 0.4% or less. Group II refers to steel with SMYS less than 360 MPa and carbon equivalent of 0.45% and higher. Using this steel for ocean structures requires the use of low hydrogen welding process, in particular. Group III refers to high-strength steel with SMYS greater than 360 MPa. This group of steel requires special welding procedures during fabrication. Further, members fabricated with this group of steel should also be investigated for fatigue-related problems, as a part of the routine design check. As seen in the grouping of steel, strength is considered as the most important characteristic to decide the choice of steel for different applications. However, it is also important to note that steel should possess superior low-temperature toughness for the base metal to avoid brittle failure of welded joints. Codes specify the impact test properties based on Charpy impact test results. They also demand that steel should possess good crack tip opening displacement (CTOD) properties. CTOD is one of a family of fracture mechanics tests that measures resistance of a material to the crack growth.

Toughness is another important structural property of steel, which is vital in selection of steel for marine applications. It is described as a measure of resistance to failure in the presence of a crack, notch, or similar stress concentrator. High toughness therefore is preferred for offshore steel. Therefore, this becomes as one of the important requirements for selecting a material for the offshore structural system as there exists a high probability of stress concentration at the joins of members in offshore structural systems. A high toughness material is one where a considerable amount of plastic deformation is required at the crack tip before the crack advances. Conversely, if the application of stress causes the elastic failure of atomic bonds at the crack tip, relatively little energy of deformation is involved, and the result is a brittle fracture. Toughness is expressed in terms of impact and fracture toughness. Impact toughness is the energy measured in joules and commonly related to the Charpy V-notch test, whereas fracture toughness is computed based on CTOD or J-integral test. The latter is useful in prescribing the critical stress intensity factor required for the design.

Steel is also grouped according to the notch toughness characteristics, computed based on the impact tests. They are grouped as class C, class B, and class A. Class C
refers to a group of steel for which no impact tests are specified. Applicability of this group of steel is limited to primary structural members involving limited thickness, moderate forming, low restraint, modest stress concentration, and subjected to quasi-static loading only. Few examples are piles, bracings in jacket platforms, and legs, deck beams, and legs. Class B refers to a group of steel that are recommended for members with larger thickness and are subjected to high stress concentration, impact loading, and so on. Class A refers to a group of steel that are recommended for use at subfreezing temperatures. Interestingly, the codal provisions guide the selection of steel as a construction material for ocean structures. Recommendations made by different codes are very prescriptive in terms of type of members, manufacturing process, loading encountered by the members, and so on. Thanks to the constant update on codal provisions from the steel manufacturers, offshore structures are relieved off from one important source of error, which is wrong material specification. This reduces the risk encountered by offshore structures from the material incapability to resist the encountered loads.

Fixed offshore structures used medium-grade structural steel with a yield strength of 350 MPa. Existing codes and standards widely cover these groups of steel through prescriptive documentation. In recent years, there has been an increasing use of higher strength steels for these installations. The primary benefit is the increase in strength-to-weight ratio, which results in savings of cost of materials. Jacket platforms are constructed using steel with a yield strength ranging from 400 to 450 MPa and installed in the North Sea. However, to date, fatigue-sensitive components such as tubular members (joints, in particular) are been fabricated using medium-strength steel only. This is mainly because of the better know-how of their fatigue performance, which is seriously lacking in case of high-strength steel. In the recent times, increased application of high-strength steel is seen in the fabrication of jack-up platforms. Steel with a yield strength ranging from 500 to 800 MPa is used to fabricate the legs, racks and pinions, and spud cans of jack-up platforms. High-strength steel is commonly used for tethers in compliance with offshore structures such as TLPs and for mooring lines in semisubmersible module offshore drilling units. On average, about more than 40% of offshore structures use steel with a yield strength of more than 350 MPa. Table 3.1 gives a brief

<table>
<thead>
<tr>
<th>Strength (MPa and Grade)</th>
<th>Process Route</th>
<th>Application Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 (X52)</td>
<td>Normalized TMCP</td>
<td>Structures</td>
</tr>
<tr>
<td>Structures and pipelines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450 (X65)</td>
<td>Q&amp;T TMCP</td>
<td>Structures and pipelines</td>
</tr>
<tr>
<td>550 (X80)</td>
<td>Q&amp;T TMCP</td>
<td>Structures and mooring pipelines</td>
</tr>
<tr>
<td>650</td>
<td>Q&amp;T</td>
<td>Jack-ups and moorings</td>
</tr>
<tr>
<td>750</td>
<td>Q&amp;T</td>
<td>Jack-ups and moorings</td>
</tr>
<tr>
<td>850</td>
<td>Q&amp;T</td>
<td>Jack-ups and moorings</td>
</tr>
</tbody>
</table>

Note: Q&T, quenching and tempering; TMCP, thermomechanical controlled processing.
summary of steel used in offshore structures; yield strength and grade of steel used along with the location of usage are also mentioned. It can be seen from the table that steel with a higher yield strength is used for jack-up and mooring lines. Different types of failure modes are encountered by the material when they are exposed to offshore structures. For example, buckling, corrosion, creep, fatigue, hydrogen, embrittlement, impact, mechanical overload, stress concentration, cracking, thermal shocks, wear, and yielding are very interestingly a wide variety of failure modes. Selection of material other than steel is instead based on Charpy V-notch test. Figure 3.4 shows a schematic view of the test setup.

3.7.1 **Charpy Test**

This impact test is a very simple experiment conducted in the laboratory to understand the impact strength of any material. It is a standardized high strain rate test and useful to determine the amount of energy absorbed by the material during fracture. Absorbed energy is given as an index of notch toughness of the material. It is a tool to study the temperature-dependent, ductile–brittle transition. The test gives results only on a comparative scale. The Charpy impact test procedure consists of a simple pendulum of a known mass and length (Kayano et al., 1993). It is dropped to cause an impact on the specimen of the material. The energy absorbed is inferred by comparing the difference in height of the hammer before and after fracture. Notch in the sample affects the test results. Results are influenced by the notch geometry. These tests provide both quantitative and qualitative results on a comparative scale. Quantitative results given by Charpy test indicate the energy required to fracture...
the material. This can be used to measure the toughness of the material. Strain rate can also be studied at which the material fails. The test gives a ductile–brittle transition temperature, which is defined by the significant change in the energy level required to fracture the material. It also gives some qualitative results, which are useful to derive the ductility of the material indirectly. If the material breaks on a flat plane, then it is considered a brittle material; if the material breaks on a jagged edge or shear lips, then it is considered a ductile material. Usually, fracture will be a combination of flat and jagged edges, which is helpful to determine the percentage of brittleness and ductile failure. The mechanical properties of steel should be based on the tensile test as well as Charpy’s V-notch test. International codes recommend these two test results as reference for selecting materials for offshore construction. Charpy’s V-notch test results should be obtained with a longitudinal axis parallel to the direction of rolling. Further, steel should be heat treated, which is also one of the prerequisites to use them in offshore applications.

3.7.2 Weldability

Generally, weldability is a very important characteristic, which is a requirement for an offshore structural member. This can be computed by cold-cracking susceptibility and carbon equivalency as given in the following two equations:

\[
C_{eq} = C + \frac{M_n}{6} + \frac{N_i + C_u}{15} + \frac{C_r + M_o + V}{5} \%
\]

\[
p_{cm} = C + \frac{S_d}{30} + \frac{M_n}{20} + \frac{C_u}{20} + \frac{N_i}{60} + \frac{C_r}{20} + \frac{M_o}{15} + \frac{V}{10} + 5B\%
\]

Formability, weldability, and toughness are the important criteria to be checked for recommending steel for offshore drilling units, in particular. In case materials are used in combination of steel, one must also check for the galvanic effects before it is recommended for offshore drilling units.

3.8 Aluminum

Aluminum is a phenomenally attractive material for offshore structures. It is widely used in hulls, deckhouses, and hatch covers of commercial ships. It is used in fabrication of ladders, railings, gratings, windows, and doors due to their maintenance-free property. Passenger vessels utilize large quantities of aluminum in superstructure and equipment. High-speed boats, in particular, are constructed using 5xxx alloy of aluminum. Aluminum alloys have strength comparable to that of mild steel, which enables to design the members with an equivalent strength of that of steel while reducing the weight up to about 60%. As the specific gravity of steel is about 2.5 times more than that of aluminum, it results in significant savings in dead weight. In addition, aluminum does not require any protective coatings, whereas steel needs to be protected from corrosion. The yield strength of aluminum alloys of 5xxx series, which are widely used in marine applications, varies from 100 to 200 MPa.
Aluminum is commonly used in pressure vessels in liquid natural gas (LNG) transport ships, where it is insulated against temperature loss or transfer.

Aluminum is also used as one of the alternate materials for construction in the arena of deep-sea mining. Deep-sea mining has limitations in terms of hyperbaric and low-temperature conditions for long-term operations. Aluminum is used for fabricating the subcomponents in the mechanical equipment used in deep-sea applications. In particular, lightweight crawlers that have been recently attempted in deep-sea mining is a candidate of favorable use of aluminum. Suitable aluminum alloys and filler wires are used in such equipment to improve the postweld strength in the heat-affected zone. Corrosion resistance of aluminum is one of the most attractive features, which makes it suitable for deep-sea mining crawler structures. Figure 3.5 shows a typical traction unit, which has aluminum components. Strength, malleability, resistance to corrosion, good conductor of heat, electricity, and capability to be polished to give high-reflective surfaces are the desired characteristics of aluminum. These are also vital for choosing them for deep-sea applications. Temper designations are used to indicate the cold-worked or heat-treated conditions of aluminum alloys. Table 3.2 shows the details of temper designations used in aluminum alloys. It is seen from the table that the structural properties of aluminum are customized based on the manufacturing process to suit to marine applications.

An alloy of aluminum has a unique designation system, which enables us to understand its alloying composition. The designation system consists of four digits, namely, XXXX. The first digit refers to the principal alloying constituent(s); the second digit signifies the variations of initial alloy; the third and fourth digits indicate individual alloy variations. However, the number has no significance, but it is unique. The following designations of aluminum alloy clarify the nomenclature: 1xxx refers to pure aluminum, whose purity is 99% and above; 2xxx indicates aluminum–copper alloys; 3xxx indicates aluminum–manganese alloy; 4xxx refers to aluminum–silicon alloys; 6xxx refers to aluminum–magnesium–silicon alloys; 7xxx refers to aluminum–zinc alloys; 8xxx refers to aluminum with other elements; and 9xxx refers to unused series. As we understand that an alloy is simply a mixture
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of metals melted together to form a new metal, whose characteristics differ from those of the parent metals. Aluminum alloy is primarily pure aluminum, mixed with different alloying elements that give rise to an entire range of materials. Each of the alloys is designed to maximize a particular characteristic such as strength, ductility, formability, machinability, or electrical conductivity.

3.8.1 AlloYing Elements

Commercially pure aluminum is a white, lustrous, lightweight, and corrosion-resistant metal. Aluminum alloys contain the principal alloying ingredients such as manganese, magnesium, chromium, magnesium, and silicon. However, these alloys in which a substantial percentage of copper is used are more susceptible to corrosive action. Among all the aluminum alloys, the non-heat-treatable aluminum–magnesium alloys (5xxx series) are the most suitable materials for marine applications. Magnesium, as the main alloying constituent, lends itself to a reasonable strength for marine applications. Corrosion resistance of these alloys makes them the most suitable materials for shipbuilding as well. The magnesium content of 5xxx alloys significantly influences the mechanical properties such as yield strength, tensile strength, and ductility. One of the principal reasons for the increase in strength is due to the formation of intermetallic particles of aluminum–magnesium, which reinforce the alloy. An increase in magnesium content adds strength to the alloy, but if added beyond 4% (approximately), corrosion resistance of the alloy gradually decreases. This is because intermetallic particles of the alloying elements will precipitate at the grain boundaries at higher percentage of

<table>
<thead>
<tr>
<th>TABLE 3.2</th>
<th>Temper Designations of Aluminum Alloys</th>
</tr>
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<tbody>
<tr>
<td>Designation</td>
<td>Condition</td>
</tr>
<tr>
<td>F</td>
<td>As fabricated</td>
</tr>
<tr>
<td>O</td>
<td>Annealed</td>
</tr>
<tr>
<td>H₁</td>
<td>Strain hardened only</td>
</tr>
<tr>
<td>H₂</td>
<td>Strain hardened and partially annealed</td>
</tr>
<tr>
<td>H₃</td>
<td>Strain hardened and thermally stabilized</td>
</tr>
<tr>
<td>W</td>
<td>Solution heat treated</td>
</tr>
<tr>
<td>T₁</td>
<td>Cooled from an elevated temperature for shaping process and naturally aged</td>
</tr>
<tr>
<td>T₂</td>
<td>Cooled from an elevated temperature for shaping process and cold worked and naturally aged</td>
</tr>
<tr>
<td>T₃</td>
<td>Solution heat treated, cold worked, and naturally aged</td>
</tr>
<tr>
<td>T₄</td>
<td>Solution heat treated and naturally aged</td>
</tr>
<tr>
<td>T₅</td>
<td>Cooled from an elevated temperature for shaping process and artificially aged</td>
</tr>
<tr>
<td>T₆</td>
<td>Solution heat treated and artificially aged</td>
</tr>
<tr>
<td>T₇</td>
<td>Solution heat treated and stabilized</td>
</tr>
<tr>
<td>T₈</td>
<td>Solution heat treated, cold worked, and artificially aged</td>
</tr>
<tr>
<td>T₉</td>
<td>Solution heat treated, artificially aged, and then cold worked</td>
</tr>
<tr>
<td>T₁₀</td>
<td>Cooled from an elevated temperature for shaping process and cold worked and artificially aged</td>
</tr>
</tbody>
</table>
magnesium. These particles are anodic with respect to aluminum and therefore results in electrochemical imbalance in the grains. This leads to intergranular corrosion, causing pitting and weight loss; it may also lead to stress–corrosion cracking.

Heat treatment is carried out to improve the mechanical properties of the alloy by developing the maximum practical concentration of the hardening constituents in solid solution. It involves heating above the critical temperature, holding the constituents at that high temperature for a designated period, and then quenching abruptly. The faster rate of cooling the alloy enables to retain a supersaturated solid solution of alloying constituents without introducing adverse metallurgical or mechanical conditions. Most common quenching media are water, air blast, soap solutions, and hot oil. Precipitation hardening, alternatively referred to as age hardening, is used on aluminum, copper, nickel, magnesium, and some stainless steel alloys to improve their mechanical properties. Aging process is divided into two main categories: natural aging and artificial aging. Heat-treatable alloys change their properties when stored at room temperature after solution heat treatment and quenching. This is known as natural aging. In case of artificial aging, by heating the solution heat-treated material to a temperature above the room temperature and holding it, precipitation accelerates. This improves its strength further compared to that of natural aging. Preheating or homogenizing is carried out to reduce chemical segregation of cast structures and improve their workability. It also reduces brittleness in the cast structure. Annealing aids in workability by softening aluminum and heat-treated alloy structures to release residual stresses. This also helps stabilize the mechanical properties and dimensions of product. Table 3.3 shows aluminum materials with

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**TABLE 3.3**

**Aluminum Materials for Deep-Sea Mining**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Description</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Bend Angle</th>
<th>Impact Energy (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA5083 MIG</td>
<td>Base material 245</td>
<td>350</td>
<td>20</td>
<td>125</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multipass weld 180</td>
<td>320</td>
<td>16</td>
<td>135</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single-pass weld 158</td>
<td>265</td>
<td>14</td>
<td>100</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>AA6082 MIG</td>
<td>Base material 285</td>
<td>305</td>
<td>10</td>
<td>60</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weld with ER4043 fillers 175</td>
<td>200</td>
<td>7</td>
<td>65</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weld with ER5183 fillers 170</td>
<td>205</td>
<td>8</td>
<td>140</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>AA5083 TIG</td>
<td>Base material 245</td>
<td>350</td>
<td>20</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>AA6061 Plasma</td>
<td>Welded material 200</td>
<td>335</td>
<td>20</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** xx - not applicable.
metal inert gas (MIG) welding and tungsten inert gas (TIG) welding. MIG welding is a process in which an electric arc is formed between a consumable wire electrode and the metal workpiece. Electrode heats up the workpiece, melts, and joins them. TIG weld uses a nonconsumable tungsten electrode to produce weld. The mechanical properties of different alloys that are useful for deep-sea mining applications are highlighted.

As seen from the Table 3.3, AA5083 MIG welds have shown a joint efficiency of about 90\% based on UTS tests. Impact strength, bend, ductility and ultimate strength of the alloy with multipass welds are comparable with that of the base material. Multipass welds have shown a better microstructure properties compared to single-pass weld. It is seen in the literature that AA5083-H116 are recommended for crawler structures in deep-sea mining.

### 3.9 TITANIUM

Titanium as an element has been in recognition for over 200 years. It gained strategic importance in the past 60 years. In 1938, Dr. Kroll developed a process for manufacturing titanium. Reduction of titanium chlorate, first with calcium and later with sodium and magnesium under inert atmosphere, was the process used. Titanium alloys are commonly available in wrought products; most of them are used in aerospace industries. The melting point of titanium is 1678°C, which is higher than that of steel. The specific gravity of titanium is 4.5, which is about 55\% of that of steel.

It has an hexagonal close packed (HCP) crystal structure with an atomic weight of 47.88 and an atomic number of 22. Being a light metal with lower density, it has higher strength-to-weight ratio, which is vital for offshore applications. Even though titanium is highly reactive, on exposure to the marine environment, it reacts with atmospheric oxygen to form a protective layer; this makes it corrosion free. With higher melting point and increased strength at higher temperature, its applicability is better than that of aluminum as it cannot be used at higher temperature. Titanium and its alloys can be used up to 540°C. Titanium undergoes allotropic transformation from α-Ti to β-Ti at 882°C; alloying elements influence this transformation. Therefore, a wide variety of microstructure can be produced by heat treatment. Manipulation of these crystallographic variations through alloying additions and thermomechanical processing is the basis for the development of a wide range of titanium alloys. Titanium can readily form an alloy with other elements because it is a transition metal with an incomplete “d” shell; therefore, it forms solid solutions and compounds with metallic, ionic, and covalent bonding. These alloys have good fatigue resistance and high fracture toughness. Other useful properties of titanium alloys include nonmagnetic, good heat transfer property with low-heat thermal conductivity, low coefficient of thermal expansion (about 9–11 ppm/°C), and nontoxic, which make them biologically compatible.

Titanium is as strong as steel but about 45\% lighter. High strength, low density, and corrosion resistance of titanium contribute toward its cost reduction in long-term maintenance even though the initial cost is prohibitively high. Titanium is commonly used in small submersibles. High strength-to-weight ratio is the most attractive
features of titanium: good corrosion resistance and relatively high modulus of elasticity are additional benefits. It is used for fabricating surfaces, which cannot be painted such as propellers, special valves, and hot and cold pipes. As titanium requires no corrosion allowance, equipment is designed to satisfy the minimum requirements for mechanical strength and handling. Titanium has an outstanding corrosion resistance even if placed in heavily polluted seawater. Titanium alloys are classified into three groups: alpha, alpha–beta, and beta; the classification depends on its microstructure. Alpha stabilizers such as peritectoid result in solid solutions, whereas beta stabilizers such as isomorphous and eutectoid form either solid solutions or compounds, respectively. Eutectoid stabilizers form compounds with manganese, iron, chromium, and nickel. Depending on the type and amount of impurities or alloying additions, the transformation temperature of α- to β-Ti can be raised or lowered. Addition of alloying elements divides the single temperature for equilibrium transformation into two temperatures: α-transus and β-transus.

3.9.1 Classifications

Titanium alloys are classified based on phase diagrams as type I, type II, and type III. In type I phase diagram, addition element has greater solubility in α than in β. Addition element stabilizes α, that is, (α+β) region, is elevated to higher temperatures by increasing the alloying element concentrations. In case of type II phase diagram, addition element has greater solubility in β than in α. It stabilizes β, that is, α/(α+β) and β/(α+β) boundaries, are depressed to lower temperatures with increasing concentration of addition element. Phase diagram includes a line to indicate the temperature at which β begins to undergo a diffusionless transformation to a supersaturated α, that is, α′; this occurs usually on rapid cooling. Type I alloys contain only transition elements to stabilize beta, whereas type II alloys contain both transition and nontransition elements to stabilize alpha. The alpha phase is stabilized by elements with an electron-to-atom ratio less than 4 (e.g., oxygen, carbon, nitrogen, and aluminum). Beta phase is stabilized by elements with an electron-to-atom ratio greater than 4 (e.g., iron, molybdenum, and manganese). Elements with an electron-to-atom ratio equal to four are neutral (e.g., zinc, tin, and silicon).

3.9.2 Effect of Alloying Elements

Aluminum, as an alloy with titanium, increases the tensile strength, creep strength, and elastic modulus. However, if the content of aluminum increases more than 6% by weight, an intermetallic compound called α2 is formed, which is brittle. Tin, if alloyed with titanium, dissolves in both apha and beta. It is a weak alpha stabilizer, which results in solid solution and hardens the alloy with aluminum, without causing embrittlement. Zirconium, if alloyed with titanium, retards the rate of transformation as it is a weak beta stabilizer. If added more than 6% by weight, it reduces ductility and creep strength. Molybdenum is a strong beta stabilizer and, if alloyed, helps to increase hardness but reduces long-time, high-temperature strength; weldability is also subsequently reduced. Niobium improves high-temperature oxidation resistance, being a strong beta stabilizer. Iron, if alloyed with titanium, reduces creep
strength, whereas carbon widens the temperature range between alpha-transus and beta-transus; it is a strong alpha stabilizer.

Pure titanium has low strength and high ductility. Addition of small amounts of elements to their chemical composition increases their strength and decreases ductility. An increase in disruptive failures of stainless steel and copper-based alloys in the marine environment raised a serious concern about safety. Thanks to the manufacturing industry for sharing information about the structural properties, chemical composition and fabrication experience of titanium in the recent times. Due to the availability of information, design engineers are attracted toward its usefulness for structural engineering applications as well. It is also evident that in flowing or static seawater at temperatures up to 130°C, titanium surfaces are immune to corrosion, whereas other metals and alloys corrode significantly. Titanium is immune to crevice corrosion up to at least 70°C in seawater, whereas steel tends to corrode even at 10°C. In recent times, titanium has been available at a very competitive and stable price in the market. One of the encouraging aspects of titanium is availability of the fabrication experience. People with fabrication skills in titanium with respect to the different methodologies of fabrication are available as a technical workforce to handle the construction and fabrication challenges. In the presence of such scenarios, titanium alloys are used for pipeline fittings and systems. Although titanium enables a maintenance-free system, its yield strength can be as high as 400 MPa, which is equivalent to that of steel. Good corrosion resistance and relatively high modulus elasticity are additional benefits of titanium alloys. Table 3.4 shows a comparison of properties that titanium possesses with other competitive materials used in offshore construction. With reference to the table, it is seen that titanium alloys are almost resistant to all types of corrosion that are common in the marine environment. Titanium has a very clear edge as a construction material for marine applications. The only demerit is the increase in the initial investment, but by including the cost of

<table>
<thead>
<tr>
<th>Mode of Corrosion</th>
<th>Copper-Based Alloy</th>
<th>Stainless Steel 316</th>
<th>Stainless Steel 6 Mo and Duplex</th>
<th>Titanium Alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>General corrosion</td>
<td>Resistant/susceptible</td>
<td>Resistant</td>
<td>Resistant</td>
<td>Resistant</td>
</tr>
<tr>
<td>Crevice corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible (&gt;25°C)</td>
<td>Resistant up to 80°C</td>
</tr>
<tr>
<td>Pitting corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible (&gt;60°C)</td>
<td>Immune</td>
</tr>
<tr>
<td>Stress corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Immune</td>
</tr>
<tr>
<td>Corrosion fatigue</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Immune</td>
</tr>
<tr>
<td>Galvanic corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Immune</td>
</tr>
<tr>
<td>Microbiological corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Immune</td>
</tr>
<tr>
<td>Weld/heat-affected zone</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Resistant</td>
</tr>
<tr>
<td>(HAZ) corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Resistant</td>
<td>Highly resistant</td>
</tr>
<tr>
<td>Erosion corrosion</td>
<td>Susceptible</td>
<td>Susceptible</td>
<td>Resistant</td>
<td>High resistant</td>
</tr>
</tbody>
</table>
maintenance over a service life of about 15 years, titanium and aluminum will become a more competitive, affordable, and replaceable material in comparison with steel.

Titanium can be hot worked, but the reaction of titanium with atmospheric gases is an important factor in hot working. It absorbs hydrogen above 300°F, oxygen above 1300°F, and nitrogen above 1500°F. Absorption of these gases in larger quantities leads to embrittlement. Hot working is therefore done in an oxidizing atmosphere to avoid hydrogen absorption; oxygen-embrittled layer is removed after hot working. Heat treatment is done on titanium to improve fracture toughness, fatigue strength, and high-temperature strength. It also reduces residual stresses developed during fabrication; this is called stress relieving. Annealing helps to produce an optimal combination of ductility, machinability, and dimensional and structural stability. Solution treating and aging increase its strength.

The first fishing boat, fabricated in all-titanium, was launched in Japan in 1998. Weighing only 4.6 tons, the boat was 12.5 m long, which could travel at 30 knots with improved fuel efficiency. Savings in the operational cost include no necessity for hull painting and easier removal of biofouling. Progressive degradation of glass fiber boats by repeated fouling and cleaning is an ongoing penalty for the Japanese fishing fleet; titanium is used as an alternate material. Titanium is increasingly used in marine applications due to its high strength, high toughness, and phenomenal corrosion resistance. The majority of offshore applications use titanium for submarine ball valves, pumps, heat exchangers, hull material for deep-sea submersibles, water jet propulsion systems, propeller shafts and propellers, exhaust stack liners, navel armors, underwater manipulators, high-strength fasteners, yacht fittings, shipboard cooling and piping systems, and many other components in the ship design.

### 3.10 COMPOSITES

Composites are materials consisting of two or more constituents. The constituents are combined in such a manner that they keep their individual physical phases and are not soluble in each other; they also do not result in the formation of a new chemical compound. One constituent is called the “reinforcing phase.” The one in which the reinforcing phase is embedded is called the “matrix.” Composites are classified based on the geometry of the reinforcing phase and types of matrices. Based on the geometry of the reinforcing phase, they are further classified as (1) particulate reinforced, (2) flake reinforced, and (3) fiber-reinforced composites. Fiber-reinforced composites are also grouped into continuous fiber, short fiber, and whiskers. Based on the type of matrices, they are classified as (1) polymer matrix, (2) metal matrix, (3) carbon fiber matrix, (4) fiber-reinforced polymeric composites, and (5) particulate-reinforced metal matrix composites. There are hybrid varieties of composites that use multiple reinforcements and matrices, for example, carbon and fiberglass in epoxy matrix. Glass-reinforced epoxy (GRE) composites are extensively used in the piping system in the offshore environment. They offer good resistance against highly corrosive fluids at various pressure, temperature, adverse soil, and weather conditions. These characteristics make them suitable for many special applications such as oil exploration, desalination, chemical plants, fire mains, dredging, and portable water. Pultruded glass or phenolic gratings are a particular type of GRE being commonly
used in such process industries. Worldwide many industries are manufacturing pultruded or compression molded composite grids and gratings, which are commonly used industrial walkways, hand rails, ladders, cable trays, and so on in chemical, pharmaceutical, transportation, and infrastructural sectors.

Performance of a composite product mainly depends on the process of its fabrication. For example, pultruded fiber-reinforced polymer (FRP) grating is an assembly of preshaped FRP pultruded sections, which are joined together by various mechanical means. Pultruded structural profiles provide extremely useful options to offshore designers. Pultruded products, due to their high fiber-to-resin ratio (70:30), help in achieving higher load-bearing capacity. Pultruded gratings have longer span with less deflection compared to that of the molded gratings. This is an added advantage to use them for decks on the topside of offshore platforms. Thus, load-bearing capacity of a pultruded product of a composite can be as good as that of any other material, which is used for structural members in offshore platforms. By comparing the performance of molded gratings with that of the composites, pultruded gratings have an edge over the molded gratings in the offshore applications. They can sustain a longer span with less deflection, which is one of the important criteria for the topside of offshore structures. To fit any modular dimensions of the floor or the plant requirements, pultruded grating panels can easily be cut and modified. In recent times, phenolic gratings are also seen at larger applications in offshore platforms where fire safety is important. The main advantage of phenolic gratings lies not only in their performance during fire but in their ability to retain a significant level of functionality even after fire exposure; one vital characteristic is the low smoke emission.

Composites meet diverse design requirements and exhibit high strength-to-weight ratio compared to other conventional materials used in the construction of offshore platforms. They are proved to be worthy alternatives under high-pressure and corrosive environmental situations. Superior corrosion resistance and resistance to cyclic loads are exclusive advantages of composites. Good resistance to temperature under extremes and resistance to wear and tear make them suitable for offshore production and process lines. Structural properties and mechanical characteristics of composites can be easily altered either by the method of manufacturing or by the method of fabrication. Properties of composites are customized to suit special features such as low thermal conductivity, low thermal coefficient of expansion, and higher axial strength and stiffness. Hence, they find increased applications in offshore installations. Extensive applications are seen in the oil and gas industry since the past two decades. Significant advances in the application of composites are made in the process line layouts used for hydrocarbon handling. High cost to replace steel piping in retrofit applications prompted to use composites, while increased longevity in the new construction is an added advantage. Heavy metal pipelines are replaced with lighter ones made of composites, which also results in cost reduction. Composite pipes are also used for fire-fighting mains, seawater intake systems, cooling towers, draining systems, and sewerage systems.

The cost advantages of composite products are much greater when they are replaced by expensive corrosion-resistant metals such as copper–nickel alloys and titanium. Their resistance to corrosion helps in improving reliability and safety. It also leads to lower life cycle costs, which is an important assessment in the construction management techniques of offshore industry. With the recent advancements in the processing methods and product development, composites have become an attractive
candidate for topside applications, down-hole tubing in subsea, and others. Selection of a suitable resin plays an important role for imparting the durability of composites when exposed to aqueous fluids. Smoke and toxicity resistance, mechanical properties including resistance to shock and impact loads, and resistance under adverse environmental conditions are a few important properties that are investigated before composites are chosen for topside applications in offshore platforms. GRE piping systems are suitable for the offshore environment against highly corrosive fluids at various pressures, temperatures, and adverse soil and weather conditions. GREs are used widely in oil exploration, desalination, chemical plants, fire mains, dredging, and so on. Figure 3.6 shows a typical GRE piping system of a topside installation.

3.10.1 Glass-Reinforced Epoxy

GRE pipes are commonly used in oil transportation where resistance to crude oil, paraffin buildup, and ability to withstand relatively high pressure are required. GRE piping system is also being used in offshore rigs for seawater cooling lines, air vent systems, drilling fluids, firefighting, ballasts, and drinking waterlines in offshore applications. Availability and lightweight modular forms of GRE help to reduce the construction cost. Established oil fields use GRE pipes for high pressure and steam injection lines for the recovery of oil preserves. GRE piping systems are capable of withstanding corrosive effects of water that are expelled under pressure from the fire mains. The effect of rupture-free GRE pipes under such shocks makes the system more reliable. GRE piping systems are therefore extensively used for firefighting systems and recovery systems in oil preservations. Chemical resistance and service temperature of such composites mainly depend on the resins and additives used for product formation and bonding. Figure 3.7 shows a typical application of composite grating on the topside of offshore installation.
3.11 NONFERROUS METALS

There are other nonferrous materials, which are also suitable for offshore construction. Cupronickel alloy, which is a mixture of 69% copper and 30% nickel, is a popular alternate for offshore applications. Cupronickel alloy is widely used for condenser applications such as tubes, tube sheets, and manifolds. The term “manifold” refers to a pipe with a single inlet and multiple outlets or vice versa. K-Monel alloy, which is a combination of 65% nickel and 30% copper, is another alternative. The next competitor is MONEL nickel–copper 400 alloy, which constitutes 66% nickel and 32% copper with rest from other materials excluding aluminum and titanium. Bronze, which is an alloy with 90% copper and 10% zinc, finds increasing applications in the offshore industry. However, a variety of these materials as discussed above makes an engineer to select the suitable material that is required for the service life of an offshore application. It is important to note unlike other structures, materials for offshore structure applications are selected not only based on their strength but also based on the desired performance criteria.

3.12 FIBERGLASS

The most prominent nonmetallic material for ocean applications is fiberglass, which is reinforced with plastic (FRP). Small boats and buoys are made of FRP. They are one of the variety of composites, which consist of plastic fibers as reinforcing materials that are bind together; the reinforcing material gives strength to the composite. Composites consist of glass fibers, carbon graphite, nylon, silica, or metals such as steel, aluminum, boron, and tungsten as reinforcing materials. Bonding materials are typically epoxies, polyesters, phenolics, and silicon. The most common is the glass fiber with an epoxy or polyester binder. The strength of FRP depends on the manufacturing process. Fiberglass polyester mat is widely used in the production of small boats and buoys. The major advantage of
this material is that it is maintenance free and highly durable under a variety of operating conditions. Fiberglass, owing to its internal damping characteristics, heats up when subjected to fast-changing stress cycles. It reaches its fatigue strength in 10 million cycles, making the ratio of fatigue to tensile strength lower than 0.25; this is an important concern to the offshore engineers and naval architects. In the marine environment, fiberglass loses strength by the absorption of water when immersed over long period; strength reduction is also seen when continuously exposed to ultraviolet rays. Although water absorption reduces compressive strength, exposure to ultraviolet rays causes brittleness, as it gets laminated upon application of heat. High-quality manufacturing methods are necessary, as many resins that are used to manufacture fiberglass are highly flammable. Resins used to manufacture fiberglass composites are carefully chosen to modify the fundamental characteristics of fiberglass to suit the marine environment. For example, tempered glass is one of such varieties. Tempered glass shows substantial promise as a material when used in compression. Because offshore structures are encountered by a combination of variety of loads, the mechanical characteristics of glass needs to be modified. This is done by the choice of resins and adopting appropriate manufacturing methods. However, it is important to note that the nonavailability of large sections of tempered glass without defect is one of the major concerns.

### 3.13 WOOD

One of the oldest materials used in the marine environment is wood; for many years, it is the only material used for ship building. Currently, wood is extensively used for pilings, docks, and similar applications. In the recent times, wooden laminates are also being used as structural members. Flammability characteristics, nonavailability in large size, and deterioration of strength under continuous exposure to seawater are a few of serious limitations of wood as the choice of construction material. One of the most important drawbacks of wood is its significant change in strength characteristics and grain orientation with respect to the loading direction; it shows a significant difference when the load is applied parallel to the grains with that of the perpendicular direction.

### 3.14 GLASS-REINFORCED PLASTICS

GRP is essentially recommended for construction of lifeboats. Lifeboats are self-righting, enclosed, motor-propelled, survival crafts, which are used in offshore oil industry for rescue operations. They are manufactured using GRP, which we call them as GRP. One important property what the GRP attains is fire-retardant resins. It is also important to note that survival crafts are required to withstand about 30-m-high kerosene flames and a temperature of about 1200°C, as a part of the safety norms of the safety directorate; GRP passes such stringent fire safety norms.

### 3.15 BUOYANCY MATERIALS

Materials that have a specific gravity considerably lower than that of water are used as buoyancy materials. Few common applications are small submarines, oil well drill pipes, deep-sea buoys, and so on. The most common buoyancy materials are wood and gasoline whose specific gravities are 0.5 and 0.7, respectively.
Buoyancy materials should possess certain desirable properties: (1) no water absorption and (2) no dis-configuration under compression.

### 3.15.1 Syntactic Foams

Syntactic foams are composite materials synthesized by filling a metal, a polymer, or a ceramic matrix with hollow particles called micro-balloons. The presence of hollow particles results in lower density and higher strength. Syntactic foams at 600 bar pressure possess 3 times higher strength than that of concrete (80 MPa). When used, similar to reinforced cement concrete structures, they can combine the advantages of strength and buoyancy. It is free from corrosion, and the structure by itself acts as a buoyancy to the system. The system, while in operation, reduces the amplitude of vibration response, and the mining becomes more reliable. Recent studies in the literature shows favorable characteristics of syntactic foams with the composition: epoxy as the base material and glass microspheres as micro-balloons. The tensile strength of the foam depends on the matrix material. Table 3.5 shows typical values for syntactic foam with epoxy resin as the matrix material. Syntactic foams are buoyancy materials that cater to certain special needs in offshore engineering. They are essentially hollow glass spheres dispersed in a plastic matrix. The most efficient syntactic foams use glass spheres of extremely small diameter called micro-balloons with an epoxy resin binder. They have a high compressive and shear strength with low water absorption. They can easily be handled with woodworking tools.

### 3.16 Coatings

Coatings are extensively used in the marine environment to protect surfaces against deterioration from salt spray, barnacles, corrosion, pollution, and all other contaminants of the sea. As fouling increases with the increase in water temperature, new plastic coatings are used in the recent times for antifouling protection. Certain epoxy coatings are also used for corrosion protection. Coatings serve as a physical and a chemical barrier and prevent materials from degradation. Protective coatings are applied up to five coats, resulting in a film of about 0.25–0.5 mm thick. Polyurethane coatings are successful in protecting wood in the marine environment. Most common anticorrosive coatings are coal tar epoxy, epoxy, polyurethane, vinyl anticorrosive coating, neoprene, and other rubber coatings.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>2.1 GPa</td>
</tr>
<tr>
<td>Density</td>
<td>640 kg/m³</td>
</tr>
<tr>
<td>Microsphere density</td>
<td>349 kg/m³</td>
</tr>
<tr>
<td>Resin density</td>
<td>1120 kg/m³</td>
</tr>
<tr>
<td>Hardener density</td>
<td>1050 kg/m³</td>
</tr>
</tbody>
</table>

**TABLE 3.5**

Properties of Syntactic Foam with Epoxy Resin
3.17 CONCRETE

Concrete is seen as a strong competitor to steel and widely used in marine construction. Various types of cement that are specially manufactured to cater to the marine environment make concrete as the most-preferred choice of offshore designers. Excellent compressive strength and high resistance to seawater attack make concrete as the first choice for marine construction. Problems of low tensile strength are overcome by reinforcing concrete with steel to form reinforced cement concrete (RCC); prestressing and ferrocement concretes are also desirable. Ferrocement concrete is widely used to construct barges, boats, and so on, which is reinforced with wire mesh to improve tensile strength and stability. Prestressed concrete, which can withstand very high compressive and tensile strength, are the best candidates for pressure vessels for LNG storage. Although concrete performs comparatively better than steel in corrosion resistance, it suffers deterioration during freezing and thawing. Therefore, one has to be careful in treating concrete if it is used at different temperature gradients in the marine environment.

3.18 CONCRETE IN THE MARINE ENVIRONMENT

Marine structures are under corrosive environment; apart from strength, durability is a subject of major concern, especially in the marine environment. Ocean structures are exposed to seawater directly, which results in the simultaneous action of a number of physical and chemical deterioration processes. Concrete, as one of the most preferred construction materials, undergoes complex problems in the marine environment. Corrosion that takes place in the marine environment is not uniform throughout the length of the member. Corrosion, based on its consequences, can be grouped in different zones: atmospheric zone, splash zone (tidal zone), and submerged zone, as shown in Figure 3.8.

FIGURE 3.8 Corrosion zones on a concrete pile in the marine environment.
The submerged zone is below the surface of the water. The surface of the concrete structure is continuously and constantly exposed to seawater in this zone. The tidal zone is limited by the extent of the tidal actions. The surface of the concrete structure is exposed to seawater in a cyclic manner in this zone. The splash zone is limited by the extent of splash from breaking waves above the tidal zone. The surface of the concrete structure in this zone is randomly exposed to seawater. The atmospheric zone is limited by the extent of spray from breaking waves above the splash zone. The surface of the concrete structure in this zone is randomly exposed to spray from breaking waves. Reinforced concrete structures that are partially or fully submerged in seawater are especially prone to corrosion of reinforcing steel due to a variety of reasons. These include high chloride concentration levels from the seawater, wet/dry cycling of the concrete, high moisture content, and oxygen availability. The tidal zone is characterized by periodical wetting and drying, and possible freeze–thaw actions. The surfaces in the tidal zone are mostly wet with a limited access of oxygen. The extension of the tidal zone varies between 0 and 15 m. The splash zone is characterized by randomly wetting and drying waves, depending on the wave actions. The extension of the splash zone depends on the wave heights and variations in tides. The corrosion rate below the water level is limited by low oxygen availability. Conversely, lower chloride and moisture content limit the corrosion rate above high tide. Corrosion is most severe within the splash and tidal zones where alternate wetting and drying result in high chloride and oxygen content. The atmospheric zone is the uppermost zone layer, whose corrosion rate is 5–10 mills per year; one mill is about (1/1000)th of an inch, which is about 0.025 mm (about 25 microns). Control methods, which are generally employed to retard the corrosion rate in the atmospheric zone, are through external coatings. These coatings are generally epoxy-based resins or chlorinated rubber vinyl or zinc sulfate. The corrosion rate in the splash zone is about 55 mills per year, which is very high. This is mainly due to alternate wetting and drying caused by splash waves. Control methods prevalent are coatings or additional cladding. The submerged zone has the corrosion rate of half of that of the splash zone, which is about 25 mills per year. Control methods are generally cathodic protection or some coatings. As seen above, corrosion results in loss of metal (material from the metal surface). This will lead to loss of desired thickness in the members. The member also substantially loses its strength or degrades from its functional purpose for which it is designed. Therefore, corrosion as a deteriorated process should be addressed very carefully.

### 3.18.1 Deterioration of Concrete

From long-term studies of Portland cement mortar and concrete exposed to seawater, it has been seen that magnesium ion attack is well established by the presence of white deposits of Mg(OH)$_2$, also called brucite and magnesium silicate hydrate. In seawater, well-cured concrete containing large amounts of slag or pozzolona in cement usually outperforms the reference concrete. This is due to the lower presence of uncombined calcium hydroxide after curing.

There is a potential loss of concrete mass by leaching away calcium from hydrated cement paste due to the carbonic acid attack. Loss of material is associated with the concentrations of carbon dioxide present in seawater. This is also accelerated in the
presence of dissolved carbon dioxide. Presence of thaumasite (calcium silicocarbonate), hydrocalumite (calcium carboaluminate hydrate), and aragonite (calcium carbonate) is responsible for deterioration of concrete in seawater. The following chemical reactions explain the deterioration of concrete in seawater:

1. Action of carbon-di-oxide:

$$\text{Ca(OH)}_2 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + 2 \text{H}_2\text{O}$$

Precipitate

Aragonite Calcite

[Coating]

2. Action of Magnesium sulphate

$$\text{Mg}^{2+} \rightarrow \text{Ca}^{2+} \text{ substitution}$$

$$\text{MgSO}_4 + \text{Ca(OH)}_2 \rightarrow \text{CaSO}_4 + \text{Mg(OH)}_2$$

Soluble Solid secondary Precipitate

Gypsum [Coating]

[Expansion]

3. Action of secondary gypsum

$$\text{CaSO}_4 + \text{C}_3\text{A} + 32 \text{H}_2\text{O} \rightarrow \text{C}_3\text{A.3CaSO}_4.32 \text{H}_2\text{O}$$

Ettringite

4. Action of Magnesium chloride

$$\text{Mg}^{2+} \rightarrow \text{Ca}^{2+} \text{ substitution}$$

$$\text{MgCl}_2 + \text{Ca(OH)}_2 \rightarrow \text{CaCl}_2 + \text{Mg(OH)}_2$$

Soluble Precipitate

[Leaching] [Coating]

5. Action of calcium chloride

$$\text{CaCl}_2 + \text{C}_3\text{A} + 10\text{H}_2\text{O} \rightarrow \text{C}_3\text{A.CaCl}_2.10\text{H}_2\text{O}$$

Chloro aluminate

$$\text{C}_3\text{A.3CaSO}_4.32\text{H}_2\text{O}$$

Ettringite

$$\text{CaCO}_3.\text{CaSO}_4.\text{CaSiO}_3.15\text{H}_2\text{O}$$

Thaumasite

The presence of thaumasite, hydrocalumite, and aragonite is reported in cement pastes derived from deteriorated concrete, which is exposed to seawater for a longer time. The major deterioration is observed in the samples having greater thaumisite. Several case studies reported by researchers show that chloride profiles indicate greater damage due to corrosion. This is seen higher on the surface of coastal structures.
3.18.2 Selection of Cement

Sulfate-resisting cement suffers less chemical decomposition in seawater than that of the ordinary Portland cement. However, the issue of which type of cement is most effective in controlling the migration of chloride ions is still debatable. Calculated addition of pozzolona can improve the durability of concrete by removing a part of free lime, reducing permeability, and protecting the reinforcement. Studies have shown that blast furnace slag cement, especially when well cured, resists the action of seawater fairly well. However, blast furnace cement cannot be always the governing cement. Deterioration of concrete is mainly due to physical, chemical, and biological processes. Physical process includes cracking, abrasion, and attack caused by frost and deicing salts. Chemical process arises from acid, sulfate, and alkali attacks. Environmental factors arise from exposure conditions, temperature, humidity, and presence of aggressive elements present in seawater. Other reasons for deterioration of concrete in the marine environment are design and construction defects, poor quality of materials, poor quality of construction, corrosion in rebar, and other technical factors. Figure 3.9 shows a typical spillway, which is corroded but subsequently retrofitted with galvanic cathodic protection.

3.18.3 Inspection Methods

There are a variety of methods by which one can assess the failure of concrete construction. They are (1) visual inspection, (2) by observing the cracking conditions of exposed metal components, (3) conditions of foundation, and (4) by observing the extent of marine growth. After successful inspection, repair methods are advocated in the following sequence:

FIGURE 3.9 Corroded spillway.
3.19 PROTECTING CONCRETE

Concrete is one of the promising construction materials for offshore structures. In the marine environment, concrete also deteriorates. Removal of deteriorated concrete is important while carrying out the repair of ocean structures. Sealing of cracks using different chemical components has also been attempted by various engineers in different capacities, all over the world to improve the performance of concrete members, especially in the sea environment. Replacement of concrete, of course, is a better alternative but as expensive as constructing a new structure. Therefore, rehabilitation of marine structures can be even higher than that of the cost of the principal structure. Alternatively, many practicing engineers attempted surface treatment. This is a cosmetic type of repair carried out to improve the serviceability from a deteriorated condition to a basic acceptable level. Different types of vapor permeable coatings or vapor barrier coatings are applied on the surface of degraded concrete. Such treatments will only protect concrete in a superficial manner but do not help to enhance structural integrity of deteriorated members. Before protection of concrete is attempted, it is important to understand the level of strength degradation. Crystalline technique is one of the interesting and recent advancements in protection of concrete used in the marine environment. As it is commonly felt that concrete is already impervious and has enough strength, it is believed that concrete should be able to withstand any worst environment. However, the fact is that concrete is porous and permeable. Figure 3.10 shows a 5000-time scanned electron microscope (SEM) photograph of concrete, which verifies this statement.

In reality, as concrete is not a homogeneous impervious material, there are a lot of possibilities of pores. This will affect the performance of concrete in the marine environment. Figure 3.11 shows the composition and characteristics of concrete. Concrete composes of coarse aggregates, fine aggregates, sand, and cement. For making it workable, water is added to its limiting water:cement ratio. More water, if added than that required for cement hydration, results in bleeding of water. This action leaves a network of capillaries and pores. As it dries, concrete shrinks and changes volume, which results in the development of micro- and macrocracks. Concrete may be
permeable on several and different scale sizes. Figure 3.12 shows the pores of different sizes and their role in the degree of deterioration of concrete. Capillary voids are essentially the residue of water-filled spaces. Water and other aggressive ions can penetrate into concrete and cause durability problems through this primary path.

Concrete may be permeable on several different size scales as well. As seen from the figure, the size scales of entrapped voids vary from 1000 to 10,000 μm. The size of the cracks varies from 100 to 3000 μm, whereas that of the entrained air is in the range of 70–400 μm. If you look at the entrained air, it can vary from 70 to 400 μm. It can also result in microcracks, which are less than 0.1 to 100 μm. Capillary pores of size 0.01 to 1 μm are responsible for making concrete permeable. Microcracks are further caused by stresses induced by loads or by shrinkage around aggregates. Figure 3.13 shows the formation of macrocracks by structural, thermal, drying, and

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**FIGURE 3.10** SEM photograph of concrete.

**FIGURE 3.11** Composition and characteristics of concrete.
plastic shrinkage, whereas Figure 3.14 shows the deterioration of concrete on marine structures due to the ingression of aggressive chemicals.

### 3.19.1 Crystalline Technology

Capillary pores present in concrete make it porous and permeable. Capillary voids are essentially the residue of the originally water-filled spaces. When this capillary voids are started attracting water from the moisture content or from the sea environment, it enables aggressive ions to penetrate into concrete, causing serious durability problems. For example, reinforcements corrode when water is entrained in these capillary voids. Concrete is a good performing material, which is widely preferred for
construction of ocean structures. Crystalline technology is one of the recent advancements in concrete technology, which addresses this problem. Crystalline material is a fine particle, which is to be mixed in concrete to fill up the voids and make it impervious. It is important to note that it is neither a coating nor an ingredient, which is added to concrete when it is being prepared. A reactive component reacts with calcium hydroxide and other by-products, during the hydration process of cement. This results in nonsoluble crystalline formation, which is permanently fixed in the pore structure of concrete. Figure 3.15 shows the by-products of cement hydration, which precipitates into the capillary tracts of fresh concrete. These by-products of cement hydration react with the crystalline reactive chemicals to initiate “crystallization.”

Crystalline formation sticks onto the pores of concrete permanently. With the passage of time, they develop into a crystalline structure, as seen in Figure 3.16. Due to the formation of this permanent crystalline structure, capillary pores that were present earlier are completely filled and permanently closed. This is the result of chemical reaction between the chemical adhesive present in the concrete and that of the crystalline material. Figure 3.17 shows the comparison of concrete with and without crystallization.
Crystalline treatment ensures permeability; pores and voids present in concrete are gradually filled up with the permanent formation of chemical, making concrete truly impervious. Crystalline formation cannot be punctured or damaged as it is within the concrete. It is therefore better than a coating or a membrane layer. It is capable of withstanding high hydrostatic pressure and also highly resistant to chemicals of pH ranging from 3 to 11 in constant contact and 2 to 12 in periodic contact. Concrete with crystalline treatment can sustain significant thermal variations ranging from −32°F to 265°F. Crystalline-treated concrete is not affected by humidity, ultraviolet light, and variation in oxygen concentration. Performance characteristics of crystalline concrete are very important issues. Crystalline concrete should be tested to accept its performance behavior in the marine environment. Common checks carried out are permeability, chemical resistance, crack sealing, compressive
strength, and freeze–thaw durability. Results of the chemical durability tests carried out by Iwate University, Tokyo, Japan, show the satisfactory performance of crystalline concrete compared with that of a protective coating. Studies also showed that there is a significant delay in the corrosion initiation in the embedded rebar. Under normal conditions, corrosion is initiated approximately after 40 years of construction with a concrete cover of 70 mm; such high cover is recommended by many international codes for severe exposure. Crystalline concrete showed a delay in the corrosion initiation by about double of this time, which is a great advantage for marine structures; this is ensured with proper periodic maintenance in parallel. Crystalline concrete is termed as “green product” as it is nontoxic and does not produce fumes. Crystalline products do not contain any volatile organic compounds, which is a common problem with most of the chemical treatments carried out on concrete surface.

Crystalline treatment can be done either by coating or by mixing the product in the green concrete during the preparation of concrete. Coatings have high concentration, which can readily diffuse in the solution of lower density until both of them equalize themselves. Any open pore surface will readily admit such chemical transfer into the substrate. Concrete surface, which needs to be coated, should be cleaned thoroughly to make it free from oil and other foreign matter. Concrete surface must be thoroughly saturated, and the surface should be in a damp condition to apply this treatment. In hot weather, it may be necessary to soak the surface overnight. In cold weather, the surface temperature must be above 33°F for at least 24 h before start applying this treatment. Crystalline material is mixed at a ratio of 5 parts of powder to 2 parts of water by volume and stirred thoroughly to ensure the consistency of the slurry formed by this mixture. Subsequently, it can be applied by either a brush similar to that of painting or using a hopper gun. Moist curing of coating with water is necessary for proper performance of this treatment. It controls evaporation, cures and hardens the cement and coating, initiates crystalline formation after 3–4 h of application. Curing should be done for at least couple of days under both hot and cold weather. This is to ensure that the surface does not get dried up before the crystalline formation happens in the voids of the concrete structure. Alternatively, this can be applied as an admixture, which is commercially available in the readymade form. The admixture can be directly mixed in concrete at the time of batching itself. The dosage rate is about 1% by weight of cement used in the mix design. It is compatible with other admixtures, which are commonly used for slump control, rapid hardening, and so on. Adding crystalline admixture at the batch plant ensures a uniform distribution throughout the concrete and therefore throughout the member. It makes concrete impermeable and reduces the shrinkage cracking. It also increases the compressive strength of concrete as a structural member. Construction cost added to the maintenance as initial investment is significantly reduced, as the service life of the structure is enhanced.

3.20 CORROSION

Corrosion is deterioration of material by chemical interaction with the environment. This term also refers to degradation of plastics, concrete, and wood, but generally refers to metals. Corrosion process produces a new and less desirable material from the original metal, which results in a loss of function of the component or system.
The common product of corrosion is “rust,” which is formed on the steel surface. The basic corrosion cell is shown in Figure 3.18. The basic corrosion cell needs three components: an anode, a cathode, and an electrolyte medium.

Electron flow during a corrosion process is shown in Figure 3.19. There will be a measurable direct current (DC) voltage, which can be read in the metallic path between the anode and the cathode. When both the anode and the cathode are electrically bonded, the anode is positively charged and the cathode is negatively charged. Conventional current flows from positive to negative, and thus, current discharges from the anode and is picked up at the cathode through the electrolyte. Current returns from the cathode to the anode through an electrical path. This flow has a detrimental effect on the anode known as “corrosion.” It is important to note that corrosion occurs at the anode and not at the cathode. Corrosion is a process in which ions are involved. For corrosion to take place, three basic requirements are necessary: (1) a medium to move, which is water in case of ocean structures as the members are continuously exposed to seawater; (2) oxygen to activate the process, which is
present in abundance; and (3) a metal, which should be willing to give up electrons to start the process. Corrosion process results in formation of a new material, which may react again or could be protective of the original metal. The anode and cathode in a corrosion process may be on two different metals connected together forming a bimetallic couple (galvanic couple), or, as in the case of rusting of steel, they may be formed on the metal surface.

### 3.20.1 Corrosion in Steel

Steel is the basic material of construction in the offshore industry. Corrosion, to a large extent, is governed by the oxygen content of seawater. The corrosion rate of steel in the marine environment is related to the rate at which a ferrous corrosion product is leached or washed from film of rust. When one of the products of corrosion becomes soluble, the formation of a protective barrier film becomes impossible. The presence of copper and nickel, even in small quantities in the low alloy steel, enhances their corrosion resistance by altering the structure of the barrier film formation. They help to produce a tighter, denser barrier film with less of a tendency to be removed by leaching or spalling. Figure 3.20 shows a typical offshore platform with different corrosion zones marked. The figure shows different regions at which the corrosion takes place in an offshore platform. The top zone is the atmospheric zone where derricks and deck modules are located. This zone experiences the minimum rate of corrosion due to the fact that the members are not in direct contact with water. Hence, leaching or washing of the thin barrier film is at a lower probability.

Atmospheric sea exposure is always present on the top portion of the topside where derrick and deck modules are present. It contains generally precipitated salt, and condensation process takes place in this region; soffit of the deck slab is the most vulnerable candidate for corrosion in this region. The corrosion rate of steel in the marine atmosphere is related to the rate at which the ferrous corrosion product is

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**FIGURE 3.20** Offshore jacket platform with various corrosion zones.
leached or washed off from film or rust. A protective barrier film is being created on the top of the member, as a by-product of the corrosion process. If there is a possibility that this barrier film can be leached off or washed off, then the corrosion process can be activated. In case of atmospheric zone, there is a least possibility that this film can be washed off. When one of the products of corrosion becomes soluble, the formation of a protective barrier film is impossible.

Severe corrosion is seen in the splash zone due to continuous wetting and drying because of tidal variations in the sea. It results in pitting corrosion in the tidal area. Due to continuous contact of seawater with a higher lateral force, thin barrier film, even if formed, will be washed away immediately; this expedites corrosion in the splash zone. Rust films in this zone have a little opportunity to become dry as this zone is subjected to alternate wetting and drying continuously. Even though the rust films may be formed, they will be leached off automatically. This is aggravated because of the presence of abundant oxygen content in this region. The rate of corrosion in this splash zone is several times greater than that of the continuous immersion part of the member. It is interesting to note that the same member (say, e.g., jacket legs) passes through different regions of corrosion, resulting in the development of a bimetallic couple. One part of the member becomes anodic and the other cathodic; the presence of an electrolyte activates the corrosion process very fast. Therefore, the rate of corrosion in this region is seen as several times higher than that of the other regions, which is continuously immersed in seawater.

In the tidal zone, corrosion reaches a minimum because of the protective action of oxygen concentration cell currents present in this region. Steel surface in a tidal zone is in contact with highly aerated seawater, and therefore becomes cathodic. As only the anodic part of the member corrodes, the adjacent submerged surface where the oxygen content is less becomes anodic, and therefore, it gets corroded severely. For example, the members that are covered with oxygen-shielding organisms like marine growth may get less oxygen content on the surface, and they become anodic and corrode faster than the members present in the tidal zone. The current flows from the anode, which is submerged surface, to the cathode, which is tidal zone in these areas in the sea environment. This enables sufficient cathodic protection to the members in the tidal zone automatically. This is caused by the differential aeration or formation of marine growth in the regions, which are immersed below.

In the immersed zone where jackets and mud lines are present, corrosion is reduced due to the decrease in oxygen concentration. In this zone, corrosion is principally governed by the rate of diffusion of oxygen through layers of rust and marine organisms. The corrosion rate is not influenced by the seawater temperature and tidal velocity. Kindly note that rate of corrosion is not determined by the temperature gradient in seawater with the increase in water depth. The corrosion rate may go up in the vicinity of the mud line, but further down, it is very less. This is due to the presence of marine organisms, which can generate additional concentration cells and sulfur compound in the vicinity of the mud line. Due to this, they become anodic compared to the remaining part and get corroded. The corrosion rate reduces well below the mud line because of lower availability of dissolved oxygen content. Barrier films, once they are formed in this region, are relatively undisturbed. Therefore, they form a protective coating automatically, and that protects the members in this region.
Various factors influence the corrosion rate of steel members in offshore structures. Considering the effect of current velocity on the corrosion rate, it is understood that any gentle motion will not affect or disturb the formation of the protective barrier on members. However, when the platform motion is larger, the barrier layer formation becomes thinner and is easily broken under higher current velocity. Therefore, current velocity plays an important role in accelerating the corrosion rate; increase in current velocity increases the rate of corrosion. Considering different methods of corrosion protection, the majority of the members of the platform present in the atmospheric and tidal zones can be protected by painting. For those present in the splash zone, special methods such as providing extra steel, Monel wrapping or sheathing is recommended as a corrosion protection measure. In case of the immersion zone, sacrificial anode technique or cathodic protection methods are employed. In the mud line below, no special methods of corrosion protection are advocated as there is a little amount of corrosion.

The effect of water depth on the corrosion rate is also an interesting viewpoint. At a water depth of greater than 1800 m, the temperature drops to less than 4°C in comparison with 24°C at the surface. This results in substantial reduction in the corrosion rate. Metal surfaces are relatively free of marine biofouling below 700 m. Dissolved oxygen drops along the depth but rises again below 820 m. This raise is significant in comparison with the surface concentration. Ocean layers are not homogeneous; various layers are differentiated by different oxygen and salinity contents. Corrosion decreases at greater water depth as the temperature decreases. Fouling and pitting associated with fouling also tend to decrease. Mooring lines, which extend to different zones of corrosion, face a critical problem. Due to part of the mooring line becoming cathodic, corrosion is set at the local level along the length of the mooring. This is called “long-line effect.” Mainly due to the typical oxygen cell concentration attack, long length of mooring lines is subjected to different layers of varied oxygen concentration. This alters the rate of corrosion in different segments along the length of the mooring line, which is a long-line effect. Galvanized mooring lines are common candidates of such problems.

3.20.2 Corrosion in Concrete

Concrete, which has embedded steel, has a high degree of protection against corrosion. As concrete is alkaline in nature, it provides barrier protection to steel reinforcement. Presence of chloride in sufficient quantities in the vicinity of steel results in cracking, spalling, and delamination of concrete. Early detection of the corrosion activity can assist to plan corrosion preventive measures. Chloride-induced corrosion is the most serious cause of deterioration in RCC structures. Structural weakening caused by corrosion can reduce its service life by 20 years. The corrosion rate is accelerated in RCC members whenever there is exposure to the source of chloride. Patching of damaged areas does not stop from corroding but spreads to other areas faster. The corrosion mechanism in RCC structures can be easily understood: Steel is in a passive state in concrete. If chlorides reach steel surface by ingress, this passive layer is broken. This initiates the corrosion process. Corrosion current flows from one part of the reinforcement (anode) to another part (cathode). Because of this
current flow, steel corrodes at the anode and produces rust. As a result, reinforcing steel develops a tendency to revert to its natural oxide state, which is not capable of withstanding the encountered stresses. Corroded steel can expand 4–5 times of that of its normal volume. This will result in cracking, spalling, and delamination of concrete. This further exposes more steel contact areas for chloride ingress and accelerates corrosion.

### 3.20.3 Realkalization

Fresh concrete has inherent alkalinity, which provides passive protection to steel. Ingression of carbon dioxide creates carbonated concrete with lower alkalinity, which results in loss of passive protection to rebar. It also accelerates the corrosion of steel reinforcement. Realkalization involves an electrochemical technique of passing sustained low-voltage current between the temporary anodes on the surface of concrete and steel reinforcement. The period of application can vary from 3 to 7 days. Electrolyte covering is done by spraying cellulosic fiber, saturated in sodium carbonate solution. Surface nodes, embedded in alkali-rich paste, draw alkali into concrete through rebar. Realkalization takes place in concrete to initiate the formation of natural protective oxide film over rebar.

### 3.21 Corrosion Prevention

There are different ways by which corrosion can be prevented: (1) by conditioning the metal surface; (2) by conditioning the corrosive environment; (3) by controlling the electrochemical reaction, which is responsible for corrosion; (4) by fighting corrosion with corrosion; (5) by coating the metal; and (6) by alloying the metal. The rate of corrosion can be reduced by retarding either the anodic or the cathodic reaction. The principle aim behind any corrosion prevention or protection method is to fight corrosion with corrosion. It means that, to actually reduce corrosion, create an additional member and allow it to corrode. By sacrificing the additional member, corrosion on the existing members of the structure can be prevented. This is called sacrificial anode method. Using another metal to coat an existing metal surface is the common case in zinc or tin coating. It is generally applied on steel as an external coating surface. A protective coating derived from the metal surface itself can also be applied. For example, the metal surface of a member can be coated with aluminum oxide; organic coatings such as resins, plastics, paints, enamel, oil, and greases are also used. Coating a metal can also help reduce the corrosion rate but pose a serious threat to the sea environment. Alternatively, one can also alloy the metal to produce a corrosion-resistant alloy. A classical example is stainless steel in which ordinary steel is alloyed with nickel and chromium. By conditioning the corrosive environment, one can control corrosion. Oxygen is one of the main components required to activate the corrosion process. Removal of oxygen can help to retard the rate of corrosion. Removal can be achieved by adding strong-reducing agents. For example, sulfites can reduce the presence of oxygen content in the sea environment. Removal of oxygen is not advisable in the open environment because of the presence of oxygen in abundance.
3.22 CORROSION PROTECTION

There are many methods to protect offshore structures from corrosion. Atmospheric zone is one where corrosion is not very severe, but marginally high. One can use coatings to protect the members. In the splash zone, where the corrosion rate is very severe, one can use Monel-400 or other metal cladding. Monel-400, an alloy of 18 gauge thick (approximately equal to 1.02 mm) is attached to the tubular member in the splash zone. This is done either by bonding the Monel sheathing on the parent member or by welding. Monel-400 has high modulus of elasticity and will not get damaged under the stress conditions, which are caused by this installation process. However, it is likely to get damaged by tearing or impact forces as the sheathing is too thin. There is a tendency that the sheathing may even peel off or tear off from the parent surface of the material. Alternatively, austenitic stainless steel 304, which is an alloy of chromium–nickel stainless steel, can be wrapped over the surface of the members in the splash zone. The advantages of these applications are high degree of weldability and increased stiffness. Another alternative material, which is also commonly deployed in the splash zone, is copper–nickel alloy of either 70%–30% or even 90%–10% composition. This adds stiffness to the members during installation. One can also use steel wear plates of 6–13 mm thickness. They also add strength and stiffness to the members and improve their resistance against impact loads. This application is more common in the Arctic regions, where the temperature variations can be very large. Splashtron and vulcanized neoprene are the two varieties of rubber products, which can be used as a sheathing layer on the members near the splash zone. Splashtron is an elastomeric rubber sheathing, which is braced to the members. It is highly resistant to corrosion and mechanical abuse. It has very high tearing strength when it is hardened. It adheres to the parent material very strongly and becomes more or less homogeneous in action with that of the parent material. Thickness usually varies from 5 to 13 mm, which is high in comparison with that of the Monel sheathing. Table 3.6 shows the summary of corrosion protection measures in the splash zone.

Use of corrosion inhibitors is also one of the effective methods of reducing corrosion. Corrosion inhibitors are of different types: anodic, cathodic, adsorption, and mixed. Corrosion inhibitors are other alternatives for corrosion protection of members of ocean structures. These are chemical additives, when added to the corrosive aqueous environment, interferes with the chemical reaction and reduces the rate of corrosion. Anodic inhibitors interfere with the reaction that takes place at anodes. They suppress the cathodic reactions that occur on a bimetallic couple. Adsorption-type corrosion inhibitors generally form a film on the surface of the member; they physically block the surface from the corrosive environment. Corrosion inhibitors are commonly deployed in deepwater platforms in the immersion and splash zones. Anodic inhibitors are more popular among all of these three types of corrosion inhibitors.

Another effective method is to control the electrochemical reaction responsible for the corrosion process. This technique is done by passing an anodic or cathodic current inside the metal. Cathodic protection is an important and one of the common methods of corrosion protection in the marine environment. In principle, it
can be applied to any metallic surface that is in contact with the bulk electrolyte. This condition is automatically fulfilled in case of offshore structures as seawater with impurities of sulfites and chemicals acts as the electrolyte. This is advantageous for members buried in soil or immersed in water, and hence cannot be applied in the splash and atmospheric zones; alternate wetting and drying condition is not suitable for this kind of corrosion protection measure. Figure 3.21 shows a schematic view of anodic and cathodic reactions on a metal surface. The figure shows
the formation of bimetallic couple in the presence of bulk electrolyte. Anodic reaction releases electron and becomes the positive, whereas cathodic reaction receives electron and becomes negative. Therefore, the anodic part is continuously corroded, but the cathodic part is protection, hence the name cathodic protection. To protect the parent member, one should provide another material as anode, which is capable of forming bimetallic couple with the parent metal; in this case, anode is sacrificed.

Cathodic protection can be achieved in two ways: (1) by using galvanic anodes, termed as sacrificial anode technique, and (2) by impressed current method. Metal to be protected is connected as cathode, whereas an external metal is connected as anode. Anode is ready to release electrons in a chemical reaction when connected to an electric DC current. The external metal, which is provided, may be a galvanic anode, where the current is a result of the potential difference between two metals. It forms a galvanic couple as well; alternatively, current is impressed from an external DC power source on the metal.

The galvanic anode systems employ reactive metals as auxiliary anodes that are directly connected to the metal, which is to be protected. Therefore, the member or the steel surface, which is to be protected, should be made as a cathode. An additional member is introduced to act as a galvanic anode deliberately. The potential difference between the anode and the parent steel, as indicated by their respective positions in the electrochemical series, will make the new material anodic; corrosion is initiated in the presence of electrolyte. The current flows from the anode to the parent metal, which results in corrosion of anode. Thus, the whole surface of steel which is now cathodic, is protected as it is negatively charged. This is termed as “cathodic protection.” As a new metal, which is provided, acts as an anode that corrodes, this is also termed as sacrificial anode technique of cathodic protection. Metals that are commonly used as sacrificial anodes are aluminum, zinc, and magnesium. They are used in the form of rods, big blocks, or wires that can be wound around the members. Big blocks can either be bolted or be welded to the structure.

This system is advantageous as it is very simple to install and requires no external source power. Localized protection is highly effective and immediately available on float-out. Moreover, this has less interaction with neighboring structures. One of the main disadvantages is that the current output available is relatively small. Therefore, monitoring a galvanic system for effective corrosion protection is very difficult under surveys. A monitor system is highly sensitive to record small variation in voltage. The flow of electrons depends on the electrical resistivity of the electrolyte. A change in the structure, say for example, deterioration of coatings, demands more current and hence more sacrificial anodes; therefore, sometimes, this method proves to be expensive.

An alternate method by which one can also use cathodic protection is by passing the impressed current on the metal. Impressed current systems employ either zero or low dissolution anodes. They use an external DC power to impress the current from an external anode onto the cathodic surface. Connections are similar to that of the cathodic protection and commonly applied to metallic storage tanks and RCC ocean structures. This is used as corrosion protection of members in the immersion zone.

Figure 3.22 shows a schematic view of the impressed current method, as applied for a steel pipeline. Anodes are externally connected to the remote pipe. The current flows from the anode to the pipeline through earth or water, which is the bulk electrolyte
Impressed current is passed at the location where the pipeline is laid; as it remains cathodic, it is protected. This method is effective only when the members are fully immersed in the medium; this method requires the contact of bulk electrolyte to activate the process. One of the main advantages of cathodic protection over other forms of anticorrosion treatments is its effectiveness to monitor continuously. This is possible by maintaining a DC circuit. One can record the amount of electronic flow between the anodic and cathodic terminals, which is the index to measure the effectiveness of the treatment. Cathodic protection is commonly applied to members that are surface coated, and there is high probability of this coating being damaged. For example, members in the atmospheric or splash zone have a tendency for coatings to get washed or leached off due to the chemicals present in the sea environment.

The impressed current method has few merits. As it can supply relatively a larger current in comparison with that of galvanic systems, an effective monitoring of control mechanism is highly feasible by impressing the current mechanism. It is able to provide high DC driving voltages and can be used in most types of electrolytes. As it is capable of providing a flexible output, it may accommodate respective changes in the structural members. However, there are some demerits of the system. For example, an intensive care should be taken to minimize the interaction with other structures. As it is uniformly available for larger protection surfaces, interaction between the structural members in elements is also highly feasible. Regular maintenance or monitoring is very important in this kind of protection system.

Cathodic protection is a common phenomenon that is implemented in the design stage of ocean structures. Exterior surfaces of ocean structures are protected by cathodic protection. Examples are pipelines, hull of ships, base of storage tanks, jetties and harbor structures, tubular joints in jacket structures, and foundation piles. Floating offshore platforms and subsea structures are common examples where cathodic protection is very largely deployed in the recent times. In the North Sea, the galvanic protection method against large uncoated platforms is found to be very cost-effective. Because the cost of coating in maintenance is very high, offshore engineers prefer to use galvanic protection techniques in the Gulf of Mexico or the North Sea for majority of the platforms. Galvanic systems are easy to install and are robust systems. As it requires no external power source, it is considered to be one of the main advantages.
Moreover, it provides protection immediately on float-out of the structure; this method of corrosion protection is instantaneous. Cathodic protection is also used to protect the internal surface of large diameter pipelines and ballast tanks in ships. The inner surface of large oil storage tanks are also common candidates of this method of corrosion protection. In a process industry that uses continuous circulation of coolant or water under differential temperature, cathodic protection is the most preferred method to control the rate of corrosion; if not, it can be completely prevented.

The cathodic protection system has certain requirements. This can be applied to members that are in contact with bulk electrolyte. In addition, a galvanic system requires a sacrificial anode, which should be direct welded to the structure; alternatively, a conductor can also connect the anode to the structure. A secured connection with a minimum resistance between the conductor and the structure is to be also ensured. An impressed current system requires inert anodes, which are cluster of anodes connected together often in a backfill. It also requires an external DC power source and electrically with a well-insulated system to ensure minimum resistance and secured connection between the anodes, conductors, and the power source. The source of DC power, which is vital in case of the impressed current method, can be ensured by using rectifiers of by transformer units in conjunction with an existing AC supply; alternatively, one can use either diesel- or gas-driven alternators. In remote areas, power source include thermoelectric generators and solar or wind generators for generating the required DC power for impressed current.

3.23 MATERIALS FOR REPAIR AND REHABILITATION

Materials for repair and rehabilitation of ocean structures are not under the recommendation of international codes. These codes only suggest repair procedures and desirable characteristics of materials for repair. Among several reasons for this limitation, the foremost is that the material choice for repair is case specific. Ocean structures are constructed for a variety of functional requirements, which are very specific to the type of the chosen structural system, as discussed in Chapter 2. Repair of ocean structures is required to be carried out without affecting their functional routine. Furthermore, they cannot be relieved off from the encountered environmental loads during repair. This means that ocean structures need to undergo repair, although they are under the influence of various environmental loads, which is an important challenge. The characteristics of a material chosen for repair should enable speedy construction and attain the desired strength at the earliest possible time. This is because the downtime available for repair of ocean structures is generally for a limited period; constraints may arise from the weather window or functional priorities. Moreover, the repair of ocean structures is not preventive in general but only prescriptive to functional failure. In such cases, special issues related to their survivability under critical load combinations encountered by them are a very critical issue. These types of structures cannot be dismantled or reconstructed but only be repaired.

There are instances where an extensive repair needs to be carried out under water (see, for example, the details of repair of ship dockyard, Pennsylvania, as shown in Figure 3.23). Repair carried out on the dockyard in the recent times involved a new approach of supporting the deck on a new set of piles, although the dockyard was
in service. Repair of the Cape May Ferry berthing Jetty in Cape May, New Jersey, resulted in enhancing the ferry-handling capacity of the Jetty (Figure 3.24). Designed constructed new boardwalks using prestress concrete bulkheads are also equipped with state-of-art fender systems. Details of the repair works carried out in Exelon Power Corporation, Philadelphia, showed that a new set of steel auxiliary piles was installed to replace the deficient piles on the front end (Figure 3.25). From the above
examples, it is clear that repair of ocean structures is a state-of-art procedure due to the update demand on functional characteristics and enhanced load-carrying capacity. Hence, material chosen for repair is not based on the existing design requirements but should also compensate for the degraded performance of materials that are deteriorated. Both the factors, namely, strength and serviceability, are required to be fulfilled.

Before the actual repair can be carried out, the following factors need to be established: (1) existing strength of the structure, (2) magnitude of the proposed repair, (3) cost factor, (4) shutdown time of the service of the structure, and (5) feasibility of the proposed repair work. If all the above factors are included in the study based on which repair methodology is suggested, then the study is termed as “integrity analysis.” Repair of ocean structures is full of challenges. Unlike land-based structures, ocean structures need to be repaired in the hostile environment. It requires a set of specialized equipment, chemicals, and construction expertise to carry out such repairs. It also requires state-of-art electronic systems to map underwater conditions before and after repair. These equipment studies include hydrographic survey equipment, side-scan sonar imaging, instruments to measure the ultrasonic thickness of steel members, underwater photography/video, and marine borer assessment.

Repair of ocean structures also poses a set of unique challenges; the foremost is that the structure has to remain in service during repair. Therefore, the load-carrying capacity should not be challenged when repairs are being attempted on ocean structures. Specialized methods and equipment are generally used for two reasons: (1) to minimize the shutdown time of the structure during repair due to limited availability of time for carrying out repair, and (2) to minimize the damage on existing structures during repair. Other factors are as follows: (1) the repair process should also be cost-effective and (2) long-term solution is demanded. It is not because such repairs need to be evaluated under an economic perspective, but for a valid reason that ocean structures cannot be intervened for repair frequently. As preventive maintenance is not a usual practice in many of the ocean structures commissioned around the world, repair processes become more complicated as they are generally requested only on an emergency situation; enough time is not available for detailed studies and verification. Hence,
offshore engineers should have a thorough understanding of various repair methodologies and chemicals available to carry out repair on emergency situation. Unlike land-based structures, ocean structures need to be repaired in the hostile condition as structures mostly have less or remote access to land. They require specialized equipment, chemicals, and construction expertise to carry out the repair of ocean structures. They also require state-of-art electronic systems to map under water conditions of the ocean structures. They include hydrographic survey equipment site scanners, and sonar imaging equipment. Underwater videography, photography, and marine borer assessment are the common methods used during repair process. Repair processes are not generally prescribed in the standard literature and are not generally recommended by international codes. This is due to the fact that various chemical admixtures that are generally used for repairs are case specific.

3.24 REPAIR OF CONCRETE STRUCTURES

Before reviewing different methods of repair of concrete structures in general and reinforced concrete structures in particular, it is imperative to understand the process of damage of concrete. Concrete structures deteriorate due to chemical reactions that occur in the marine environment. Loss of strength is mainly associated with degradation of rebar in reinforced concrete structures, which is due to corrosion of steel reinforcement. Figure 3.26 shows a graphical representation of various factors that influence deterioration of concrete along with their significance, expressed in percentage (Gettu, 2015). It is seen from the figure that presence of external chlorides influences to the maximum. Figure 3.27 shows the causes for failure of concrete structures in general but not specific to the failure of ocean structures (Gettu, 2015). It is seen from the figure that the major factor that causes failure arises from improper material specification and even incorrect choice of material amounts close to about half

FIGURE 3.26 Factors for deterioration of concrete.
of the total factors that influence the failure of concrete structures. Hence, selection of material, both construction and repair, plays a major role in successful functioning of concrete structures, in general.

### 3.2.4.1 Deterioration Due to Chemical Reaction

Leaching and sulfate attack are considered to be serious problems for deterioration of concrete under chemical reactions. Dissolved calcium hydroxide reacts with carbon dioxide to form calcium carbonate. This forms a white powder, which is deposited within concrete core and on its surface as well. Extensive leaching could decrease the strength of concrete and also facilitate the ingress of aggressive agents into the concrete. It further reacts with rebar-embedded concrete and causes corrosion.

Sulfate attack deteriorates the strength of concrete. Sulfates react with calcium hydroxide to form a compound called “gypsum.” Gypsum, in turn, reacts with hydrated compounds to form “ettringite,” which results in expansion of concrete in manifold volume but initiated from the surface. Once initiated, concrete is exposed to a corrosive marine environment. This further admits the penetration of chlorides under the humid weather conditions, which in turn initiates severe corrosion in steel. In addition, attack by magnesium sulfate is more damaging because magnesium hydroxide, which is formed from the reaction, replaces calcium ions with those of magnesium. It destroys the cementing effect in concrete; further, alkali–silica reaction is one of the important reasons for deterioration of concrete. Alkali–silica reaction occurs in the presence of hydroxides of sodium and potassium that are present in cement. They react with silica aggregates to form “silicate gel,” which absorbs water and further expands. Although all pores are filled with water, further expansion causes cracking. Although dehydration of gel leaves the cracks in open condition, this further deteriorates concrete. Figure 3.28 shows the damage of columns and beams of a port structure.

Alkali–carbonate reaction in concrete in the marine environment initiates the loss of bond strength and develops microcracking; this is the consequence of reaction of dolomitic limestone aggregates with alkaline material. The steps involved in the reaction are as follows: in the first step, the release of alkali from cement during
hydration increases the concentration of hydroxide ions in the pore solution. In the second step, the initial hydrolysis of siliceous fraction of aggregate, present in the highly alkaline solution, destroys the integrity of aggregates. This results in swelling of alkali silicate gel by inhibition of water. This causes local swelling and increases the internal pressure, which results in the cracking of concrete. Finally, liquefaction of alkali silicate gel takes place due to further inhibition of water. This results in the expulsion of liquid gel through cracks. Figure 3.29 shows the damaged jetty.
in the marine environment. Due to alkali–carbonate reaction, an expanded concrete resulted in spalling of cover. As seen in the figure, reinforcement is extensively corroded. Figure 3.30 shows the deterioration of fenders of the jetty due to chloride attack. Exposure of steel reinforcement is the most serious consequence of chemical attack in concrete, as this initiates a series of failure, followed in order.

3.24.2 Role of Chemical Admixtures in Repair

Admixtures play an important role in inculcating corrosion resistance to the reinforcement embedded in concrete. They influence the performance behavior of concrete under various compositions and their role is case specific. Without compromising on strength, plasticizers help to limit the water:cement ratio. This can yield concrete with low permeability, better contraction, and good quality top layer. In the presence of plasticizers, the top layer of concrete will remain dense and free from bleeding water. Retarding and plasticizing admixtures will help to achieve rapid workability when concreting is done at higher temperature. It will result in quick setting of concrete, which is not desirable as far as ocean structural construction is concerned. Corrosion-inhibiting admixtures increase the corrosion threshold of steel by providing additional resistance to rebar. High-strength superplasticizers improve the resistance to abrasion. Corrosion inhibitors provide the second line of defense to prevent corrosion of steel reinforcement; protection is provided by the alkaline nature of concrete. The most commonly used corrosion inhibitors are nitrite-based compounds. They result in the formation of a protective ferric oxide layer on steel, which protects steel from direct access. Corrosion inhibitors provided resistance at lower water:cement ratio.
3.25 ADVANCED METHODS OF REPAIR

3.25.1 Cathodic Protection

Cathodic protection forms a very major role in corrosion protection of concrete structures. It is one of the effective methods to stop corrosion of reinforcement bar in concrete. This method uses the DC from an external source through the anode that is embedded in concrete cover. When the electrons flow in between the supplemental anode and the rebar, the rebar becomes cathodic and therefore protected. Figure 3.31 shows the cathodic protection to rebar of RCC beam. As seen in the figure, cathodic protection is enabled through the current flow from an external supplement node, which is acting as an anode to the embedded reinforcement. As the supplemented anode is connected to the embedded rebar, which was corroded earlier, now they are protected by cathodic protection. Ribbon anode is also used in RCC beam prior to concrete as seen in the figure. All ribbon anodes are allowed to corrode, whereas the rebar embedded in concrete is protected.

3.25.2 Electrochemical Protection Systems

The electrochemical protection systems (EPS) is an advanced method of protection. Embedded steel remains in the passive state in concrete. In the presence of chlorides, the passive layer formed on the steel surface is attacked. This enables corrosion to progress freely. Therefore, corrosion current flows from one part of steel, which becomes the anode through concrete into another part, which becomes the cathode. This makes the steel corrode and produces rust. It is important to note

![Figure 3.31 Cathodic protection to a rebar.](image-url)
that corroded steel can expand 4–5 times that of its normal volume, which cracks concrete. This can result in spalling and delamination of concrete. This, in turn, exposes the steel further and accelerates the corrosion process. Early detection of corrosion, therefore, is a very important stage in planning corrosion prevention measures. One of the possible solutions could be a well-designed corrosion monitoring system. This provides information with respect to the rate at which the rebar is corroded. Early detection of chloride contamination of concrete is also an integral part of the corrosion monitoring system. This system consists of corrosion monitoring units embedded in concrete itself. It detects corrosion by measuring the galvanic current between carbon steel and stainless steel electrodes. It measures the corrosion rate by measuring the reinforcement potential of the embedded steel using the electrochemical polarization technique.

### 3.25.3 Nanolayered Coatings

Nanolayered coatings enhance surface resistance against corrosion. Nanolayered coatings are a form of gel solution, which are prepared using alkoxide tetra-n-butyl orthotitanate (also named as TNT). As the coating is in the form of a gel, it can be easily applied; its advantages are simplicity, homogeneity, and high uniformity of the applied coating. It forms a very thin film on application, and hence termed as nanolayered coating. Ethanol and ethyl acetoacetate are mixed together at room temperature. Tetra-n-butyl orthotitanate (TBT) is added to the solution, and it is stirred well; while stirring, some drops of distilled water are also added. For polymeric reactions to take place, the prepared solution is left for about 6 h. After surface preparation is done using titanium oxide, nano coating is then applied on the surface of steel by the submerging method.

### 3.26 Admixtures for Repair

Admixtures are added to concrete to modify the properties of fresh and hardened concrete. There are different types of admixtures, which are available in the commercial market. Although they have different functions, all of them modify the properties of fresh and hardened concrete. Water-reducing admixtures, also called plasticizers, superplasticizers, retarding plasticizers, accelerators, surface retarders, and corrosion inhibitors, are commonly used admixtures. They are added to green concrete when poured into the formwork. A few of the admixtures can also be sprayed on the concrete surface. Water-reducing admixtures are used where improved density and quality of concrete is required. Use of these admixtures in the construction of ocean structures can result in saving of cement without affecting the workability and the strength of concrete. A typical dosage of these admixtures is about 100–300 mL per bag of cement depending on the type of admixtures. Generally, manufacturers advise the recommended dosage depending on the variety and chemical composition of the plasticizers. Typical commercial brands available in the Asian market are Conplast P211 and Conplast P505.
3.26.1 **Superplasticizers**

Higher range of water-reducing admixtures, also called superplasticizers, are also used in precast construction of offshore structures. Precast elements play a very major role in offshore construction as they are used in large scale. Precast members are mostly preferred due to many reasons: (1) good quality control as they are factory cast, (2) speedy construction as there is no delay time for casting and curing, and (3) repetitive size of members that makes construction easy and well organized. To enable easy compaction of concrete in the heavily reinforced precast elements, superplasticizers are added to concrete. They improve the compaction of concrete in reinforcement dense shuttering. However, they also improve the workability and cohesion between the aggregates. They aid pumping of concrete by reducing friction of flow and dry packing. It results in low porosity and improved resistance to water penetration, which is very important to protect the reinforcement from corrosion. A typical dosage is about 200–500 mL per bag of cement. A few of the commercial brands available in the Asian market are Conplast SP337 and conplast SP430, which are used as superplasticizers for marine structural systems.

3.26.2 **Retarding Plasticizers**

Retarding plasticizers are used to retain concrete in a fresh state when placing of concrete is delayed. This is a very common problem in offshore construction as it is controlled by the weather window and sea states. These admixtures retard the setting time and help concrete to remain green during the delayed time of placement. Such delayed construction activities in offshore engineering are termed as “cold joints.” They are useful in the construction of piles in offshore structures. The usual dosage of retarding plasticizers, added to fresh concrete, is about 10–300 mL per bag of cement. One of the commonly used and commercially available brands of retarding plasticizers in the Asian market is Conplast RP264.

3.26.3 **Air-Entraining Agents**

Low-permeable concrete is preferred for ocean structures as it improved service-ability. Air-entraining agents, when added as admixtures to fresh concrete, ensure low permeability of concrete. The improved resistance to salt in marine and coastal structures, which is an outcome of low-permeable concrete, is also important for ocean structures. Air-entraining agents improve cohesiveness with harsh aggregates. It may be required as a fundamental requirement for massive foundation; for example, in case of gravity-based structures (GBS) platforms, seawalls, and jetties. A commercially available product in the Asian market is Conplast PA21(S). The normal dosage of this air-entraining agent varies from 10 to 200 mL per bag of cement.

3.26.4 **Accelerators and Surface Retarders**

Accelerators and surface retarders can be also used as admixtures in the construction of concrete structures in ocean environment. Accelerators are essentially required
for concrete placed in cold weather. As we all know, in the ocean environment, the weather window varies drastically. During the construction process, if the weather window varies unsuitably for the construction process, then accelerators are required to be used in concrete to place it in cold weather. They are also required when attempting a quick repair on ocean structures. Coastal structures of strategic importance, for example, jetties used by naval bases, have very less shutdown time available for repairs. One has to therefore undertake the repair of such structures in a quick mode of construction. Accelerators are admixtures; when added to the quick repair process, they reduce the time of hardening of concrete. Concrete attains the desired strength earlier than the scheduled time, which ensures preparedness of the structure to perform the intended function. Surface retarders, when added to concrete, can improve the concrete finish in the facedown of precast members. Accelerated drying due to wind in open sea can be controlled using these kinds of retarders. Therefore, they allow enough moisture to be available for concrete to have a fresh finish. Commercial products available in the Asian market are Conplast-NC, which is an accelerator, and Conplast-SR, which is a retarder. The recommended dosage is about 1–2 L per bag of cement.

### 3.26.5 Integral Waterproofing Compounds

Integral waterproofing compounds are added as admixtures to fresh concrete to protect it from the penetration of water. Continuous moisture will initiate the corrosion of reinforcement; waterproofing compounds reduce the permeability of concrete and protect the rebar from corrosion. They also improve the workability of concrete and minimize shrinkage cracks. Commercial products available are Conplast X4211C and WP90, WP112. The usual dosage is about 125–200 mL per bag of cement.

### 3.26.6 Sprayed Concrete Accelerators

Shotcrete and Gunite are highly common in the repair of marine structures. Sprayed concrete accelerators, when added to fresh concrete, accelerate the setting time. This is a very useful admixture for underwater applications. For example, sprayset HBL is a commercial product available and commonly used in marine construction. The usual dosage of sprayed concrete accelerators is about 23 L per bag of cement.

### 3.26.7 Hyper Plasticizers

Hyper plasticizers are admixtures used in fresh concrete to achieve high early compressive strength and improve workability. They aid pumping of concrete because batching plants cannot be located as close to the construction site of offshore structures. Pumping of large volume of concrete can therefore becomes essential; to aid pumping, hyper plasticizers are added to fresh concrete. It is an inevitable admixture in case of self-compact concrete. Generally, they are used in narrow formwork, for example, in repair of jetties. They also aid placing of concrete in underwater construction very fast. Commercial
products of hyper plasticizers are, for example, Structro-100 and Structro-485. The recommended dosage by the manufacture is about 0.25–1.5 L per bag of cement.

3.26.8 Curing Compounds

Surface treatments are also equally important for maintaining the integrity of offshore structures. They are carried out to improve the load-carrying capacity and serviceability. They are required to improve the surface finish of exposed concrete structures. Curing compounds are used as surface treatment. As a spray applied onto the surface, it will retain the moisture in concrete for effective curing. In case of deck slabs of jetties where a large area of concrete is exposed, curing compounds can be advantageous. Commercial products available in the Asian market are, for example, Concrete WB and LP 90. The usual dosage of surface admixtures varies from 200 to 270 mL per square meter area of application.

3.26.9 Grouts and Anchors

Anchors are an integral part of any mooring system, provided in ocean structures. The essential requirements of anchors and grouts are as follows: (1) They should be nonshrinking; (2) they should be free flowing; and (3) preferably the material should be cementitious. This is due to the fact that cementitious products have a good bounding with concrete, which is being repaired. In addition, they should have characteristics similar to those of shrinkage-compensated admixtures and are available in the liquid or plastic state. They should not be a solid material as compaction of grout material in a narrow hole available for the bolts becomes difficult. They should also have high strength as anchor grouts are subjected to high axial pull. It is also required that these kinds of admixtures ensure rapid setting to attain strength within shorter span of time. Epoxy-based resins are used as injected grouts. They are generally preferred for injection grouting of repairs where there are narrow gaps on the surface of concrete. In case of the occurrence of where chemical spillage may occur, epoxy resin-based grouts are more effective. Polyester resin-based chemical anchor grouts are specifically used in case of rock bed anchors, fenders, and fixing of any marine equipment. For example, Lokfix and Conbextra EUW are a few of the commercially available products for anchor grouts.

3.27 SPECIAL REPAIRS OF CONCRETE MEMBERS

Spalling of concrete is a very common problem in marine structures as it is exposed to a severe corrosive environment; presence of salt and continuous moisture is the essential factor. In the splash zone, when rebar corrodes, it expands. This results in external pressure on the cover of concrete, which makes the cover to wither off from the parent member. This is termed as “spalling.” The problem associated with such special repairs is to access such kind of repairs. Such repairs are generally restricted on newly placed materials or members undergoing excessive vibration under lateral loads or operation of the equipment. In such special repairs, temporary patching is done rapidly as it is essential to plug the concrete segments from
undergoing further damage; blow holes are also filled in parallel. It is required to eliminate such minor irregularities, so that major repairs of the structure can be avoided in the near future. Therefore, the emergency reinstatement of the damaged part of the structure is repaired in a small possible time; this is termed as “temporary patching.” Materials to carry out such special repairs are to be carefully chosen. The chosen materials should have a proper structural grade as the parent grade of concrete used in the marine environment is generally very high. The basic grade of concrete recommended for ocean structures is M45. A material chosen for repair should have higher grade of concrete and should be preferably a cementitious material. It is important to understand that the repair attempted in ocean structures is not a cosmetic task but a functional task. Repaired members need to have the same (or even higher, if possible) load-carrying capacity for which they are originally designed. After repair, structural member should remain functional as it was earlier. A few important requirements for special materials used for such repair are as follows: (1) They should be light in weight grade; (2) they are readily available in a prepacked mode; (3) they should remain as anti-washout materials; (4) they should be nonshrinking compounds; (5) they should have high strength; and (6) they should be cementitious materials, preferably. In addition, the chosen material should enable crack sealing completely and should have a rapid setting characteristic. It should also be waterproof.

3.28 PROTECTION OF COASTAL EMBANKMENT

Prior to the selection of materials for repair of coastal structures, it is important to understand the various reasons for strength and functional degradation of coastal structures. Coastal structures are subjected to severe erosion due to natural causes and anthropogenic reasons. Various natural causes are as follows: action of waves and wind, new-shore current, tidal and storm, catastrophic events such as tsunami, slope deterioration along the coastal line, vertical movements that arise due to seabed compaction, and due to instantaneous sea-level rise because of geographical changes. Various anthropogenic reasons are as follows: dredging at the tidal entrance, construction of harbor in the near shore area, construction of other protection structures such as groins and jetties, construction of riverwater regulatory works near the shore area, and also due to hardening of shorelines by construction of seawalls and revetments. It can also result from the construction of sediment-trapping upland dams.

The primary solution for the coastal erosion problem is construction of an embankment; such embankment is termed as “saline embankment.” The primary objective is to prevent the tidal ingress into adjoining paddy fields, located along the coastlines. This is a very common problem along the coastline of peninsular India. Many locations where agricultural cultivable lands are located in near proximity of the coastal sector are seriously affected by the tidal ingress. In addition, saline embankments also establish connectivity for saving people in case of flood and cyclone which are unforeseen activities. Saline embankments are constructed along the length of the coastline to protect essentially the hinterland from the coastal erosion. Figure 3.32 shows a typical coastal erosion case.
As seen from the figure, a heap of sandbags are placed along the embankment to protect the coastal embankment. Alternatively, as seen in Figure 3.33, temporary wooden poles are provided to improve slope stability of the embankment, which is not an effective and technical solution. In such cases, critical geological characteristics of the site govern the design of embankment and material selection. It is common
that such sites have a rich content of montmorillonite clay, which varies from about 7% to 21%. Soil has a very high moisture content. Pore fluid is highly corrosive with enrichment of gypsum, and such regions are also enriched with groundwater potential, which adds to the complication. The retardant embankment soil acts as an impervious layer, creating high pore pressure in the soil column. If the constructed embankment has a very low slope gradient, it will result in instability. Excessive pore pressure warrants a flexible system instead of a rigid system such as rubble-mound embankment. Material selection should also meet the appropriate coastal regulations as applicable. Conventional sandbagging will not be effective for sites where the erosion rate is very high.

Geotube embankment is an alternative solution to address such site-specific problems. Figure 3.34 shows a typical cross section of a geotube embankment. Geotubes are cost-effective and have long service life. They remain noncorrosive in marine environment and are durable with high tensile strength. Apart from enabling speedy construction, they are very effective in dissipating wave energy by using gabion boxes filled with stones. Gabion boxes are tied together with armour units to maintain the slope stability. Figure 3.35 shows a schematic view of the Geotube embankment with layers of gabion boxes.

**FIGURE 3.34** Cross section of geotube embankment.

**FIGURE 3.35** Geotube embankment with layers of gabion boxes.
embankment, layered with gabion boxes. Table 3.7 shows a technical comparison of geotube embankment with that of a conventional rubble-mound embankment.

Geosynthetic tubes are used as breakwaters to prevent soil being eroded by waves and current. Geosynthetic tubes are used as artificial dunes, reefs, dyes, or groins. SoilTain tubes are one such common application being widely used in practice. SoilTain tubes are geotubes manufactured by HUESKER Synthetic GmbH, Germany. Figure 3.36 shows an embankment constructed with geosynthetic tubes.

### TABLE 3.7

Comparison of Geotube and Rubble-Mound Embankments

<table>
<thead>
<tr>
<th>Description</th>
<th>Geotube Embankment</th>
<th>Rubble-Mound Embankment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitability of site with high pore pressure</td>
<td>Suitable as it is a flexible system</td>
<td>No as the system is rigid</td>
</tr>
<tr>
<td>Risk of soil erosion to adjacent unprotected area</td>
<td>Minimizes the risk as it dissipates the wave energy effectively</td>
<td>No such mechanism is in place</td>
</tr>
<tr>
<td>Design adaptability</td>
<td>Most suitable due to extensive flexibility offered by geotubes</td>
<td>Rubble-mound design is stiff</td>
</tr>
<tr>
<td>Eco-friendliness</td>
<td>Remain noncorrosive in the marine environment</td>
<td>Remain noncorrosive in the marine environment</td>
</tr>
<tr>
<td>Time of construction</td>
<td>Comparatively faster</td>
<td>Comparatively slower</td>
</tr>
<tr>
<td>Inspection and maintenance</td>
<td>Easy to inspect and to carry out periodic repair</td>
<td>No effective procedures are devised and practiced</td>
</tr>
<tr>
<td>Geotechnical considerations</td>
<td>Suitable for mud-sliding soil</td>
<td>Not suitable for such sites</td>
</tr>
</tbody>
</table>

![FIGURE 3.36](SC/IITM) Embankment with geosynthetic tubes.
Dewatering of dredged material is necessary for its effective and compact disposal. This addresses the dredge disposal problems and handling capacity of dredgers. As shown in Figure 3.37, dewatering tubes are used in the recent times for clear-off dredged material. These tubes are made of special geo-textiles, which execute the gravimetric drainage of the sludge. This results in a significant reduction in volume of the dredging material. Slurry is captured inside and water escapes; this process makes it convenient to handle and dispose the slurry and dredge spoil.

3.29 STRUCTURAL ASSESSMENT OF A JETTY FOR ENHANCING LOAD-CARRYING CAPACITY: CASE STUDY

In this section, we will discuss a case study that necessitated a detailed static (and dynamic) analysis of a jetty. Assessment for enhancing load carrying capacity of the deck is carried out as additional loads are expected from the crane with enhanced capacity. The study demands a detailed mathematical modeling of the jetty with the material characteristics of the in situ condition. This is one of the classical examples, which integrated experimental and analytical investigations as applied to structural assessment and failure analysis of a marine structure. Assessment of the in situ strength of reinforced concrete members is done through NDT and destructive tests as well. Deduced strength of the reinforced concrete members is used in the analytical model for checking the load-carrying capacity with respect to the new crane of double the capacity of the existing ones. It is interesting to note that in such situations, it is not possible to refuse/constrain the...
enhanced load capacity of the jetty as this is an obligation from a strategic point of view. No conventional repairs can enhance the strength even if it could restore the original strength. Existing reinforcement details of the beam and reinforced concrete panels are modeled using a finite-element software.

3.29.1 EXPERIMENTAL INVESTIGATIONS

Detailed experimental investigations were carried out on the jetty to assess the in situ condition of the jetty. Ultrasonic pulse velocity (UPV) values indicate that the integrity of concrete in RCC walls will be considered as “medium.” UPV values in the cores indicate that the integrity of concrete may be considered as even “good.” Results of the rebound hammer test indicate that the near-surface characteristics of concrete are good. Results of the core tests indicate that the equivalent cube compressive strength of the concrete in RCC walls is in the range of 11–48 MPa. Majority of the core samples showed equivalent cube compressive strengths in the range of 20–27 MPa. Carbonation test revealed that the penetration of CO₂ is negligible in most of the locations. Results of the half-cell potential tests indicate that the probability of corrosion is high in the deck slab and RCC walls as well. Results of the chemical analysis of the powder samples in RCC walls indicate that chloride contents are below the threshold limit of 0.6 kg/m³. pH values of the concrete powder samples indicate the availability of sufficient alkalinity in the concrete, which is a good sign for strength restoration.

3.29.2 ANALYTICAL INVESTIGATIONS

Figure 3.38 shows the details of the analytical model generated for the study. The details of the structural model and the corresponding loading details are shown in the figure. A detailed 3D analysis is carried out to ascertain the critical stresses in the members and conclusions are drawn. Figure 3.39 shows the results of the analytical studies.

Based on the failure analyses carried out, it is seen that the maximum stresses in the deck plate are within the permissible limits. The actual in situ strength that is computed based on the equivalent cube strength of RCC samples obtained from destructive tests shows 20–27 MPa; these are used in the analysis. Stresses at corners are more than the permissible values due to the uplifting of corners of the deck slab resulting from torsion. However, it is seen that there is a possibility of redistribution of these stresses as the structure has very high degree of indeterminacy. von Mises stress values, indicating the yield criterion for deck slab, also show values closer to principal stresses. Shear stress yield criterion, shown by Tresca stresses, is not a governing criterion for the current problem under investigation as the deck slab is governed predominantly by bending and not by shear. Figure 3.40 shows a detailed insight of stress exceedance nodes. It is seen that the nodes where the stress exceedance levels are seen in the analysis are not in the vicinity of the crane rails.

Based on the above study, it is seen that strength assessment is done based on the NDT/destructive tests on various concrete members of the jetty. In addition to
FIGURE 3.38 Details of an analytical model.
the dead load of the structure, wheel loads are also applied onto the crane rails for the enhanced crane capacity. It is also seen that the stress levels in the deck slab are within the permissible limits; however, stresses at corners are more than the permissible values. These stresses will get redistributed as the structure is highly indeterminate. This is probably imposed due to the rigid connection of the deck with the RCC walls. Principal stresses in the deck at a few critical nodes exceed desirable values. Von Mises stress values, indicating the yield criterion for deck slab, also show values closer to principal stresses; these nodes are not seen in the vicinity of crane rails. Shear stress yield criterion, shown by Tresca stresses, is not a governing criterion for the current problem under investigation due to the fact that the deck slab is governed predominantly by bending and not by shear. RCC walls, tie beams, and the deck beam do not show undesirable stress values under the considered loads and load combinations.
3.30 REPAIR OF OCEAN STRUCTURES USING CHEMICAL ADMIXTURES

In this section, we will discuss a few recent advancements in the repair methodologies of ocean structures.

3.30.1 ELECTROCHEMICAL PROTECTION SYSTEM

This is a recent development for cathodic protection of reinforced concrete structures and steel structures. The RECON control system, developed by SAVCOR Group Ltd, Australia, is one of the advanced corrosion control and monitoring system. It consists of a full-monitoring and corrosion control using EPSs. Constant current and potentiostatic mode of control allow an automatic adjustment of the circuit current based on selected values of multiple reference electrodes. EPS can also be employed for corrosion protection of new RCC structures. Chloride-induced corrosion is one of the major causes of concrete deterioration in RCC structures in the marine environment. EPS is one of the recent methods that has been found to be effective in addressing such problems. It has a proactive approach to address such durability problems. EPS components of a fresh construction include activated titanium anodes, monitoring probes and sensors, and high durability anode and steel connections.
It is important to understand the cause of corrosion before addressing strength degradation of materials and members due to corrosion. Rebars in RCC are initially protected from corrosion by a passive layer, which is formed due to high alkaline nature of concrete. Corrosion occurs when this passive layer is destroyed or perforated. Many studies are carried out to assess the condition of concrete in the marine environment using visual and delamination surveys, electric continuity testing of rebars, half-cell potential and resistance mapping of RCC, corrosion rate measurement of steel, resistivity testing, measure of cover to rebar, alkali–aggregate reaction tests, and predictive deterioration modeling. It is seen that restoration of alkalinity in concrete is the most effective method of rehabilitation of concrete in the marine environment. New concrete has natural inherent alkalinity, which offers passive protection to rebar. Ingress of carbon dioxide creates a carbonated concrete of lower alkalinity, resulting in the loss of passive layer; this also accelerates the corrosion of rebar. Realkalization is one of the nondestructive methods of concrete rehabilitation. This involves an electrochemical technique of passing a sustained low-voltage current between the temporary anodes on the surface of concrete over a short period of time (3–15 days). Paste of cellulosic fibers, saturated in sodium carbonate solution, is used as an electrolyte covering the concrete surface. As surface anodes are embedded in this alkali-rich paste, alkali is drawn into the concrete and reaches rebars, which in turn realkalize the concrete. A natural protective (passive layer) film is then formed, which offers protection against corrosion of rebar.

### 3.30.2 Methodology of Realkalization

Prior to realkalization, the following tests are carried out to ascertain the nature of treatment: (1) visual inspection, (2) depth of carbonation, (3) chloride analysis, (4) cover to rebars, (5) delamination survey, and (6) alkali–aggregate reaction tests. Rebar connection is installed in the concrete by connecting cables (black in color) to the rebar. These cables are extended to a transformer rectifier circuit. Continuity of the rebar is to be checked and established, which is vital. Anode connections are then made using red cables, which are subsequently extended to the transformer rectifier unit. A reservoir is used to house the anode mesh and alkaline electrolyte. The common practice is to use a cellulosic fiber that can be sprayed onto the concrete surface. Wooden battens are fixed to the concrete surface, which act as spacers between the concrete and the anode mesh. The anode mesh is fixed to the battens and the cellulosic fiber is sprayed onto the mesh. A regular wetting of the fiber with an alkaline electrolyte is to be ensured during the repair period. Cables from the rebars (cathode) and mesh (anode) are connected to negative and positive poles of the transformer rectifier unit to supply the design current density. During the test period, if required, the concrete surface can be realkalized after switching off the power. The whole arrangement is monitored during the test period by means of current and voltage readings; pH levels of concrete are also periodically tested. Cables are disconnected after the test period and the concrete is cleaned with water.