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OFFSHORE ENGINEERING MATERIALS

1.1 INTRODUCTION

The commonly used materials in offshore applications can be classified as metallic (steel) or non-metallic (composite). Their usage and choice vary depending on the functions, loading conditions, as well as environments to which the materials are exposed.

1.2 METALLIC MATERIALS IN OFFSHORE APPLICATIONS

Structural steel comprises about 98% of iron, with the main alloying elements comprising carbon, silicon, and manganese. Moreover, copper and chromium are added to produce weather-resistant (i.e., stainless) steels that do not require any corrosion protection.

1.2.1 Types of Steels

There are different types of carbon steels which may be used in offshore applications. These are alloy, tool and stainless.

Carbon Steel

Carbon steel, also known as plain carbon steel, is a type of steel in which the main alloying constituent is carbon. Carbon improves strength/hardness on one side but reduces ductility and toughness on the other. It is to be noted that low-carbon steels are not used as structural materials. Carbon has the maximum influence on the mechanical properties of steel. Steel with low carbon content has properties like iron. With the increase in carbon content, the metal becomes harder and stronger but less ductile and more difficult to be welded. Higher carbon content generally lowers the melting point and its temperature resistance. Depending on the carbon content, there are generally three classes of steel,

1. Mild Carbon Steel (up to 0.25%)
2. Medium Carbon Steel (0.25% to 0.45%)
3. High Carbon Steel (0.45% to 1.50%)

It is noteworthy that mild steel is the most used because of its relatively low price and the added advantage of its material properties being acceptable for many applications.

Alloy Steel

Steel is alloyed with various elements to improve its mechanical properties, with their amounts varying between 1 and 50% by weight. Alloy steels are further broken down into two groups,

1. Low alloy steel (less than 8% alloying element)
2. High alloy steel (more than 8% alloying element)

Commonly used alloy steels are low alloy steel. Alloy steels have greater strength, hardness, wear resistance, and hardenability (or toughness) compared to carbon steel. However, they may require heat treatment to achieve such properties. Common alloying elements are molybdenum, manganese, nickel, chromium, vanadium, silicon, and boron.

Tool Steel

This type of steel refers to a variety of carbon and alloy steels that are particularly well-suited to be made into tools. This suitability comes from their distinctive hardness, resistance to abrasion, ability to acquire a cutting edge, and/or resistance to deformation at high temperatures. Tool steel is generally used in a heat-treated state. It is the process of heating metal without letting it reach its molten or melting stage and then cooling the metal in a controlled way to select desired mechanical properties.

Stainless Steel

The offshore oil and gas industry greatly benefits from stainless steel, including duplexes and super duplexes. This steel offers improved strength and corrosion resistance with lower weight and lifecycle costs. The most common type of stainless steel used in offshore applications is an austenitic stainless-steel grade 316L. It bears enhanced structural strength at high temperatures and protects structures in extremely acidic conditions.

Stainless steel differs from carbon steel by its amount of chromium. Carbon steel gets rusted when exposed to air and moisture. On the other hand, stainless steels contain sufficient amounts of chromium to form a passive film of chromium oxide, which prevents surface corrosion from spreading into the metal's internal structure. Examples of some typical components of offshore structures that are made up of stainless steel,

1. Submerged components include risers, grills, pipelines, coastal power plants and heat exchangers.
2. Platform structure components include pumps, winches, storage vessels, process vessels, blast gates, umbilical tubes, rebars, cable trays, stairs, tread plates, walkways, oil and gas coolers, gravity separators, etc.

3. Deck components for boats and ships.
4. Coastal handrail, ladder, and lamp post

1.2.2 Standard Structural Steel Sections

Structural steel sections are produced in various forms to suit the structural design and their application. The production process listed below would differentiate the type of steel products,

1. Hot rolled sections. These are formed by repeatedly squeezing the heat-softened steel through a set of rollers that shape them into the desired cross-sectional shape.
2. Cold rolled/formed sections. These are formed by bending thin materials such as sheet steel or plate into the desired shape without heating.
3. Wire sections. These are formed by pulling (also called 'drawing') the steel through a small opening.
4. Extrusion. This procedure is like drawing, although the sections produced using this procedure are other than simple round shapes.
5. Casting. It is formed by pouring molten steel into a mould.
6. Forging. Softened steel is pounded into a mould until it takes the shape of the mould.

Hot Rolled Sections

Hot rolled sections are formed by repeatedly squeezing the heat-softened steel through a set of rollers that shape it into the desired cross-sectional shape. Structural members include universal beam (UB), universal column (UC) sections, channel, Tee, angle, tube, bars, flats, plates, sheets, and strips. A description of these examples is given in Table 1.1.

Table 1.1 Various types of hot rolled sections [1]

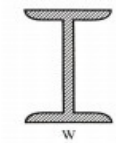
Section	Description
 Wide-flange	This section is normally designated by a capital W. These sections have greater flange widths and relatively thinner webs than the standard I-beams. The inner faces of the flanges are parallel to their outer faces. These sections are designated by the alphabetical symbol W followed by the nominal depth in inches and the weight in pounds per linear foot. Thus, the designation 'W 12 × 26' indicates a wide-flange shape of nominal-12 in. depth, weighing 26 lb per linear foot. The actual depths of W sections vary within the nominal depth groupings. Note that a W 12 X 26 has an actual depth of 12.22 in., whereas the depth of a W 12 × 30 is 12.34 in. This is due to the rolling process during manufacturing, in which the cross-sectional areas of W shapes are increased by spreading the rollers vertically and horizontally. These sections are usually used as a column in a structure.

Table 1.1 (cont.)

 Standard I-beam	American standard I-beams are identified by the alphabetical symbol S, the designation S 12×35 indicating a standard I-beam section 12 in. deep, weighing 35 lb per linear foot. Unlike the previous one, these have uniform depths in a given depth group, and shapes of greater cross-sectional area are made by only spreading the rolls in one direction. Thus, the depth remains constant, whereas the width of a flange and the thickness of the web are increased. These sections are used in any situation, such for constant depth, narrow flanges and thicker webs.
 Standard Channel	The shape is identified by the alphabetical symbol C. The designation C 10×20 in. indicates a standard channel 10 in. deep and weighing 20 lb per linear foot. This section has an area of 5.88 in.2, a flange width of 2.739 in., and a web thickness of 0.379 in. Like standard I-beams, the depth of a particular group remains constant, and the cross-sectional area is increased by spreading the rolls for increasing flange width and web thickness. These are generally used as elements of built-up sections such as columns and lintels and are particularly suitable for framing around floor openings.
 Angle	Angles are designated by the alphabetical symbol L, followed by the dimensions of the legs and their thickness. Thus, the designation L 4×4×½ indicates an equal leg angle with 4 in. legs, having ½ in. thickness. Single-angle sections are often used as lintels, whereas pairs of angles are often used as members of light steel trusses.
 Structural Tee	A Structural Tee section is made by splitting the web of a W shape or a standard I-beam (S shape). The cut, normally made along the centre of the web, produces Tees with a stem depth equal to half the depth of the original section. Structural Tees obtained from the W section are identified by the symbol WT, while those obtained from the standard S section are identified as ST. The designation WT 6×53 indicates a Structural Tee section with 6 in. depth and weighing 53 lb per linear foot. This section is produced from a W 12×106. Similarly, ST 9×35 is 9 in. deep and weighs 35 lb per linear foot; that is cut from S 18×70.

Table 1.1 (cont.)

 Pipe	A pipe section is designated as 'standard,' 'extra strong,' and 'double extra strong' in accordance with its thickness and is also nominally prescribed by its diameter; thus, a '10 in. diameter double-extra strong' is an example of a particular pipe designation.
 Hollow Structural Steel	Hollow Structural Steel (HSS) section is used where a pleasing architectural appearance is desired with exposed steel. The outside dimensions and thickness, such as HSS 8×6×¼, designate its tubing. The first number refers to the height, the second the width and the third is the thickness.
 Plate  Bars	Plates and bars are made in many different sizes and are used in many different structural steel applications. Flat steels for structural use are generally classified as follows, a. Bars: 6 in. or less in width and 0.203 in. or more in thickness. b. Plates: i. More than 8 in. in width and 0.203 in. or more in thickness. ii. More than 8 in. in width and 0.180 in. or more in thickness. c. Sheet: Generally, any flat material less than 0.180 in. in thickness. Bars are available in varying widths and any required thickness and length. The usual practice is to specify bars in increments of ¼ in width and 1/8 in. in thickness.

Cold Rolled/Formed Sections

Cold-formed steel structural members are the sections that are commonly manufactured from steel plate, sheet, or strip material. Such sections include corrugated steel roofs, floor decks, steel wall panels, storage racks and steel wall studs. Various manufacturers produce many proprietary shapes, with examples as shown in Figure 1.1.

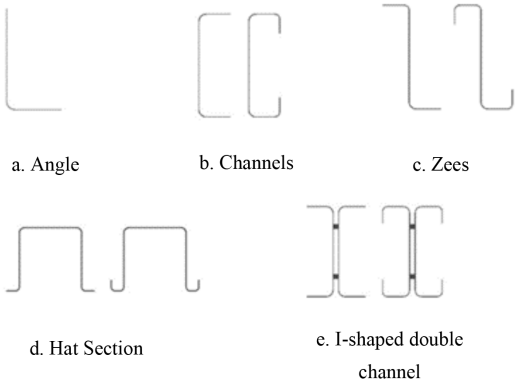


Figure 1.1 Examples of cold rolled/formed sections

Built-up Sections

The above-mentioned standard steel sections for most structural constructions will satisfy the design requirement. If non-standard/unique steel shapes are required in the design, then built-up sections may be needed, as shown in Figure 1.2. Sometimes a standard shape is augmented by using additional cross-sectional elements, such as a cover plate welded to one or both flanges of a W-shape section. Building up a section is an effective way of strengthening/retrofitting an existing structure that is being rehabilitated or modified for intended use other than the one for which it was designed. Built-up sections can also be created by attaching two or more standard rolled shapes to each other.

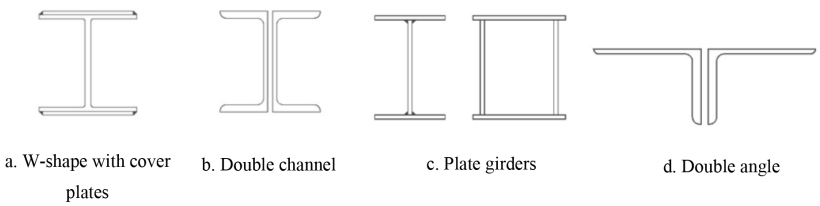


Figure 1.2 Examples of built-up sections

1.2.3 Properties of Steels

The physical and mechanical properties of steel include the following,

1. Strength
2. Toughness
3. Ductility
4. Weldability
5. Durability
6. Low weight

The mechanical properties of steel largely depend on its chemical composition; thus, they are used to describe the material's strengths under certain loading conditions. The common stress-strain curve, as shown in Figure 1.3, is normally referred to when describing the strength of steel. The yield strength is defined as the stress at which a material begins to deform plastically. In other words, it is the stress level at which material strain changes from elastic deformation to plastic deformation, causing the material to get deformed permanently. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible. The typical mechanical properties of steel are summarised in Table 1.2.

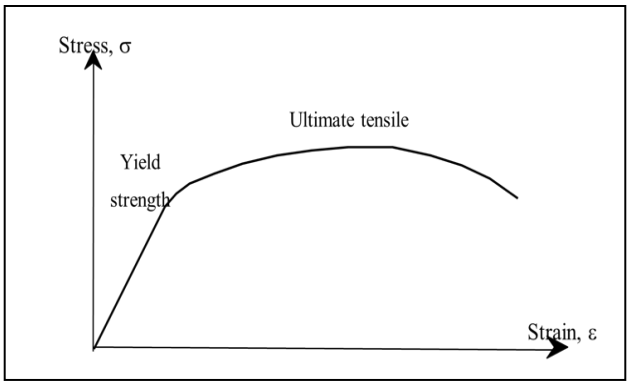


Figure 1.3 Typical stress-strain curve of a material

As mentioned earlier, steel comprises about 98% iron and main alloying elements, including carbon, silicon, and manganese. Details on the chemical composition of steel and its effect on its properties are further described in Table 1.3.

Table 1.2 Typical mechanical properties of steel [2]

Property	Value
Yield stress, fy	220 – 540 N/mm2
Ultimate tensile strength	1.2 x fy
Elongation (low carbon steel)	20%
Modulus of elasticity, E	2 × 105 N/mm2
Shear modulus, G	0.4 x E
Poisson's ratio,	
elastic range	0.3
plastic range	0.5

Table 1.3 Effect of alloying elements on steel properties [3]

Alloying Element	Effect on Mechanical and Corrosion Properties of Steel
Carbon, C	It increases tensile strength and hardness but reduces toughness. It also reduces weldability and increases corrosion.
Manganese, Mn	It increases the tensile strength, hardness, and abrasion resistance but decreases porosity and cracking. It also forms sulphides that may cause hydrogen-induced cracking.
Phosphorus, P	It increases brittleness and cracking. It is increasingly being restricted to <0.025% for sweet and <0.015% for sour service pipe.
Sulphur, S	It increases porosity, brittleness, and cracking. It forms manganese sulphide that traps hydrogen, which leads to internal cracking. Also, surface emergent sulphides initiate pitting.
Silicon, Si	It increases tensile strength but markedly reduces toughness. It is also added as a deoxidiser to kill the steel (remove gases). Usage is restricted to 0.35-0.40%
Aluminium, Al	It is used to refine the grain size. It also increased hardness and was added as a deoxidiser to kill the steel. It aids the weld toughness when added in content ranging from 0.02 to 0.05%.
Copper, Cu	It improves sour cracking resistance for environments at pH >4.5. it affects the corrosivity of weld HAZ. It is claimed to stabilize corrosion films and reduce corrosion in conjunction with Ni.
Chromium, Cr	It increases tensile strength and hardness and decreases weldability. It has a major effect on corrosion resistance. The material becomes stainless steel if its content is ≥12%
Calcium, Ca	It is a deoxidiser and desulphurise. Its secondary addition is used for inclusion shape control for sour service pipe steel.
Molybdenum, Mo	It increases tensile strength and corrosion resistance and reduces pitting attack.
Titanium, Ti	It is a micro-alloying element which increases tensile strength, hardenability and wears resistance. It is Combined with carbon to form carbides that may reduce toughness.
Niobium, Nb	It is used as a micro-alloying element in carbon steel.
Vanadium, Vn	It increases tensile strength, hardenability, and wear resistance.
Nitrogen, N	It increases the strength but reduces low-temperature toughness. Its use is restricted to 0.01%
Nickel, Ni	It increases tensile strength and toughness at low temperatures and improves corrosion resistance. It also reduces the susceptibility of weld corrosion and improves weld strength.

1.2.4 Advantages and Disadvantages of Steels

The advantages of steel are summarised below,

1. Its high strength and less weight make its use good for long-span structures.
2. It is lightweight compared to concrete, and can be handled, transported, and prefabricated.
3. It has uniformity in properties which do not change with time.
4. It is a ductile material which does not fail suddenly but gives visible evidence of failure in the form of large deflections.
5. Additions and alterations can be made easily in it.
6. It can be erected at a faster pace.
7. It has the highest scrap value and is reusable.

Contrary to the benefits mentioned above, its disadvantages are highlighted as follows,

1. It can easily get corroded in harsh environments, thus increasing the maintenance and repair costs.
2. It requires fireproofing treatment, which also increases the cost.
3. It easily gets fatigued under repetitive/cyclic loads.

1.3 COMPOSITE MATERIALS IN OFFSHORE APPLICATIONS

These materials, commonly called Composites, have been widely used in various industries as an alternative to traditional materials due to their ability to withstand high pressure and aggressive environmental situations. A composite material is produced from two or more separate constituent materials with dissimilar chemical or physical properties. Unlike the individual elements, these constituent materials are merged to create a composite material with properties.

1.3.1 Types of Composite Materials

Composites are usually made of two constituent materials, reinforcement and matrix, as shown in Figure 1.4. The reinforcement is intended to provide strength and stiffness. It is usually harder, stronger, and stiffer than the matrix, which is either made from fibres or particles. The matrix protects and transfers the load between the fibres in conjunction with reinforcement. The final product in the form of a fibre composite matrix creates a material with superior performance properties than the individual materials.

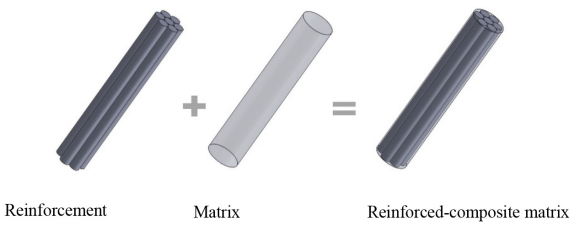


Figure 1.4 Basic principle of producing composite materials

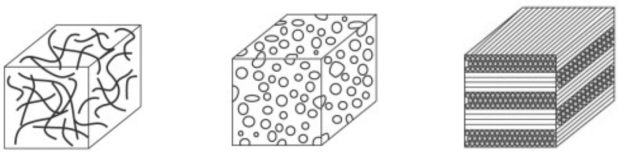
Reinforcement can be in the form of fibres or particles. A fibre can be a material with a length much greater than its diameter. The length-to-diameter ratio (l/d) is known as the aspect ratio. The smaller the diameter of the fibre, the higher its strength will be, but the cost often increases as the diameter becomes smaller. Moreover, continuous-fibre composites are often made into laminates by stacking individual sheets of continuous fibres in different orientations. Typical fibres include glass, aramid, and carbon (high strength, HS; high modulus, HM), which may be continuous or discontinuous. A comparison of their material properties is given in Table 1.4. On the other hand, the particles can be spherical, in platelet form, or in any other regular or irregular geometry. These are much weaker and less stiff than continuous fibre composites, but they are usually much lesser expensive.

Table 1.4 Comparison of fibre strengths [4]

Material	**E-glass**	**S-glass**	**Aramid**	**Carbon-HS**	**Carbon-HM**
Density (g/cm3)	2.54	2.59	1.45	1.81	1.85
Tensile Strength (MPa)	2400	3500	3000	5000	2700
Tensile Modulus (GPa)	73	86	130	240	390
Elongation at break (%)	4	4	2.1	1.8	0.7
Thermal expansion (10-6/mK)	5	5	-2	-0.1	-0.5

Matrix, the second composite material component, is continuous and can be polymeric, metallic, or ceramic. Polymers have low strength and stiffness, while metals have intermediate strength and stiffness with high ductility. Ceramics have high strength and stiffness but are brittle. The polymer and metal matrix composites normally form a strong bond between the fibre and the matrix, which allows the matrix to transmit loads to the fibres through shear loading at the interface. However, in ceramic matrix composites, the objective is often to increase the toughness rather than the strength and stiffness. Therefore, a low interfacial strength bond is desirable. Besides transferring loads between the fibres, the matrix also protects the fibres from environmental and external damage.

Based on the above-described designs of reinforcement and matrix, there are three common types of composite materials, as shown in Figure 1.5, namely, fibre-reinforced composites, particle-reinforced composites and laminated-reinforced composites. The fibre-reinforced composites may be made of continuous (aligned) or discontinuous (short) fibre particles suspended in a matrix. The particle-reinforced composites may compose of large particles or dispersion-strengthened particles in a matrix. Finally, the laminated-reinforced composites consist of multiple layers of oriented or randomly oriented fibres bound together by a matrix.



a. Fibre-reinforced composites | b. Particle-reinforced composites | c. Laminated-reinforced composites

Figure 1.5 Types of reinforced-composite materials [5]

Laminated-reinforced composites originated from the concept of laminates. Lamina is defined as a single ply or a lay-up in which all the layers or plies are stacked in the same orientation. On the other hand, laminate is the one in which the plies are stacked at various angles. Unidirectional (0°) laminates are extremely strong and stiff in the 0° direction. However, they are very weak in the 90° direction because the much weaker polymeric matrix must carry the load. Laminate in which the plies are in the 0°, +45°, -45° and 90° directions are called quasi-isotropic laminate because it carries equal loads in all four directions.

1.3.2 Classification of Materials

It is noteworthy that materials can be classified as either isotropic or anisotropic. The isotropic materials have the same material properties in all directions, and normal loads create only normal strains, while the anisotropic materials have different material properties in all directions at a point in the body. Moreover, orthotropic materials are defined as if their mechanical or thermal properties are unique and independent in three mutually perpendicular directions. Bulk materials, such as metals and polymers, are normally treated as isotropic materials, while composites are treated as anisotropic. However, even bulk materials such as metals can become anisotropic.

1.3.3 Properties of Composites

The physical characteristics of composites are significantly different from those of metals. Composites tend to have high strength, high modulus, low density, excellent fatigue resistance, creep, creep rupture, corrosion and wear, and low coefficient of thermal expansion (CTE). The structural properties of composite materials are derived from their fibre reinforcement, which contributes to tensile strength. The fibre reinforcement further enhances its strength and stiffness, including in-plane stiffness and bending stiffness, thus helping it resist any kind of crack or fracture damage.

The mechanical characteristics of fibre-reinforced composite not only depending on the properties of the fibre but also on the degree to which an applied load is transmitted to the fibres by the matrix phase. As mentioned earlier, the transmitted load is the magnitude of the interfacial bond between the fibre and the matrix phase. The fundamental property relationships between fibres and matrix may be described with Equations 1.1 and 1.2 concerning the angle of the load being transferred to the fibre direction.

0° in direction: $E = EfVf + EmVm$ (1.1)

90° in direction: $1/E = Vf/Ef + Vm/Em$ (1.2)

where Ef is the fibre modulus, Vf is the fibre volume percentage, Em is the matrix modulus, and Vm is the matrix volume percentage.

1.3.4 Composite Materials and their Manufacturing Methods

Two common composite materials are available, namely thermoplastic and thermosetting (or thermoset). A thermoplastic is usually a plastic polymer, which can easily become soft when heated and hard when cooled. Thermoplastic materials can be cooled and heated several times without any change in their chemical or mechanical properties. When thermoplastics are heated to their melting point, they melt to become a liquid. On the other hand, thermosetting is a polymer that is irreversibly hardened by curing from a soft solid or viscous liquid prepolymer or resin. Curing is induced by heating or exposure to suitable radiation and may be expedited by high pressure or mixing with a catalyst. The main difference between the two composites is that thermosetting is a material that gets strengthened when heated but cannot be remoulded or heated after the initial forming, while thermoplastics can be reheated, remoulded, and cooled down as deemed necessary without causing any chemical changes. Both thermosetting and thermoplastic can be fabricated using various reinforcement types, namely long, short, woven, mat, chopped and particulate, part of which have been briefly introduced earlier. The fibre placement may be done using hand or auto layup, filament winding, stylus weaving, pultrusion or random. The process required to complete the mixing is normally referred to as the autoclave, press cure, oven cure, compression moulding or injection moulding. A summary of their description is shown in Figure 1.6. However, this chapter will not cover the details of these processes.

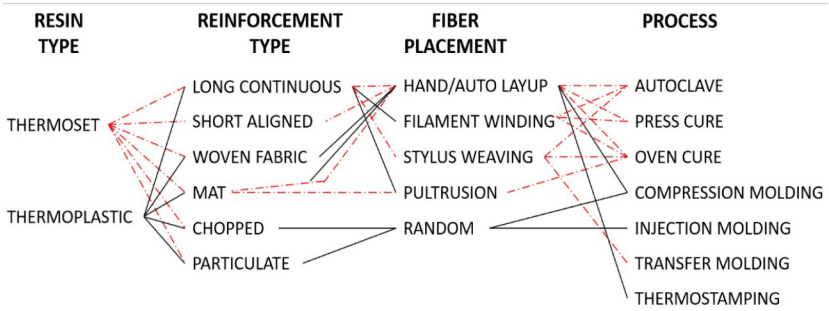


Figure 1.6 Summary of composites mixing procedures and manufacturing methods

1.3.5 Advantages and Disadvantages of Composites

The main advantages of composite materials are their high strength and stiffness, combined with low density and lighter weight when compared to bulk materials. Moreover, the application of composites improves fatigue life and, most importantly, offers corrosion resistance to a greater extent.

The major disadvantage of composites is their high cost due to the high costs of raw material, fabrication, and assembly. Besides the cost, composites experience poor strength in the out-of-plane direction where the matrix carries the primary load, thus making it highly susceptible to impact damage. Moreover, composites are somehow slow to be recognised due to a lack of standards and testing procedures.

1.3.6 Application of Composites

In general, high-performance but more costly continuous-carbon-fibre composites are used where high strength, stiffness, and lighter weight are required. Lower-cost fibreglass composites are used in less demanding applications where the weight is not considered critical. Applications of composites are included in the aerospace industry, marine and sporting goods manufacturing, and, more recently, the infrastructure industry, with the construction and transportation sectors being the largest ones. Some examples of the use of composites in offshore applications include the following,

1. Composite grids/gratings
2. Handrails and ladder components
3. The piping system and storage tanks/vessels
4. Low-pressure composite valves
5. Cable support systems
6. Flexible and floating risers, drill pipe
7. Subsea structural components

1.4 FAILURE OF MATERIALS AND STRUCTURES

Failure of a material or structure may originate from various sources and problems, depending on their application. However, it is convenient to group the failure of a material or structure into five main types,

1. The first type of failure is that the structure is not strong and tough enough to support the applied loads, which may result in failure when the structure is stressed beyond its critical stress level. A particular structure not being strong and tough may be due to the wrong size, shape, or material selection. The level of toughness of a particular material is defined by its resistance offered to resist failure. Failure related to the materials' toughness is normally referred to as its fracture and is measured using the tensile test. During this test, some materials may fail after absorbing huge stresses. In this case, the failure mechanism

is regarded as a ductile fracture. However, when low stress is applied to a material that leads to fracture, this is described as a brittle fracture.

2. The second type of failure is due to fatigue and/or corrosion, normally caused by instability in the structure's geometry, design, or material properties. These failures may originate from the formation of microcracks at certain stress points. These cracks keep growing under continuous loads and eventually reach a critical limit which causes the structure to fail even under normal loading conditions.

Corrosion is defined as metal loss and is one of the most common reasons for structural damage, especially for structures exposed to harsh environments – corrosion results from electrochemical reactions between steel material and its surroundings. Any reduction in metal loss also reduces the capacity of the structural member. For structures such as pipelines, corrosion may occur at the pipe's internal and external surfaces. Internal corrosion occurs due to a chemical reaction between the transported hydrocarbon material and the steel pipe's interior surface. External corrosion, on the other hand, occurs due to environmental or metocean conditions.

Cyclic stresses below the ultimate tensile stress normally cause fatigue failure. Repetitive loads applied on the structure, even at normal operating loads, would negatively impact its performance. At times, fatigue damage would cause the formation of cracks at the material surface, which occur within the structure at points where the concentration of stresses is high. The stress concentration factor is normally used to describe a particular crack's severity level. In the case of a round notch crack, it may be three times severe as the total applied stress. When these cracks propagate, the entire portion or system becomes vulnerable to failure. Particularly in the case of laminated composite structures, the fibre may fracture when the matrix cracks, resulting in delamination. Details on delamination, however, will not be covered in this chapter.

3. The third type of failure is normally due to manufacturing errors, including the improper selection of materials, incorrect sizing, and poor workmanship.
4. The fourth type of failure is due to the use of defective materials that may originate from the imperfect condition of the materials during fabrication or installation. A defect or flaw is usually an imperfection in the form or structure. This failure is unpredictable since the material may have been improperly manufactured or damaged.
5. The fifth type of failure is due to unexpected problems that arise on-site. This failure can also be called third-party damage or accidental load that may happen in the form of vandalism, sabotage, or natural disasters (i.e., impact, earthquake, fire, or blast loading).

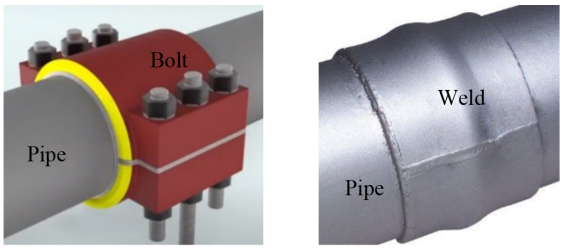
1.5 REPAIR OF DAMAGED OFFSHORE STRUCTURES

Three common terminologies that describe the rehabilitation of engineering structures are repaired, strengthening and retrofit.

1. Repair: This represents an improvement in the structural deficiency in the structure, such as crack or corrosion, to restore a damaged structure member to its original capacity.
2. Strengthening: This represents an enhancement in the capacity of an undamaged structure or component to accommodate the anticipated increase in loading.
3. Retrofit: This represents an upgradation in structure performances which experienced damage due to calamities, such as an earthquake or flooding.

Bolting and welding are common rehabilitation techniques used to restore the stiffness and strength of damaged steel structures. The bolts and welds are normally attached to the main structural members, as shown in Figure 1.7a. These techniques increase the effective cross-sectional area of the repaired structure, thus adding weight to it. Moreover, the heat generated from welding may provide additional stress distributions to certain areas of the structural member. The bolting technique may introduce additional defects to the steel member being repaired. Also, the choice of metal steel for rehabilitation may produce areas that will be prone to corrosion in future. Besides, special tools or equipment may also be needed for rehabilitation work.

The provision of welded sleeve with a full encirclement split sleeve, as shown in Figure 1.7b, is a common method used for circular or tubular steel structures. A sleeve may be made with either no-end closure welds or two-end closure welds, depending upon the nature of the damage and the pipe's application on site. Another type of sleeve is the split and seal steel sleeve clamp. It is a fast and effective way to repair tubular structures, such as pipelines, without cutting out and replacing the damaged section.



a. Bolting and welding b. Welded sleeve

Figure 1.7 Two different methods of repair [6]

Several drawbacks were encountered in using steel as rehabilitation materials because non-metallic materials such as composites were used instead. Using non-metallic materials minimizes future potential corrosion and eases the rehabilitation activities carried out at offshore structures. Lesser or minimum support from platform services will be required, which will reduce the impact on the platform operations as well. Moreover, using composite materials should make them capable of withstanding high working temperatures and bonding well to any imperfect substrates or surfaces.

Composite wrapping in Figure 1.8 is a repair technique for corroded or dented pipes and pipelines that does not require welding. This technique is widely used because its strength is comparable to steel materials. A resin-impregnated fibreglass, being light and easy to handle, is wrapped by hand several times around the damaged structure, as shown in Figure 1.8b. If applied on a corroded structure, this technique would help to avoid outward bulging of the surface. Moreover, the wrapping procedure around the damaged part of the structure does not require specific tools or machines, thus giving another advantage for its application in hard areas with limited access. The rehabilitation work done using this method may get completed faster as well, which allows for saving time or avoiding delays during operations.



Figure 1.8 Pipeline composite wrapping [7]

1.6 INSPECTION TECHNIQUES

Non-Destructive Testing (NDT) is a wide group of analysis techniques used in the offshore construction industry to evaluate the service life of a material, component, or system without causing damage to the specimen. NDT is commonly used in all oil and gas industries as a method to detect defects. Some of the organizations that have developed NDT standards and codes of practice are given below,

1. API (American Petroleum Institute)
2. ASME (American Society for Mechanical Engineers)
3. ASTM (American Society for Testing and Materials)
4. ASNT (American Society for Non-destructive Testing)
5. COFREND (French Committee for Non-destructive Testing Studies)
6. CSA Group (Canadian Standards Association)
7. CGSB (Canadian General Standards Board)

Various NDT techniques are utilised to monitor the structural performance of offshore structures, which are normally categorized under five groups: visual inspection, ultrasonic, radiography, thermography, and acoustic emissions. Details of these techniques are compiled and summarised in Table 1.5.

Table 1.5 Description of various NDT inspection methods

Name	Description
Visual inspection	An inexpensive method for detecting flaws and defects through naked-eye inspection. A trained technician will likely detect improper/faulty structural installations, certain types of impending structural failure, welding flaws, corrosion development, and cracks.
Ultrasonic	A technique which applies sound waves to inspect the internal structure or component. The ultrasonic waves can be transmitted to and received from within the tested structure. The technique detects damages (thickness changes, welds, cracks, voids etc.), delamination, and other material or structural defects. A data acquisition (DAQ) system is required, and a trained technician will evaluate its results. Hence, precision in data acquisition is a key factor to be kept in mind if using this technique.
Radiography	A method utilizes X-ray or gamma rays (i.e., electromagnetic radiation) to examine the internal structure and integrity of the structural component at shorter wavelengths.
Thermography	A method which measures the difference between the temperature of a structure (e.g., a pipeline) and the surrounding environment. This measurement helps to detect defects in pipeline insulation and/or oil or gas leakage from the structure.
Acoustic emissions	A method which detects the presence of rarefaction waves produced by leaks in pipelines. Negative pressure waves propagate in both directions within the pipeline. Detection of these acoustic waves helps identify leakage in pipelines.