## Disclaimer

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# 7

# Offshore Structures

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## 7.1 Analysis of Offshore Structures

Oil and gas are the dominant sources of energy in our society. Some of these hydrocarbons are recovered from reservoirs beneath the seabed. Various kinds of platforms are used to support exploratory drilling equipment and the chemical (production) plants required to process the hydrocarbons. Pipelines or tankers are used to transport the hydrocarbons to shore.

Structures for offshore oil and gas exploitation have been developed for more than 50 years. Initially they were piled, wooden structures in shallow, benign waters. Today a variety of structures are employed. They are supported on the seafloor or by buoyancy or a combination—in severe environments and water depths up to 2,000 m. The largest production platforms (e.g., in the North Sea), represent a capital investment of billions of U.S. dollars and significant operational costs. The continuous innovation to deal with new serviceability requirements and demanding stochastic environments, as well the inherent potential of risk of fires and explosions, has lead to an industry that has been in the forefront of development of design and analysis methodology. Figure 7-1 shows the life cycle phases of offshore structures. The focus here is on analyses for design and reassessment of design during operation.

Current practice is implemented in new offshore codes, such as those issued by the American Petroleum Institute ([API] 1993/97), International Standards Organization ([ISO] 1994, 2001), and Norwegian Technology Standards ([NORSOK] 1998, 1999), as well as by many classification societies, and is characterized by:

- design criteria formulated in terms of serviceability and safety limit states (ISO 1994)
- semiprobabilistic methods for ultimate strength design that have been calibrated by reliability or risk analysis methodology

- fatigue design checks depending upon consequences of failure (damage-tolerance) and access for inspection
- explicit accidental collapse design criteria to achieve damage-tolerance for the system
- considerations of loads that include payload; wave, current and wind loads; ice (for arctic structures); earthquake loads (for bottom supported structures); as well as accidental loads such as fires, explosions; and ship impacts
- global and local structural analysis by finite element methods (FEMs) for ultimate strength and fatigue design checks
- nonlinear analyses to demonstrate damage tolerance in view of inspection planning and progressive failure due to accidental damage

The complexity of the analysis for design is due to complex geometry; the 3D and stochastic, dynamic and nonlinear nature of environmental loads and, hence, their effects; the need to deal with very local stresses for fatigue design checks; and nonlinear ultimate strength associated with the effect of accidental loads and global collapse of damaged structures.

Moreover, reassessment of design is required during operation, for instance, because of planned change of platform function that may increase payload or because of the occurrence of damage or need to extend service life. Structural modifications to maintain an acceptable safety level for existing structures are much more expensive than during initial design, before the structure is fabricated. This applies especially to platforms permanently located offshore. For this reason other strategies than structural modifications/strengthening is used to achieve the necessary safety for existing structures. For instance, information about material and geometrical properties of the relevant structure, which is collected during fabrication, and information about structural response that is recorded during operation would normally imply reduced uncertainties in predicted resistance and load effects, and hence additional safety margins, than those envisaged at the design stage. Moreover, deterioration phenomena can be controlled by more frequent inspections and possibly repairs of smaller damages than otherwise would have been done.

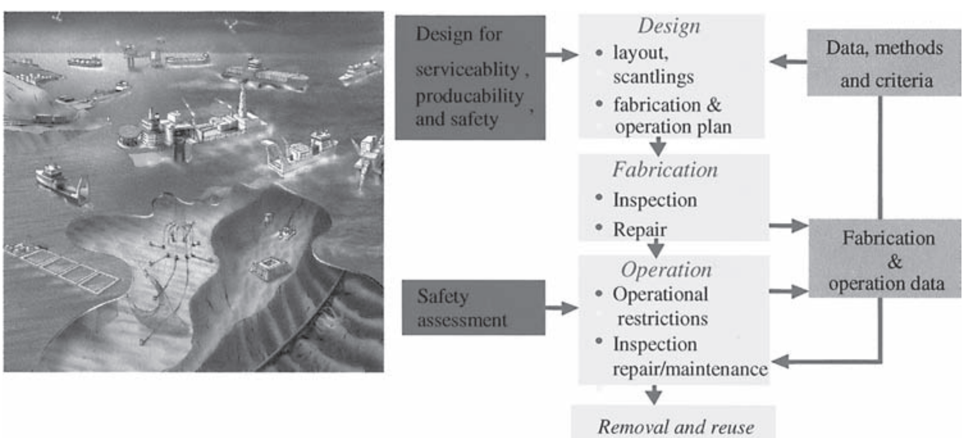


**Figure 7-1.** Life cycle phases of offshore structures.

In particular, analyses for demonstrating compliance with safety requirements tend to be more refined during reassessment than initial design. In this way the conservativism in simplified methods is avoided. The refinement of analysis methodology applies to all aspects of the analysis, but especially by introducing case-based risk and reliability methodology.

Section 7.2 addresses characteristic features of different types of offshore structures. Relevant design criteria are briefly described in Section 7.3. Section 7.4 deals with methods to calculate sea loads and their effects. Sections 7.5 and 7.6 describe structural analyses of space frames with fixed steel-plated and floating structures, respectively. Section 7.7 describes analysis of effects of accidental loads such as fires and explosions as well as ship impacts, while Section 7.8 deals with analysis issues relating to reassessment of design during operation.

## 7.2 Characteristic Features

### *7.2.1 General*

The size and other principal features of offshore structures are primarily determined by their intended function and their environment. Different types of structures are required in the exploitation of subsea oil and gas resources.

Platforms may be used for exploratory drilling to identify producible hydrocarbons. The main mission in this case is to drill a well from the seabed to the possible hydrocarbon reservoir. Drilling operations take place by a drill string that is contained in a tube (riser) from the seafloor to the platform deck. To avoid excessive stresses in the drill string and riser, the platform needs to have limited motion. When an exploratory well has been drilled in 1 to 3 months, the platform is moved to the next location, several km away. Exploratory drilling platforms, therefore, need to be easy to relocate—to be mobile.

The most attractive mobile drilling platforms are drill ships, jack-ups and semisubmersibles, as illustrated in Figure 7-2. Drill ships are applicable in benign waters; jack-ups are limited to small water depths, while semisubmersibles are preferable in deep, harsh waters.

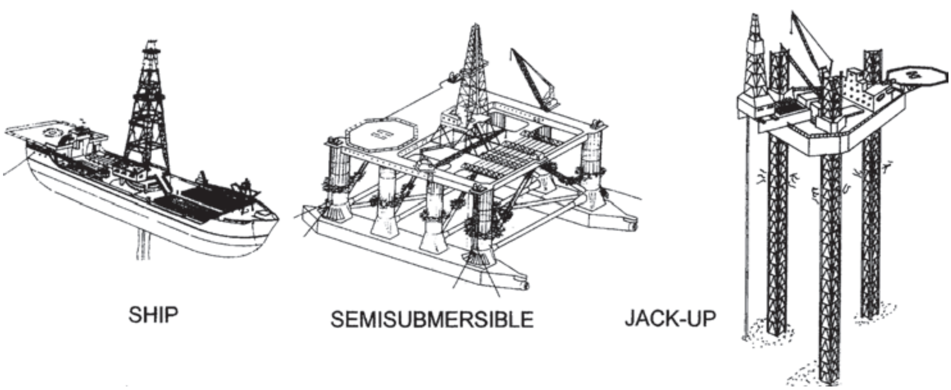


**Figure 7-2.** Drilling platforms.

Production platforms serve as a base for drilling and completion of the production wells, the hydrocarbon production itself, and for transporting hydrocarbons to shore. Hence, they need load carrying capacity and space to accommodate separators, pumps, piping, as well as to support risers and other parts of the chemical process plant used to produce hydrocarbons say for 20 years or more. Figure 7-3 shows a production facility on a floating platform. Storage capacity may be an additional requirement, depending upon the transport infrastructure used. In harsh environments limited motion is desirable to reduce the stress level in steel risers and maintain efficiency of the separation process. If flexible risers are applied, however, the motion constraint would be relaxed.

In small water depths the functional requirements are fulfilled at the lowest costs by using structures supported on the seafloor (Fig. 7-4a). However, in increasing water depths installation of fixed platforms may not be feasible or very expensive. Moreover, the sea loads on a platform tower structure primarily act at the water surface level, implying that load effects will increase very fast with water depth and make fixed platforms less economically feasible with depth. In greater water depths buoyant structures shown in Figure 7-4b are more attractive.

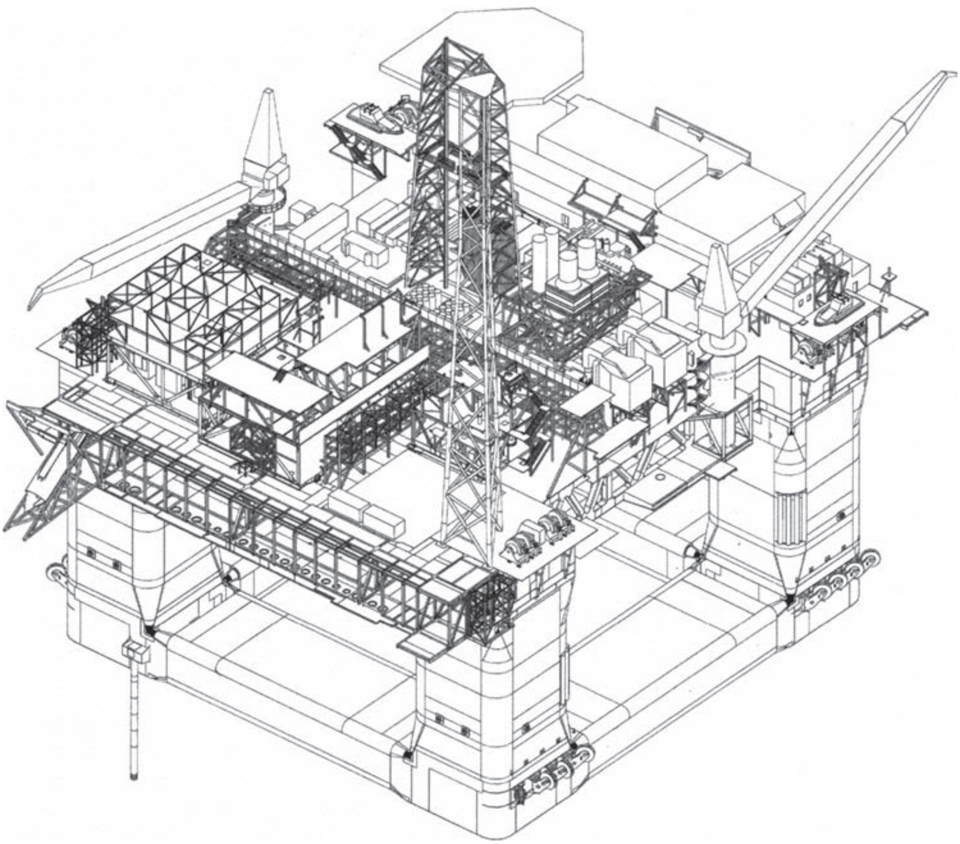

**Figure 7-3.** Production plant supported on a semisubmersible floating body with main dimensions 85 by 85 m. Figure courtesy of Aker Technology.

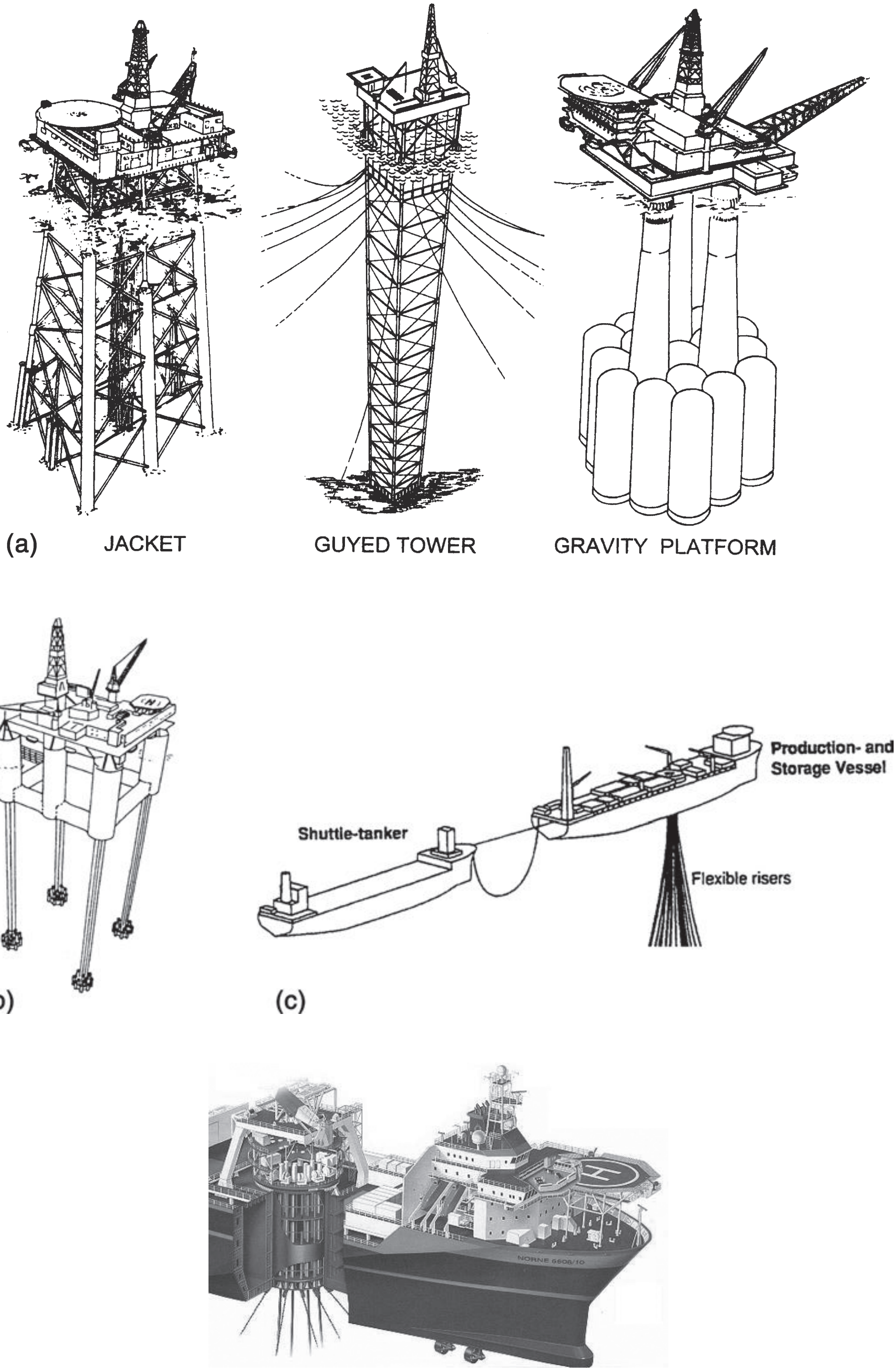


**Figure 7-4.** Production platforms. a) Platforms supported on the seafloor. b) Buoyant structures, semisubmersible platform with tension-leg mooring. c) FPSO and shuttle tanker at offshore site. d) Turret arrangement for FPSO bow with turret.

Figures 7-2 through 7-4 show a variety of structural layouts. The overall layout is to a large extent governed by functional requirements such as payload capacity (e.g., riser support, and limited motion) and water depth.

The deck structure of a production platform is a complex and compact chemical process plant, consisting of three to seven stories. The significant latent energy associated with hydrocarbons flowing through or stored in production platforms obviously represents a significant hazard.

The environmental and hydrocarbon hazards make safety an important issue for offshore platforms. Safety requirements are specified to avoid fatalities, environmental damage, and property damage and are related to the following failure modes:

- overall rigid body instability (capsizing) under permanent, variable, and environmental loads
- failure of (parts of) the structure foundation or mooring systems, considering permanent, variable, and environmental as well as accidental loads

Safety criteria have been issued by various kinds of regulatory bodies—including national authorities, classification societies, and bodies such as API and NORSOK—set up by the industry. Currently a significant effort is underway by ISO to establish codes for offshore structures that could serve as harmonized international codes.

Stability requirements for floating platforms affect the layout and the internal structure—subdivision in compartments. Moreover, criteria to prevent progressive structural failure after fatigue failure or accidental damage would have implications on overall layout of all types of platforms. Otherwise, structural strength criteria affect the scantlings of the stiffened flat and cylindrical panels that constitute offshore structures.

The location far offshore makes evacuation and rescue difficult, but on the other hand accidents on offshore plants affect the general public less than accidents on similar facilities on land.

In the subsequent sections the characteristic features of some typical offshore structures are described.

### *7.2.2 Template Platforms*

The most common type of offshore platform is the fixed, pile-supported steel template platform, often called jacket. Jackets consist of a plate girder or truss deck structure, supported by a welded tubular steel space frame that is piled to the seafloor. The legs are battered and the area/volume exposed to waves and current are reduced toward the surface to increase the overall moment capacity and reduce the loads, respectively. Jackets are installed by transporting the space frame as a self-floating body or on a barge to the offshore site, where they are lifted or ballasted in upright position on the seafloor and piled to the seafloor. Finally the deck is lifted in one or more pieces and joined to form a space frame. The largest structure is the 67,000 tons Bullwinckle platform that was placed in 492 m water depths in the Gulf of Mexico and designed to resist 23 m high waves, winds of 76 m/s, and current of 1.2 m/s.

The design of jackets is primarily determined by requirements associated with the permanent operational conditions but may be influenced by temporary conditions during transport, launching, and offshore installation.

In deep water and soft soils, the natural period of jackets may exceed 4 to 5 s and lead to dynamic amplification.

The design of the joints between the circular tubular members in the truss is challenging because they exhibit complex shell behavior and may suffer ultimate or fatigue failure.

### *7.2.3 Compliant Towers*

An alternative to piling the steel space frame to the seafloor would be to provide some kind of hinge at the seafloor and support the tower by mooring lines (e.g., guyed tower, Fig. 7-4a) or buoyancy provided by tanks located below the water surface to minimize wave forces, yet high enough to provide the uprighting moment when the platform heels. With a natural period of say 25 to 40 s above wave periods, such a platform will move with waves, and wave loads will essentially be balanced by inertia forces set up by the "rigid body" motion.

### *7.2.4 Jack-Ups*

Jack-up platforms are mobile drilling platforms with a floatable deck and axially moveable legs. Jack-ups are moved between sites with raised legs. On location the legs are lowered to the seabed, and the deck is lifted above the sea surface by hydraulic or electric jacks. During operation the platform behaves like a fixed platform. The unfavorable motion and stability characteristics of the jack-up during transit phase with elevated legs above the deck, make this phase critical from a stability and strength point of view and make it necessary to have relatively long periods with calm weather to carry out transit operations. Due to the frame type structure during permanent operation, the response induced by environmental loads, partly because of dynamic effects, increases rapidly with water depth. Jack-ups have been used up to a water depth of about 130 m in benign waters, and about 70 m in harsh waters. To limit the penetration of the legs into soft soils, spud cans are used at the base of the legs to provide additional seafloor bearing areas.

### *7.2.5 Gravity Platforms*

Gravity platforms are used as production platforms and consist commonly of a steel deck, a concrete framework and caisson as well as steel skirt foundation. Gravity platforms have been made of reinforced concrete for water depths up to 300 m in harsh North Sea environments. The risers are contained in the caisson and shafts, and are hence protected against the action of severe wave loads and ship impacts. The caisson provides storage space. Gravity platforms are built in upright position, towed out to the offshore site, and installed by ballasting. The largest body moved on earth is a concrete gravity platform (Gullfaks C in the North Sea) with a tow-out weight of 1.5 million tons.

Since the deck and equipment are in -place on the substructure already during tow-out, and skirt penetration takes place directly during installation, the offshore installation time is reduced to a minimum.

The concrete structure consists of cylindrical, conical, and spherical shells. Thus, the caisson consists of 12 to 24 cylinders with spherical end caps (domes). In particular the 3D intersections between shells are challenging from analysis and design point of view.

Gravity steel platforms have also been designed, but only for relatively shallow water. They are trusswork platforms with a relatively wide base and are equipped with large buoyancy tanks at the base.

### 7.2.6 Semisubmersibles

Semisubmersible platforms may be used as exploratory drilling or production platforms. They consist of submerged horizontal pontoons, columns, and a deck. Both steel and reinforced concrete have been used as hull material. Pontoons and columns provide buoyancy while columns stabilize the platform. The fact that a large part of the hull is submerged and the small waterplane area of such platforms results in small wave excitation forces and small motions. While typically two pontoons are used on drilling platforms (Fig. 7-2), a ring pontoon is used for production platforms (Fig. 7-3, 7-4b). This is because exploratory drilling platforms need to be mobile and hence exhibit limited hydrodynamic resistance when they are moved from location to location. To reduce the effect of wave forces (and, hence, steel weight) in the deck of such semisubmersible drilling platforms (Fig. 7-2), they are equipped with a bracing system that is located above the transit water line.

However, the stability and draught of semisubmersibles are sensitive to payload and position. Owing to this fact they do not normally have any oil storage capacity.

Many current floating production systems are based on converted drilling rigs. However, a larger payload capacity is required for production than for drilling. Converted units can, hence, only produce from small reservoirs. Purpose-built semisubmersibles are required in order to produce from large reservoirs such as the North Sea (Fig. 7-3).

Pontoons and columns are subdivided into compartments to store ballast water and to limit the buoyancy loss in case of flooding (e.g., due to impact on the platform).

The deck is a grillage of girders or trusses. It may have to be designed to ensure survival of the platform in case of accidental damage that causes buoyancy loss in pontoons or columns.

While requirements of payload, buoyancy, and limited motions determine the overall size and shape of pontoons and columns, a possible bracing system, internal structure, and scantlings are determined by structural strength requirements.

Semisubmersibles are kept in position by a mooring or thruster system. Such systems are designed to resist the "steady" wind, current, and slow-drift wave forces and not the first order wave loads, which are balanced by inertia forces. Mooring forces are hence an order or two of magnitude smaller than the first order wave forces acting on the platform.

### 7.2.7 Tension-Leg Platforms

A tension-leg platform (TLP) hull made of steel or concrete is similar to that of semisubmersibles with ring pontoons (Fig. 7-4b) and is used as a permanent production platform. However, the hull is designed with excessive buoyancy to provide a vertical-tension mooring system (tethers). As a consequence, the platform will move as an inverted pendulum. The tension should be so large that tethers do not experience compression (slack) in waves and would typically be 10% to 25% of the total buoyancy. By the use of pretensioned tethers, the heave and pitch motions are almost eliminated, and conventional steel risers can be applied. Usually there are three to four tethers in each of the four platform corners. A tether is a tubular made of 12- to 15-meter-long sections connected by welds or threaded joints. The tether foundation is by gravity skirts or piles.

TLPs are fabricated in upright position, towed to the site, and installed.

### *7.2.8 Ship-Shape Structures*

Ships may be used for exploratory drilling or production. Such vessels can easily be designed as combined floating production, storage, and offloading (FPSO) units. However, due to the large volume displaced close to the water line, ships have poor heave (and pitch) response characteristics and can only be used for drilling operations using steel risers in areas with long periods of calm weather. Production, however, can take place in heavy weather by using flexible risers that can sustain the motions. Figure 7-4c shows an FPSO.

The hull structure of an FPSO is similar to that of an oil tanker. For this reason many FPSOs have been converted tankers, especially for benign waters. However, the trend is to use purpose-built FPSOs. Such vessels are designed more like barges with larger block coefficient than tankers.

Ship-shape facilities are positioned by thrusters or catenary mooring systems. In harsh environments the mooring system needs to be combined with a turret arrangement (Fig. 7-4d). The turret is made possible by a cylindrical opening in the forepart of the hull. In this opening a cylindrical structure is supported in such a way that the vessel can rotate relative to this cylinder. The cylindrical structure is made geostationary by a catenary mooring system anchored to the seafloor. The turret arrangement and production equipment on deck make up the main differences in the hull design compared to conventional tankers. In addition there are differences in operations that have implications on still-water and wave-induced loads. For instance, FPSOs are located offshore all the time while tankers partly are at sea and partly in ports and may be operated to avoid severe sea conditions.

## 7.3 Limit State Requirements

### *7.3.1 General*

Adequate performance of offshore structures is ensured by designing them to comply with serviceability and safety requirements for a service life of 20 to 40 years. Serviceability criteria are introduced to make the structure provide the function required and are specified by the owner.

Safety requirements are imposed to avoid ultimate consequences such as fatalities, environmental damage, or property damage. Depending upon the regulatory regime, separate acceptance criteria for these consequences are established. Property