Risk Assessment of FPSOs, with Emphasis on Collision

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ABSTRACT

Functional and safety design criteria for FPSOs are briefly reviewed, with a focus of design for safety according to a Accidental Collapse Limit State formulation. The risk of failure is examined by summarizing accident experiences with FPSOs as well as by using a risk assessment methodology. Particular emphasis is placed on methods to estimate the probability of ship collisions and the damage caused by such events, considering relevant impact scenarios relating to supply vessels, shuttle tankers, and passing ships. It is briefly described how accidents induced, e.g. by ship collision, may escalate.

NOMENCLATURE

ALS	Accidental Limit State
CPP	Contraollable Pitch Propelleler
DARPS	Diffstar Absolute and Relative Positioning System
DP	Dynamic Positioning
FLS	Failure Limit State
FPSO	Floating Production, Storage, and Offloading Unit
GPS	Global Positioning System
HSE	U.K. Health and Safety Executive
ISO	International Organization for Standardization
NLFEM	Non-linear Finite Element Method
NORSOK	Norwegian initiative to reduce development and operation cost for the offshore oil and gas industry
NPD	Norwegian Petroleum Directorate
QRA	Quantitative Risk Assessemnt
ULS	Ultimate Limit State
WOAD	Worldwide Offshore Accident Databank

1 INTRODUCTION

A floating production unit is a vessel that receives oil and gas from subsea wells through flowlines known as risers. The vessel can be either a purpose-built ship or semi-submersible, or a converted tanker. This review is limited to tanker-type systems, commonly known as floating production storage and offloading units (FPSO), see Figure 1.1.

The FPSO concept has been around for about three decades. Initially floating production systems were introduced for early production or marginal field development. Today, their potential for deep water development is of interest. There are now over 70 FPSOs working all over the world or under construction. Most of the applications are conversions of ocean-going oil tankers in relatively benign environmental areas such as Southeast Asia, West Africa and offshore Brazil near the Equator. Some vessels operate in the North Sea, for which the design events are winter storms. A few FPSOs are used in the tropical cyclone prone areas of the South China Sea and offshore Northwestern Australia, and several are under consideration for the Gulf of Mexico.

The FPSO is becoming a very popular concept in the oil and gas industry. Configuration decisions are driven primarily by the need to meet *functional* and *safety requirements*. The *functional requirements* vary widely, and may involve well or reservoir testing, pilot or early production, or full field development.

The principal functional requirements of the floating facility are sufficient load-carrying capacities for process and possibly work-over equipment, and maximum availability and efficiency of the production system. This implies that the unit should remain safely on location, with minimum motions, during all environmental conditions. The well workover requires the use of rigid risers and is more sensitive to motions than production.

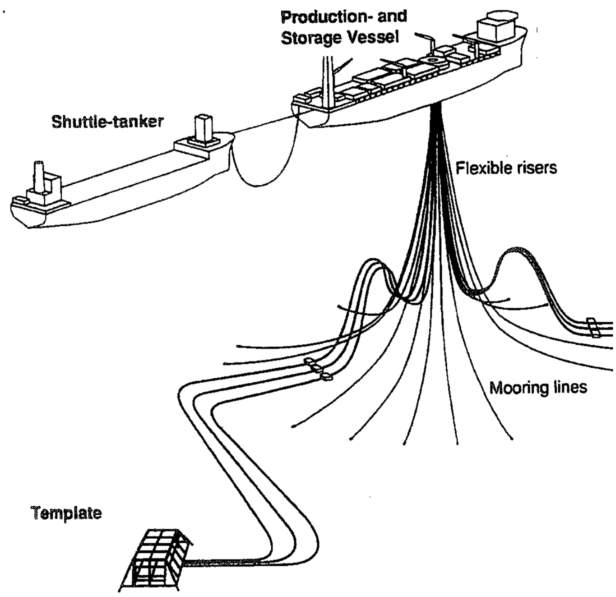


Figure 1.1 A Floating Production System

Many marginal fields, especially where the unit is used for production testing or early production, are located far from pipeline systems. In such cases the production systems consist of an offshore loading facility and shuttle tankers. In severe sea states, storage capacity may be required in order to maintain continuous production.

Initially FPSOs were converted tankers. However, the FPSO is more than just a tanker with processing facilities on deck; the vessel should perform five functions:

- Process oil and gas through the production processing facilities;
- Receive oil and gas through the riser system:
- Discharge oil, gas, and water through the riser and/or offloading systems;
- Store oil on board the vessel, using tanks, piping, and inert gas systems;
- Remain on position by means of a mooring system or station-keeping system.

The primary function is to process oil and gas from wells and, in some cases, from other fixed or floating installations, using onboard production processing facilities. The processing facilities normally consist of process control and safety systems and equipments, including utilities and auxiliary systems and equipments.

The differences in operations and equipment pose different hazards. Particular hazards arise in connection with topside and marine operations, such as production processing and offloading.

The consequences of a failure of an FPSO may be more significant than for a conventional tanker in trade. For this reason the target risk level for FPSOs should be contemplated considering the risk level implied for tankers and for offshore structures.

Safety requirements may be formulated either as prescriptive or performance-based criteria. Traditional technical solutions are prescribed by specifications and deterministic calculations of scantlings, mooring components, process plant, etc. At the opposite end of the spectrum, a performance-based approach based on probabilistic calculations can be used. For instance, safety requirements may be formulated in terms of risk of fatality and pollution, while economic loss could be based on cost-benefit considerations. Risk assessment is a tool to demonstrate that target safety levels are met.

In the offshore industry in Norway and the UK it is the responsibility of the operator to use risk assessment to demonstrate compliance with safety target levels, or to show that the risk to persons is as low as reasonably practicable. (HSE, 1992; NPD; 1981, 1990, 2000).

In the shipping industry the International Maritime Organization (IMO) and classification societies apply risk assessments as the basis for prescriptive regulations for dealing with hardware, operational procedures and personnel qualifications.

The regulatory approach may be a mixture between prescriptive and performance-based criteria. In particular the information obtained by following a performance-based approach may provide the basis for a more rational prescriptive approach. This would balance the use of probabilistic performance based approaches and prescriptive criteria to reflect a target safety level better than other methods. In this way the flexibility and rationality of probabilistic methods can be used by experts to provide an improved design basis that is straightforward and faster to implement by the industry. Moreover, the subjectivity and confusion that arises when risk methodology is inappropriately applied by non-specialists, undermining its legitimacy, is avoided.

For instance structural reliability analysis has been used extensively in the offshore industry to calibrate semi-probabilistic design codes for ultimate limit state (ULS) design criteria [Moan (1995)]. An unresolved issue in connection with structural reliability analysis is whether the effect of human error should be accounted for. While some researchers have proposed approaches to do so, no code today is actually based on ULS and failure limit state (FLS) requirements that reflect human errors. Rather, the so-called accidental limit state (ALS) was established to ensure adequate safety in connection with man-made hazards. The importance of this issue is demonstrated by the experiences with accidents and failures of offshore installations (WOAD, 1996). Human or so-called gross errors in design, fabrication and operation cause most, if not all serious accidents.

In general, a primary safety measure is to design to avoid situations associated with human errors and technical faults that can escalate into progressive failures with catastrophic consequences. This implies ensuring the damage tolerance of structure, safety barriers (firewalls, escape ways, etc.) and equipment. This issue can be dealt with in a semi-probabilistic manner by the ALS approach. In this approach initial accidental conditions corresponding to a given exceedance probability for different hazards are identified, and the survival of the damaged system is checked by a conventional design check.

This paper addresses risks associated with the FPSO concept; in particular, that events in terms of structural failure, sinking or capsizing can be dealt with based on consideration of the Accidental Limit State. Direct effects, such as heat and smoke from fires, are not pursued. The emphasis is on methods that can be used to establish improved prescriptive or semi-prescriptive methodologies. Structural arrangements and safety design criteria for FPSOs are summarized in Sections 2 and 3, respectively. Section 4 gives an overview of risk analysis of FPSO systems, and sections 5 and 6 deal with impact hazards and their effects.

2 STRUCTURAL ARRANGEMENT

There are various options in selecting vessel size, turret location, mooring pattern, line configuration and anchoring points. A typical FPSO consists of turret area, process area, storage and offloading systems, hull structure, utilities and marine systems, and means of escape and evacuation. Some of the features most relevant for the *safety* of the system are briefly outlined below.

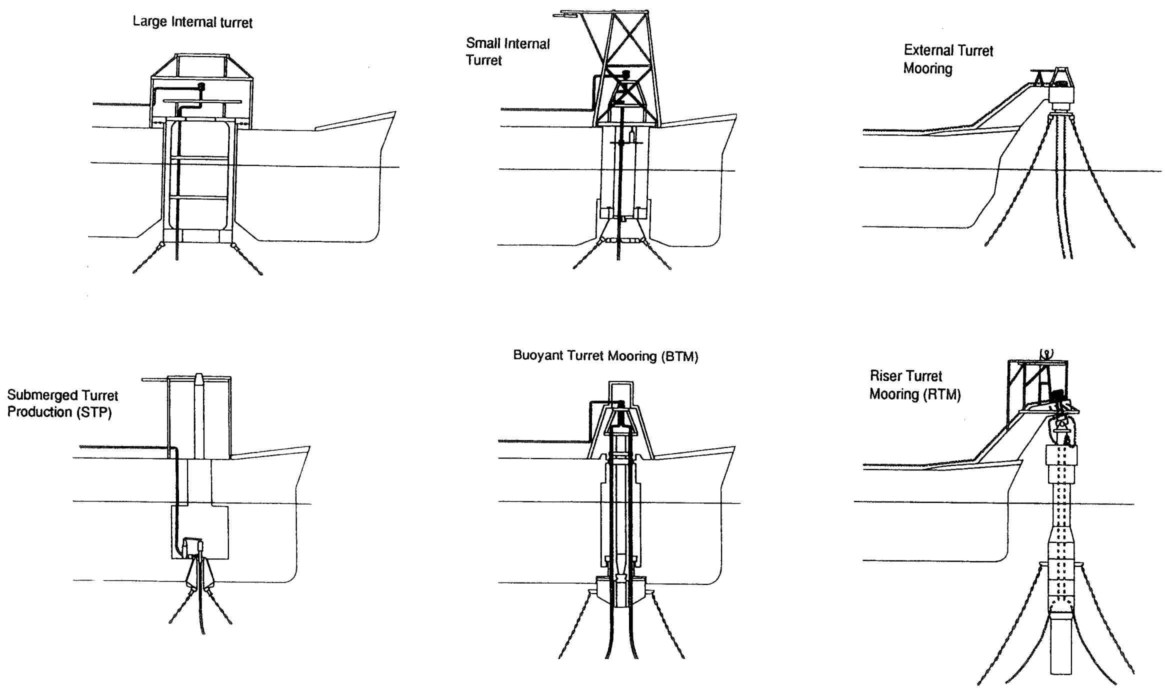


Figure 2.1 Different Types of Turret Mooring Systems

2.1 General arrangement of the hull and topside

For any floating structure trim and stability is one of the starting points of the design. This relates directly to the hull arrangements and general layout of the FPSO. The choice of a turret or spread moorings and the layout of topside modules affect the design. Consideration should be given to where the most hazardous systems, such as gas compression and the relatively "safer" systems, such as power generation and utilities, will be located.

For spread moored FPSOs riser hang-off points are attached at the side of the vessel. The arrangement of the risers along the vessel depends not only on the field, topside layout, and sea state, but also on the trim and stability of the vessel. Terpstra et al. (2001) describe how this problem can be dealt with.

Arranging all risers on one side and the shuttle tanker interface on the other side does away the need for a complicated riser protection structure. For this arrangement both the process layout and vessel stability must be taken into account. Operational aspects must also be considered, because the arrangement restricts the flexibility for a supply vessel approaching the FPSO.

When a conventional oil tanker is used as an FPSO, it is not required to comply with the provisions of regulations 13 to 13G of the International Convention for the Prevention of Pollution from Ships (MARPOL), unless specified otherwise by the coastal state. This would mainly involve the adoption of special ballast arrangements and double hull requirements. In general new build FPSOs are provided with only a single bottom if they are not self-propelled, but double sides are usually fitted to provide some protection against collision.

2.2 Turret arrangement

2.2.1 General

Early mooring designs for FPSOs had their origin with tanker offloading systems, initially being of relatively simple design. Environmental conditions tend to vary considerably by region and may be accommodated in a number of different ways. In severe situations, the mooring system may be either a disconnectable type or, more recently, a central turret design, see Figure 2.1.

In tropical cyclone prone areas, such as the Gulf of Mexico and the South China Sea, personnel are usually evacuated before a severe tropical storm reaches the project site. The turret should be located at or near the bow so that the FPSO can weathervane passively without thruster assistance. The further forward the turret is located, the easier it becomes for the vessel to weathervane. This is important in reducing the environmental loads on the hull and positioning systems and reduces the likelihood of beam seas and rolling.

Locating the turret amidships reduces vertical accelerations in that area. However, the greater bending moments and stresses amidships may increase deformations on the turret. In the North Sea, a typical FPSO has a turret located about one third of the vessel length from the bow; and bow and stern thruster assistance is required for vessel heading control. These FPSOs are manned during 100-year return period design events, and they are subject to the additional hazard of possible failure of thruster power and control systems.

The main function of the turret is to allow uninterrupted transfer of fluids to take place while the vessel is free to rotate and the risers and anchor lines remain fixed in a geostationary system (including the turret). The turret area consists of the production system,

water and gas injection systems, and the oil export system. The production flowlines are routed up through the turret to the hang-off point on the turret deck.

2.2.2 Top and bottom interface

To bridge the gap between the riser top and the deck of the FPSO, a variety of links may be used depending on the type of riser and FPSO. Typically, flexible jumper hoses are used to accommodate relative motions between the FPSO and the top of the riser. Flexible pipe may be considered for accommodating weathervaning relative motion by employing a drag chain arrangement on the deck of the turret to limit the range of rotation. However, turret-moored vessels and FPSOs generally employ reliable, pressure-rated, mechanical swivels.

If flexible risers are used, they will end on the turret deck with a connection to the production manifold at the platform deck through emergency quick disconnects (EQDC) and fixed piping. The EQDCs and the manifolds are located on the turret deck. The purpose of the EQDC is to allow rapid, remote-controlled release of the lines. The EQDC has isolating valves in both ends. The valves are automatically closed prior to disconnection.

The interface design of the riser bottom connector and the sea floor equipment depends on several factors such as the type of FPSO, type of sea floor equipment, water depth, riser size, and whether the riser is tensioned or not. Decisions about sea floor manifolding or active components, such as valves, influence the bottom interface. Subsea valves may be integrated into the riser bottom connector, allowing recovery of the active components for maintenance and repair. The loads imparted to the seafloor equipment by the riser are a major factor.

2.3 Accommodation module construction and location

Since risers are a significant contributor to the risk profile of an offshore facility, it is desirable to minimize the exposure of personnel to this risk. At any one time the majority of personnel usually are located within the accommodation module. Maximizing the distance between the risers and accommodations is a fundamental element in managing the personnel risk.

For an FPSO with a bow turret, the safest location of the accommodation module is at the stern of the FPSO. This reduces the potential for incidents associated with the risers to directly impact the accommodation module. A further benefit of locating the accommodation at the stern is that the vertical accelerations at this point are less than further forward, improving the living environment for personnel. On the other hand potential incidents that occur in the machinery space, such as smoke/gas migration or fire loading, could affect the integrity of the accommodation module. Consideration must be given to the requirement for personnel to access the machinery space, particularly in bad weather. Because of the weathervaning nature of the FPSO, any riser or process incidents resulting in gas or smoke evolution has the potential to engulf the accommodation module.

With a turret located amidships or aft of the bow location a forward mounted accommodation is more appropriate. For facilities with a centrally mounted turret locating the accommodation module requires consideration of the following issues:

- Gas/smoke risk associated with hazards due to nearby process facilities and risers
- Helicopter operations (flight-path & vertical accelerations at helideck)
- Evacuation facilities, with specific consideration for lifeboat launch capabilities, particularly towards bow, considering prevailing currents and vertical accelerations.

2.4 Process facilities layout

The process area consists of the gas separation and compression systems and metering systems. The separation and compression systems are located on deck in the open, which implies that escalation of an accident should be relatively easily prevented, since there is only one deck level with equipment.

Due to the high pressures and relative ease of igniting any gas inadvertently released, gas compression facilities are a significant risk contributor. It is thus essential that the distance between these facilities and the accommodations is maximized. The separation facilities also pose a risk to personnel, so it is therefore appropriate that these facilities are located at the maximum reasonably practicable distance from the accommodation module.

For an FPSO with a turret mounted amidships, the accommodation module should be located at the bow of the vessel. The process area is located behind the turret to achieve the lowest risk to personnel. Moreover, due to the weathervaning character, any release of gas from the facilities area will blow in the downwind direction.

For an FPSO with its turret located at the bow, the accommodation module is located at the stern of the vessel, and the separation and compression systems are located just behind the turret. Locating the gas compression and separation facilities near the turret also has the advantage of reducing the lengths of high pressure gas lines required to carry the compressed gas to the turret and through the swivel to the subsea flowlines. See Figure 2.2 for a typical North Sea FPSO.

The fuel gas system (relatively low operating pressures) can be located aft of the compression and separation facilities, while still maintaining a reasonable distance from the accommodation module. Less hazardous systems like power generation, utilities, etc. can be located further aft.

2.5 Storage and offloading systems

Storage is provided in the center tanks, with water ballast in the double bottom (if fitted) and side tanks. Water ballast tanks also surround the turret moonpool. The cargo tanks are normally protected by inert gas

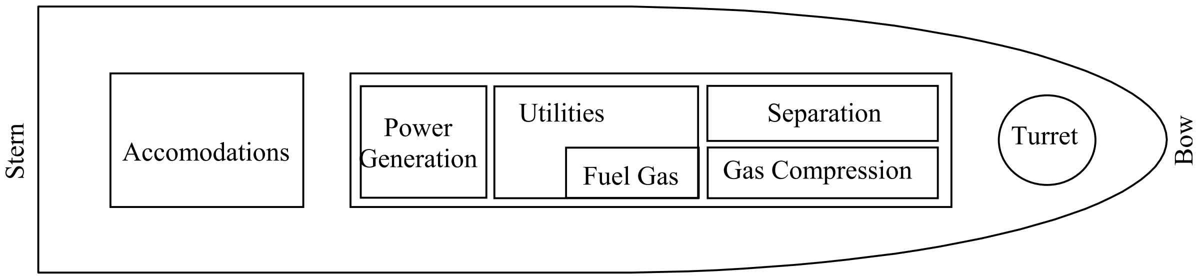


Figure 2.2 Layout of FPSO with the turret located forward

blanketing, which is an essential feature of the vessel. The fire risks on ordinary tankers decreased significantly when the inert gas protection was made mandatory for all oil tankers.

A common way of exporting crude oil from a FPSO is by shuttle tanker transport to a shore terminal. The export may take place by direct transfer from the FPSO to a shuttle tanker by a hose, or by transfer from FPSO via separate offloading system (hose-riser-pipeline-riser). The former method is mainly used when the production/storage unit is a ship or barge shaped floating production, storage and offloading unit (FPSO). Both alongside transfer and tandem transfer methods can be used, depending on operational criteria.

Alongside, or side-by-side transfer of crude oil, is often used for offloading crude oil from a FPSO usually during mild weather conditions. This method involves berthing or mooring a transfer vessel, which may be a shuttle tanker or a barge, on either or both sides of the FPSO.

Tandem transfer (see Figure 2.3) is another commonly used crude oil export system, which involves offloading oil from the FPSO to a transfer vessel (usually a shuttle tanker) which is moored in-line aft, or to the leeward of the FPSO. As compared to alongside transfer, the tandem transfer method of exporting crude oil can be used for harsher environments and is adapted for use with both a weathervaning and a spread-moored FPSO.

Tandem transfer floating hose systems are limited by the number of hose strings which can be used, the availability of floating hose sizes (usually 6 to 24 inches), and by available FPSO pumping pressures which can limit the size and length of hoses used. The size of floating hose strings may also be limited by the hose-lifting capacity of the shuttle tanker. A modern, harsh environment system, where the hose is partly submerged is shown in Figure 2.. The shuttle tanker is some 60-100m aft of the production vessel.

2.6 Hull structure, utility and marine systems

It is standard marine practice to provide a cambered deck on a tanker to ensure that green water is shed. If the scuppers on the upper deck are left open, the camber of the deck will allow any major spillage of liquid hydrocarbons to be directed overboard, minimizing the potential for prolonged pool fires to exist on the main deck. This feature can be considered as achieving inherent safety through *elimination.*

However leaving the scuppers open during normal operations introduces an environmental risk, i.e. any small operational spillage on the upper deck will be directed into the sea. This problem can be overcome by developing a system where a drainage channel capable of dealing with operational spillage is provided inboard of the scuppers. Spilled cargo is then directed to a holding tank or separator. This system is illustrated in Figure 2.4.

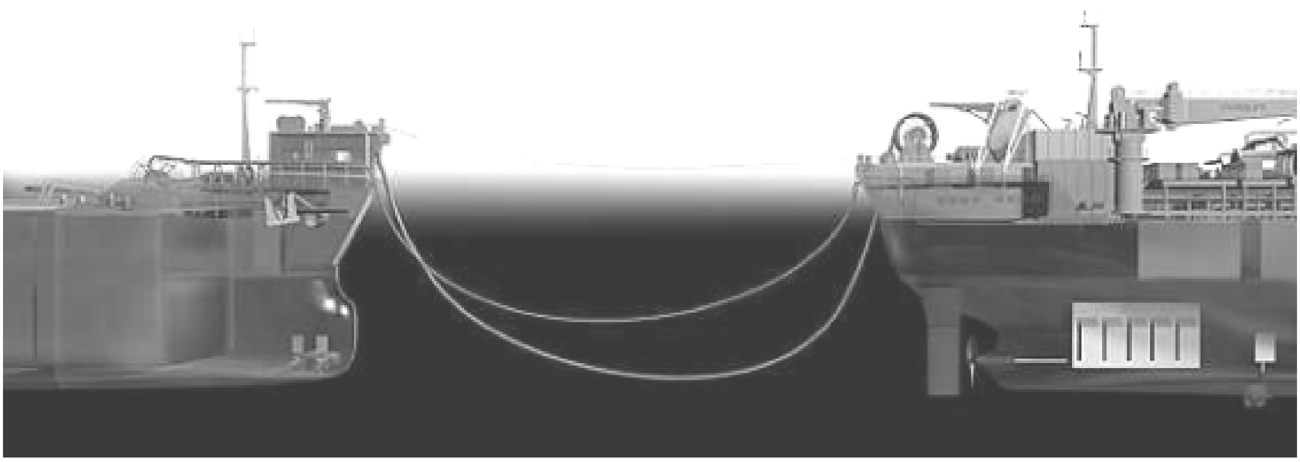


Figure 2.3 Tandem Offloading with Submerged Hose

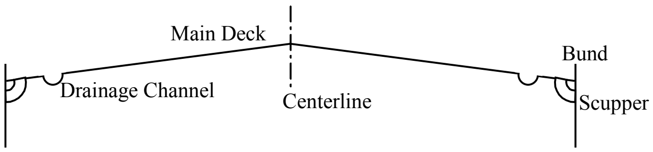


Figure 2.4
Representation of Main Deck Scupper/Drainage Channel Arrangements

2.7 Escape ways and means of evacuation

There are two fundamental philosophies applied to providing escape routes on the decks of an FPSO, namely, fully enclosed tunnels or protected open walkway. Although experience has shown that both philosophies can be applied successfully, protected open walkways is considered inherently more safe because there is no reliance on the mechanical systems required for a fully enclosed system, such as a pressurization/HVAC system. Two protected escape routes should be provided so that no single event requiring personnel to escape to the accommodation spaces can result in simultaneous impairment of both routes within the evacuation time. Two protected open walkways can be considered to achieve inherent safety through s*implification* of the design. However in certain scenarios a fully enclosed pressurized tunnel is a more appropriate option.

The main escape routes are normally along the two sides of the vessel. Four main lifeboats (two on each side), providing 100 percent spare capacity, and one auxiliary lifeboat, all of the conventional gravity davit-launched type, are recommended. The protected escape way should be shown to give adequate escape possibilities in realistic accidental events.

2.8 Dynamic positioning (DP) system

FPSOs are subjected to forces from wind, waves and currents as well as from forces generated by the propulsion system, if so equipped. The vessel's responses to these forces, such as changes in position, heading and speed, are measured by the position reference systems, the gyrocompass and the vertical reference sensors. Wind speed and wind direction are measured by the wind sensors. The control system calculates the deviation between the measured (actual) position of the vessel and the required position, and then calculates the forces that the thrusters must produce in order to make the deviation as small as possible. The system controls the vessel's motion in three horizontal degrees of freedom: surge (fore/aft), sway (port/starboard) and yaw (heading). Typically DP systems are used to maintain absolute position in relation to a predetermined point on the seabed or on a fixed installation. However, for dynamically positioned shuttle tankers the DP system may be used to maintain vessel position in relation to a moving target, such as the stern of an FPSO.

3 ACCIDENTAL COLLAPSE LIMIT STATE CRITERIA

A rational safety assessment of FPSOs requires considerations of various failure modes relating to stability, structural strength and positioning. Hence, the stability and strength under service and environmental loads as well as the survival in accident conditions need to be ensured. This is achieved by Ultimate (incl. fatigue for the structural strength) as well as Accidental Limit States (ALS), (ISO, 1994). The focus here will be on ALS.

3.1 Hull

ALS have been described in international model codes since the mid-1970s, including the recent ISO code for offshore structures, (ISO, 1994). However, quantitative criteria were introduced for the first time in Norwegian Petroleum Directorate (NPD) regulations in 1984. This design criterion is a response to the fact that human errors cause effects that can lead to abnormal stresses or accidental loads on the structure (Moan, 1983; WOAD, 1996).

This robustness criterion for structural strength was long due, since analogous requirements relating to the stability of ships has been recognized for decades. Initially such damage stability criteria were based on survival of a single compartment flooding associated with ship impacts. In more recent codes various accidental events are recognized.

The ALS design check according to the NPD was motivated by accident experiences, to ensure that small damages do not cause disproportionately large consequences. This design check is a survival check, and local damages are permitted. The design check is carried out in two steps, as follows (NPD, 1992):

1. **Capacity to resist abnormal or action effects** (fires, explosions, ship impacts, as described in Section 4). The loads in permanent operation refers to an annual exceedance probability 10^{-4}, with a resistance and load factor equal to 1.0. These accidental loads or damage conditions should be established using risk analysis.
2. **Capacity in the damaged condition.** After having demonstrated that the damages estimated in step 1) or other specified local damage is local, the structure must resist specified environmental conditions without extensive failure (total collapse). Environmental loads for this check should correspond to an annual exceedance probability of 10^{-2}. Resistance and load factors are equal to 1.0.

It is interesting to compare the Step 1) ALS check of abnormal environmental loads to the ULS check. Considering steady-state wave loads and assuming linear behavior, the load with an annual exceedance probability of 10^{-4} of the ALS check is about 1.25 times the 10^{-2} load (for the ULS check). Since the load factor is 1.3 for the ULS and 1.0 for the ALS, the ULS design check is seen to be most critical. This is also true for small nonlinearities in the load effects. However, the relative motion for the 10^{-4} condition may be 20% larger than for

the 10^{-2} condition, and implies a much larger slamming force.

The accidental loads in Step 1) correspond to an annual exceedance probability of 10^{-4} and should be determined by risk analysis. In this way the particular factors that affect the loads can be rationally accounted for. For instance, ship collision events depend upon the traffic in the area. Independent accidental loads are considered one at a time, in this check. Fires and explosions should be assumed to occur simultaneously due to their strong dependence.

It is also necessary to specify variable (functional) loads, acting together with the accidental load. Hydrostatic pressures should obviously be considered for local loads. Turkstra's rule (Turkstra 1970) states that the maximum value of the sum of two independent random processes occurs when one of the processes is at a maximum, and the second process is assumed to be at its mean value. This approach may be used to estimate the relevant hull girder moments and shear forces due to still-water and wave loads combined with accidental loads. Moan and Jiao (1988) describe this for the combination of still water and wave induced loads. The mean still water and wave loads are combined with the 10^{-4} accidental load to give the maximum combined load. The mean wave moment is quite small (less than 10%) compared to the design wave moment. The mean still-water moment may be taken to be 30-40% of the design still-water moment, based on measured data as reported by Moan and Jiao (1988).

In Step 2) the survival of the damaged structure under functional and environmental actions is checked.

Risk analyses to determine abnormal resistance, e.g. due to fabrication defects, are even more uncertain. Up to now, such damages (abnormal resistance) is explicitly specified by generic values for specific types of structures. For instance, the Step 2) ALS check of platforms with slender braces, include damage in terms of failure of individual braces. This condition was established in the aftermath of the Alexander Kielland accident and was initially supposed to cover ship impact hazards and abnormal fatigue cracks. For catenary and tether mooring systems a similar check with one component severed, is required.

The design checks in the ALS criterion should be based on a characteristic value of the resistance corresponding to a 5% confidence limit. ALS checks apply to all relevant failure modes, instability/capsizing of the hull, and failure of the positioning system, as discussed below.

The hull girder bending capacity may for instance be checked based on:

$$M_u / \gamma_m \geq \gamma_s M_s + \gamma_{WL} M_{WL} + \gamma_{WNL} \Delta M_{WNL}$$

where

M_u	- ultimate bending capacity of the hull girder
M_s	- still-water bending moment
M_{WL}	- linear wave bending moment
ΔM_{WNL}	- nonlinear "correction" to the wave bending moment
γ_m	- material resistance factor
$\gamma_s, \gamma_{WL}, \gamma_{WNL}$	- load factors corresponding to M_s, M_{WL} and ΔM_{WNL}, respectively

However, the ultimate strength moment, $M_{u(d)}$ is reduced to due damage. To use the same wave load, with an annual exceedance probability of 10^{-2}, as used by NPD (1992) for all accidental conditions, is not consistent. In principle the characteristic values of still water and wave moments should actually depend upon which accidental condition causes the damage (in Step 1) and the correlation between the accidental damage and the subsequent load condition. All loads and resistance factors are taken to be equal to 1.0 for this ALS check, as compared to the ULS check, where a load factor of 1.0 for still-water bending moment, a load factor of 1.15 for wave bending moment and a resistance factor of 1.15 are applied

ABS (1995) presents an interesting approach to check the hull girder resistance of tankers after collision and grounding, based on specified damage conditions. Based on the specifications given, this damage condition check will be governing if the strength reduction due to damage is more than about 25-30%.

In principle, ALS criteria should be considered for both the permanent operation phase as well as temporary phases. The definition of characteristic loads given above, refers to permanent operation. Analogous criteria should be established for temporary phases. However, it is often found that accidental events can be neglected for temporary phases, since good control can be exercised in the relatively short term that the hazardous activities last. Also, the ALS check may be omitted if it can be demonstrated that ultimate collapse will not lead to loss of lives, significant pollution, or significant economic losses.

3.2 Station keeping system

The two-step approach described for hull structure can be applied for station-keeping systems, by considering the following scenarios:

- damaged system
    - failure of one or more component (mooring line, thruster) caused by excessive weld defects, wear at fairleads, or thruster failure
    - failure of turret system (turret cannot rotate relative to the hull), implying abnormal environmental loads on the hull and the mooring system
- possible collision at the stern of FPSO by a shuttle tanker

Failure of individual station keeping elements rarely leads to serious consequences. It is the excessive motions or drift-off due to multiple failure of mooring

components that represent the largest risk, as they, for instance may lead to:

- collision between the FPSO and other installations
- impacts or wear on pipelines or other subsea equipment, caused by dragging anchors
- blowout, fire or explosion or oil spill
- possible grounding and breach of the cargo tanks
- failure of risers

Obviously, the nature and severity of such consequences depend on the operation, the prevailing weather at the time, the number and location of other installations, whether the installations are manned or not, the availability/reliability of possible active actions to control the motions or drift-off, etc.

4 RISK ANALYSIS

4.1 General

The objective of a quantitative risk analysis is usually to determine the level of risk in terms of probability versus magnitude of the consequences for fatalities, pollution and property loss. The consequences can be expressed in specific units, such as lives lost or gallons spilled, or they can be in terms of general economic consequences, assuming values can be placed on human life or degradation of the environment. This may be done for an industry as a whole basis and be compared with the risk level in other industries.

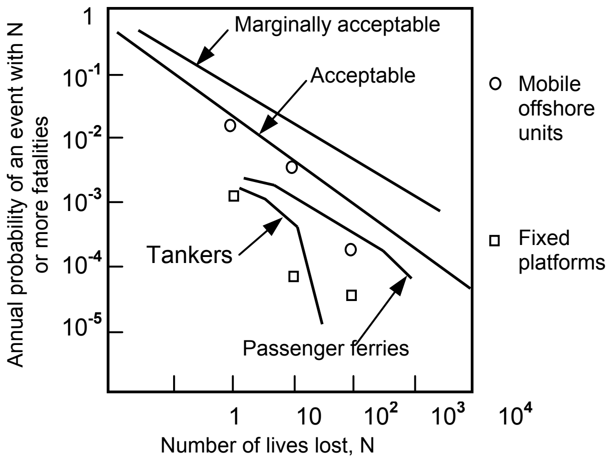
Figure 4.1 shows frequency and consequence diagrams based on the historical accident data for offshore activities, prepared on the basis of WOAD (1996). It should be noted that these data include accidents caused by all kinds of hazards. Human errors, leading to loss of strength and accidental loads, dominate. Data for trading ships (Aldwinckle, 1990) are also given for comparison. The data in Figure 4.1 are based on historical accident data, and represent the technology and operational practice applied at the time.

The risk picture for different regions/countries may also be estimated. Historical data in WOAD (1996) provides a basis for such estimates for major geographical areas, such as Europe, Gulf of Mexico etc. For other areas, theoretical analyses are necessary.

4.2 Accident Experiences with FPSOs

The limited operational history of FPSOs does not allow a statistically significant assessment of risk from accidents or failures. WOAD (1996) contains information for drill ships, but it is not separated from that of other mobile (drilling) units.

Experience with tankers provides some useful information. According to the statistics presented by Aldwinckle (1990), nearly 70% of fatalities involving tankers are caused by fires and explosions, and 18% and 6% of the fatalities are caused by groundings and collisions respectively. The three types of accidents contributed to outflow of cargo in a roughly equal number of casualties.



Fatality risk for platforms and merchant vessels

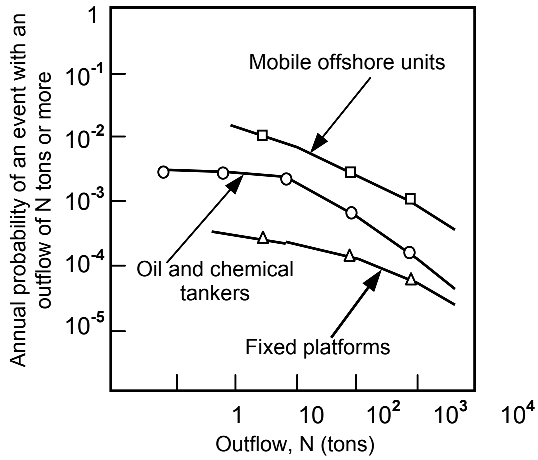


Figure 4.1 Frequency-consequence diagrams for offshore and ship structures in world-wide operation, considering all hazards. The historical data for offshore structures are based on WOAD (1996) while the data for ships stem for Aldwinkle (1990) for the period 1980-89.

The differences in the mode of operation, hull and topside system between tankers and FPSOs need to be observed. Accident experiences with FPSOs have been reported by HSE (2001) for world wide operations, Millar and White (2000) for operations in UK; and Kvitrud et al. (2001), for operations in Norway. There have been no total losses worldwide of FPSOs nor any serious accidents to personnel.

The converted tanker *Lan Shui* has been described as experiencing a structural total loss due to engine room fire on 21. January 1990. The fire is described in Lloyds' List as lasting 29 hours, with extensive damage to the engine room, but with no damage to process or storage areas, and no pollution. The information further shows *Lan Shui* remained on location for several weeks afterwards, and was later converted for production on the Bongkot field (Thailand) after 1993. The accident should therefore be considered as a severe engine room fire, not as a constructive total loss. An engine room fire also occurred on *Griffin Venture*, 10 November, 1997,

western Australia, but it was not as serious as that on *Lan Shui*. Such accidents may indicate the need for improvement of safety standards when converted tankers are employed as FPSOs.

Another serious accident took place when overpressure developed in a cargo tank on the FPSO *Uisge Gorm*, 4 April 1999, due to a valve in a vent line not having been reopened after maintenance. The vessel sustained severe hull damage requiring shipyard repair. The vessel was back in operation after some 100 days, in mid August 1999.

It may be a coincidence, but it is interesting that both of these accidents occurred on converted tankers, and both were associated with ship systems rather than hydrocarbon processing systems. With only two events however, the number is far too low to draw any firm conclusions. No other serious fire and explosion events are known for North European waters.

There have, however, been several ship impacts with FPSOs. In five incidents a shuttle tanker caused the impact. Another near contact of a shuttle tanker is reported. None of these impacts was critical and in fact, the consequences were very marginal. However, they focus attention on operational safety aspects. Also the overpressure in the cargo tank on *Uisge Gorm* was associated with operational aspects.

The fact that these incidents occurred without serious effects should not be taken to imply that there is limited potential for serious accidents. There is a significant potential for major accidents from such operational errors, even though the impacts that have occurred during the last few years have been limited in intensity. The following is a brief overview of incidents that are known from operations with FPSOs in the North European waters.

In the North Sea several incidents of green water damage have occurred, in both the bow and midship areas. In one instance (*Petrojarl Varg*), safety equipment was damaged, and water entered the living quarters through broken windows. Obviously, this kind of damage depends upon structural arrangement and freeboard. Green water protection walls have been added on some FPSOs.

One FPSO has experience multiple anchor line failure in January 1994. The same FPSO previously had individual line failures. The multiple line failure (4 of 8) was gradual, and occurred over a period of approximately 8 hours, initially losing two lines due to a 20-25 m high wave. After that incident, production was shut down, and the vessel kept on station by remaining lines and main propulsion. She was never off station and started reconnecting of the lines the day after. Personnel were never taken off, and the vessel always had the possibility of quick disconnection.

There have been two situations where problems with heading control of an FPSO with turret mooring in the North Sea. The first situation was when the wind direction suddenly changed 180^o, and the FPSO was not able to turn accordingly. This resulted in the aft heading towards the wind. At the time of the incident the wind velocity was approximately 25 m/s and significant wave height 6-7 m. Turning the FPSO could not be easily done. Fortunately the weather calmed down before serious twisting of mooring lines occurred.

The other situation occurred when one of the two gyros for the DP system, failed, resulting in signals to the starboard thruster to give maximum effect. The FPSO changed heading, but due to swift crew reaction, a situation that may have led to uncontrolled turning of the FPSO and consequently excessive twisting or tension of mooring lines, was avoided. Twisting of mooring lines was limited to less than 10 degrees, but in less favorable weather conditions they could have been damaged. Immediately after the incident the failing gyro was replaced and installation of a third gyro is being evaluated.

While the problems with heading control, were due to operational issues, rotation of the FPSO may also be obstructed by mechanical failures, such as of the rail system. In this connection it should be noted that cracking in rails has been experienced for at least one kind of turret system.

4.3 Risk Assessment for Design

Risk analyses for design could be established for each offshore field, but are in practice performed for individual installations (CEC, 1987; Vinnem, 1999; ABS, 2000).

The main idea of a risk assessment is to estimate, integrate and link risks and risk trade-offs among the hull, mooring system, marine system and topside process plant and the utility, power and control systems that support them. Such comparative analyses yield realistic results only if adequate risk estimates of the components are available.

Risk analyses have up to now been focused on personnel risk, and to a lesser extent on environment and assets. Rather than to determine the frequency-consequence diagram or the fatality accident rate, the impairment (total loss) frequency is determined. The risk depends on design and operational loads. In principle, risk analysis provides a tool for accounting for such factors and represents a functional way to fulfill certain safety target levels.

In reality, different subsystems, like load-carrying structure & mooring systems, process equipment, and evacuation and escape system are designed according to criteria given for the particular subsystems. For instance, safety criteria for structural design are given in terms of ULS, FLS and ALS with specific target levels, implying a certain residual risk level.

The implicit risk associated with ultimate and fatigue limit state criteria and normal functional and environmental loads can be assessed by structural reliability methods, by taking the effect of a possible inspection into account for FLS. ALS is carried out by checking the system strength after the effect of accidental loads or abnormal damage. The accidental loads, which are determined by risk analysis, have usually an annual exceedance probability level of 10^{-4}.

Evacuation and escape operations could influence the fatality rate, and should be assessed by a particular risk analysis. This paper shows how potential accidental situations can be dealt with in a risk based design perspective. The full scope of risk assessment is not performed.

4.4 Risk Analysis Methodology

4.4.1 Background

The focus in this context is on risk analysis to determine characteristic accidental loads. The risk analysis can be based entirely on experience, e.g. statistics of historical data or on system analysis, or on both, see Vinnem (1999).

A direct determination of low probabilities, such as 10^{-4} per year, requires a significant amount of data. If, for instance, the occurrences of a given type of accidental event are independent, and each has an annual probability of occurrence of 10^{-4}, 23,000 years of experiences would be required to have a 90% chance of one occurrence. In the period 1970-95 the accumulated number of platform years worldwide was 110,000 and 15,000 for fixed and mobile structures, respectively. Even today there are only about 800 mobile units and 5300 fixed platforms worldwide. Hence, many years of service experience would be needed to estimate probabilities empirically. A further complexity is that the factors that influence the probabilities of accidental events vary significantly among the actual platforms and over the years. Therefore, the probabilities cannot be directly estimated without careful interpretation, and they will be subject to significant uncertainty. But limited historical data are better than nothing. Furthermore, by adopting risk analysis methods based on a systems approach, improved estimates of probabilities may be obtained.

4.4.2 Method

The basis of the systems approach is the following observations:

- almost every major accidental event has originated from a small fault and gradually developed through a long sequence (or several parallel sequences) of increasingly more serious events, culminating in the final event;
- each single event in the chain occurs more frequently than the whole event sequence;
- it is often reasonably well known how a system will respond to a certain event.

By combining knowledge about system build-up with knowledge about failure rates for the elements of the system, it is possible to achieve an indication of the risks in the system (CEC, 1987; Vinnem, 1999).

The risk analysis process normally consists in the following steps:

- definition and description of the system (hardware, operational procedures, etc.) for the following subsystems: structure, mooring, marine and process (topside)
- identification of hazards (based on failure and accident data)
- analysis of possible causal event of hazards
- estimation of risk

In connection with accidental loads the last step would be to determine the design accidental event (corresponding to an annual probability of exceedance of 10^{-4}).

Due to significant uncertainties associated with quantifying accidental events it is generally accepted that they can be documented by engineering analyses and judgment, without detailed analyses.

The analysis of accidental events should include the following steps:

- definition of the accident spectrum
- personnel qualifications, procedures, quality assurance and control functions
- determination of the influence of active/passive safety systems (capacity; reliability, accident load integrity, maintenance system, etc.)
- determination of the influence of the environmental conditions
- analysis of possible escalation of the event
- estimation of event probabilities/event magnitudes

An Event-Fault Tree technique will in most cases be the most appropriate tool for systematizing and documenting the analyses made.

The main idea is to identify critical events (Figure 4.2), and by logical reasoning determine which (sequence of) events may lead to and develop from the critical events. A main problem when applying this method is to identify and select critical events so that all relevant hazards are covered, but not duplicated. Historical data on accidents are useful in this connection.

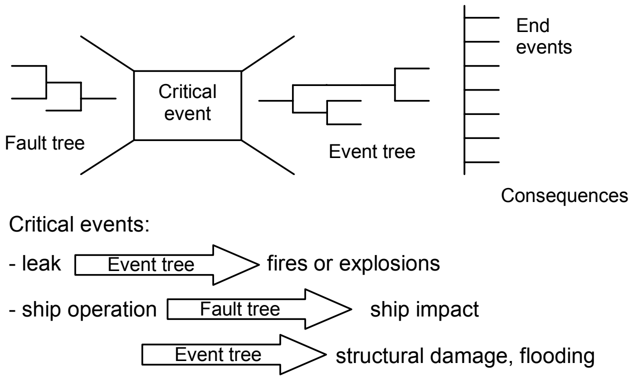


Figure 4.2 Schematic sketch of the event – fault tree method.

4.4.3 Model

Critical events for a given system cannot be uniquely defined, as critical events can be selected at any level of the event trees. One critical event may appear in an event tree developed from another critical event (secondary critical event), or two different critical events may develop into identical secondary critical events. Such situations must be properly taken care of if the total risk is to be quantified.

Figure 4.3 shows a crude generic sequence of events following critical events such as hydrocarbon explosion/fire, ship collision and other impacts, and other events such as subsea blowout, ballast operation error. The ultimate consequences are fatalities, environmental damage and material loss. Indirect costs of production stop/delay are also of concern.

Estimation of the *personnel risk* (fatalities, injury) is based on more detailed event trees that include the following aspects:

- Top event frequency (likelihood of the critical event and its severity)
- Day or night (affects the emergency response and the rescue and recovery operations)
- Good or bad weather (affects the decision making process for evacuation as well as the rescue and recovery operations)
- Escape times and the likelihood of escape prior to impact
- Fatality levels associated with the escape method

The event logic used to assess the *risk of pollution* considers the following:

- Frequency (likelihood) of critical event
- The intensity of the critical event – which indicates the extent of damage of the cargo tanks
- Location where the event/damage takes place on FPSO
- Probability of a cargo tank being impaired (depends on location and intensity of the critical event)
- Probability of outflow given a damage location

In a risk assessment the probability of total loss is estimated by the probability of initial damage and total loss given that damage. A simplified design method to ensure compliance with an acceptable risk level is to design the FPSO to survive the damage caused by an accidental event with a specified exceedance probability. By properly defining the characteristic loads (and load factors) for this design check, the design method will yield an implied probability of total failure corresponding to a target value.

The main challenge in risk analysis is to estimate the event that is considered the "critical" event. Normally, the probability of occurrence of this event is small, and a fault tree and appropriate data based on experiences are required. It is important to include all relevant combinations of events. One can easily construct a large number of event combinations. The problem is, however, to identify the combinations that have a reasonably high probability of occurrence while excluding combinations with negligible probabilities.

4.4.4 Simplified risk-based design

The idea of the ALS check can be illustrated with reference to Figure 4.3. The ALS is based on the fact that a critical events occurs, and causes structural damage or an abnormal floating condition, i.e. on the level next to the top event in Figure 4.3. ALS requirements are expressed as checks of surviving this critical event, with respect to capsizing/sinking and overall structural failure (total loss).

For each physical phenomenon (fire, explosions, collisions, etc.) there is normally a continuous spectrum of accidental events. A finite number of events has to be selected by judgment. These represent different load intensities at different probabilities. The characteristic accidental loads on different components of a given installation, can be determined as follows:

- establish the exceedance diagram for the load on each component
- allocate a certain portion of the reference exceedance probability (10^{-4}) to each component
- determine the characteristic load for each component from the relevant load exceedance diagram and reference probability.

Alternatively, the following, more refined consideration of risk may be used to determine the accidental load:

- component (i) is assumed to be designed for an accidental load with an exceedance probability of p_i for that component
- estimate the probability of total loss due to failure of component (i) – implied by the residual risk associated with the accidental load
- estimate the total probability of failure (p_f) associated with the given accidental load on all components
- compare p_f with the target level
- reallocate p_i's in order to get a more optimal design, while complying with the target level

If the accidental load is described by several parameters (e.g. heat flux and duration for a fire; pressure peak and duration for an explosion) design values may be obtained from the joint probability distribution by contour curves (NORSOK N-003, 1999). However, in view of the uncertainties associated with the probabilistic analysis, particularly related to the influence of human factors on the risk, a more pragmatic approach will normally suffice. Such analyses have been applied to platform concepts since about 1980. Only limited information about such studies has been published; most is kept confidential.

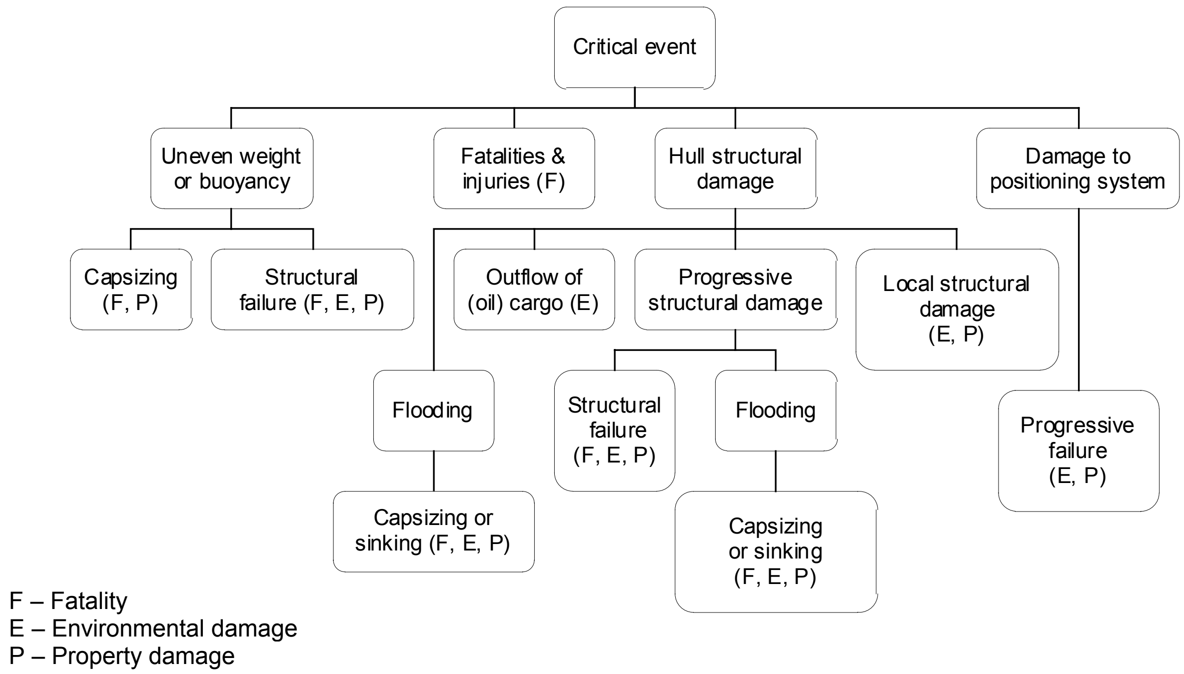


Figure 4.3 Schematic event tree for the development of consequences in terms of fatalities, environmental damage and material loss from a critical event.

4.5 Overview of Accidental Events

4.5.1 Types of accidental events and their combination

As mentioned above it is assumed that the structure is designed to have stability and structural integrity to withstand wind loads, and still-water and wave loads, respectively, that have normal variability and uncertainty. The corresponding failure probabilities may be estimated by structural reliability analysis (e.g. Moan, 1995). However, both still-water and wave loads are affected by operations (e.g. turret operations) i.e. human factors, and, therefore operational errors. In addition there are uniquely accidental events, i.e. accidental loads and abnormal resistance which have no normal counterpart. The *accidental loads* to be considered in step 1) of an ALS check of the hull should include the effect of

- fires and explosions
- ship impacts
- dropped objects (e.g. from crane operations)
- unintended pressure or ballast/cargo distribution due to operational errors, which may cause global and local effects.
- abnormal environmental loads (with annual exceedance probability less than 10^{-4})
- sub-sea gas blow-out

While the first three categories are obvious, the other categories require some explanation.

WOAD (1996) and Aldwinkle (1990) show that fires and explosions are important causes of accidents on installations used in the offshore petroleum industry as well as for tankers in commercial shipping. The *Piper Alpha* fire/explosion and other accidents have shown that hydrocarbon fires and explosions can lead to catastrophic consequences. Hydrocarbon fires on platforms can in certain cases be continuously supplied with fuel. Under such circumstances fire protection can only delay the destruction of the structure affected. Explosions are sudden, and can proceed or follow a fire.

Explosions above the main deck might cause pressures that damage the deck. Explosions in cargo holds, if they occur, certainty have the potential of damaging the deck. The main question for the latter explosions scenario is whether the likelihood implies that risk control is necessary. It is noted that even a local rupture of the deck due to explosions may lead to an escalation of the explosion. As for explosions, the main threat of a fire is associated with possible propagation into a cargo hold.

In offshore structures there is often a differential pressure between the outside and inside of the structure and between various compartments. The intended pressure difference may be accidentally disturbed by faulty operation of ballast pumps, vents etc., as in connection with *Ocean Ranger* (1984). Another cause of disturbance of the normal pressure difference is a leak of highly pressurized hydrocarbons from a pipe in a closed compartment. Such an event has even been experienced in an FPSO (*Uisage Gorm*). Equipment or piping failures will depend upon equipment redundancy, maintenance procedures, etc. Operational errors are most likely associated with a situation which for other reasons already has become critical. Accidental differential pressure loads and ballast conditions caused by faulty operations or equipment failures, should be considered, applying risk analysis methods.

Abnormal wave loads may occur from particular wave conditions (sometimes denoted: "freak waves"). To some extent nonlinear phenomena have been revealed (mainly in the North Sea) during greenwater and slamming events. Those effects have caused large local loads but have not posed any threat to the hull girder. One could, however, envisage another situation where high local loading from green water in the midship area in combination with an extreme hull girder sagging condition could lead to hull girder failure. By providing the vessel with adequate freeboard, this situation will be less likely. The main concern about global strength is the possible effect of severe wave slamming.

Another abnormal environmental load condition can occur if, due to technical faults/operational errors, the turret fails to maintain the vessel head-on to the predominant environmental load direction. Such incidents have been experienced. Two situations may occur when the direction of environmental loads changes and the turret is prevented from rotating, namely: 1) the vessel stays on the same heading while the load changes direction; 2) the vessel rotates with the environmental load, causing twisting of the mooring (and riser) system. In the first case the total environmental loading and motion of the FPSO that the mooring system needs to carry, may increase by a factor of 5-10 times compared with the head-on condition. Depending on the intensity of the environmental loading in the case when turret locking occurs, failure of the mooring and riser systems may take place. In the second case the twisting of the mooring and riser is a problem that may lead to failure. These issues have been addressed by Chen et al (2002).

Sub-sea gas blowouts may impose loads, other than possible fire loads, on the ship in two ways. First, the presence of gas reduces the density of the water and hence, the buoyancy. Second, the water velocities set up by a gas release, cause forces on the ship. While several critical events have occurred to moored barges, this hazard is not considered a significant risk to FPSOs (Moan and Amdahl, 2001).

Accidental loads depend on system layout, structural arrangement, equipment etc. and must be determined in the following steps:

- preliminary estimate before the system is known, as input to preliminary design. These loads are obtained by engineering judgment, using experiences from previous projects, studies and research. Such information may be based on anticipated "as built" layout, equipment, etc.
- estimates of accidental loads for detailed engineering based on quantitative risk analysis.
- verification of accidental loads when the detailed design is completed.

Abnormal resistance is associated with fabrication errors and is commonly manifested in steel structures as crack defects, misalignment and corrosion or wear (in mooring chain, wire).

Total failure of the relevant turret mooring/dynamic positioning system may be initiated by a single line failure caused e.g. by excessive weld defects, wear at fairlead, and operational damage; or of thruster system. While the historical experiences until mid 1980's indicate a failure rate of approximately 0.04 per line year for K3/K4 chain mooring lines, the annual probability of single line failure has decreased to about $5\text{-}10 \cdot 10^{-3}$.

4.5.2 Reduction of risk

The magnitude of accidental loads can be controlled somewhat by reducing the probability of the initiating event. Passive or active measures can be used to control the magnitude of the accidental event. For instance, the fire load could be limited by sprinkler/inert gas systems or by structural fire protection. Similarly, through inspection and repair of the structure, suitable strength can be maintained.

5 PREDICTION OF SHIP COLLISION SCENARIOS

5.1 General

Ship and other impact events may cause

- structural damage of the hull that may eventually cause global collapse of the hull girder
- penetration of the hull and, hence, lead to:
  - flooding and loss of buoyancy, capsizing or sinking
  - outflow of oil (pollution) – including crude and processed oils on in FPSO vessels
  - fire/explosion (especially if in the future gas is also produced and stored in the FPSO vessels)

Flooding may also cause fatalities. Only one scenario with this potential consequence is pursued, in Section.5.3. Pollution risk is not explicitly assessed. In some cases, the damage could lead to fire and explosion.

The risk of total loss in the various failure modes may be estimated by combining the probability of occurrence of the relevant impact scenario and the conditional probability of local damage and consequential global failure. If the ALS criteria are fulfilled, they would implicitly reduce the risk of total loss according to the relevant acceptance criteria applied.

Fatalities may result from total loss or a severe impact to the machinery spaces.

Pollution will result if the cargo tanks are punctured. Minor leaks may occur if offloading hoses/pipes are damaged. Passing vessels and shuttle tankers contribute most to this risk.

Loss of property results from any damage that needs to be repaired. Relatively frequent impacts by supply and standby vessels and the like may contribute significantly to the costs of repair and downtime.

Collision scenarios should include in-field supply vessel collisions and ship traffic in general. The categories shown in Table 5.1 should be considered.

Vessel categories			
	Traffic category	Vessel category	Remarks
External	Trading	Trading ships Cargo, ferries etc.	Commercial traffic passing the area
	Naval traffic	Surface vessel	Both war ships and submarines
		Submerged vessels	Submerged submarines
	Fishing vessels	Fishing vessels	Sub-categorized into vessels in transit and vessels operating in the area
	Pleasure	Pleasure vessels	Traffic passing the area
	Offshore traffic	Standby boat	Vessels going to and from other fields
		Supply vessels	Vessels going to and from other fields
		Offshore tankers	Vessels going to and from other fields
		Tow	Towing of drilling rigs, flotels, etc.
Field related	Offshore traffic	Standby boats	Dedicated standby boats
		Supply vessels	Visiting supply vessels
		Working vessels	Special services / support as diving vessels, etc.
		Offshore tankers	Shuttle tankers visiting the field

Table 5.1 Categories of colliding vessels

The collision energy can be determined on the basis of masses, velocities and directions of ships (or helicopters) that may collide with the installation. Vessel traffic in the surrounding areas should be mapped, accounting, if possible, for future changes in vessel operational patterns. Design values for collisions are determined based on an evaluation of all possible events.

Trading vessels are often found to represent the greatest collision hazard to the FPSO.

Powered collisions will cover situations like navigational/maneuvering errors (human/ technical failures), watch keeping failure (e.g. no navigator on the bridge, watch keeper asleep, or radar malfunction), bad visibility/ineffective radar use, etc

5.2 Prediction of collision events

5.2.1 Previous experiences

Previous experiences have been presented e.g. by J.P. Kenny (1988), Haugen (1998), MacDonald et al. (1999). A total of 95 collision accidents that have occurred in the Gulf of Mexico between 1960 and 1998 are includede in the U.S. Minerals Management Service databases. Twenty-five of those accidents resulted in injuries, fire, explosion, blowout, or pollution incidents. The vessel and platform damage reported was minor to significant. Impacts have been more frequent in the North Sea.

A total of 491 collision incidents for offshore oil and gas installation in UK were documented during the period from January 1975 to the end of April 1997. The majority (>90%) of the incidents were caused by supply vessels and other support vessels. Eight were caused by passing vessels, including offloading shuttle tankers. Based on the estimated 3,200 operational platform years during this period, the overall annual frequency is in the order of 0.0025 and 0.15 for impact by passing and visiting vessels respectively. The collision frequency for installations on the Norwegian Continental Shelf is significantly smaller than in the UK (Kvitrud and Nilsson, 1995).

5.2.2 Collision probabilities

There are a number of possible collision scenarios that need to be addressed, but based on North Sea experience the three main collision scenarios that require detailed assessment are:

- Supply vessels (high frequency with the majority resulting in low consequence)
- Passing vessels (low frequency and high consequence)
- Shuttle tankers involved in offloading operations (medium frequency with high potential consequences)

Visiting vessels

The first collision scenario that can be foreseen for these vessels is collision during approach. Supply vessels may set their course straight for the installations and if a failure of some sort occurs in the final approach phase, a collision may occur. The frequency of collision in this scenario will in most cases be negligible if operational procedures are followed.

The second scenario is collision while a vessel is operating at or close to the offshore installation. This is the most frequently occurring type of collision. Because of the relative high frequency of such events, it is possible to estimate collision frequencies on basis of historical data (J.P. Kenny, 1988; Kvitrud and Nilsson, 1995; Haugen, 1998). An estimate of the frequency of impacts per installation year, is indicated in Table 5.2.

These estimates are based on installations other than FPSOs, and consideration should be given to their relevance to impacts on FPSOs. Moreover, the estimates are made based on typical North Sea data and should be modified if e.g. the number of approaches of supply vessels etc. is different.

In the early phases of platform design, the mass of supply ships should normally not be selected less than 5000 tons and the speed not less than 0.5 m/s and 2 m/s for ULS and ALS design checks, respectively. The latter event corresponds to an annual exceedance probability

of about 10^{-3} for visiting vessels in the North Sea (Haugen, 1998). A hydrodynamic (added) mass of 40% for sideways and 10 % for bow and stern impact can be assumed. With an annual impact probability of 10^{-3}, the probability of hitting a transverse bulkhead may be of the order of 10^{-4}.

	Vessel type		
Method of estimate	Authorized dedicated (supply vessel)[1]	Shuttle tankers/ FPSO[2]	Passing vessels (all)[3]
Historical data/ estimates	0.1-0.03	0.5-0.05	10^{-3} -10^{-6}

1 North Sea
2 The incident frequency is 0.7 per installation year, $5{\cdot}10^{-3}$-$5{\cdot}10^{-4}$ per loading operation
3 Very site dependent. Also the collision frequency would depend upon the time in service of FPSO. The collision frequency will decrease as the passing vessels become familiar with the FPSO location.

Table 5.2 Ship collision frequency per installation year

Passing vessels

Based on experience in the North Sea, the main contributor to collision risk is the route-based traffic of commercial shipping. In this category, collisions can be sub-divided into two groups:

- *Powered collisions*. Vessel is steaming towards the installation without the crew being aware of the situation.
- *Drifting collisions*. Vessel is out of control and drifting towards the installation under the influence of environmental factors.

The overall collision frequency associated with this traffic can therefore be expressed as:

$$P_{CP} = P_{CPP} + P_{CPD}$$

where

P_{CP} = frequency of passing vessel collisions
P_{CPP} = frequency of powered collisions
P_{CPD} = frequency of collisions due to a passing vessel adrift

For powered passing vessels various models (Technica, 1986; Haugen, 1991; Cain, 1995) have been developed. In the recent model by Safetec (Haugen, 1991; MacDonald et al., 1999), the vessels are assumed to move in shipping lanes that are characterized by (1) number of vessels and (2) probability distribution across the lane. Traffic data are required for the relevant area (Cain, 1995; MacDonald et al., 1999). The probability of being on a collision course depends on the distribution of vessel location across the lane, the size of the installation and how the installation is taken into account in the navigation of the vessel. See Figure 5.2. Second, the ship crew may fail to discover that the vessel is on collision course and correct the situation.

Shuttle tankers used for offshore loading may collide in transit as passing vessels, or they may collide with the loading buoy or storage tanker on approach or while in position when unloading from the FPSO (Vollen, 1997).

The frequency P_{CPP} of collision by powered passing vessels can be estimated as illustrated in Figure 5.1

P_{CC} (Figure 5.1) is represented by a relatively complex model, taking into account a number of different factors, of which the most important is the distance between the centerline of the shipping lane and the installation. As was mentioned earlier, the ships are assumed to travel in shipping lanes. The lanes are represented by a centerline and a statistical distribution around this centerline. The most common distribution is the normal distribution. This distribution is illustrated in Figure 5.1. The further away from the installation the centerline of the lane runs, the less likely it is that the ship will be on a collision course. The calculation of this probability is straightforward, by looking at the width of the installation and calculating the probability that a ship will fall in this part of the distribution.

Another factor that affects the statistical distribution of the ships is the pre-planning of the voyage. Offshore installations are marked on charts and most ship masters will plan their voyage so as to avoid coming too close. Alternatively, they may also in some cases choose to travel close to the installation to obtain positive identification and thus a verification to their position. Both of these effects may mean that ships need not travel in straight lines, and also that the statistical distribution of ships across a shipping lane is skewed rather than normal.

Even if a ship is on a collision course, the collision itself could still be avoided by keeping a proper lookout. It is therefore only in situations where the watch-keeping fails that a collision will occur. The probability of this event is taken into account by P_{FR} in the model.

The probability P_{FR} (Figure 5.2) is the product of two probabilities factors, P_{FSIR} and P_{FPIR} given by:

P_{FPIR} = probability of failure of vessel initiated recovery, i.e. probability of the vessel's crew itself failing to discover the pending collision and correcting the situation.
P_{FSIR} = probability of failure of platform (FPSO) initiated recovery, i.e. probability of actions taken by the crew of the FPSO or the standby vessel failing to alert the incoming ship of the pending collision.

P_{FSIR} is modeled using a fault tree. The fault tree includes a number of causes of watch-keeping failure, including:

- navigator asleep
- navigator absent from bridge
- navigator occupied with other tasks
- radar failure combined with poor visibility

Failure probability values are assigned to each of the branches in the fault tree to enable calculation of the total failure probability. The failure probabilities are also dependent on ship size, manning levels, flag, etc.

P_{FPIR} is used to modify P_{FSIR}, taking into account that the FPSO itself may alert the incoming vessel, by

calling the vessel on radio, using sound and light signals, using pyrotechnics, etc. The effect will depend on the type of measures and the way they are used.

This model can be applied to calculate the collision frequency for all vessels that travel past an installation (FPSO) in a route pattern. Some of the parameter data going into the model will however depend on the type of vessels that are being considered (Haugen, 1991).

Traffic data need to be collected for the specific area which is being considered. This information can be obtained by two general methods;

- Accessing a database on shipping movements (if available for the area of interest), e.g. Lloyds movement data.
- Performing a local traffic survey for the area

In the North Sea significant efforts have already been devoted to collecting ship traffic data (Safetec, 1998/99, 1996/97, Cain, 1995). Data are also established for Gulf of Mexico operations (MacDonald et al., 1999; Karsan et al., 1999). This method is implemented in the computer program COLLIDE (Haugen and Vollen, 1989). Other collision models have been developed by DNV Technica (1986) and Van der Tak and Glansdorp (1995).

The above model and the parameter data have been validated through comparisons with actual collision records from the North Sea (Haugen, 1991). This has been done by calculating the total collision frequency for all installations in the North Sea over the entire time that they have been on location. This total collision frequency has subsequently been compared with the actual number of collisions that has occurred and the model has been calibrated. Due to limited data, there is still significant uncertainty in the prediction methodology.

Typical levels for collision frequency of passing vessels are impossible to provide as it is so location dependent. In particular, the distance between the installation (FPSO) and center line of the shipping lane is crucial. In the North Sea, risk levels ranging from the order of 10^{-6} passing vessels collisions per year to 10^{-3} per year has been calculated.

The probabilities indicated will vary on different sites depending upon the traffic pattern. Hence, the passing vessels are predominantly trading ships of large size in the Ekofisk area, while e.g. in the Frigg/Statfjord area fishing vessels dominate. In addition the effect of e.g. traffic control and intervention actions planned in case of drifting vessels should be taken into account. Furthermore, environmental conditions type of location (open water/coastal), type of vessel (FPSO vs. platform), propulsion/steering performance, bridge watch-keeping and collision avoidance measure.

The conditional probability of vessel speed depends on the cause of the collision. In case of navigational error of passing ships, the speed is assumed to be the service speed. The following options are available for potential reduction in the risk from passing vessel collisions:

- Using the Radar on FPSO to monitor traffic
- Using a Standby Vessel to respond to any radar alarm and guard the FPSO
- Develop Hazard Management Plans specific to the location
- Install (additional) thruster on FPSO
- Use a Radar beacon (RACON) to increase the FPSO return signal
- Establishing an exclusion zone around installation (marked on charts)

A recent research project commissioned by the HSE

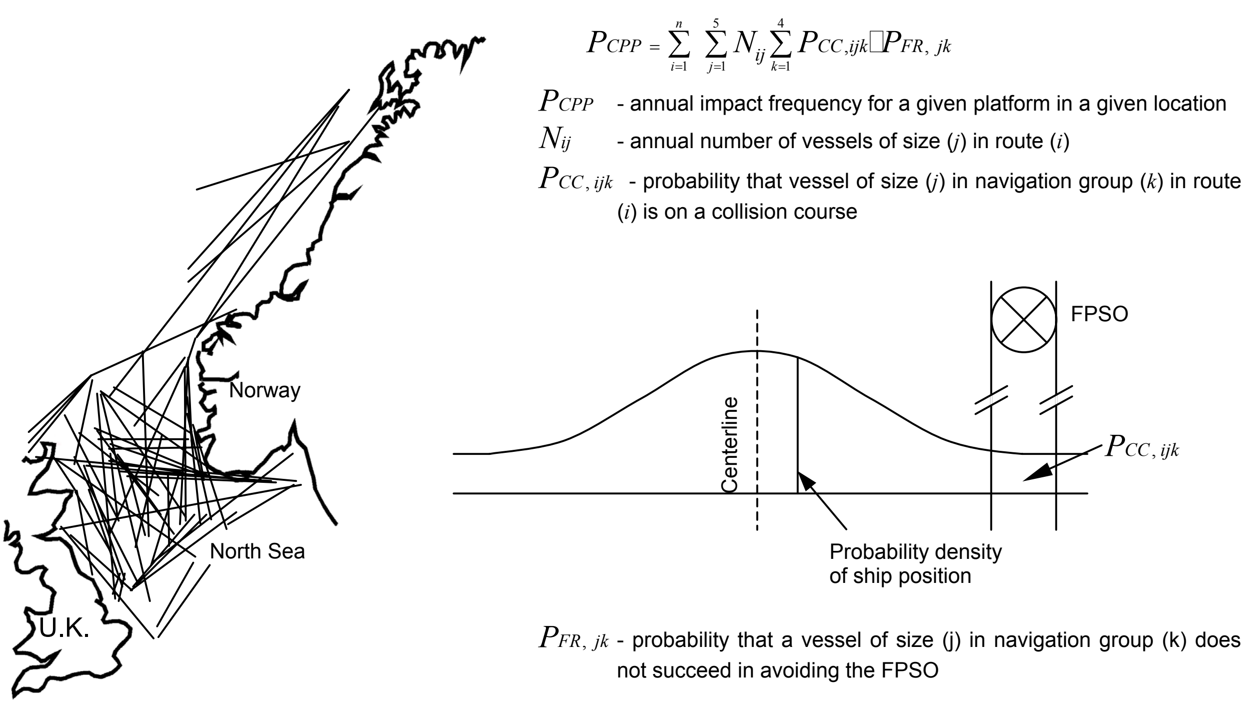


Figure 5.1 Determination of the frequency, P_{CPP}, of powered passing vessel impact on FPSO

looked at a number of different systems being used to aid in the management of collision risks associated with offshore installations (Safetec AS, 1998/99). However, there is not a clear conclusion yet as to which measures should be prioritized.

Besides the (minimum) ship impact events due to supply vessels, mentioned above, collisions by powered passing vessels may amount to 10 MNm and upwards, to some hundreds of MNm.

The frequency of collision for a *drifting vessel* can be estimated by:

$$F_C = N \cdot P_d \cdot P_{ch} \cdot P_{nr}$$

where

F_C = frequency of collision

N = number of units (ships or barges, if drifting passing vessels are considered)

P_d = probability of unit starting to drift (lost propulsion or steering)

P_{ch} = probability of unit drifting towards an installation

P_{nr} = probability of no effective recovery actions (e.g. restart engine, tug assistance)

This model is briefly discussed by Haugen (1998). The crucial parameter is P_d. In COLLIDE (Haugen and Vollen, 1989) a frequency of main machinery "breakdown" of $2 \cdot 10^{-5}$ per hour is applied. The number of units, N, is taken to be those within a radius of 15-20 nautical miles and P_{ch} is based on ocean meteorology data and geometrical considerations. P_{nr} depends upon time available to control hazardous situation, machinery restart probability (0.9 within one hour) and emergency towing probability.

The speed of a drifting ship depends upon the distance from the target when power is lost and the environmental conditions. The speed of dedicated vessels attending the platform varies from zero to almost full speed.

Other drifting objects may include platforms with mooring (positioning) system failure.

Various efforts to reduce the risk associated ship impact should be considered and taken into account in the risk assessment. Such effort may be directed towards reducing the probability or the consequence of the impact. Reduction of the impact probability has been achieved by radar surveillance systems and by the provision of a 500 m radius designated safety zone around the platform with restrictions on entry by unauthorized vessels.

Shuttle tanker collision

Tankers which are used for offshore loading may be involved in several types of collisions:

- Collision of powered or drifting tanker with installation (FPSO). This can be treated as for collisions for other passing vessels with platforms, defining the tanker route as part of the shipping traffic data. This scenario is treated as a passing vessel.
- Collision of shuttle tanker with FPSO during offloading. This may be due to human error or machinery failure on approach or due to a mooring or Dynamic Positioning (DP) failure during offloading operations.

The latter scenario is of interest here. The offloading operation can take place in two different modes, namely alongside transfer and tandem moored transfer, according to the relative positions assumed by the FPSO unit and the shuttle tanker during offloading operations.

In the tandem moored case, the shuttle tanker is moored to the FPSO by hawsers and/or Dynamic Positioning (DP), while the cargo is off loaded through floating hoses. Depending on the environmental conditions and the offloading procedures adopted, the shuttle tanker could be equipped with DP and/or assisted by tugs and/or a supply/standby vessel during offloading operations (approach, mooring, cargo loading and disconnecting mooring/ departure). The DP on shuttle tankers is mainly implemented to reduce the risk of collision and give greater uptime in harsh conditions. It is commonly used in the North Sea, but not in Africa, SE Asia and South American/Caribbean areas. One or more tugs or a support vessel usually helps avoid collision during FPSO mooring, offloading and disconnecting mooring.

Shuttle tanker operation can be summarized according to the following five operational modes:

1. Approach of the shuttle tanker to the FPSO system.
2. Mooring of the shuttle tanker to the FPSO system.
3. Connection of loading hose.
4. Cargo loading.
5. Disconnection of loading hose and mooring; and departure.

A (tandem) offloading operation is basically a complex marine operation with long duration. The FPSO is continuously weather vaning around its turret located either internally (as in Figure 5.2) or externally. It is also subjected to significant motions in the horizontal plane (surge, sway and yaw) due to waves and wind if in harsh environments. In order to stay connected and maintain the separation distance, the shuttle tanker must position itself to follow the FPSO whenever it changes heading or position during offloading period, which on average may last more than 20 hours.

The field production rate, tanker size and storage size of FPSO determine the frequency and duration of offloading operation. Typically, this is a frequent operation, ranging from every 3 to 5 days, and with duration of 15 to 24 hours. Further, the operation has to rely on suitable environmental conditions, for example, significant wave height should be smaller than 5.5 m for two vessels staying in connection. However, commercial pressure, "get things done" culture, and other factors may influence the decision.

The major risk in offloading between an FPSO and shuttle tanker is collision, but, as incidents have shown, hawser or hose breakage – that may cause oil spill and production delays, should also be noted. These risks are rooted in the technical design and are triggered by

certain environmental conditions. Last but clearly not the least, human factor plays a big role during the incidents. This is reflected by human errors that initiate or escalate incidents, human intervention of crisis that avoided more severe damage, or organizational factors, e.g. tanker bridge resource management.

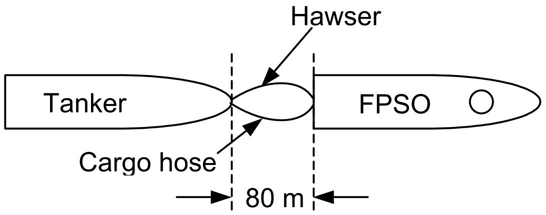


Figure 5.2 FPSO- Shuttle Tanker offloading operation

Risk assessment of this kind of operation needs to be based on previous incidents involving FPSO/shuttle tanker contact. But experiences (HSE, 1997) with offloading with shuttle tankers from an articulated loading platform or buoy are also very useful.

Actually, based on observed collisions between shuttle tankers and loading buoys in the Norwegian sector, Kvitrud and Nilsson (1995) estimated the frequency of such events to be 10^{-3} per loading. Previous estimates indicate $1.4 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$ per loading. Theoretical studies on the reliability of the DP system (Signoret et al., 1985) account for technical reliability but not for the human reliability of DP operators on tankers, which seem to dominate.

Collisions are caused by uncontrolled relative movement between the vessels. Based on data from HSE, SYNERGI databases as well as FPSO and Tanker Operations some pattern in the accident causation emerge (Chen and Moan, 2002). This movement can be initiated when active operation need to be carried out during cargo loading and temporary modes: approach, connecting and disconnecting mooring and hose

Uncontrolled movements may be initiated by technical failures (DP positioning, reference system, main engine/propeller) which require countermeasures, and human response is inadequate, and erroneous DP operation in temporary modes; or when changes occur during loading operations due to weather changes, and especially when particular relative movement (surging and yawing – e.g. fishtailing) between the FPSO and tanker occur. The critically is worsened if technical failures occur during temporary modes, e.g. in the approach mode.

The human errors are due to operators' wrong expectations of DP functions, which lead to improper use of DP to position and maneuver the tanker. On the other hand, human intervention (evasive maneuvering) right before collision is an important issue, as born out by the incidents experienced so far.

Both incident rate and calculations (e.g. Haugen, 1998; MacDonald et al., 1999) indicate a fairly high annual probability of contact (say, 0.05–0.5). The crucial issue then is the conditional probability of impact speed. Even a relative speed of 0.4 m/s between the vessels, each with a mass of the order of 100,000 tons, imply a corresponding minimum impact energy. Collisions at larger speeds may be relevant (Vollen, 1997).

To reduce the risk of shuttle tanker collision, among others the following measures are envisaged:

- Use of dedicated tankers with high degree of redundancy (twin engines, CPP etc.), and bow thrusters
- Use of a dedicated crew, and improve training
- Use stringent procedures for shuttle tanker approach (Intertanko is going to introduce new guidelines for shuttle tanker operational procedures)
- Improve reliability of machinery
- Improve reliability of GPS (use DARPS on FPSO)
- Add thrusters on FPSO
- Assess dynamic interaction between tankers in different environmental conditions

5.3 Design collision events

The following scenarios impact on the FPSO need to be addressed: supply vessel on FPSO side, passing trading vessel on FPSO side and shuttle tanker bow- FPSO stern

When the probability of impacts from different types of ships have been determined, the associated collision energy can be estimated from their mass and speed. Variation in speed can be accounted for by a conditional probability. An energy spectrum, showing the cumulative frequency of collision versus the collision energy can then be generated and the event corresponding to an annual exceedance probability of e.g. 10^{-4} may be determined.

The most probable impact locations (bow, stern, side) and impact geometry should be established based on the dimensions and geometry of the structure (FPSO) and the impacting vessel, and should account for draught variations, operational sea-state and motions of the vessel and structure.

When dealing with collision energy and damage it may be convenient to use the following categories: energy or damage given by prescriptive requirements and energy or damage beyond what is current prescriptive requirements.

The prescriptive requirements (for North Sea operations) include specification of collision events, with a collision energy of 14 MJ for broad side collision with a supply vessel and 11 MJ for head-on collision, and one/two – compartment damage in stability requirements.

The distribution between the different types of energy will depend on the actual scenario being considered and is difficult to generalize. Among the most important factors which will influence the energy distribution are:

- Impact geometry: With a glancing blow, part of the impact energy will remain as kinetic energy in the ship and will not contribute to the damage to the FPSO.
- Vessel and impact geometry: Bulbous bows (bulbs) are stiffer than raked bows, implying that a greater percentage of the collision energy is absorbed by the FPSO.

The ship collision hazard is very site dependent, and no general criteria for the risk or relevant accidental events for design can be provided.

6 ASSESSMENT OF COLLISION DAMAGE

6.1 Principles for analysis/design

The ship collision action is characterized by a kinetic energy, governed by the mass of the ship, including hydrodynamic added mass and the speed of the ship at the instant of impact. If the collision is non-central, i.e. the contact force does not go through the center of gravity of the two structures, a part of the kinetic energy may remain as kinetic energy after the impact. The remainder of the kinetic energy has to be dissipated as strain energy in the FPSO and the vessel. Generally this involves large plastic strains and significant structural damage to either the installation or the ship or both. With respect to the distribution of strain energy dissipation there may be distinguished between strength design, ductility design, and shared-energy design. As shown in Figure 6.1 the distribution depends upon the relative strength of the two structures.

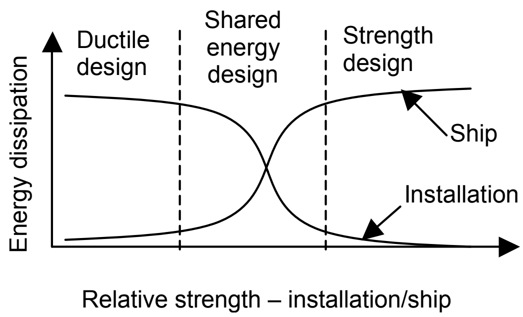


Figure 6.1 Energy dissipation for strength, ductile and shared-energy design

Strength design implies that the installation is strong enough to resist the collision force with minor deformation, so that the ship is forced to deform and dissipate the major part of the energy.

Ductility design implies that the installation undergoes large, plastic deformations and dissipates the major part of the collision energy.

Shared energy design implies that both the installation and ship contribute significantly to the energy dissipation.

From a calculation point of view, strength design or ductility design is preferred. In this case the response of the "soft" structure can be calculated on the basis of simple considerations of the geometry of the "rigid" structure. In shared energy design both the magnitude and distribution of the collision force depends upon the deformation of both structures. This interaction makes the analysis more complex. In most cases ductility or shared energy design is used. However, strength design may in some cases be achievable with little increase in steel weight.

In the case of a ship collision with an FPSO traditional ductile analysis/design assumes that the bow of the ramming vessel remains undamaged. The shape of the striking bow determines to a large degree the shape of the deformation field in the FPSOs side structure. Having determined the deformation mechanism or velocity field, plastic methods of analysis can be used to assess the energy dissipation in the side structure.

Conversely, if the side is assumed strong enough to crush the bow structure, plastic analysis can be applied to determine the energy dissipation associated with crushing of the bow. By this, the relationship between force and deformation of the bow is established. In addition the distribution of the force over the contact area needs to be determined, in order to detect local hot spots, i.e. local concentrations of the total collision force. The FPSO side structure must then be checked to ensure that it resists the total collision force as well as local concentrations of collision force without significant deformations during the entire impact history. This task is analogous to checks carried out in the ultimate limit state (ULS). The approach is illustrated for supply vessel collision against a large diameter stiffened column in the Section 6.1.1.

If neither ductile – nor strength "behavior" can be guaranteed, shared energy design must be assumed. This renders calculations significantly more complex, because of the interaction between the structures. The analysis has to be carried out incrementally on the basis of the current deformation field, contact area and force distribution over the contact area. The weaker structure is forced to deform most, whereas the damage to the other may remain virtually unchanged during an incremental step. The relative strength of the two structures may vary both over the contact area as well as over time. It is noted, however, that the condition for shared energy behavior may be very unstable; small modifications to one structure may cause the behavior to switch to strength or ductile behavior.

6.1.1 Force-deformation relationships for ship

Recommended design curves for supply vessels with a displacement of 5000 tons can be found in the NORSOK code. The curves are shown in Figure 6.2 for broad side-, bow-, stern end and stern corner impact for a vessel with stern roller.

The curve for supply vessel bow impact is based upon collision with an infinitely rigid, plane wall and may be used for large diameter column impacts and *collisions with tankers like FPSOs*. They are not representative for significantly different collision scenarios, e.g. impact against tubular braces in jackets.

Force-deformation relationships for tanker bow impact against a plane, rigid wall are given in Figure 6.3 for the bulbous part and the bow structure, respectively. The idealized geometry of the total contact area is indicated in both figures. The curves may be used for stern impacts from the bow of shuttle tankers (~ 125.000 dwt) provided that the rammed stern does not undergo substantial deformation i.e. *strength analysis/design*

requirements are complied with. If this condition is not met, interaction between the bow and the stern structure must be taken into consideration.

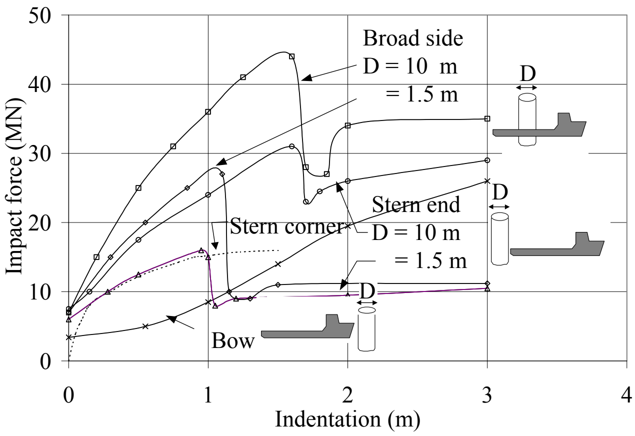


Figure 6.2 Recommended deformation curve for beam, bow and stern impact

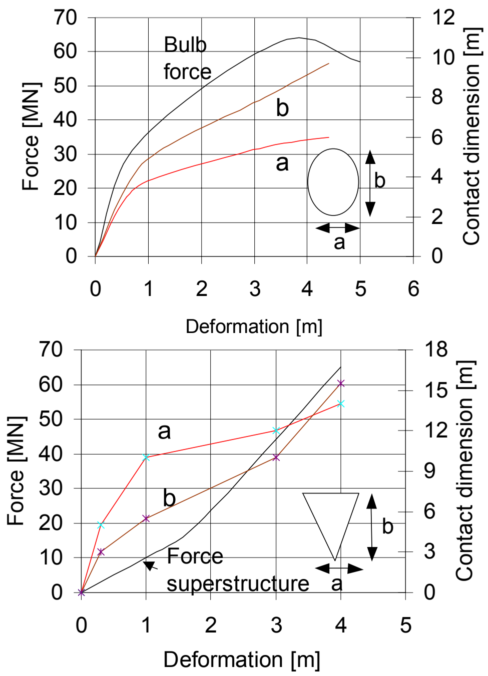


Figure 6.3 Characteristic Force-deformation relation-ship for tanker bow impact (~ 125.000 dwt), e.g. shuttle tanker against FPSO (NORSOK Appendix A, 1998). FPSO complying with strength design require-ments, i.e. no damage to FPSO.

6.1.2 Collision mechanics

The collision problem comprises internal mechanics related to large, inelastic deformations at the point of contact as well as global hull bending of the struck vessel, and interaction with the surrounding fluid (added mass, viscous forces etc.). A fully integrated analysis is fairly demanding. It is, therefore, often found convenient to split the problem into two uncoupled analyses, namely, the external collision mechanics dealing with global inertia forces and hydrodynamic effects, and internal mechanics dealing with the energy dissipation and distribution of damage in the two structures. In the present case this is considered to produce satisfactory results, in view of the uncertainties that will persist in a fully integrated analysis.

External mechanics. The purpose of the external collision mechanics is to determine the amount of collision (kinetic) energy to be dissipated as strain energy. This is achieved by assuming that the dominant forces during a collision are inertia forces (including hydrodynamic added mass) and the collision force. Viscous forces are neglected. Applying the principle of conservation of momentum and conservation of energy the amount of kinetic energy to be dissipated as strain energy, E_s, is given by the formula (see NORSOK Appendix A, 1998):

$$E_s = \frac{1}{2}(m_s + a_s)v_s^{\,2}\frac{\left(1-\frac{v_i}{v_s}\right)^2}{1+\frac{m_s+a_s}{m_i+a_i}} \tag{6.1}$$

where m_s is ship mass, a_s is ship added mass, v_s is impact speed, m_i is mass of FPSO, a_i is added mass of FPSO, v_i is velocity of FPSO. In most cases it is natural to assume that the velocity of the FPSO can be disregarded, i.e. $v_i = 0$.

The strong dependence of the mass ratio is noticed. In most cases the mass of the FPSO is significantly larger than the mass of a supply vessel, implying that the entire collision energy has to be dissipated as strain energy. In case of collision with a shuttle tanker, however, the mass ratio may be significant, and a significant fraction of the collision energy may be transferred into kinetic energy of the FPSO, yielding a relatively less demand for strain energy dissipation in the two structures.

Internal mechanics. The structural response of the ramming ship and FPSO can formally be represented as load-deformation relationships as illustrated in Figure 6..

The strain energy dissipated by the ship and FPSO equals the total area under the load-deformation curves:

$$E_s = E_{s,s} + E_{s,i} = \int_0^{w_{s,max}} R_s dw_s + \int_0^{w_{i,max}} R_i dw_i \tag{6.2}$$

where $E_{s,i}$, $E_{s,s}$, are strain energy of FPSO and ship, respectively, R_i, R_s are resistance of FPSO and ship, dw_i, dw_s are deformation of FPSO and ship.

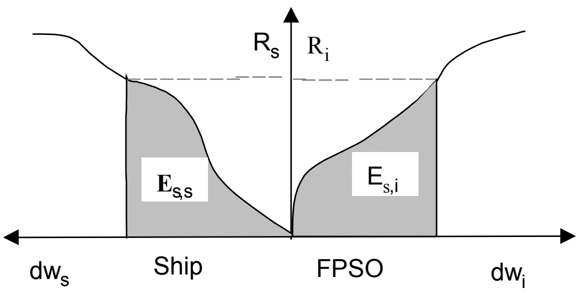


Figure 6.4 Dissipation of strain energy in ship and FPSO

As the load level is not known *a priori* an incremental procedure is generally needed. It is customary to establish the load-deformation relationships for the ship and the FPSO independently, assuming the other object infinitely rigid. As discussed in Section 6.1 this method may have severe limitations, because both structures will inevitably dissipate some energy regardless of their relative strength.

Often the stronger of the ship and FPSO will experience less damage and the softer structure more damage than predicted with this approach. As the softer structure deforms, the impact force is distributed over a larger contact area. This is beneficial for the stronger structure, which tends to maintain its shape during this stage of deformation. Accordingly, the resistance of the strong structure increases compared to that obtained with the soft structure assumed rigid. This may be interpreted as an "upward" shift of the resistance curve for the stronger structure at a given deformation level (Figure 6.4). Care should therefore be exercised that the load-deformation curves calculated are representative for the true, interactive nature of the contact between the two structures.

6.2 Energy dissipation in ship side structures during collision

6.2.1 Nonlinear Finite Element Analysis

Recent advances in computers and algorithms have made nonlinear finite element analysis (NLFEM) a viable tool for assessing collision. There are generally two methodologies available: *implicit* analysis and e*xplicit* analysis. Implicit methodologies require the solution of systems of equations. This places demands on the equation solver and the computer capacity especially in terms of memory resources. *Explicit* systems do not require equation solving. Equilibrium is solved at the element level. In order to comply with stability requirement for equation solving, very small time steps are needed.

There are two important factors to consider in modeling structures for NLFEM: element type and mesh fineness. Higher order elements perform better and allow a cruder mesh, but require more computational effort for each element. The importance of mesh fineness has been studied by Servis et al. (2001) and Amdal & Kavlie (1992). It is found that a very large number of elements is required in order to obtain accurate results for components deforming by axial crushing.

A major challenge in NLFEM analysis is prediction of ductile crack initiation and propagation. This problem is not yet solved. The simplest approach to the problem is to remove elements once the critical strain is attained. This is fairly easily done in an explicit code because there is no need to assemble and invert the effective system stiffness matrix. However, deleting elements disregards the fact the large stresses can be maintained parallel to the cracks. An improved modeling is to introduce a double set of nodes such that the elements are allowed to separate once the critical stress is attained (ref. e.g. Amdahl & Stornes 2001). Recently, one-dimensional line spring elements have been developed (Amdahl & Skallerud 2001) for use with shell elements. The key point is that crack initiation and propagation is based on fracture mechanics analysis like the J-integral or Crack Tip Opening Displacement method rather than simple strain considerations. A drawback with a double set of nodes or the line spring elements is that the potential location of cracks has to be defined prior to analysis.

The critical strain for fracture depends on the stress-strain measure as well as the mesh size. Various options exist for the stress-strain relationship. Most often engineering stress-strain or true stress-strain is used. The true stress-strain relationship models the physical process more accurately than the engineering stress-strain, but it is more complex as the volume change of the element needs to be calculated. Experience obtained thus far indicates that the difference between the two approaches is very small up to ultimate stress as far as load – displacement and energy dissipation are concerned.

The dependency of fracture strain on element size has been studied by Simonsen and Lauridsen (2000). Strain rate may influence the stress levels. The most commonly adopted formula is that proposed by Cowper and Symonds (1957). Another formula is also proposed by Reckling (1976).

Analysis of ship collisions. NLFEM analysis has been used repeatedly over the past decade, but no direct analysis of supply vessel collision with FPSOs is available. Considerable effort has been expended under the auspices of the Shipbuilding Research Association of Japan (JSRA). Kitamura (2001) has investigated several aspects related to side collision of a purpose built ship for transport of spent nuclear fuel. It is shown that the horizontal, global hull girder bending moment is important if the ramming ship is very large, but can be ignored if the ramming ship is small. Supply vessels are considerably smaller than typical FPSOs, which means that global bending of the FPSO may be neglected.

6.2.2 Simplified methods

Simplified methods of predicting damage resistance generally follows three different lines:

- Empirical – relating energy dissipation to volume of damaged material
- Analytical (buckling)
- Analytical (plastic)

The empirical methods were first formulated by the pioneering work of Minorski (1959). It relates the energy dissipation to volume of damaged material in the colliding ships. A disadvantage with the method is the large scatter in the calculated damages at moderate and low energies, characteristic of supply vessel/FPSO impacts. Several modifications to Minorski's method have been proposed, e.g. by Jones (1979), Woisin (1979) and Frieze and Smedley (2001), notably to account for membrane action in the side plating and stiffeners. These components contribute over-proportionally (relative to their volume) to the energy dissipation. Despite modifications proposed, the Minorski's method is considered too crude for credible assessment of the deformation of the sides of double hull tankers/FPSOs up to the inner shell.

The analytical approach based upon buckling of complex structures is particularly due to Gerard (1957). The method postulates that the maximum strength is a function of plate slenderness ratio of basic elements, obtained by introducing conceptual cuts which reduce the cross-section to a series of flange element. Gerard's method with distorted edges has been used with success by Minorski (1977, 1983) to assess the energy dissipation by recorded in a test of a model of a 195.000 dwt tanker. The method is intended for the *maximum* strength, only. Hence, it is somewhat surprising to observe the good agreement between tests and predictions as concerns *average* crushing resistance.

The analytical approach based upon plastic methods of analysis aims at assessing the *average* collision force because the entire crushing process is calculated. This is satisfactory as long at the force does not oscillate wildly about the mean level (typically for transversely farmed ships) or energy dissipation only is concerned. The method is based upon a description of the governing deformation fields. The basic idea is that the actual structure is assumed to be composed of a few fundamental components by which the idealized deformation field can be described. The energy dissipation in each component is calculated and summarized to obtain the total energy dissipation. Similar to the method suggested by Gerard, conceptual cuts are introduced so that the bow cross-section is reduced to an assembly of fundamental elements such as angles, T-sections and cruciforms. In accordance with the concept of the kinematic methods of plasticity, the contributions to the internal energy dissipation from each element are added up and equated to the work done by the external load over the specified distance.

6.3 Side collisions – simplified analysis

The structural damage to an FPSO caused by various collisions was studied by Amdahl and Kavlie (1992). The colliding ship is assumed to be a chemical tanker of 18,000 tons displacement and an oil tanker of 42,000 tons displacement. The bow of both vessels is fitted with

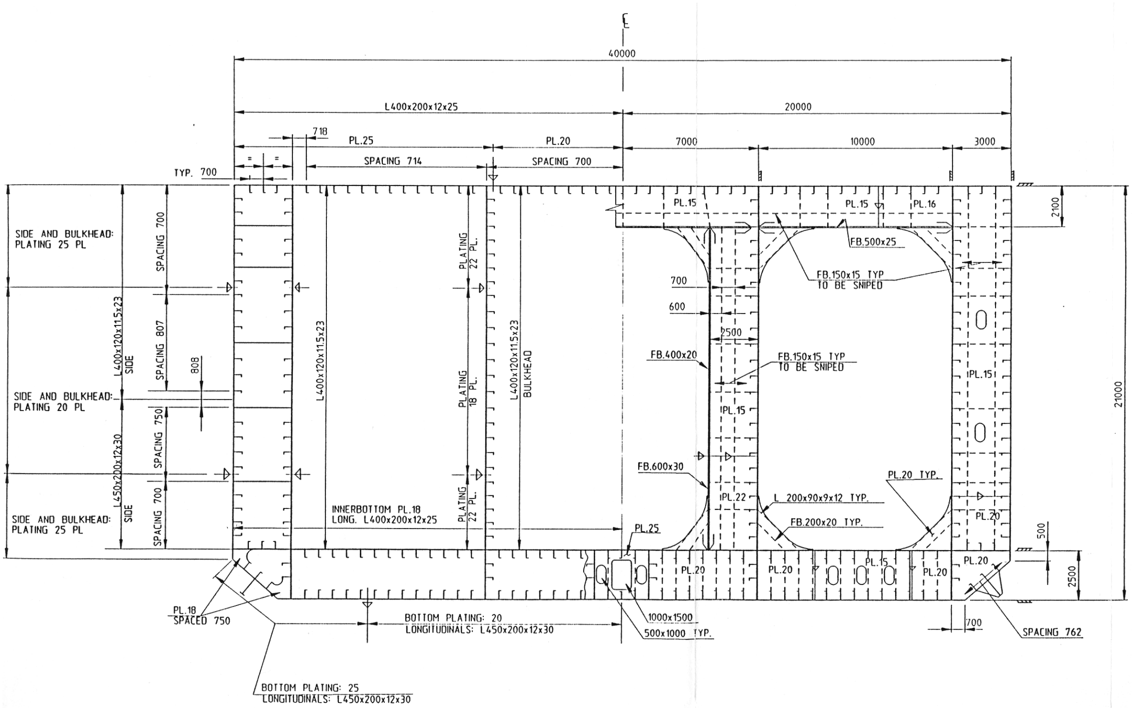


Figure 6.5 Midship section and web-frame for tanker analysed in the 1992 project and present NLFEM analyses

a bulb. Three different concepts are analyzed. They show different properties with respect to resistance against collisions, notably due to different side stiffener dimensions and different side tank width. Results are primarily reviewed for the ship used in the present NLFEM analyses, see Figure 6.5.

The analyses are based upon simplified techniques. The capacity of the side shell of the FPSO is calculated by means of plastic theory considering finite deformations, similar to the approach described in Section 6.2. Finite ductility is considered, and fracture in the stiffener is predicted by means of the ductility criterion given in DNV 1989. Fracture in the shell plating is assumed to occur for an average strain of 0.05. The strength and energy dissipation in transverse frames is calculated by means of Gerard's method.

Bow structure vs. ship side. Figure 6.6 shows the capacity of the ship side – on the assumption that it remains virtually intact - as a function of the deformation of the bow structure, i.e. the bow from the waterline up to the forecastle deck. The area of contact is in the upper 1/4 of the side, between two transverse frames. Please observe that the capacity curve for the side should not be interpreted as a load-displacement curve.

The contact area increases rapidly with bow structure deformation. Accordingly the capacity of the tanker side increases. For impact with the chemical tanker, the FPSO has excess capacity, especially for large deformations, so that the side is likely to undergo moderate deformations. When it comes to impacts with the 42,000 tons tanker, the side capacity is virtually identical to the demand from the bow structure, so it is more likely that it will be subjected to significant deformation. According to this calculation the situation is somewhat unpredictable, and slight changes in the structures may have a substantial impact on the resulting damage.

In the case of collision on a transverse frame or on a transverse bulkhead the side capacity will be greater resulting in less damage to the FPSO side.

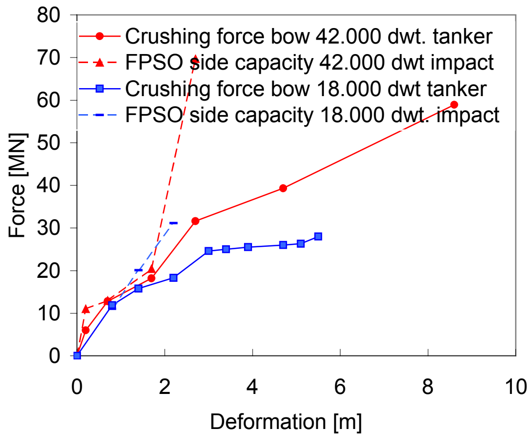


Figure 6.6 Bow structure force versus side capacity

Bulb vs. ship side. Bulbs are significantly more compact compared to bow structures. It is, therefore, anticipated that the ship side is not capable of resisting penetration of the bulb. Tentatively, ductile deformation of the side is assumed, implying an infinitely stiff bulb. The resistance of the side is then calculated on the basis of the deformation field of the penetrating bulb. The validity of this assumption is checked by comparison with bulb deformation characteristics.

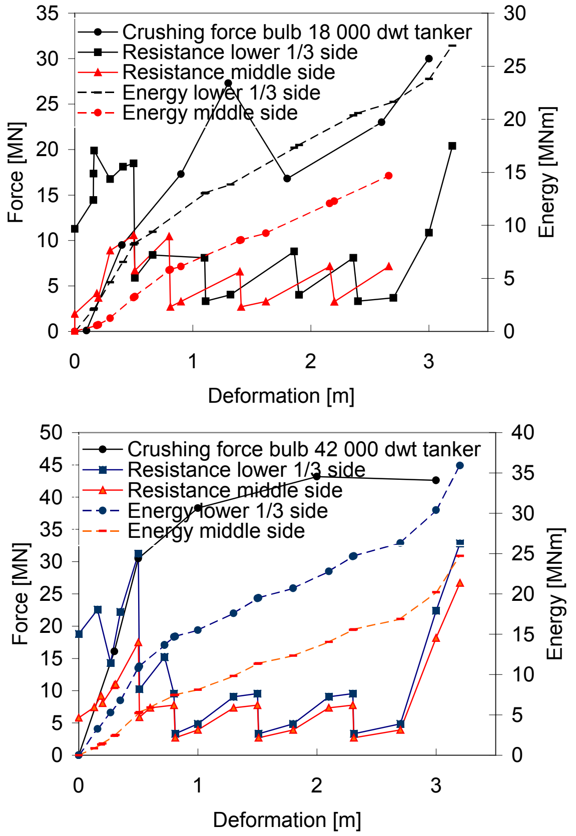


Figure 6.7 Force and energy versus tanker side deformation (middle part) assuming rigid bulb for 18.000 tons dwt chemical tanker and 42.000 tons dwt. tanker.

Figure 6.7 shows load-displacement and energy absorption relationships for bulb impact between two transverse frames. The various troughs in the diagrams correspond to rupture of a stiffener and associated plate flange. Maximum collision force occurs fairly early before extensive fracture takes place in the side. The lower 1/3 of the FPSO side has a larger capacity than the middle part. The increased stiffener size and plate thickness along with the reduced spacing has double effects: i) the strength of the stiffener with associated plate flange increases; and ii) increased strength yields a larger bulb deformation and contact area, thereby activating more stiffeners. In the case of the 18,000 ton chemical carrier impact the maximum resistance is in the range 11 MN for the middle part to 19 MN for the lower 1/3 of the side while the maximum bulb force is 27 MN. In the case of the 42,000 ton tanker impact the maximum resistance is in the range of 17 MN for the middle part to 31 MN for the lower 1/3 of the side as compared to a maximum demand of 43 MN. Consequently, according to these considerations, in neither of the cases the side is capable of resisting penetration of the bulb.

If contact takes place on a transverse frame, it is possible that the side *may* be strong enough to crush the bulb, notably that of the 42,000 ton tanker due to the large contact area. It is, however, pointed out that in all cases the margins are very low. The conclusions are therefore not firm.

Tanker	Wing tank		Center tank	
	Lower 1/3	Middle	Lower 1/3	Middle
18 000 dwt	55	40	160	135
42000 dwt	18	8	105	85

Table 6.1 Critical energy [MJ] for penetration of wing tank and center tank

Critical energy. The critical energy for penetration of the wing tank and center tank is given in Table 6.1. Since the side is capable of crushing the bow structure, it is penetration of the bulb that is assumed. The major reason for the small energies related to the 42,000 ton vessel is that the bulb and the bow structure come into contact with the tanker side almost simultaneously whereas the bow structure protrudes forward of the bulb in the case of the 18,000 ton vessel and contributes more to the energy dissipation. The figures should not be considered as exact, but rather indications of order of magnitude. The results depend considerably on the actual bow/bulb configurations used. If wing tank breadth is increased without loss of structural strength, there is a significant effect on critical energy with respect to center tank penetration.

6.4 Shuttle tanker impact

The large mass of shuttle tankers implies that collisions by these vessels have the potential to involve large amounts of energy. It is indicated that the probability of stern impact by the shuttle tanker is relatively high. However, the relative velocity could vary from zero to some maximum value. Incidents that have been experienced show that the intervention to reduce speed in one case was very successful. In the relative limited number of accumulated operational years, the most severe shuttle tanker impact so far involved an energy of 37 MJ (BOMEL, 1999). In this section some deliberations on the potential maximum velocity and corresponding energy than can be attained in a drive off situation. The purpose is especially to investigate when penetration of the machinery room occurs. Since this event may cause fatalities, it is a critical event. Furthermore, this event may cause excessive forces in the mooring and riser system. An indication of the damage is obtained by using the bow of typical 140,000 dwt tanker and an FPSO with the same displacement. Two impact situations are considered - both assuming the production vessel loaded to the mean water line:

Shuttle tanker in ballast condition: the bulb hits the stern of the FPSO midway between horizontal and vertical stringers/decks. The upper part of the bow above approximately 17 m from baseline is free of the poop deck, so that only the bulb will be in contact with the stern until this is deformed 5.6 m, refer Figure 6.8.

Shuttle tanker in fully loaded condition: the forecastle deck is positioned at approximately the same height as the upper deck of the FPSO. The bulb is free of the stern and the deformation takes place in the bow structure only, refer Figure 6.9.

Impact energy- Assessment of damage. The assessment of energy dissipation in the bow and the stern is based upon simple methods of plastic analysis outlined in Section 6.3. The crushing force of the bow is calculated assuming the entire cross-section is subjected to uniform deformation by a "rigid wall". Similarly, the crushing force of the stern section is calculated assuming an infinitely rigid bow. The affected area is assumed to be approximately defined by the cross-section of the bow for a given indentation. The interaction between bow and stern deformation is simply calculated from the respective force-deformation relationships applying the condition of equal collision force. As discussed in Section 6.1 this is an oversimplification, but is considered to of moderate significance in the present case.

The force deformation curves for bulb impact from a shuttle tanker in ballast condition is depicted in Figure 6.10. It appears that the bulb is considerably stronger than the stern, due to the small contact area and heavy stiffening of the bulb. Penetration of the machinery room is assumed to occur for a relative deformation of the two structures equal to 2.6 m, corresponding to 3 m deformation on the stern side minus 0.4 m deformation on the bulb side. The total energy dissipation at this stage amounts to 38 MJ.

For a collision with the shuttle tanker in a loaded condition, the strength of the bow structure and the stern are more equal. The force-penetration relationships are shown Figure 6.10. It is not obvious when the machinery room will be penetrated, but the associated energy dissipation is substantially larger than that for the bulb impact.

Kinetic energy. The energy to be dissipated as strain energy can be estimated by means of equation 6.1. Assuming the mass of the shuttle tanker to be 70,000 tons in ballast, the mass of the FPSO 140,000 tons and added mass of 0.1 times the above values it is found that 2/3 of the impact energy has to be dissipated as strain energy. If penetration of the machinery room is found to be critical, the critical kinetic energy is 57 MJ. This corresponds to a traveling speed of 1.2 m/s for the shuttle tanker. With both the shuttle tanker and FPSO in fully loaded conditions the mass of the two vessels is equal. This means that the only 1/2 of the kinetic energy has to be dissipated as strain energy.

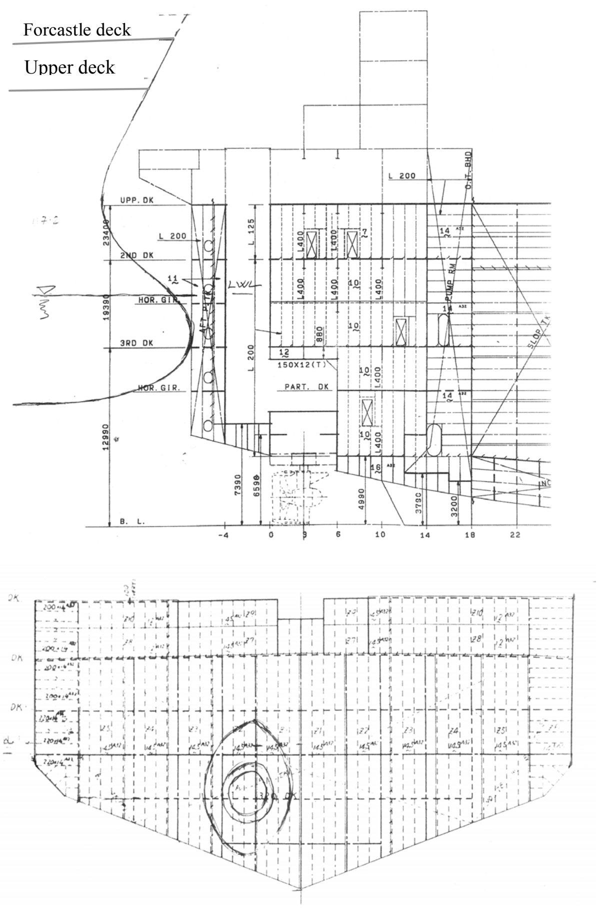


Figure 6.8 Shuttle tanker – FPSO collision. Ballast condition.

The impact speed for penetration of the machinery room may be related to a theoretical speed that can be calculated on the basis of the following assumptions: The shuttle tanker is positioned a distance, s, from the FPSO. If the shuttle engine is put on full speed ahead, and full power is maintained during the entire period, maintaining constant thrust equal to the thrust at full speed (reasonably accurate), the speed, v, after a sailed distance, s, can be estimated from the following equation:

$$v = v_t\sqrt{1-e^{-\frac{s}{s_c}}} \approx v_t\sqrt{\frac{s}{s_c}} \qquad \text{when } s << s_c \tag{6.3}$$

where v_t is the full speed of the shuttle tanker (assumed to be 7.7 m/s ≈ 15 knots) and s_c is the characteristic distance for the shuttle tanker, assessed to be 2160 m in ballast condition and 2750 m in fully loaded condition. From Equations (6.1) and (6.3) it is observed that:

1) The energy is proportional to the traveled distance and inversely proportional to the characteristic distance
2) The energy is proportional to the terminal velocity squared

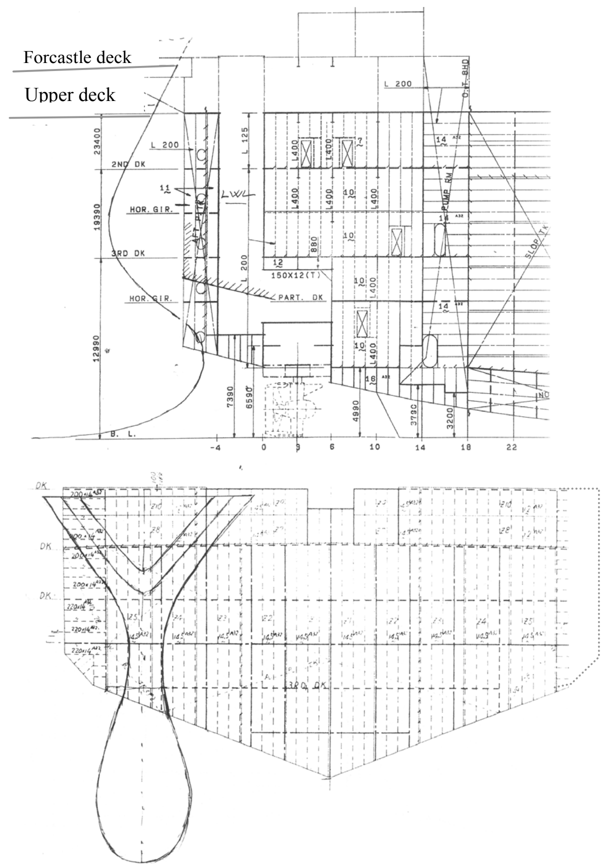


Figure 6.9 Shuttle tanker – FPSO collision. Loaded condition.

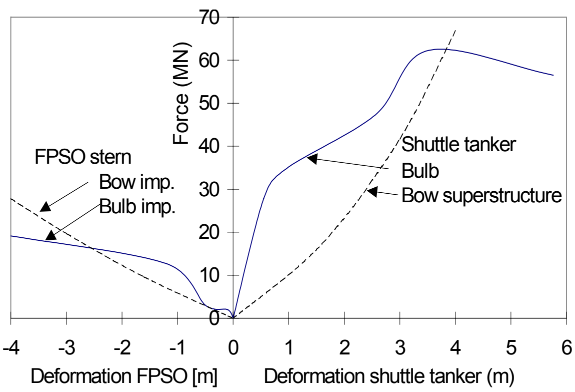


Figure 6.10 Force deformation-relationships for bow and bulb impact from shuttle tanker impact against FPSO stern.

3) The energy is less than proportional with the mass (displacement) of the shuttle tanker

Accordingly, with increasing displacement of the shuttle tanker, the impact speed is reduced (for the same distance, s). This is, however, more than compensated by the increase of the vessel's mass so that the kinetic energy is increased. On the other hand, the fraction of the kinetic energy that is to be dissipated as strain energy is reduced due to the increase of the relative size of the two vessels (denominator term). This means that the

speed corresponding to a traveled distance of 50 m is 1.16 m/s and after 100 m 1.62 m/s. Hence, the critical speed (1.2 m/s) for penetration of machinery room, as determined above, corresponds to a critical distance of approximately 50 m. These considerations might imply that a smaller distance between the shuttle tanker and the FPSO is beneficial. This is only true, however, if no corrective/evasive action is taken. A larger distance allows, of course, more time to react. However, a typical distance in North Sea operations has been 80 m up to now. Recently, an increase of the distance to 100 m is being considered.

Recognizing the uncertainties associated with the calculations it is reasonable to conclude that the energy to be dissipated as strain energy is *independent* of the displacement of the shuttle tanker.

Comments on damage potential. Given that the collision is most likely to occur against the stern of the FPSO, the most likely outcome for the Base Case design is flooding of the engine room. In the event of a higher energy impact, the potential for damage to the helicopter fuel tank exists. It is considered highly improbable that the collision will threaten the overall integrity or stability of the FPSO. The estimated consequences are limited to a global impact on the FPSO and could be:

- Rupture of FPSOs ballast tanks and engine room located at the stern
- Rupture of the fuel tanks located at stern of FPSO
- Damage to the living quarters

The overall hull girder structural integrity is not threatened. However, the buoyancy in the aft part is reduced, and a possible hogging still-water moment is probably increased. Damage to the FPSO turret, mooring system or risers seems to be improbable considering the impact energy associated with these collisions.

6.5 Side collision – NLFEM analysis

In order to verify the resistance of FPSO side structures to ship bow impact nonlinear finite element analysis is carried out with the code LS-DYNA (1997). The FPSO studied is the same as the one analyzed using simplified methods, and is shown in Figure 6.11. A FE-model of a midship side section between two bulkheads of the FPSO is created. All stringers and stiffeners are modeled, and cutouts and manholes are excluded to some extent. This may overpredict the FPSO resistance somewhat, but the effect is considered to be marginal.

The bow selected for the study is considered representative for vessels in the range of 2,000 to 5,000 tons displacement. The bow model is a generic model, in the sense that it is not a real design. The bow structure is mainly taken from a real ship, while the bulb is constructed on the basis of similar bulbs. The bulb is cylindrical with an almost elliptical cross-section. This modeling represents a rather strong bulb. Most supply vessels are not fitted with bulbs. The bulb is included in order to cover typical merchant vessels of similar size. The model is considered to represent a strong bow. Emphasis is placed on modeling all stringers and decks. Cut-outs and manholes are excluded to some extent. This is conservative as concerns deformation and forces. The material in the side of the FPSO and the bow of the shuttle tanker is modeled as piecewise linear with strain hardening included.

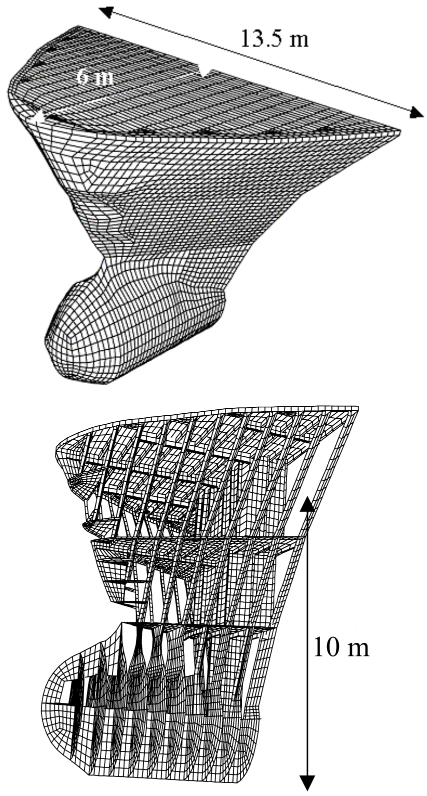


Figure 6.11 FE-model of bow

Three analyses are carried out using different assumptions regarding the behavior of the structures. First, the bow (with bulb) is assumed to be infinitely rigid, so that all energy is absorbed by the FPSO side ("ductile design"). It is found that the limiting energy for rupture of outer side is ~ 10 MJ (700mm bow displacement). The energy at 1500mm bow displacement is ~ 43 MJ and the limiting energy for rupture of inner side of the FPSO is ~ 230 MJ, at 3700 mm bow displacement. This corresponds to a critical speed of 9.5 m/s = 18.5 knots for a 5,000 ton displacement vessel. It should be recalled that rupture of plate material is very uncertain so that the energy level should be assessed carefully. However, since energy dissipation in the bulb is neglected, the values should be conservative.

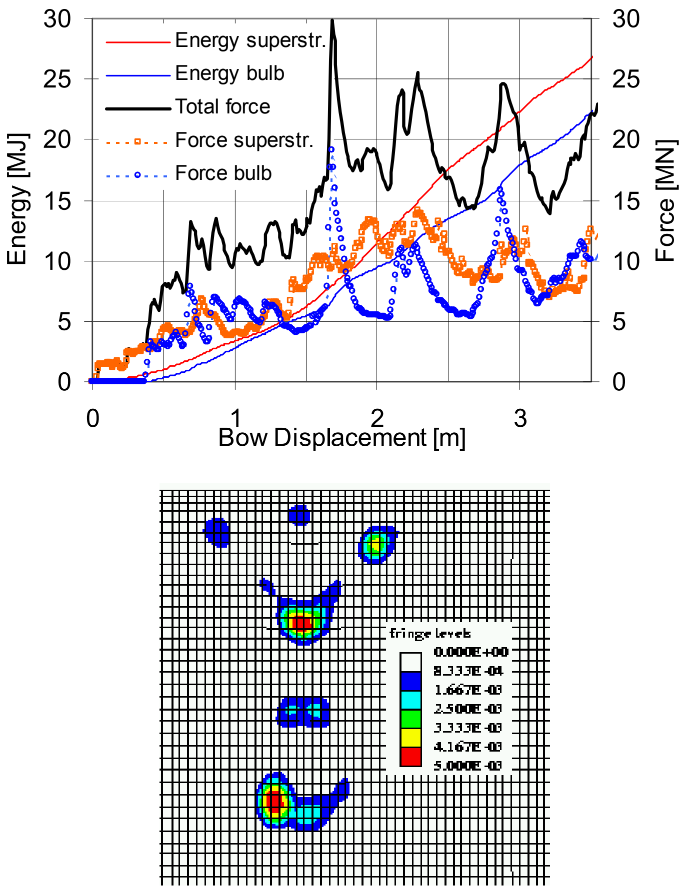


Figure 6.12 Force and energy evolution for rigid side, Footprints and contact pressure.

Next, the side of the FPSO is assumed sufficiently stiff so that all energy is absorbed by the bow. The relationship between force and bow deformation for the bow structure and the bulb is shown in Figure 6.12. The maximum total collision force (peak force) is 30 MN, but most of time the force oscillates between 15-25 MN. Force intensities recorded are shown in Figure 6.12. This information may be used to design stiffeners so as to resist the distributed contact forces. If strength design is intended, the side should allow for a contact force of 20 MN at locations exposed to bulb impacts and 15 MN at locations exposed to bow structure impact The force can be assumed uniformly distributed over a rectangular area 1.5 m wide and 2 m high for bulb impact and a triangular area 2 m wide and 2 m high for bow structure impact

Finally, an integrated collision analysis is carried out with the actual dimensions and strength properties for the bow and the FPSO. As illustrated in Figure 6.13 the FPSO side undergoes very small deformations (< 200 mm), resulting in contact forces very close to those obtained for a rigid side. This shows that it is feasible to design the side of FPSO sufficiently strong to impose most of the energy dissipation to the bow of the ramming ship for this vessel size category. This holds true even if the stiffeners in the side plating fail, provided that the shell plating can undergo sufficiently large deformations without rupture so as to develop necessary membrane forces. This was the case for the vessel analyzed.

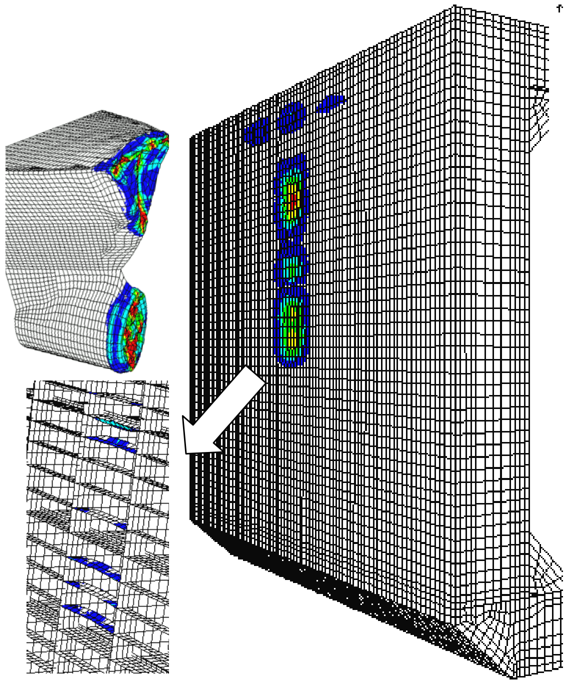


Figure 6.13 Integrated analysis of deformations in bow and side.

6.6 Further evaluation of consequences

Ship impact traditionally has been considered to be the main hazard in connection with damage stability. If an impact entails damage to transverse bulkheads between two spaces, the possibility of flooding of both spaces should be taken into account.

Often only minimum ship impacts have been considered. Other scenarios have also been considered, and should also be addressed. Impacts by powered passing merchant vessels with bulbous bow may be particularly critical from a stability point of view. A shuttle tanker impact on the FPSO stern may be relevant especially if it causes an unsymmetrical flooding condition, since it is not usually considered to have implications on stability. If collisions by powered vessels are considered, damage/flooding scenarios beyond the minimum requirements may occur. The passing vessel collision scenario may imply flooding of one wing and center tank. Flooding of two center tanks could only occur if the bulkhead between the center tanks and the corresponding wing tanks is damaged, hence, implying flooding of two wing tanks and two center tanks. Clearly, this event is less likely than having a penetration through a wing tank into the corresponding center tank.

A stern impact by the shuttle tanker induces a motion of the FPSO that can cause mooring system failure. After the impact, the two ships move together with the same speed. For the case discussed with the shuttle tanker in ballast hitting the FPSO at a speed of around 1.2 m/s, the velocity (v_c) after impact is v_c = 0.4 m/s, and the kinetic energy is

$$E_c = \frac{1}{2}(m_1 + m_2 + m_{1'} + m_{2'})v_c^2 = 18.5MJ \qquad (6.4)$$

The kinetic energy is reduced by dissipating it into potential energy of the mooring system (and riser system), set-down of the ship, etc. Assuming that the mooring system is more taut than the riser system, the mooring system will first act to stop the motion. Based on partly related case studies reported in (Fylling and Holthe, 1988), it seems that mooring can absorb 40 MJ energy or more. Hence, this rough estimate indicates that this collision scenario does not seem to be critical.

In this example a specific velocity after impact was assumed. If the velocity is twice as high, the energy is four times larger and the mooring system may not stop the vessel, which will have a kinetic energy after the mooring failure which is the initial kinetic energy minus that stored as potential energy in the mooring system before it breaks. The damage to the riser system can then be estimated. The most relevant failure mode of the (flexible) risers is by bending at the locations where risers are connected to the turret. A very limited bending moment would be required to cause leakage. Primarily this scenario should be handled by limiting the probability (and intensity) of the initial event - collision by the shuttle tanker.

7 CONCLUSIONS AND RECOMMENDATIONS OF FUTURE STUDIES

Structural reliability methods for ultimate strength as well as fatigue limit states with due account of normal uncertainties, have been reviewed. It is stressed that the uncertainty measures in probabilistic analyses should reflect the physical characteristics of the loads and resistance, and be based on critical assessment of uncertainties. Reliability analysis of catenary mooring systems is less developed than for hull structures. This is partly due to the difficulty of separating the effect of normal uncertainties from the effect of gross errors, in load effects or resistance. Abnormal mooring loads may occur due to errors in active winching operations or operations of the DP system performed to reduce the tension. Abnormal resistance may result from fabrication defects, wear, or other faults that are not accounted for in design.

Limited studies on the probability of capsizing of intact FPSO have been carried out. There is significant uncertainty associated with the model for stability analysis. For instance, current models account for the destabilizing effect of wind, but not waves.

The FPSO is a novel concept and relatively limited service experience is available, especially in terms of reliability level (annual probability of failure). Experience confirms that abnormal pressure increases in cargo tanks due to valve failures, collisions associated with shuttle tanker offloading operations, loss of heading control for turret moored vessels, and multiple mooring line failures are of concern. Moreover, near-misses have been experienced. Critical events include: collisions and other accidental impact, subsea blowout (effect on buoyancy/stability), leak of high pressure gas into cargo tanks, erroneous weight condition or ballast operation, abnormal ballast and cargo condition, and abnormal wave load due to operational error.

It is important to take a systems view of risk, i.e. how these critical events may escalate in hull, topside, and mooring subsystems. At the same time the challenge is to control the risk to be within an acceptable level.

An important measure to avoid catastrophic accidents is to design the subsystems to survive certain design accidental events, i.e. corresponding to, say, an annual probability of occurrence of 10^{-4}. This is already implemented for Norwegian codes for offshore structures, and was recently also introduced for passive safety equipment. However, the design procedure for other (active) safety equipment has not yet been spelled out.

To achieve a risk based design for accidental events that occur in many locations of an installation, a simplified approach is proposed, in which a certain fraction of the 10^{-4} probability is used at each location to define the design accidental event. The sum of these fractions is 1.0. This procedure can be further developed as indicated in this study.

Collision scenarios involve impacts by supply ships, relatively less frequent impacts by a shuttle tanker used in tandem offloading operations, and passing vessels. Colliding supply ships may cause penetration of the side shell, but there is limited likelihood of damaging the inner bulkhead to cause oil outflow, or instability or overall hull girder failure.

Stern impact by a shuttle tanker is a very possible event and may cause flooding of an aft machinery room and damage to an aft flare tower. Further assessment of the likelihood of this impact scenario, including the conditional impact velocity, is necessary.

Collisions by passing vessels are dependent on the location of the FPSO relative to ship lanes. Studies for sites in the North Sea and the Gulf of Mexico show that the annual impact probability may vary from about 10^{-3} down to 10^{-6} or less. Such impacts may be associated with high speed and large mass, and significant impact energy and damage potential. Flooding and outflow from one or two wing tanks and a center tank is envisaged. Further assessment of the collision probability is needed to gain more insight and acceptance of the estimates, and to implement risk reduction measures when necessary.

A leak of high pressure gas in a cargo tank is likely to cause significant damage. Consequential failure depends upon the size and location of the damage.

Capsizing may be caused by erroneous weight conditions in terms of height of center of gravity or ballast errors. In addition abnormal still-water bending moments and wave loading might result in failures. If operations manuals are not complied with, ballast and cargo may be distributed in such a way that design values are exceeded.

While greenwater loads have been of concern for FPSOs, such loads primarily have a local effect on the structure and on safety equipment on the deck which can cause an escalating accident. Nonlinear effects associated with wave slamming can increase hull girder loads, and if underestimated in design, they can cause hull girder failure.

System failure of a positioning system, consisting of mooring lines and DP, can be initiated by single line failure due to abnormal resistance (due to wear etc.) and technical/operational error in heading control of a turret moored vessel. Stern collision by a shuttle tanker is not considered likely to cause mooring system failure.

Further work is required to

- establish a procedure for risk-based design of active safety equipment (to complement the design of the structure and passive safety equipment against an accidental load with exceedance probability of 10^{-4})
- establish a risk-based procedure for design against accidental events of the same kind at different locations of the installation (FPSO)
- establish the probability of impacts by shuttle tankers at different speeds
- improve the method/data for estimating the probability of collision by a passing vessel
- establish a method to estimate the probability of capsizing a damaged vessel
- investigate possible abnormal still-water and wave conditions for the hull girder
- integrate structural reliability in a risk assessment of system failure of mooring system, considering initiating events due to abnormal resistance and loads, especially due to operation error.

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