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Recent Advances and Future Trends on Design and Strength Assessment of Ships and Offshore Structures

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Abstract: Ships and offshore structures are subjected to various ocean environmental phenomena which can cause highly nonlinear action effects. In this case, the limit states-based approach is a much better basis for strength assessment and design than the traditional allowable-working stress-based approach, because it is not possible to determine the true margin of structural safety as long as the limit states remain unknown. To determine the limit states, the use of nonlinear structural mechanics and analysis is essential. The limit states-based methods together with nonlinear structural mechanics and analysis are a key for consequence analysis that is required for risk assessment and management. The present paper addresses recent advances and possible future trends of core technologies that are required for design and strength assessment of ships and offshore structures in association with nonlinear structural mechanics and limit states.

Keywords: Nonlinear structural mechanics, serviceability limit states, ultimate limit states, fatigue limit states, accidental limit states, limit states-based design, risk-based design.

1 Introduction

For producing oil and gas in deep and ultra-deep waters reaching more than 1000m water depth, the use of floating-type offshore structures is required while the use of fixed-type offshore structures that have been used for producing oil and gas in relatively shallow waters is now much less feasible. Among floating-type offshore structures, ship-shaped offshore units that successfully serve multiple functions such as production, storage, and offloading are some of the more economical systems and especially attractive when developing oil and gas fields in deep- and ultra-deep water areas and locations remote from existing pipeline infrastructures.

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Ships and ship-shaped offshore installations are likely to be subjected to rough weather and various ocean environmental phenomena that in principle include freak (i.e., non-sinusoidal extreme) waves, winds, currents, impact pressure actions (arising from sloshing, slamming, and green water), accidental events (e.g., dropped objects, collisions, grounding, fire, gas explosion), corrosion attack, and so on.

In some cases, such phenomena can lead to catastrophic failures including total losses. In the last few decades, there have reportedly been a large number of vessel casualties including total losses. Over a thousand seafarers could have lost their lives in the related incidents, and some serious pollutions of the ocean environment could have occurred. This certainly indicates that there are still many issues related to design, building, and operation to be resolved for achieving high integrity in terms of safety, health, the environment, and economics / financial expenditures.

Although such environmental phenomena noted above may be caused by different scenarios, it is interesting to note that they commonly give rise to highly nonlinear structural consequences in terms of geometric nonlinearity (associated with buckling and large deformation) and material nonlinearity (associated with yielding and plasticity), together with various other parameters of influence such as temperature (e.g., low temperature under operation in arctic region or with LPG/LNG cargo, or high temperature due to fire and gas explosion), strain rate (due to high loading speed or impact actions), fabrication related initial imperfections (e.g., initial distortions, welding induced residual stresses), and age-related degradation (e.g., corrosion wastage, cracking damage, local denting).

Therefore, it is evident that it will not be possible to design unquestionably robust, yet sufficiently economical ships and offshore structures as long as the nonlinear structural consequences under rough weather and various ocean environmental phenomena remain unknown and/or not directly accounted for. Such treatment of nonlinearities is clearly an emerging area of challenge for the profession.

It has also been recognized with some certainty that the risk-based design method together with the first principles-based direct method and the limit states-based method is a way to go for robust design of ships and offshore installations. In this regard, substantial efforts are now being directed by various stakeholders in maritime industry such as IMO (2007), ISO (2007, 2008) and IACS (2006a, 2006b) towards the following:

- Goal-based design using first principles methods;
- Limit states-based methods;
- Risk-based methods.

The limit state approach is a better basis for design and strength assessment than the traditional working stress approach that is predominantly based on linear elastic method solutions alone. This is because it is not possible to determine true margin of structural safety as long as the limit state remains unknown (Paik and Thayamballi 2003, 2007). Because the margin of structural safety can be determined by a comparison with the limit states and the design working stress (or actions), it is of course essential to accurately predict the limit states for that purpose which require the application of nonlinear structural mechanics.

Risk is typically defined as either the product or a composite of (a) the probability or likelihood that any accident or limit state leading to severe consequences, such as human injuries, environmental damage, and loss of property or financial expenditure, occurs, and (b) the resulting consequences. In the design and operation of ships and offshore installations, there are a number of hazards that must be dealt with in the process of risk assessment. Wherever there are potential hazards, a risk always exists. To minimize the risk, one may either attempt to reduce the likelihood of occurrence of the undesirable events or hazards concerned, or reduce or mitigate the consequences, or both. For risk assessment and management, therefore, it is essential to identify the consequences by nonlinear structural mechanics and analysis.

As structures get older, they suffer various types of age-related degradation such as corrosion and fatigue cracking damage. Condition assessment or health monitoring of aged structures is required for keeping structural integrity and/or structural longevity in association with relevant schemes of inspection and maintenance. Nonlinear structural mechanics and analysis associated with limit states and risk assessment is a key within the framework of condition assessment of aging structures (Paik and Melchers).

The present paper addresses recent advances and future trends on core technologies that are required for limit states- and risk-based design and strength assessment. Technologies for ships and ship-shaped offshore installations are focused on.

2 Nonlinear structural mechanics

Operational and/or environmental phenomena cause actions on structures which are usually normal but are abnormal (i.e., with features of non-linearity that are outside those directly considered by design methods) including in extreme or even accidental cases. Structural design must in principle be performed so that the structure can withstand such demands throughout its expected lifetime.

Figure 1 illustrates the relationship among structural mechanics, structural analysis, and structural design. Structural analysis is a task that calculates structural response or action effects of the structures which are subjected to in-service and/or environmental phenomena. For the purpose of structural analysis, structural mechanics is required to identify the response characteristics of structural system and its components in terms of relating actions versus action effects. The aim of structural design is to determine structural scantling and arrangement of structural components that meet the requirements of structural safety and risk in accordance with design criteria.

The use of linear structural mechanics that uniquely relates actions versus action effects is enough for design and strength assessment when actions cause neither nonlinear response nor structural failures. However, most real world economically-designed structures are likely to be subjected to various types of actions and action effects (e.g., deformations, stresses) involving nonlinearities. As a result, structural failures potentially take place and the relations between actions versus action effects are no longer linear or are not even perhaps determined uniquely, and in this case nonlinear structural mechanics must be essentially applied for the structural analysis.

Factors in association with nonlinear structural mechanics include the following:

- Geometrical factors – buckling, large deflection, crushing, and folding;
- Material factors – yielding, plasticity, rupture, brittle fracture, damage and cracking;
- Fabrication related initial imperfections – initial distortion, residual stress, softening;
- Temperature factors – low temperature (due to operation in frigid areas, icing), high temperature (due to fire, gas explosion);
- Dynamic factors (strain rate sensitivity, inertia effect) – freak waves, impact pressure (sloshing, slamming, green water), overpressure (gas explosion), impacts (collisions, grounding, dropped objects);
- Age-related deterioration – corrosion, fatigue cracking.

3 Trading vessels versus ship-shaped offshore installations

A ship-shaped offshore unit utilized for the offshore oil and gas development is similar to that of a trading tanker in terms of the hull structural arrangement as shown in Fig.2. However, large differences between the two systems do of course

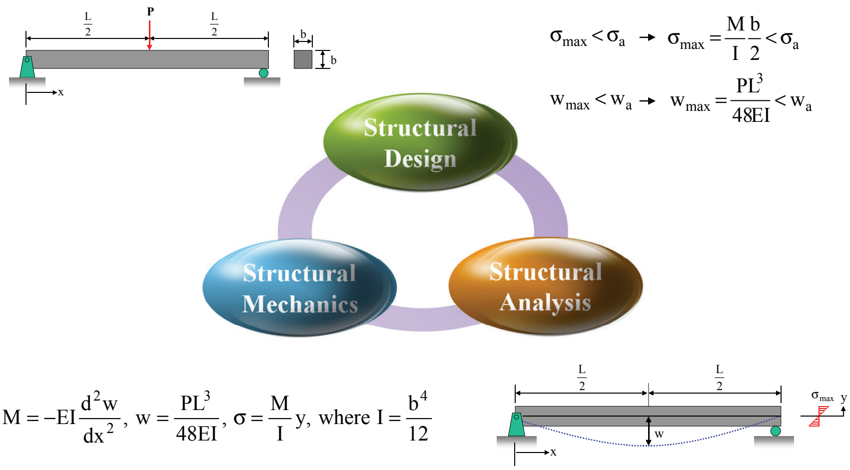

Figure 1: An illustrative example of structural mechanics versus structural analysis versus structural design.

exist in a variety of items. A key difference between trading tankers and ship-shaped offshore units is in the consideration of design environmental conditions. For the design of trading tankers, the North Atlantic wave environment is typically considered as the design premise for an unrestricted vessel to make worldwide trade possible.

However, the design actions of ship-shaped offshore units will be based on the environmental phenomena specific to their operational sites, their transport to field before installation and the installation and the commencement of operations as the case may be.

For historical reasons, the return period of waves for the hull girder strength design of ship-shaped offshore units is typically taken as 100 years, although that of trading tankers for the same purpose is considered to be 20 to 25 years or so. Winds and currents as well as sea and swell waves among other factors may induce significant actions and action effects on offshore structures, whereas waves are often the primary source of environmental actions on trading ships at sea.

Trading tankers are typically loaded and unloaded at still-water condition in harbor, but ship-shaped offshore units are subjected to significant environmental loads even during loading and unloading (or offloading). The number of loading / offloading cycles on ship-shaped offshore units can be more frequent than that on trading tankers.

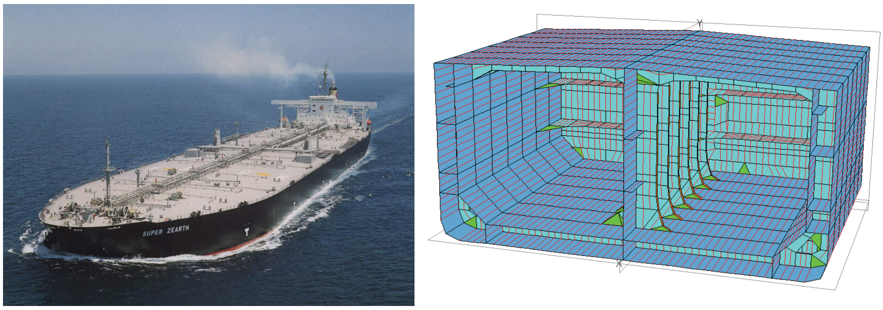

Figure 2a: A trading tanker.

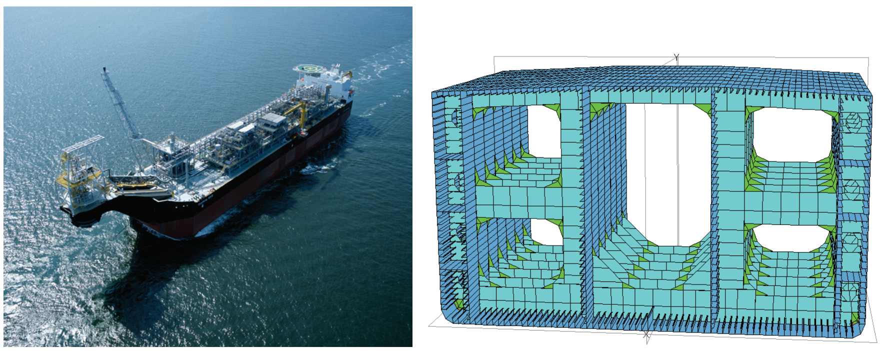

Figure 2b: A ship-shaped offshore unit (FPSO: floating, production, storage, and offloading unit).

Ship-shaped offshore units are typically offshore for 100% time of their design life, or at least certainly desired to be, while trading tankers are at open sea for perhaps 70% of the lifetime. Certainly, the fatigue failure characteristics of ship-shaped offshore structures may somewhat differ in comparison to trading tankers, e.g., in the need to consider low cycle fatigue related to loading and offloading. This can be important because large still-water forces and moments can be created in ship-shaped offshore units due to loading patterns that may be very different from those of trading tankers, and also loading / unloading cycles are much more frequent.

In terms of operating conditions, trading tankers normally operate in either full load condition or ballast condition, but ship-shaped offshore units will be in varying states of loading and unloading. These characteristics in turn imply the possibility of frequent -draft variations between the fully loaded and the minimally loaded and ballast conditions, compared to trading tankers. It follows that strength considerations must then address a number of loading conditions at varying drafts, and a number of environmental conditions with different return periods.

Trading tankers may avoid rough weather or alter their heading in operation by ‘weather routing’, but ship-shaped offshore units must be continuously located in the same area with site-specific environments.

Trading tankers are regularly dry-docked in 5 years intervals, while ship-shaped offshore units will not necessarily be dry-docked (and in any event are preferred not to be dry docked) during the entire production period in the field, possibly more than 10 years to even 20 years. This means that repairs in a dry-dock are not economically realistic in many cases, primarily because of the potential production interruptions that must be dealt with. Also, welding or flame cutting which is common for traditional repairs of trading tankers in a dry-dock may not be as easily used for the repair work of offshore structures in situ for reasons of high fire and gas explosion risk.

Unlike trading tankers, ship-shaped offshore units would have topsides, turret, flare towers, riser porches, drill tower, etc. which are items of large mass, high center of gravity and large windage area, which affect vessel motions and responses to environmental phenomena. Undesirable motion characteristics leading to green water, sloshing, slamming, mechanical downtime on equipments, crew discomfort, etc. can then be among the very specific design considerations. For a turret moored ship-shaped offshore unit, the vessel may head into the weather and other differences can arise. For instance in comparative terms, the hull girder strength for FPSOs meant for turret moored operation in the North Sea must be significantly greater than that of trading tankers in unrestricted service. On the other hand, in some areas such as West Africa the wave environment can be considerably benign and this can be an advantage in terms of the strength required, whether turret moored or not.

In any event, the design considerations for ship-shaped offshore units may be more complex than those for trading tankers. This is not necessarily because ship structural design is any less complicated in principle, but because of the relative importance of site-specific conditions offshore and the need to consider many aspects in their design explicitly and specifically, unlike a trading ship wherein many of the same considerations may be implicitly considered by well-established rules and procedures.

4 Environmental phenomena in ships and offshore instalations

Various environmental phenomena occur in ships and offshore structures. In design, the structure is required to have an adequate margin of safety against such environmental phenomena. It is interesting to note that actions arising from environmental phenomena on offshore structures are different from those on trading vessels.

As previously noted, the nature of the offshore structures and their operation is such that winds and currents as well as waves among other factors may induce significant actions and action effects on structures, whereas waves are often the primary source of environmental actions on trading ships at sea; considerations related to specialized operations such as berthing being admittedly somewhat different.

In the case of offshore structures, a good knowledge of the environmental conditions at the areas where the structures will be installed is necessary in order to appropriately design and assure the required high operational uptimes. Such information is also important for specialized weather sensitive operations such as installation on site, the berthing of supply boats, and for the design of mooring and station-keeping. Essentially, offshore facilities may themselves serve as berthing terminals in a sense.

4.1 Waves

For both trading ships and ship-shaped offshore structures, wave characteristics are primary design parameters. The wave characteristics include form, heights, periods and directions together with associated probabilities and persistence times. It is important to realize that the waves inducing the most severe response in the global system structure may be different from those resulting in the maximum response in structural components and also that the structural response is wave period dependent. It is noted also that more frequent waves rather than extreme waves will typically govern fatigue life although their magnitude may be smaller.

Wave-induced maximum actions and actions effects may be applied for design by using any one of a few approaches, for example extreme amplitude design waves, extreme response design waves or the more fundamental wave energy spectra-based methods. An extreme amplitude design wave may be calculated for a specified return period, usually 25 years for trading vessel design and 100 years for ship-shaped offshore structural design of long-term deployment. A frequency domain or a time domain treatment or even hybrids of the two may be used.

It should be recognized that, depending on the structure, some maximum actions may in principle develop from a wave or group of waves with a lower amplitude than a higher amplitude wave because of the potential sensitivities of the actions concerned to the wave frequencies involved. Also, several different design wave combinations from various directions and frequencies with crests and troughs at various locations will need to be considered for the different types of responses of interest (e.g., maximum roll, maximum vertical hull girder bending moment, etc).

4.2 Winds

Wind is usually not a parameter for trading vessel design, but it is a primary metrological oceanographic (metocean) parameter which is important to the design of offshore units, e.g., during normal operations. The structure must also withstand the forces exerted by the wind itself and this depends not only on the structural characteristics such as windage area but also on the speed, direction and persistence characteristics (e.g. gusting) of the wind.

For offshore structural design, extreme wind speeds for specified return periods must be obtained and are specified with averaging times ranging from 3 seconds (i.e., an extreme gust value) to 24 hours, for example. The speeds are usually estimated at a standard height of 10m above mean sea level, with corrections to more specific values at other heights.

In addition, the spectra of fluctuating wind gusts are necessary because wind gusts can excite resonant oscillations of offshore structures. For example, slow-drift horizontal motions of moored structures can be caused by wind. Also, wind can lead to phenomena such as vortex shedding, together with associated vibrations in some instances, such as for a flare tower.

4.3 Water depths and tidal levels

Water depths and tidal levels are only sometimes parameters of influence for ocean-going trading vessel design, but they typically play a more important role for offshore structural design. The overall depth of water at any location can be characterized by the mean depth and its variations from mean sea level. The mean water depth is defined as the vertical distance between the sea bed and an appropriate near surface datum. The variations of water depth are primarily due to tides and storm surges. The tide related variations are usually regular and predictable in terms of the highest astronomical tide and the lowest astronomical tide.

On the other hand, meteorologically generated storm surges are more irregular in nature. The effects of tides can approximately be superimposed to the effect of storm surges to estimate the total water levels; these could in some cases be above the highest astronomical tidal level or below the lowest astronomical tidal level.

4.4 Currents

Currents are usually not a design parameter for trading vessels, but currents, together with waves and swells can affect the orientation of offshore installations, and hence directly and indirectly affect both short-term and long-term loads imposed on the structure and its mooring system. Currents affect the hull drag forces together with the wave system. Currents also ultimately affect the station-keeping of the offshore unit and the performance of its thrusters (where used).

The nature of currents can be very complex, depending on the local conditions. A number of current types may be relevant, e.g., oceanic currents, eddy currents, thermal currents, wind driven currents, tidal currents, surge currents and inertial currents. The common ones are usually astronomical tide and storm surge related. But this is by no means a certainty in any specific case or region, and if at all possible specific on-site measurements need to be made before locating an offshore unit at any given site.

4.5 Air and sea temperatures

The temperature is now a primary design parameter for vessels trading in frigid regions and offshore units installed in polar water. The information on sea temperatures is important for fracture toughness design, among others, while air temperature information is of interest for applications where a structure responds slowly to air temperature changes and for various onboard systems.

4.6 Ice and snowing

Depending on the areas of operation, the extent to which snow and ice may accumulate on various parts of the offshore units may need to be estimated. Associated risk mitigation measures include the provision of adequate strength and stability, and local heating. Physical removal procedures also need to be specified based on the maximum permitted accumulations in specific cases.

In many cases, snow accumulations may be more likely than icing; particularly on windward-facing non-horizontal parts of the unit. Snow, if it remains, can freeze into ice and hence will need to be usually removed prior to that by blowing once dry, or other means.

4.7 Marine growth

Ships and offshore structures are both likely to become fouled with marine growth. In the case of trading ships or some special types of offshore units such as drill ships, the removal of marine growth is simple once dry-docked, although such growth may increase resistance and powering when underway. For design purposes of offshore structures, a marine growth profile (thickness and roughness as a function of water depth) is found to be specified as part of the metocean data in a design basis document.

4.8 Sloshing

The accelerations arising from the motions of a ship in a seaway can produce sloshing actions on the structures of partially filled tanks. Motions of liquid cargo in oil tanks may often produce significant sloshing actions, and the affected structure must be adequate to withstand them. This is of particular concern in tanker conversions to FPSOs because it is not always the cases that trading tankers were designed for partially filled cargo tanks, unlike their ballast tanks. Cargo tanks of moored ship-shaped offshore structures are continuously loaded and unloaded, and hence sloshing in the tanks may not be avoidable.

4.9 Slamming

Bow structures are likely subjected to impact pressure actions arising from what is termed bow flare slamming, when the vessel bow encounters the waves. Bow slamming and wave slap impact has been known to cause structural damage (e.g., buckling, tripping) in forecastle plating, bow flare plate and stiffeners, and the like. Depending on the hull form, the wave environment and several other factors including forward speed and heading, bow slamming may need to be investigated for trading ships and also ship-shaped offshore structures in transit or during operation.

At a relatively benign location of ship-shaped offshore units, bow impact pressure actions may be less serious than those for normal trading tankers. However, bow slamming may be of interest for weathervaning vessels in harsh environments with the bow pitching downwards in certain cases, particularly when the waves approach with heading angles within some 15 to 30 degrees off the bow.

4.10 Green water

Green water can be considered to consist of unbroken waves overtopping the bow, side or stern structures of trading ships or ship-shaped offshore units; its occurrence depends on various factors including the relative motion between the structure and the waves, the speed, the freeboard and the harshness of the environment.

The occurrence of green water implies that the available freeboard is exceeded. The green water problem on ship-shaped offshore structures can be an important design issue under harsh environmental conditions, because green water can cause damage to deck houses, deck mounted equipments (e.g., switch room compartments), watertight doors, walkway ladders, cable trays, and similar.

4.11 Corrosion attack

While in service, most structural systems such as ships, offshore structures, bridges, industrial plants, land-based structures, and other infrastructure will be subjected to corrosion deterioration which can potentially cause significant issues in terms of safety, health, the environment and financial expenditures. Indeed, such age and maintenance dependent deterioration has reportedly been involved in many of the known-failures of ships and offshore structures including perhaps total losses. While the loss of the total system typically causes great concern, maintenance of deteriorated structures is generally complex and costly. It is thus of importance to develop advanced technologies which can allow for the proper management and control of corrosion.

4.12 Accidental flooding

If one or more internal spaces of a vessel are opened to the sea by structural damage, then cargo leakage and/or water ingress can potentially take place until stable equilibrium is established between these spaces and the sea. Accidental flooding and/or cargo leakage can cause significant changes draft, trim and heel. When such changes subsequently immerse non-watertight portions of the vessel, stable equilibrium may not be attainable due to progressive flooding and the vessel can sink either with or without capsizing.

It is required under these circumstances to ensure that ships or offshore units must survive any reasonable damage resulting in flooding. In particular, reserve stability in damaged conditions with unintended flooding must be sufficient to withstand, say, the wind heeling moment imposed from any direction on the damaged unit. Also, the structural safety must be sufficient enough to survive applied actions even with flooding and structural damage.

4.13 Dropped objects

Mechanical damage may occur in plate panels of steel-plated structures in many ways depending upon where such plates are used. In inner bottom plates of cargo holds of bulk carriers, mechanical damage can take place by roughly handled loading or unloading of bulk cargoes such as iron ore; Inner bottom plates have mechanical damage during loading of iron ore, because iron ore cargo or parts of the cargo handling equipment strikes the plates. In unloading of bulk cargoes such as iron ore or coal, excavator hits the inner bottom plates mechanically. Deck plates of offshore platforms may be subjected to impacts due to objects dropped from a crane.

4.14 Collisions

Regardless of various efforts to prevent collision accidents, they do take place from time to time. While there have reportedly been a number of collision accidents between two trading ships, several collision accidents of ships with offshore oil and gas installations have also occurred.

A ship collision involves at least one body and a striking or struck object, or two deformable bodies. The nature of the collision is usually described as being right angle or oblique, referring to the relative position of the struck structure centerline to the vector of velocity of the striking object or ship. The majority of the in-field vessel collisions, i.e., collisions between ships and ship-shaped offshore structures is known to be with supply vessels and shuttle tankers, while there are also a few cases involving passing vessels, i.e., involving a vessel that was not being operated in connection with the offshore installations.

4.15 Grounding

A floating offshore structure is usually not designed for grounding at a specific operating site, while trading ships and also floating offshore structures during transit generally need to consider grounding as a design possibility. The grounding process may generally be characterized as one where an obstruction deflects the bottom inward and/or enters into and cuts through the structure as the vessel moves forward. The amount of deformation depends on the resistance of bottom structure to the penetration as well as some other ship characteristics including hydrodynamic stability.

There are two loading situations pertinent to grounding of ship bottom structures: vertical loading and loading in the ship length direction, corresponding typically to a stranding and a typical raking accident, respectively. A stranding situation is similar to a collision where the struck side is subjected to mainly out-of-plane impact. A raking accident, when the impact load is applied mainly in the ship's longitudinal direction, often causes a very long gash in the bottom.

4.16 Fire

In offshore oil and gas installations, fire sources are usually classified into two types, namely liquid or gas. Liquid fire may be classified into a few types, namely (Nolan 1996, Skallerud and Amdahl 2002)

- Pool fire in the open air when there is an ignition of a liquid spill which is released on a horizontal solid surface in the open air, e.g., on the ground;
- Pool fire on the sea surface;
- Pool fire in an enclosed area, when liquid fuel is released within an enclosed space which may suffer from various degrees of air deficiency;

- Fire ball, which results from boiling liquid expanding to vapor explosion where an immediate ignition of the pressurized and liquefied fuel occurs;
- Running liquid fire, when the liquid fuel is released on a surface which is not horizontal, e.g., the sloping walls of a tank container, where the fuel burns as it flows down the surface;
- Spray fire, when the liquid fuel is released under high pressure and subsequently dispersed into droplets.

On the other hand, when a flammable gas is released into the atmosphere, somewhat different types of fire phenomena may take place according to the release mode and the degree of delayed ignition. Gas fire may be classified into the following types, namely

- Flash fire or cloud fire, which results from a delayed ignition of a release of gas or vapor forming a cloud, which may disperse downwind. A flash fire is transient during a very short time period and its hazard to human beings may be limited to thermal radiation effects;
- Jet fire or flare fire, which results from a high pressure leakage of a flammable gas. The jet fire is often said to be momentum-controlled because the momentum force prevails over the buoyancy force in large part of the flame plume;
- Diffusive gas fire, which results from a diffusive release of a flammable gas through a relatively large opening. The diffusive gas fire is often said to be buoyancy-controlled because the buoyancy is dominant in the entire flame plume, in contrast to the jet fire.

4.17 Gas explosion

In offshore oil and gas installations, the risk of gas explosion can be considered to be relatively high particularly for the topside modules. Impact pressure actions or blast arising from gas explosion can cause severe damage on the structure and also to various equipments; this may in turn lead to a threat to structural integrity, health and the environment.

The principle of accidental limit state (ALS) design for gas explosion is to reduce the explosion probability and the potential explosion forces (blast, impact pressure) as well as explosion consequences (e.g., damage). To reduce the probability of gas explosion, the following must be reduced, namely

- Potential for gas leaks;

- Possible ignition sources;
- Potential for gas clouds.

Gas explosion risk assessment must therefore be performed to develop safety measures for risk mitigation (Nolan 1996, Czujko 2001). In terms of structural layout, the following measures may help reduce explosion consequences, namely

- Prevention of high equipment congestion or blockage to reduce turbulence;
- Installation of blast and fire resisting walls.

5 Limit states based design

A limit state is formally defined by the description of condition for which a particular structural member or an entire structure fails to perform the function that has been assigned to it beforehand. From the view point of a structural designer, four types of limit states are considered, namely (Paik and Thayamballi 2003, ISO 2007)

- Serviceability limit state (SLS);
- Ultimate limit state (ULS);
- Fatigue limit state (FLS);
- Accidental limit state (ALS).

5.1 Serviceability limit state design

Serviceability limit states (SLS) address the following:

- Unacceptable deformations which affect the efficient use of structural or non-structural components or the functioning of equipment affected by them;
- Local damage (including corrosion, small dents, limited permanent set) which reduces the durability of the structure or affects the efficiency of structural or non-structural components;
- Intact vessel stability and watertight integrity;
- Vessel station-keeping;
- Vessel weathervaning or heading control in the case of ship-shaped offshore installations;

- Vessel motions (or excursions) that exceed the limitations of equipment or mooring systems, risers, etc.;
- Vibration or noise which can injure or adversely affect the habitability of the unit and the performance of personnel or affect the proper functioning of equipment (especially if resonance occurs);
- Deformations which may spoil the aesthetic appearance of the structure.

The divisions are one of convenience, in that the limit state behaviors can be interlinked. For example, excessive deformation of a structure may also be accompanied by excessive vibration or noise as well as buckling. The acceptable SLS limits will normally be defined by the operator of a structure, the primary aim being efficient and economical in-service performance, usually together with a planned program of maintenance and upkeep for the unit. The SLS criterion is generally expressible as follows

$$\delta_{\max} < \delta_a \tag{1}$$

where $\delta_{\max}$ = factored maximum value of the serviceability parameter in terms of actions effects (e.g., displacement, stress); δ_a= factored serviceability limit value of the consistent parameter.

The SLS criterion in Eq.(1a) is expressed in terms of action effects, and the same may be sometimes cast in terms of actions (e.g., forces, load-carrying capacity) and given in the following form,

$$F_{\max} < F_a \tag{2}$$

where $F_{\max}$ = factored maximum applied actions (loads); F_a = factored load-carrying capacity.

A 'factored' value indicates that an appropriate factor of safety associated with uncertainties is applied by multiplication to loads or by division to strength. The acceptable limits necessarily depend on the type, mission and arrangement of the structure. Further, in defining such limits even for structural behavior, other disciplines such as machinery and equipment designers will also need to be consulted.

5.2 Ultimate limit state design

Ultimate limit states (ULS) include the following:

- Structural instability of part or all of the global structure resulting from buckling collapse of its structural components;

- Attainment of the maximum load-carrying capacity of the structure or its components by any combination of buckling, yielding, rupture or fracture;
- Significant in-flooding and loss of watertight integrity of the hull due to extreme actions under harsh environmental conditions;
- Loss of static equilibrium in part or for all of the global structure considered as a rigid body, i.e., capsizing or overturning.

The structural design criteria for the ULS are primarily based on buckling collapse or ultimate strength. To be safe in the ULS, the design criterion can be expressed as follows

$$C_d - D_d > 0 \tag{3}$$

where C_d is design capacity (strength) and D_d is design demand (actions or action effects). The subscript d denotes the 'design' value which considers the uncertainties associated with capacity or demand. In ULS design, C_d indicates the ultimate strength and D_d is the extreme working load or stress in consistent units.

When the structure is subjected to multiple load components, C_d and D_d need to be expressed as the corresponding interaction functions taking into account the effect of combined actions. Eq.(2a) may be rewritten in the form of a conventional structural safety check as follows

$$\eta = \frac{C_d}{D_d} > 1 \tag{4}$$

where η = measure of structural adequacy which must be greater than unity to be safe.

Using the partial safety factor approach, Eqs.(2a) and (2b) can be rewritten, since $C_d = C_k/\gamma_C$ and $D_d = \gamma_D D_k$, as follows

$$\frac{C_k}{\gamma_C} - \gamma_D D_k > 0, \quad \eta = \frac{1}{\gamma_C \gamma_D}\frac{C_k}{D_k} > 1 \tag{5}$$

where C_k, D_k = characteristic values for capacity and demand, respectively; γ_C, γ_D = partial safety factors associated with capacity and demand, respectively, both of which are defined to be greater than unity. The partial safety factors must be obtained by probabilistic analysis involving associated uncertainties.

As an example, and similar to trading ships, the ULS design criterion of ship-shaped offshore unit hulls under vertical bending moments may be expressible as follows

$$\frac{M_u}{\gamma_u} \geq \gamma_{sw} M_{sw} + \gamma_w M_w \tag{6}$$

where M_u = ultimate bending moment; M_{sw} = still water bending moment; M_w = wave induced bending moment; γ_u, γ_{sw}, γ_w = partial safety factors for M_u, M_{sw} and M_w, respectively.

For ULS calculations of ship-shaped offshore structures, gross thickness, i.e., as-built thickness, is usually applied, although the net thickness (i.e., as-built thickness minus a nominal corrosion margin or allowance) is used for trading tanker structural design today in many cases (IACS 2006a, 2006b). The choice between use of gross and net scantlings is often simply a matter of practice; but for the given situation it will be appreciated that the accompanying safety factor values will in principle be different.

In usual operational condition of vessels, tensile strains of structural components at acceptable yielding may be small enough such that no fracture may occur. However, for offshore units operating in cold waters or for aged vessel structures, the structural material is more likely to become brittle and/or the fracture strain of the structural components may become smaller. In such cases, the structural components may experience brittle or ductile or a mixed mode of fracture; and thus this type of failure must also be additionally considered in design.

5.3 Fatigue limit state design

Fatigue limit states (FLS) represent the fatigue crack occurrence at structural details due to stress concentration and damage accumulation under the action of repeated loading. In the relatively common context of use of S-N curves derived from small specimen fatigue test data, the related state of failure is often assumed to correspond roughly to the initiation of a through thickness crack at a particular location. It will be appreciated, however, that for practical purposes a crack that is even so initiated may not be visually observed until it is longer. Surface cracks are even more difficult to observe without specialized means such as dye penetration or magnetic particle testing.

In any event, it is worth pointing out that there exists a certain amount of ambiguity as to how exactly the FLS failure of the real structure physically correlates to the fatigue data used in design. For this and many other reasons, the FLS design in a particular case is carried out so that it is ensured that the structure has an adequate fatigue life which is longer than the design service life by an adequately appropriate factor of safety. Also the predicted fatigue life is an input consideration for purposes of planning efficient inspection programs during the operation of the structure.

5.4 Accidental limit state design

Accidental limit states (ALS) potentially lead to a threat of serious injury or loss of life, pollution, damage and loss of property or significant financial exposure. The intention of ALS design is to ensure that the structure is able to tolerate specified accidental events and, when accidents occur, subsequently maintains structural integrity for a sufficient period under specified (usually reduced) environmental conditions to enable the following to take risk mitigation and recovery measures to take place, as relevant:

- Evacuation of personnel from the structure;
- Control of undesirable movement or motion of the structure;
- Temporary repairs;
- Safe refuge and firefighting in the case of fire and explosion;
- Minimizing outflow of cargo or other hazardous material.

Different types of accidental events may require different methodologies or different levels of refinement of the same methodology to analyze structural resistance or capacity during and following such events (demands). The ALS design is then necessarily an important part of design and operation risk assessment and management which consists of hazard identification, structural evaluation and mitigation measure development for specific types of accidents. For ship-shaped offshore installations, accidental events such as unintended flooding (damage stability), collisions, dropped objects, fire, explosion and progressive accidental hull girder collapse must be considered.

For purposes of ALS design, the following three main aspects must be identified, namely

- Significant accident scenarios taking account of frequency of occurrence;
- Structural and other evaluation methods of the accident consequences;
- Relevant acceptance criteria.

Accident scenarios must reflect accidental phenomena which affect the safety of the installation and the surrounding environment in an unfavorable fashion, but must also be credible. The largest credible accident possible of a particular type is often of interest. The frequency of occurrence of the corresponding accident must fall within an acceptable range. The structural evaluation methods should be adopted so that the accident consequences can be analyzed to the needed accuracy.

While in some cases simplified approaches may often be enough, more sophisticated methodologies are in other cases necessary for analysis of the accident consequences which usually involve highly nonlinear aspects by their very nature. The acceptance criteria format depends on the accident situations to be avoided. Typical measures of the acceptance criteria include reserve stability, damage extent, quantity of oil outflow and residual load-carrying capacity for example. Required or limit values for accidental action effects (e.g., damage amount, material property change) and structural crashworthiness (e.g., energy absorption capability) are often used to represent the measure of safety level.

The ALS design format may hence be a set of deterministic rules representing acceptable safety level or some given limits to the probability of occurrence to adverse events or some specified bounds on the probability (likelihood) of consequences or some combination of these. A deterministic ALS design format may be expressible in terms of limits of deformation or energy absorption capability until the critical consequence occurs, as follows

$$w \leq w_a, \quad E_k \gamma_k \leq \frac{E_r}{\gamma_r} \tag{7}$$

where w = factored accidental action effects (e.g., deformation, strain); w_a = allowable (factored) accidental action effects; E_k = characteristic value of kinetic energy loss due to accidental actions; E_r = characteristic value of energy absorption capability until a specified critical damage occurs; γ_k, γ_r = partial safety factors taking into account the uncertainties related to kinetic energy loss and energy absorption capability, respectively.

The partial safety factors used of the second equation in Eq.(3) may be chosen to represent one or more or perhaps even all of the following uncertainties, namely

- Natural variation of design variables;
- Modeling uncertainties of the assessment method;
- Return period of hazard event;
- Societal factors including risk perception;
- Consequences including economic factors.

6 Risk based design

In contrast to deterministic ALS design criteria, the risk based design format can be given by

$$R \leq R_a \tag{8}$$

where $R = \sum_i F_i C_i$ = risk; F_i = frequency (or likelihood) of the (i)th failure event resulting in the consequence C_i; R_a = acceptable risk level.

To identify the consequences, limit states together with nonlinear structural mechanics must in principle be essentially applied. Typically taking into account fluid-structure interaction effects and hydroelasticity is desirable for the consequence analysis, although the analyses of actions and action effects (consequences) are often performed separately for simplified design purpose.

Risk-based criteria are more general in nature, but also usually more complex to apply than the prescriptive approaches. Risks to humans may be categorized into two main types, namely

- Individual fatality risks which are perhaps approximately the same as those typical for other occupational hazards;
- Societal fatality risks associated with frequency of accidents and hazards.

Any risk should not exceed a level defined as unconditionally intolerable, and the level of the consequences of any accident should be acceptable to the various stakeholders, primarily the owners, operators, regulatory bodies such as governments and the public. To achieve these aims within a risk based format to ALS, the well-known and general ALARP (As Low As Reasonably Practicable) technique can be applied for risk assessment.

7 Concluding remarks

For the last decade, increasingly advanced and emerging technologies for design and strength assessment of ships and offshore structures have been developed. This is due that direct analyses from first-principles, advanced engineering and practices are being increasingly desired for practicing engineers. Academic and other researchers now aim to resolve the issues that remain, reconcile differences in standards and practices, and implement improved structural and other design procedures and criteria, in the never-ending quest for safe, reliable, yet economical structures and systems. Such structures and systems must be effectively and reasonably rapidly designed and constructed often to a very demanding schedule and considering other accompanying constraints and challenges.

Also, many diverse international organizations in maritime industry such as IMO (International Maritime Organization), ISO (International Organization for Standardization), IACS (International Association of Classification Societies) and the industry in general are now increasingly seeking to apply the limit states design approach for both trading ships and ship-shaped offshore installations, making the related knowledge and training even more relevant. Another emerging and increasingly more important technology consists of risk-based approaches to design, operation, and human and environmental safety, with much of the same accompanying knowledge, training and familiarization needs.

The present paper addresses and discusses recent advances and possible future trends for design and strength assessment of ships and offshore installations. It is considered that some technologies are mature enough to enter the practices of limit states and risk based design while some others must be further developed by resolving the remaining issues.

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