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ScienceDirect

Procedia Engineering 173 (2017) 17 – 24

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Symposium on Plasticity and Impact Mechanics, Implast 2016

Recent Advances and Future Trends on Plasticity and Impact Mechanics of Ships and Offshore Structures

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Abstract

While in service, ships and offshore structures are likely subjected to various types of extreme and accidental events that essentially involve plasticity and impact issues. Ships and offshore structures are typical examples of thin-walled structures, but their environments in construction and operation are quite unique compared to other types of thin-walled structures. Those include welding induced high temperature causing initial imperfections (e.g., initial distortions, residual stress or softening in the heat-affected zones of welded aluminium structures); abnormal waves/winds/currents; dynamic pressure loads arising from sloshing, slamming or green water; low temperature in Arctic operations; cryogenic conditions resulting from liquefied natural gas cargo; ultra-high pressure in ultra-deep waters; elevated temperature due to fire; blast loads due to explosion; impact loads arising from collision, grounding or dropped objects; age-related degradation such as corrosion, fatigue cracking and local denting damage; and hull girder collapse or sinking. Such events sometimes result in catastrophic consequences that lead to casualties, property damage, and pollution. This paper presents recent advances and future trends with the focus on plasticity and impact mechanics of ships and offshore structures in association with extreme and accidental conditions.

Peer-review under responsibility of the organizing committee of Implast 2016

Keywords: Ships; offshore structures; plasticity; impact mechanics; accidental conditions; extreme conditions

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Peer-review under responsibility of the organizing committee of Implast 2016
doi:10.1016/j.proeng.2016.12.011

1. Introduction

Ships and offshore structures usually operate under normal conditions while in service, but they can face various types of extreme and even accidental conditions, resulting in various action effects, as shown in Fig. 1 [1]. The sources of such actions and action effects include (without consideration of any specific order): welding induced high temperature causing initial imperfections (e.g., initial distortions, residual stress or softening in the heat-affected zones of welded aluminum structures); abnormal waves/winds/currents; dynamic pressure loads arising from sloshing, slamming or green water; low temperature in Arctic operations; cryogenic conditions resulting from liquefied natural gas cargo; ultra-high pressure in ultra-deep waters; elevated temperature due to fire; blast loads due to explosion; impact loads arising from collision, grounding or dropped objects; age-related degradation such as corrosion, fatigue cracking and local denting damage; and hull girder collapse or sinking. Such events sometimes result in catastrophic consequences that lead to casualties, property damage, and pollution.

Fig. 1. Extreme and accidental events involved in ships and offshore structures [1].

Plasticity and impact mechanics is certainly a key element of nonlinear structural consequences associated with extreme and accidental events [2]. This paper presents recent advances and future trends with the focus on plasticity and impact mechanics of ships and offshore structures in association with their causative mechanisms and nonlinear structural consequences against extreme and accidental events.

2. Causative mechanism and structural consequences

Various extreme and accidental events exposed to ships and offshore structures while in service cause highly nonlinear problems associated with non-Gaussian, multi-physics, multi-scale, and multi-criteria where plasticity and impact effects are always involved as challenging issues.

2.1. Fabrication related initial imperfections [3-6]

Ships and offshore structures are typically fabricated by flame cutting and welding reaching up to over 1,200 deg. C, and thus they always have initial imperfections in the form of initial distortions and residual stresses, caused by the successive expansion and shrinkage during the heating and cooling. In a welded steel plate, the heat affected zone is formed with a band width, in which the stress is approximately equal to the tensile yield stress because the molten metal can expand freely, as a liquid, whereas after welding it quickly reverts to a solid and the shrinkage that occurs during cooling involves “plastic flow”. The compressive residual stress is developed in the rest of the plating to achieve an equilibrium condition. In the heat affected zone of welded aluminum structures, in contrast to steel structures, a softening phenomenon occurs in which the yield strength within the heat affected zone is reduced relative to that of the base metal. Because such fabrication related initial imperfections may have an effect on the structural properties and load-carrying capacities of structures, they must be dealt with as parameters of influence in structural design and strength assessment.

2.2. Abnormal waves, winds, and currents [4]

Actions arising from environmental phenomena on offshore structures are different from those on trading ships. The nature of offshore structures and their operation are such that waves, winds and current, among others, while waves are the primary source of environmental actions on trading ships at sea where considerations related to specialized operations such as berthing are somewhat different.

The wave parameters for offshore structural designs include heights, periods, and directions with associated probabilities and persistence times. It is important 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 response of floating offshore structures is wave-period dependent. Extreme waves often give rise to not only geometrical nonlinearity but also plasticity. It is noted that more frequent waves rather than extreme waves will govern fatigue life although their magnitude may be smaller.

Wind is a primary metocean parameter that is important to the design of offshore structures that must withstand the forces exerted by the wind, and this depends not only on the structural characteristics such as windage area but also on the speed and direction of the wind. For design, extreme wind speeds for specified return periods must be obtained and specified with averaging times ranging from 3 seconds, i.e., an extreme gust value to 24 hours, for example. The wind 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. Wind can cause phenomena such as vortex shedding together with associated vibrations in flare tower of offshore platforms.

Currents can affect the orientation of floating offshore structures and therefore, directly and indirectly affect both short-term and long-term loads imposed on the structure and its mooring system. Currents can increase the hull drag forces over and above the values due to the wave system alone. Currents also ultimately affect the station-keeping of floating offshore structures and the performance of the thrusters where used.

2.3. Dynamic pressure [4]

Sloshing, slamming and green water are typical sources of dynamic pressure loads in ships and offshore structures that cause dynamic pressure issues associated with strain rate effects. Sloshing happens on partially filled tanks produced by accelerations arising from the motions of ships and floating offshore platforms at sea. Resonance between the natural sloshing period of the tank with liquids and the roll or pitch periods of the structure is of concern. Slamming and wave-slap impact may also cause structural damage such as buckling involving plasticity and dynamic effects. Green water is unbroken waves overtopping bow, side or stern structures of ships and offshore structures. The occurrence of green water depends on various factors including the relative motion between the structures and waves, the speed, the freeboard, and the harshness of the environment, exceeding the available freeboard. The green water problem can be an important design issue under harsh environmental conditions because it can cause damage to deck houses, deck-mounted equipment such as switch room compartments, watertight doors, walk-way ladders, and cable trays.

The dynamic pressure actions arising from sloshing, slamming or green water are generally characterized by four parameters: (1) rise time until the peak pressure, (2) peak pressure, (3) pressure decay type beyond the peak pressure, and (4) pressure duration time. For practical design purposes, the problem of dynamic pressure actions in terms of structural response is sometimes idealized within three domains of response depending on the ratio of the duration time (t) of dynamic pressure loads to the natural period (T) of the structure, namely

- Quasi-static domain when $3 \leq t/T$
- Dynamic or impact domain when $0.3 \leq t/T<3$
- Impulsive domain when $t/T<3$

2.4. Air and sea temperatures [4]

Ships and offshore structures are often subjected to lower or higher than room temperature. The probable extremes of the temperature at the sea surface are sometimes more severe than the corresponding 50-year return period temperatures, and also extremes of sea surface temperature occur less frequently than air temperature extremes. The information on sea temperatures is important for fracture toughness design in many cases in an Arctic operation where mean value of temperature in winter season is -40 deg. C while the lowest temperature is reportedly -68 deg. C. Year-round temperatures and humidity are also of interest in association with corrosion damage.

2.5. Cryogenic condition

Liquefaction of natural gas can be achieved by either lowering temperature or increasing atmospheric pressure, while the former technique is more often adopted in today’s maritime industry. To process liquefied natural gas (LNG), the temperature should be lowered by -163 deg. C, while it is -43 deg. C for liquefied petroleum gas (LPG).

As the mechanical properties of materials are significantly affected by low temperature, and those used for LNG carriers or LNG FPSO (floating, production, storage and offloading unit) can be exposed to the cryogenic conditions, caused by an accidental leakage of LNG, it is very important to manage brittle fracture issues in design and engineering of the structures in cryogenic condition.

2.6. Ultra-high pressure

Developments of offshore oil and gas in deep and ultra-deep water areas, reaching more than 1,000m water depth are now typical. Subsea equipment in deep water is subjected to high external pressure that can cause structural failure involving plasticity. Effects of elevated temperature due to produced oil are often challenging issues to be resolved in subsea pipelines together with such high pressure loads.

2.7. Elevated temperature due to hydrocarbon fires [4, 7-9]

In offshore oil and gas facilities, more than 70% of accidents stem from hydrocarbon explosions and fires. Hydrocarbons can explode through ignition when combined with an oxidiser (usually oxygen or air). Thus, when temperatures rise to the point at which hydrocarbon molecules react spontaneously with an oxidiser, combustion takes place. Fire is a combustible vapour or gas that combines with an oxidiser in a combustion process that manifests in the evolution of light, heat, and flame.

The effects of elevated temperatures generated by fires are the primary concerns regarding the actions that result from hazards within the risk assessment and management framework. The thermal characteristics of steel are the main factors affecting structural integrity in fires. The specific heat of steel varies with temperature. At temperatures above 400 deg. C, the mechanical properties of steel significantly decrease. The heat from fire flows relatively ‘rapidly’ in steel, which is a good heat conductor compared to other materials, e.g., concrete. Thus, fire can lead to the collapse of steel structures involving plasticity, and the severity of fire loads usually requires an application of passive fire protection (PFP) for critical structural elements.

2.8. Blast loads due to hydrocarbon explosions [4, 7, 8, 10]

Hydrocarbon explosions in offshore installations cause a blast or a rapid increase in pressure. Drag forces are also developed. The effects of overpressure and drag forces from explosions are the primary concerns regarding the actions that result from hazards within the risk assessment and management framework. Not only plasticity but also strain rate issues are always involved in association with nonlinear structural responses under blast loads. Similar to dynamic pressure loads described in *2.3*, the profile of blast loads can also be characterized by the four parameters.

2.9. Impact loads [3-6]

Ships and offshore structures can be subjected to impact loads arising from collision, grounding or dropped objects. Collision is a phenomenon where side, bow or stern structures are damaged accidentally. Collision accidents are associated with impact issues because they involve two colliding objects where one or both are moving with a speed, e.g., between two ships, between a ship and an offshore platform, between a ship and an iceberg or between an offshore platform and an iceberg.

Grounding is a phenomenon where ship’s bottom structures are damaged by some accidental causes. Three types of grounding are relevant, namely grounding with a forward speed, stranding, and squatting. The first type of grounding is characterized as one where obstruction deforms the bottom inward and/or enters into and cuts through the trading ship structure as the vessel moves forward on a rock. This type of damage is called a raking damage, forming a very long gash in the bottom when the impact load is applied in the ship’s length direction. The second type of grounding accident happens when the vessel is out of control with engine failure and the subsequent ship’s bottom damage or penetration mostly in the ship’s depth direction as a result of hydrodynamic instability with tidal differences. A stranding situation is similar to a collision where the struck side of a ship is subjected to mainly out-of-plan impact. The squatting occurs when a vessel moves in shallow water where bottom plates may deform due to the difference between external and internal pressures as external pressure in rapid water particles can decrease.

Deck plates of offshore structures may be subjected to impacts due to objects dropped from cranes resulting in damage. Such mechanical damage can lead to denting, cracking, and residual stresses or strains due to plastic deformation or coating damage causing pit corrosion.

2.10. Age related degradation [3-6]

Typical types of deterioration involved in ships and offshore structures while in service include corrosion, fatigue cracks, coating breakdown, and out-of-tolerance misalignments. Corrosion can be of various types such as general corrosion and localized corrosion. Cracking may be caused by fatigue due to the dynamic actions arising from environmental phenomena, operation, and other causes such as high local stresses and hard spots. Low temperature exposure may make the material brittle resulting in brittle fracture given the appropriate high stress-strain rates, although brittle fracture is much less common today with the attention now being paid to materials and their selection for use. Inadequate fabrication can result in significant initial defects and misalignments that may also increase the probability of fatigue cracking.

2.11. Hull girder collapse [3, 4, 6]

In ships and ship-shaped offshore structures, the collapse of hull girders is the most catastrophic failure event because it is almost always entails the complete loss of the structure. As applied hull girder loads increase, the most highly stressed structural components of hull girders buckle in compression or yield in tension. A vessel can of course withstand further hull girder loading even after the buckling or yielding of a few structural components. However, the structural effectiveness of the hull decreases due to local failures, and eventually the overall hull structure reaches the ultimate limit state as the redundancy of the hull becomes exhausted due to the progressive structural failures under hull girder loads applied. Hull collapse is more likely to occur in ships suffering age-related degradation, such as corrosion wastage and fatigue cracking damage, or in those with in-service or accidental damage associated with accidental events such as collision, grounding, fire, or explosion. Although the strength performance of hull structures is not necessarily insufficient for their designed loads, which are determined for the most unfavourable environmental conditions, hull girders can break due to accidental flooding or unintended water ingress into the ship because this causes the hull girder loads to increase to the extent that the hull cannot sustain them.

Hull girder actions are likely to be cyclic in accordance with wave actions. Even though several hull girder actions may be extreme, they may not lead to hull girder collapse. In this case, shakedown phenomenon can occur where the load effects in local regions may well exceed the yield stress, resulting in plastic behaviour. Shakedown limits can be used to assess the safe range of the cyclic loading of a structure [11].

3. Recent advances for nonlinear structural response analysis and design [3-6, 12]

In the past, criteria and procedures for the structural analysis and design of ships and offshore structures were primarily based on allowable stresses and simplified buckling checks for structural components. However, it is now well recognized that limit state-based approaches are much better methodologies for structural design and strength assessment than the traditional working stress-based approaches, as the latter are typically formulated as a fraction of material such as yield strength. This situation exists because it is difficult to determine the true margin of structural safety using linear elastic methods alone when the remaining limit states are unknown. It follows that determining the true limit state is of crucial importance to obtain consistent measures of safety that can form a fairer basis for comparisons of structures of different sizes, types, and characteristics. The ability to correctly assess the true margin of safety would also inevitably lead to improvements in related regulations and design requirements.

To obtain a safe and economic structure, limit state-based capacity and structural behaviour under known loads must be accurately assessed. The structural designer can perform a relatively refined structural safety assessment even in the preliminary design stages if there are simple expressions available for accurately predicting the limit state behaviour. A designer may even desire to do this not only for the intact structure, but also for structures with premised or accidental damage as a way of anticipating their damage tolerance and survivability.

A limit state is defined as the condition beyond which a structural member or entire structure fails to perform its designated function. Four types of limit states are relevant here, namely

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

ULS is the collapse of a structure due to a loss of structural capacity in terms of stiffness and strength that typically arises from the buckling and plastic collapse of structural components. SLS represents failure in normal operations due to deterioration in routine functionality. Typical examples of SLS include local damage, unacceptable deformation, and excessive vibration and noise that affect the proper functioning of structural elements or equipment. FLS is the fatigue cracking of structural details as the result of stress concentration and damage accumulation under repeated loading actions. ALS is the excessive structural damage that results from accidents such as collisions, grounding, explosions, and fire – all of which affect the safety of the structure, the environment, and the personnel.

Nonlinear structural consequences can be represented as a function of various factors, namely

$$\textit{Nonlinear structural consequences} = \textit{function of a, b, c, d, e, f, and g,} \tag{1}$$

where,

a = geometrical factors associated with buckling, large deflection, crushing, or folding,
b = material factors associated with yielding/plasticity, ductile/brittle fracture, rupture, or cracking damage,
c = fabrication-related initial imperfections such as initial distortion, residual stress, and softening,
d = load types/components (quasi-static),
e = dynamic factors (strain rate sensitivity, inertia effect) associated with freak/rogue/abnormal waves and the impact pressure actions that arise from sloshing, slamming, or green water; overpressure actions arising from explosions; and impacts due to collisions, grounding, or dropped objects,
f = temperature factors such as low temperatures associated with cold water operation and/or low-temperature cargo and high temperatures due to fire and explosions,
g = age-related deterioration such as corrosion and fatigue cracking, and
h = human factors related to unusual operations in terms of ship speed (relative to the maximum permitted speed or acceleration), ship heading, and loading conditions.

The design condition of a structure can be expressed as follows.

$$G = C_d - D_d \geq 0\,, \tag{2}$$

where G = a performance function, C_d = the design value of capacity (strength), and D_d = the design value of demand (load).

In ULS-based design and safety assessment, capacity is the ultimate strength and demand represents extreme actions or action effects such as those in the most unfavourable conditions to which the structure may be subjected. In accidental condition, capacity represents the residual ultimate strength of structures with damages caused by the corresponding accident. Two types of format for design or safety assessment are usually applied to ensure that a structure has an adequate degree of safety and reliability, namely partial safety factor format and probabilistic format.

The partial safety factor format considers the effects of uncertainties in the following form.

$$C_d = C_k / \gamma_C\,,\ D_d = \gamma_D D_k\,, \tag{3}$$

where C_k and D_k = the characteristic values of capacity and demand, respectively, and γ_C and γ_D = the partial safety factors associated with the uncertainties of capacity and demand, respectively.

The probabilistic format, in contrast, is more rigorous when considering the effects of uncertainties. The performance function of equation (2) can be rewritten as a function of the basic variables, $x_1, x_2, \cdots, x_i, \cdots, x_n$, as follows.

$$G\left(x_1, x_2, \cdots, x_i, \cdots, x_n\right) = 0\,. \tag{4}$$

When $G > 0$, the structure is in the desired state. When $G \leq 0$, it is in an undesired state. In this regard, it is clear that the primary tasks that need to be accomplished by the structural design criterion of Equations (2) and (3) are how to determine C_k , D_k , γ_C , and γ_D for the partial safety factor design format, and mean and standard deviation values of the limit state function for the probabilistic design format.

The primary aim of the ALS design for steel structures may be characterized by the following three broad objectives, namely (1) to avoid loss of life in the structure or the surrounding area, (2) to avoid pollution of the environment, and (3) to minimize loss of property or financial exposure. In ALS design, it is necessary to achieve a design such that the main safety functions of the structure must not be impaired during any accidental event or within a certain time period after the accident. The structural design criteria against for the ALS are based on limiting accidental consequences such as structural damage and environmental pollution. Since the structural damage characteristics and the behaviour of damaged structures depend on the types of accidents, it is not straightforward to establish universally applicable structural design criteria for the ALS. Typically, for a given type of structure, design accidental scenarios and associated performance criteria of steel structures must be decided upon the basis of risk assessment.

In the case of merchant ships or war ships, possible accidental events that may need to be considered for ALS include collisions, grounding, significant hydrodynamic impact (slamming) leading to deck buckling or bottom damage, excessive loads from careless loading, berthing or dry docking, internal gas explosions in oil tanks or machinery spaces and the underwater or atmospheric explosions for naval ships. In land-based structures, the accidental scenarios may include fire, explosion, foundation movements or related structural damage from earthquakes. In selecting the design target ALS performance levels for such events, the approach is normally to tolerate a certain level of damage consistent with a greater aim such as survivability or minimized consequences; not to do so would result in an uneconomical structure.

4. Future trends for nonlinear structural response analysis and design

Successful design and engineering should meet not only functional requirements but also health, safety, environment and ergonomics (HSE&E) requirements. Functional requirements represent operability under normal conditions, and HSE&E requirements address safe performance and integrity in extreme and accidental conditions. The paradigm shift is now pertinent in design and engineering for ships and offshore structures, as described in Fig. 2. Paik [1] suggested to modify the original concept of IMO (International Maritime Organization) to achieve the goal-based standards by including a new tier dealing with HSE&E requirements as addressed in Fig. 3.

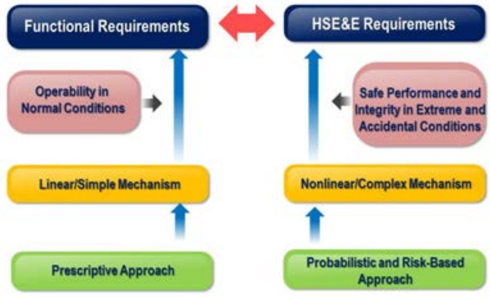

Fig. 2. Paradigm shift in design and engineering of ships and offshore structures [1].

It is now well recognized that risk-based approaches are the best way to assess and manage issues associated with hazards and their consequences, considering that a lot of uncertainties are essentially involved in extreme and accidental events [4]. Typically, the term 'risk' may be defined as either the product or a composite of the following two; (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 exposure occurs; and (b) the resulting consequences. In the design and operation of ship-shaped offshore units like in many other types of structures, 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.

Fig. 3. Suggestions of modifying the IMO's original concept for goal-based standards with six tiers [1].

To minimize the risk, one may either attempt to reduce the likelihood of occurrence of the undesirable events or hazards concerned, or contain, reduce or mitigate the consequences, or both. In the lifecycle of ships and offshore structures, it is required that one should assess, manage and control the risk so that it remains under a tolerable level. The risk management and control should in fact be an on-going process throughout the lifecycle of the structure. The different stages of the lifecycle will offer different opportunities for risk management and control as may be expected. In this regard, integrated and multidisciplinary approaches should be applied as illustrated in Fig. 4. Computation by itself is not enough, and testing is essential with large- and full-scale test models as scaling laws to convert small scale test results to real full scale structures are not usually available in association with extreme and accidental conditions. Also, operations must be monitored to provide feedback to a service database relevant to the design stage. Relevant test facilities are then required to meet the needs where full scale or at least large scale models should be dealt with [13].

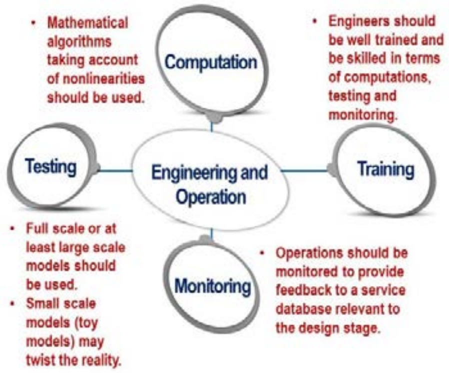

Fig. 4. Multidisciplinary approach for meeting HSE&E requirements [1].

5. Concluding remarks

Ships and offshore structures are likely subjected to various types of loads and deformations arising from service requirements that may range from the routine to the extreme or accidental. The mission of the structural analysts and designers is to identify structural responses and to design a structure that can withstand such demands throughout its expected life time. Failure of ships and offshore structures subject to extreme and accident conditions is usually related to either one or both of geometric nonlinearity associated with bucking or large deflection and material nonlinearity due to yielding or plastic deformation, where plasticity and impact mechanics are key elements of such nonlinear structural responses.

Advanced technologies are now available for daily practices in terms of characterizing such nonlinear structural responses. However, there are still many challenging issues to be resolved with a lot of uncertainties involved in association with extreme and accidental events. Risk-based approaches are considered to be the best way to manage such issues. It is strongly encouraged to take advantage of test database obtained from full scale or large scale model tests as computations alone using mathematical algorithms are not always sufficient enough to identify such highly nonlinear problems involving non-Gaussian, multi-physics, multi-scale, and multi-criteria.

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