Design loads for marine facilities

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ABSTRACT: For design of marine facilities, a design basis is needed. This design basis will include selection of safety level and codes to be used during the design process. The design basis will include all aspects necessary to design safe facilities, including methods for load calculations. In this paper the design basis for offshore structures and marine vessels is discussed. Particular emphasis is put on robust facilities which will not collapse under loads slightly higher than the design load. Furthermore, the new types of fuel introduced in the marine industry for vessels give rise to concern as these fuels are highly flammable with high explosion pressure. Mitigating measures to reduce the consequences of large loads represent important considerations.

1. INTRODUCTION

For the design of marine facilities, it is important that a design basis for load and load effects be agreed. Norsok Standard N003 (Standard Norway, 2017) was updated in 2017 with respect to loads and load effects from waves, ice and ship impacts etc. The wave crest for design of structures was slightly increased, while the energy to account for an accidental ship impact was substantially increased. The loads from drifting ice and sea spray icing were highlighted due to increased activities in the Barents Sea.

Actions from fires and explosions are also of great concern. The oil and gas industry has developed models to identify fire- and explosion loads following release of gas, and specialized computer models (for example, FLACS, FLame ACceleration Simulator, see Gexcon, 1992) are based on substantial testing. Fire protection to resist temperatures in fires, as well as relevant explosion panels have been developed.

However, with the new types of fuel introduced for maritime vessels, there is an urgent need to develop design basis for the challenges arising from use of these new types of fuel. These challenges include:

- fires and explosions from use of large power-banks like lithium batteries
- cooling effects, fires and explosions in case of escape of LNG from storage tanks
- explosions and fires in case of leakage of hydrogen used for fuel
- fires in transformer stations where electricity is transformed from DC to AC and vice versa.

Fire protection and explosion walls are normally in the oil and gas industry introduced to withstand the loads from explosions and fires caused by burning of traditional fuel or from leakages of methane gas. The challenge to define a design basis for the new types of fuel is urgent, as vessels are being rebuilt or new vessels are built to use the new fuel systems.

Storage of batteries, LNG and hydrogen onboard vessels potentially represents the accidental release of large quantities of energy. Considerations related to load and load effects from accidents alone are, however, not sufficient. Although it might be possible to prepare a design to resist the load, the *probability* of a release and the *consequences* of a subsequent accident shall always be reduced.

Furthermore, the *consequences* of an extreme load/ load effect (collision, fire or explosion) shall be reduced by a *robust design* so that a load larger than the design value, does not cause the escalation of the damage of the facilities into a progressive collapse (for example the sinking of a vessel). Also, the protection of personnel/ crew must be carefully considered when using the new types of fuel to avoid that fires/explosion escalate into the quarters onboard the vessel. Therefore, new design standards are required, possibly separating the quarters on vessels with new fuel machinery, using separation walls or moving the quarters away from storage tanks, like done in the oil and gas industry.

2. THE DESIGN BASIS

For the design of any facilities, a design basis must be agreed on. The design basis shall cover the following aspects:

- the intended use of the facilities, for example:
  - a vessel for transport of highly explosive materials needs to be designed to resist a defined explosion load
  - a vessel for transport of large deck load must be designed with a strong deck
  - a vessel transporting toxic fluids must be designed with double sides to avoid leakages to the water in case of hull damage
  - most vessels are designed with double bottom to avoid sinking after a grounding
- the selection of safety level for the design is to be made, as the safety level depends on the importance of the facilities for the society and the owners:
  - a cruise ship has to be designed to a high importance class as the vessel is carrying a large number of passengers and crew
  - a vessel transporting nontoxic gravel will not carry large crew and will not pollute in case of damage to the hull
  - a wind turbine structure could be designed for a higher probability of damage as the consequences of damage are lesser than for manned structures
  - an offshore oil and gas production platform must be designed to ensure that an environmental disaster is avoided
- the planned design life of the facilities
  - to ensure sufficient fatigue resistance over the planned operational life of the facilities, often set to 30 years, however, longer for specialized facilities
- the standards selected for the design of the facilities
  - normally the applicable international standards, the IMO or ISO standards, supplemented with design codes as those of Det Norske Veritas, Lloyds or the American Bureau of Shipping (ABS)
  - possibly with the addition of national requirements, like the Norsok Standards (Standards Norway) for offshore structures, or company specific requirements
- the requirements for the construction stage
  - a vessel must for example be checked for the launching operation
  - a module for an oil and gas platform must be designed for the forces during lifting
  - wind turbine facilities must be designed for lifting at the offshore location
- any other requirements set by the legislators or the owner
  - for example, a requirement to local contents during fabrication
  - use of same set of operational procedures as other assets operated by the company

It is noted that new types of fuels challenge the adequacy of existing design basis for marine facilities and there is a need to remind the authorities and owners that any design must be safe with regards to personnel (including the crew) and the environment. The design basis must, therefore, include loading from fires and explosions as some of these fuels can cause highly energetic explosions and are highly flammable.

In addition to the design basis, a risk analysis of the facility during its intended lifetime should be carried out to ensure that the facility is sufficiently ***robust*** to withstand possible unexpected/ abnormal situations without collapse or without causing irreparable damage to the environment:

- The requirement to robustness can be achieved through implementation of redundant members:
  - in a steel truss structure, an x-bracing is redundant while a single strut represents a non-redundant design
  - in a vessel, a certain number, n, of watertight compartments represent n-compartment damage stability. It must be noted that real robustness has to be ensured, “watertight” compartments with openings for piping are not watertight and pipes within pipes is a possible way to ensure the required robustness.
- The requirement to robustness can also be achieved though implementing of operational measures, as for example limiting the size of vessels supporting the operations of the facilities.

3. SELECTION OF OPERATIONAL LOADS

The operational loads are split between:

- The “dead load”/ “permanent load”, which is the weight of the facilities themselves. The effects of any additional structural strengthening must be analyzed to check the structural capacity. This type of loading is considered a static load.
  - A library is typically designed for very high floor loads.
  - Note the large and concentrated weights of battery storage packs onboard vessels.
  - When changing to new and more modern machinery, the weight and also the dynamic effects must be considered. This also applies to vessels during upgrading.
- The “live load”, which is the variable load due to operations of the facilities. This load is determined by the operating company in

accordance with the planned use of the facilities. This load will, for example, include the weight of people onboard the vessel and could be considerable for ferries.
   - It is recognized that resonances could occur due to movements of people. In Israel, the floor of a building collapsed when the guests at a wedding started the dance (Guardian, 2001). The structure was close to collapse prior to the disaster and the dynamic motion initiated the collapse.
   - The cargo represents variable loading. The structural strength must be checked in case heavy items are transported.
   - The loading from fluids in storage tanks varies considerably during operations.
   - Walls between storage tanks must be designed for the differential pressure between the tanks which may have different levels of filling.

Mitigating measures to avoid failures are recommended as follows:

- The designer shall consider the use of the facilities and add dynamic effects whenever such effects could occur
- The design brief, including the design basis, drawings and codes applied for the analysis must be part of the key documents of the facilities. This also applies to all marine facilities.
- The operational documents shall clearly state any limitations for the use of the facilities

4. DESIGN BASIS FOR THE LOADING FROM THE PHYSICAL ENVIRONMENT

The estimated loading from the physical environment is used to calculate the load in the Ultimate Limit State (ULS), the Fatigue Limit State (FLS) and the Abnormal Loading Limit State (ALS). The load is determined through statistical analysis of data collected over several years, 30 years of data is recommended for statistical analysis (ISO, 2016).

4.1. Waves

The latest version of the Norsok Standard N003 (2017) gives clear recommendations regarding use of wave theories for load calculations. Higher order wave theories (taking the nonlinear surface boundary conditions into account) are recommended to obtain best possible values of the wave crest heights and the water wave kinematics in the surface zone and It should be noticed that the maximum load acting on facilities is found for a specific combination of wave height and period so the design wave condition be determined by searching the design contour in the wave height/ wave period space (Norsok Standard N003, 2017).

Hindcast data are considered to be reliable metocean data when a hindcast model is calibrated to known datasets (measurements of waves when the wind conditions are known). Statistical extreme value models are tested to check if they fit to the data and extrapolations are made to the level of exceedance probability decided according to the selected safety level. For offshore oil and gas platforms, this safety level is selected as an annual probability of exceedance level of 10^{-2}. A safety factor (load factor) of 1.3 is applied to the load calculated. For structures of less importance, a load factor of 1.15 can be used.

Furthermore, for wind turbine foundations, an annual probability of exceedance level of 2×10^{-2} can be applied according to DNV-GL-ST-0437 (2016), as the standard refers to design “events with a recurrence period of 50-years”.

4.2. Currents

When relevant, the loading from currents shall be added to the wave effects. Realistic, site specific combinations of waves and currents shall be identified. Notice that currents can cause vortex induced vibrations of structures placed in the sea.

4.3. Winds

For vessels, the loading from wind is important to address vessel heel. A vessel will normally take a course against the direction of the wind and waves to avoid large roll motion of the vessel. It must be noted that vortex induced vibrations of slender structural members may occur. Furthermore, together with winds, strong atmospheric icing may occur.

4.4. Ice; drifting ice and sea spray icing

The design basis shall give values for design ice conditions.

- Note that drifting ice represents impact loading and that only 10% of an iceberg is seen above the water level. This means that the ice will be substantially larger under the surface and that an “ice-foot” could be present under the water surface. The impact between a vessel and an “ice foot” could represent a substantial loading (Gudmestad and Alme, 2016, Lu et al., 2018, Amdahl, 2019). Vessels for transfer in the Arctic are designed to withstand impacting ice in accordance with ice-class requirements. Notice that the speed of the vessel must be adjusted in case of drifting ice.
- Sea Spray icing will lift the center of gravity on vessels and loss of initial stability could result. The design basis shall include considerations related to safe voyages when sea

spray icing occurs. The period of roll of the vessel increases when the stability parameter, the value of the metacentric height, GM, reduces towards non-acceptable values. An increase of the roll period, could, therefore be interpreted as a warning sign as the safe sailing condition is being reduced.

Mitigating measures to account for loading from the physical environment are discussed below under the heading "Abnormal environmental loading".

5. ABNORMAL ENVIRONMENTAL LOADING

As the environmental data in certain cases will exceed the value representing an annual probability of exceedance level of 10^{-2} (Ultimate Limit State analysis), the facilities have to be checked that collapse under events having lesser probability of exceedance does not occur. The ISO 19900 suite of standards requires that facilities be checked for a load resulting from environmental data having an annual probability of exceedance of 10^{-4}. The load factor is set to 1.0 in this check. Furthermore, it is required that collapse shall not occur should the environmental load with annual probability of exceedance of 10^{-2} occur following the abnormal environmental situation. A load factor 1.0 is used for this check (Abnormal Loading Limit State/ Limit State of Progressive Collapse).

5.1. Waves and currents

It is well known that extreme waves (rouge waves) often occur at sea, however, the probability that such waves occur at a specific site is low. On the other hand, breaking waves occur at known sites.

- Rouge waves (freak waves) occur due to nonlinear interaction between large waves (Osborne, 2019). These waves are extremely dangerous to ships and have caused damage to numerous vessels (Faulkner and Buckley, 1995). An abnormal wave was reported to hit the Draugen oil and gas platform located offshore Norway in March 1995 (Gudmestad, 2020). The load caused vibrations ("ringing") of the platform. The loading was within the abnormal design loading for the platform.
- Waves approaching shoals and sloping shoreline, will break causing an impact type load on structures placed at the location of breaking. As wind turbines often are placed at such locations, wind turbine foundations have to be checked for breaking wave loading (Jose, 2017). The loading from breaking waves may be difficult to predict, references are often made to Wienke and Oumeraci (2005).
- Interaction between waves and opposing currents increases the steepness of the waves and is known to cause extreme ship damages, including sinking. The Agulhas current offshore South Africa is an example of a dangerous area, where shipping is avoided.
- Rouge waves can be modeled in a wave tank by focusing wave energy at a location in the tank. Lian (2020) has, furthermore, studied the generation of abnormal waves being generated from normal irregular wave trains, and the associated slamming loads. Local loads can be extreme, however, global loads on facilities are limited.

Mitigating measures to cope with the consequences of abnormal waves and currents should be put in place:

- Fixed offshore structures should be designed with sufficient air gap between still water level and the underside of the deck to avoid waves hitting the deck, causing large forces on the structures
- Wind turbines located on shoals must be designed to resist breaking waves (Chella, 2016) occurring with a certain probability of exceedance, decided by the authorities/ owners.
- The meteorologists should attempt to predict situations when rouge waves could occur, and ships must be directed away from such locations.
- In case of large currents, vortex induce vibrations are of concern for slender structures, like pipelines and cables. Also, larger structural elements, like Spar buoys can be exposed. Such structural elements must be equipped with vortex suppressing devices, for example a helix mounted along the exterior of the element.

5.2 Impact loading from floating ice and sea spray icing

- Large ice floes are drifting in the ocean. These floes could be composed of multiyear ice having high compressive strength transferring high impact load to the vessel in case of a collision. Of larger concern is the collision with a large iceberg, a smaller iceberg, a bergy-bit or a piece of an iceberg, termed a growler.
- Under certain combinations of wind, waves and temperatures, the sea spray icing on vessels cold be extreme, (Johansen et al., 2020). This situation could occur quite far south in the North Sea (for example along the west coast of Denmark where 14 fishermen were lost in 1979 due to capsizing of fishing vessels, (Fiskeritidende, 14th Jan 2016). The action of meteorologists to issue warnings is requested. The Norwegian Meteorological

Institute is regularly issuing warnings in case of probability of large sea spray icing.

Mitigating measures to cope with the consequences of abnormal ice events should be put in place:

- Impacts from large ice floes are of concern in case vessels without sufficient ice strengthening are in the region. The Northern Sea Route administration (NSR) has, for example strict requirements to vessels allowed to traverse the route.
- Impacts from large icebergs are of grave concern. Vessels are always separated into compartments to avoid sinking; however, captains will avoid sailing in iceberg alleys and look out carefully for "bergy-bits".
- For floating structures located permanently in regions where iceberg could occur, the vessels should be capable of moving from locations in case iceberg management is not successful. The oil and gas industry is reluctant to implementing the required disconnection capabilities in production vessels located in areas with low probability of occurrence of icebergs. The re-connection time is of concern for the economy of the field production. The potential for large release of pollution in case of collision between iceberg and vessel should, however always be considered.
- To control the situation under a sea spray icing event, the accumulated ice must be removed. A clear warning is when the roll period increases, as the roll period is inversely proportional to the square root of the GM of the vessel. This situation calls for immediate action to remove the ice. A heavy snowfall with subsequent freezing of wet snow has the same effect as sea spray icing. Of particular concern is the situation in Polar Low situations which are followed by heavy snow showers. Meteorologists must warn vessels from these Polar Low situations. A complication is the fact that the track of a Polar Low pressure is difficult to forecast.

6. ACCIDENTAL LOADING

6.1 Impact load from ship collisions

Supply vessels' sizes increase and some of those vessels' design is improved for sailing in the Polar region for ice navigation. Improvement in bow design and reinforced ice belts are factors to be considered in order to avoid severe accidents or, in the worst-case scenario, a total loss in case of impact/ collision with another vessel or a fixed facility like an offshore platform or a wind turbine support structure. It is essential to evaluate the risk these improvements in supply ship design poses in case of collisions with existing installations.

Based on a frequency of impacts by attendant vessels of the order of 10^{-3} per installation year, the calculated maximum impact energy for minimum damage was by DNV in the 1980s estimated to be 11 and 14 MJ (Mega Joules) for head-on and sideways impact, respectively (Moan, Amdahl and Ersdal, 2019). As a reference, however, for vessels with displacement between 2000-5000 tons, the impact energy can be up to 60MJ, with a velocity of 6 m/s (Travanca & Hao, 2015). Table 1 gives a list of few accidents occurring in previous years on the Norwegian Continental Shelf (NCS), as an example to reflect on how much impact energy does one collision encompasses (Kvitrud, 2011).

Table 1 Impact energy from collisions with offshore platforms (Kvitrud, 2011).

Year	**Collision Energy**	**Vessel**	**Installation**
2004	About 39MJ	Far Symphony	West Venture
2005	About 23MJ	Ocean Carrier	Ekofisk
2006	About 61MJ	Navion Hispania	Njord B
2007	About 2MJ	Bourbon Surf	Grane
2009	About 70MJ	Big Orange	Ekofisk
2010	Low (Multiple)	Far Grimshader	Songa Dee

The Norsk Standard N003 (2017) gives recommendations for the energy to be considered in a ship impact event: Visiting supply and intervention vessels: 50 MJ, Shuttle tanker collisions 100MJ. The document also provides a discussion related to energy sharing between the visiting vessel and the facilities where the modern supply vessels designed with ice-breaking capabilities are of main concern.

Mitigating measures to limit the design basis to lesser impact energy values are as follows:

- Operational measures may be put in place to limit the vessel size admitted within the safety zone of the facilities. In case the vessel size and velocity is limited, see Figure 1.

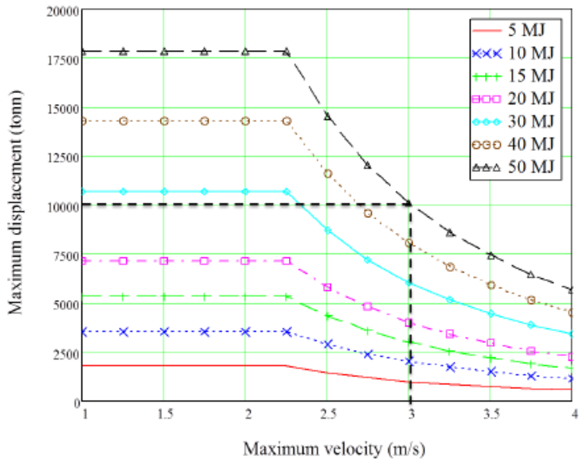

Figure 1. Operational restrictions in the safety zone – acceptable combination of vessel size and velocity is found beneath the respective curve for the documented impact energy capacity (MJ). Based on head on collision and sideways collision in drift condition (Moan et al., 2016, Norsok Standard N003, 2017).

- As most vessels are weaker sideways compared to bow or stern, another mitigating measure is to ensure that the orientation of the vessel is always away from pointing towards the facilities. The shuttle tankers operating at the circular Goliat Floating Production Storage and Offloading (FPSO) platform in the Barents Sea, are always operated in compliance with this requirement to avoid any puncturing of the FPSO.
- In case the Dynamic Positioning (DP) system for a vessel can be documented to be reliable with redundant back-up being mobilized immediately in case of failure of the main system, the probability of a collision will be much reduced.
- Finally, with a market characterized by an abundance of available vessels, there should be no reason to involve vessels designed for ice navigation in non-arctic areas like the North Sea, thereby reducing the consequences of a collision.

6.2 Loading from fires and explosions

Loads caused by fires and explosions are becoming more of concern with the implementation of new fuel systems onboard vessels. This applies to hybrid fueled vessels and vessels only fueled by use of batteries, liquefied natural gas and hydrogen. Firewalls must resist a defined temperature acting over a certain time and explosion panels must resist the explosion load. For a summary of the situation, the following applies:

- Lithium batteries:
  - Thermal run-away can occur in case the energy in batteries is released and the temperature can quickly reach to 600°C followed potentially by explosion and fire. The electrolyte, one of the main components in a Li-ion cell, consists of organic carbonates. Venting and thermal runaway release organic carbonates and when mixed with air, these gases can result in fires and explosions. Note that wood would catch fire at about 300°C and that the melting point of Aluminum is 660°C. In case the oxygen is closed off during a fire, the battery will continue to generate heat and could re-ignite when access to oxygen is again available. During a fire, toxic gases are also released, including hydrofluoric acid.
  - Regarding explosion loads, gas concentrations between 2.5 and 17% could cause explosion with pressures up to 760kPa and an explosion rate of 41MPa/s. (Henriksen et al., 2019).
  - For reference see also DNV-GL, (2015).
- Liquefied natural gas is methane cooled down to -162°C. During a leakage the following occurs:
  - The LNG is transferred to methane gas and a LNG leakage would therefore cause cooling of the environment to temperatures that cause materials to become brittle
  - Methane gas could lead to explosion when the volume percentage reaches 5% - 15%. The explosion pressure could be 670Pa with an explosion rate of 27MPa/s. (Henriksen et al., 2019).
  - Following an explosion, a fire would be initiated, methane burns at 1950°C.
  - An alternative to use of LNG would be to use the fluid methanol (CH_3OH). Methanol has the highest hydrogen to carbon ratio of any liquid fuel. However, methanol is very toxic and when used as fuel, there is also CO_2 emission from the engine.
- Hydrogen is in liquid state at temperature of -253°C
  - Liquid hydrogen will evaporate, causing the environment to become extremely cold
  - An explosion could take place when the hydrogen volume in the air is 10% to 50%. The explosion pressure could be 653kPa with an explosion rate of 102MPa/s. (Henriksen et al., 2019). An extreme impact will occur in case of an explosion.
  - Following an explosion, it should be noted that hydrogen in air has flame temperature of 2111°C. The transport of

Hydrogen for vessel fuel is regarded as extremely hazardous.
  - The alternative is to use ammonia (NH_3). Ammonia does not need to be stored in high pressure tanks or in refrigerated condition. It could represent a breakthrough with respect to reduce greenhouse gas emission from marine vessels (Gallucci, 2021). According to Brown (2019), Maritime fuel mix could be 25% ammonia by 2050. Unlike ammonium-nitrate (NH_4NO_3; a very explosive product used for fertilizer), ammonium can safely be stored anywhere and be transported onboard vessels.
- Offshore wind farms are dependent on transforming the alternating current (AC) generated to direct current (DC). This is necessary to limit the electric loss in the cable during transfer to shore. The transformer stations are vulnerable as overheating could lead to gas formation and explosions. Care must be taken to ensure the integrity of such stations. It is not recommended that personnel stay overnight on these stations, regular visits for maintenance should be sufficient.

The highly flammable gases introduce as new types of “renewable fuel” are explosive and burn at high temperatures. This is of concern for the safety of vessels. An example illustrates this:

- “On December 30, 1975 the oil/ore carrier M/S "Berge Istra" sank in the Molucca Sea. Two of the crew were rescued. They reported a rapid series of three massive explosions followed by immediate sinking of the ship. In October 1979, the sister ship M/S "Berge Vanga" disappeared in the Atlantic Ocean. Practically nothing is known about that incident. No-one was rescued. The rapid sinking of "Berge Istra" indicates that a gas explosion in the double bottom of the ship ripped the ship structure open and water flooded the double deck and the engine room” (Gexcon, 1992).

  This incident shows that the damaging potential of flammable gas cloud in a confined room (like the double bottom of a ship) can generate damaging pressure. Note that such volumes onboard vessels today are filled with inert non-flammable gas.

Possible mitigating measures in case the new types of fuel are introduced in new or retrofitted ships:

- Batteries must be stored in a safe way to ensure there is an over-pressure in the room, so the oxygen is used quickly in case of fire. Formal procedures must be in place to handle the fire so an explosion is avoided (DNV-GL, 2015).
- Liquefied Natural Gas must be stored away from the living quarter of a ship to avoid that any leakages of methane get to the quarter. The alternative use of methanol has drawbacks due to the toxicity of methanol and the CO_2 emission.
- Explosion panels and fire walls must be in place to secure the integrity of the vessel. International standards for design of facilities and operations of these must be fully in place to ensure acceptable safety. In no way shall an explosion threaten the integrity of a vessel.
- Hydrogen onboard vessels must be handled with extreme care, (DNV-GL, 2018 and 2019, IGF, 2017). Continued research to ensure safety of a vessel using H_2 as fuel is required. The alternative storage of the fuel in form of ammonium (NH_4) is, however, recommended.

7. CONCLUDING REMARKS

In this paper a review of design basis for offshore vessels, oil and gas platforms and offshore wind turbine foundations is given. Reference is made to international IMO and ISO standards as well as to the Norsok Standard N003.

The main contribution in this paper is the discussion and summary regarding measures to mitigate the consequences of large loads and load effects.

Furthermore, concern is raised regarding the safety of vessels incorporating the new types of fuel the maritime industry is considering: Batteries, LNG and Hydrogen. International rules for personnel safety and design basis for structural elements are called for, and measures to mitigate possible explosions and fires must be developed.

A fire and an explosion could well be a rare event; however, it must be documented that the consequences of such an event do not lead to fatalities, large environmental pollution or loss of the vessel, which are unacceptable consequences.

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