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Review

A review of structural responses and design of offshore tubular structures subjected to ship impacts

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ABSTRACT

Over the past decades, the offshore oil and gas industry has developed rapidly. A large number of offshore structures, notably jacket and jack-up platforms, were constructed and installed worldwide. As they are often exposed to safety threats from impacts by visiting vessels and dropped objects, there has been a continuous interest in understanding the impact mechanics of tubular structures and proposing practical design standards to protect from collisions. This paper reviews the state-of-the-art with respect to the response dynamics and mechanics of offshore tubular structures subjected to mass impacts, covering material modelling, ship impact loading, energy absorption in the ship and platform, global and local responses of tubular structures, the residual strengths of damaged tubular members and design considerations to mitigate against ship impacts. A wealth of information is available in the literature, and recent findings and classical references, which have a wide influence, are prioritized. The collected information is compared and discussed. The findings in this paper will help understand the impact response of offshore tubular structures and assessment procedures, and provide useful indications for future research.

1. Introduction

Ships and offshore structures operating at sea are exposed to risks of ship collisions and impacts from dropped objects. Potential consequences may vary from minor local structural deformation to major threats to structural integrity, causing great economic loss, severe environmental pollution and fatalities. In extreme conditions, accidental loads may cause the global collapse of entire structures and put human lives in jeopardy. The huge losses from several catastrophic marine collision accidents such as the sinking of the *Titanic* after hitting an iceberg and explosion of the Mumbai High North platform after suffering a collision from a supply vessel, have aroused continuous public concern regarding the operational safety of ships and offshore structures. Tremendous efforts have been made mainly in two directions:

1) to reduce the probability of occurrence of ship collisions with the application of advanced navigational tools and administration procedures.
2) to obtain crashworthy design of structures based on a thorough understanding of fundamental collision mechanics.

Based on research outcomes, rules and standards relevant for the design of crashworthy structures have been introduced, e.g., DNV-RP-C204 (2010), ISO 19902 (ISO, 2007), API-RP2A-WSD (2014), ABS (2013) and HSE (2004). The standards have been continuously updated to include novel knowledge and address new challenges.

A few review articles are available in the literature, and they mainly focus on general procedures of risk analysis and structural assessments in ship collisions and groundings (Ellinas and Valsgard, 1985; Moan and Amdahl, 1989; Pedersen, 2010; Wang et al., 2002). However, no specific review exists that addresses the complicated collision mechanics of tubular structures. The authors consider it highly important that researchers understand the theories and principles developed over the long time span, so that they can provide a solid foundation for future research works. It is therefore the purpose of this paper to bridge the gap in knowledge by presenting a comprehensive review of structural response assessments and design considerations specifically for offshore tubular structures in the accidental limit states (ALS), covering both classical references and more recent progress as well. The review focuses especially on the NORSOK N-004 code and the DNV-GL recommended practices for design against accidental loads because they contain the most detailed provisions.

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Nomenclature

L	Length of the tubular member
D	Diameter of the tubular member
D_{min}	Refer to Fig. 14(c) and (d)
D_{max}	Refer to Fig. 14(c) and (d)
t	Tube wall thickness/Time
B	Contact width of the indenter
ξ	Transverse extension of damage along the tube length
w	Lateral deflection of the leading generator
w_b	Beam deflection of a tubular member
w_d	Indentation depth
$w_{d,tran}$	The transition indentation from local denting to global bending
σ_{dyn}	The dynamic stress
σ_{stat}	The quasi-static stress
σ_y	Yield stress of the tube steel material
σ_u	Ultimate stress of the tube steel material
σ_{dp}	Initial plastification stress of a damaged tube under compression
E	Young's modulus/Dissipated energy
F_{max}	The maximum collision force for a ship structure crushing into a rigid tube
K	A constant coefficient representing the shape of the indenter in Eq. (5)
k_s	Tangential stiffness of the force-deformation curve of the ship
k_i	Tangential stiffness of the force-deformation curve of the installation
$m_0 = 1/4\sigma_y t^2$	Plastic bending moment of tube wall per unit width
M_p	Plastic bending capacity of the tube cross section
M_{res}	Residual bending capacity of a dented cross section
N	The axial loads (positive in compression)
N_p	Plastic yield resistance in tension
N_{sd}	Design axial compressive load
N_{rd}	Design axial compressive resistance
R	Lateral deformation resistance of tubular members
R_c	Characteristic denting resistance factor
R_0	Plastic bending collapse load of a tubular member with fixed ends
$R_{0,eff}$	Effective bending collapse load of a dented tubular member with fixed ends
R_s	Deformation resistance of the ship in Eq. (29)
R_i	Deformation resistance of the installation in Eq. (29)
R_d	The design resistance of the structure
S_d	The design load acting on the structure
γ_1	Effective bending capacity coefficient of tube cross sections at the ends
γ_2	Effective bending capacity coefficient of a dented tubular cross section
λ_R	Column slenderness parameter
C	The Cowper-Symonds constant (s^{-1})
p	The Cowper-Symonds constant

Design against extreme ship collision should be carried out in the accidental collapse limit state using risk based techniques (Moan, 2009). The probability of system loss due to a collision of a certain intensity (kinetic energy) at a given location may be calculated as the product of the probability of collision with a given intensity and location multiplied with the probability of damage for the given event and the probability of system loss conditioned on the calculated damage of the structure subjected to relevant permanent loads and environmental loads. It is necessary to integrate over all possible collision intensities and locations. The calculated probability of system loss shall comply with the target safety level. The target safety level considering all kinds of accidents implies a probability level for system loss in the range of 10^{-4} per year for ALS according to NORSOK N003 (NORSOK, 2017). With approximately ten different accidental categories, collision accidents should therefore have an annual failure probability of 10^{-5}. Taking that into account, the characteristic values are used for loads and resistance. The conditional probability of failure for structures nominally at the brink of collapse is estimated to be in the range of 0.1 (Moan, 2009).

In practice, it is very cumbersome to calculate the probability of failure for all intensity levels and locations. Simplifications are necessary. It has therefore become customary to design the structure by a deterministic analysis of ship collisions with an annual probability of occurrence of 10^{-4}. Thus, characteristic kinetic energy is typically determined via risk analysis as adopted in ship-ship collisions analysis (Pedersen, 2010).

The design collision event that has been used for decades is the impact from a standard supply vessel with a displacement of 5000 tons travelling with a speed of 2 m/s based on risk analysis. This gives a design energy of 11 MJ for bow impacts and 14 MJ for broad side impacts considering added mass effects (DNV-RP-C204, 2010). Over the years, kinetic energy has increased significantly with the increased ship displacements and impact velocities identified in Moan et al. (2017) and Kvitrud (2011) based on an overview of collision accidents in recent years. Moreover, newly designed ship structures such as bulbous bows, X-bows and ice strengthened vessels may change impact consequences. According to the new version NORSOK N003 standard (NORSOK, 2017), if no operational restrictions on allowable visiting vessel size are implemented, supply ship displacements should not be selected less than 10, 000 tons, and unless further evaluations are performed, the kinetic energy should be 50 MJ for bow impacts, 22 MJ for stern impacts and 28 MJ for broad side collisions. This represents a substantial increase in the demand for collision resistance of an offshore structure.

The design scenarios of the new version NORSOK N003 standard with increased design energy may be classified as high energy collisions. Under high impact energies, tubular members will undergo significant deformations and may fracture and fail, threatening the integrity of the platform. A noticeable example is the well workover vessel Big Orange XVIII collision with the Ekofisk 2/4 jacket platform, in which the estimated kinetic energy was 60 MJ. The accident caused severe damage to the three-legged jackets and also to the bow (see Fig. 1). Several braces were ruptured, and the jacket had to be dismantled. Such high collision energies cannot be absorbed by a single member. It is therefore essential to design tubular members such that they have sufficient strength to penetrate the bow, and the ship bow absorbs considerable energy (Amdahl and Johansen, 2001).

Minor ship collisions and dropped objects often occur and cause small damage to the platform braces and legs. According to Taby (1986), operational damages occurring almost every year for North sea jackets are a dent depth of 10% of the tube diameter and/or a permanent deflection of 0.004*L*, where *L* is the span length of the member. As timely repair of a damaged offshore structure is difficult and expensive, it is important to have knowledge about the ultimate and post-ultimate strength of damaged tubular members under various loading conditions so as to make optimal decisions regarding safety and economy. A good illustration of minor ship collisions and subsequent damage assessment, safety evaluation, and repair was reported by Sveen (1990) when a West German submarine collided with the eight-legged Oseberg B jacket on the Norwegian Continental Shelf in 1988 with an estimated energy of 5–6 MJ (refer to Fig. 2). The struck diagonal brace absorbed 60 percent of the energy and suffered major damage with a large local dent