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Review

A review-analysis on material failure modeling in ship collision

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ABSTRACT

Ship collisions and grounding of tankers continue to occur regardless of continuous efforts to prevent such accidents and their inherent potential danger to provoke oil spill environment disasters. Nowadays, finite element modeling became a powerful tool to predict the structural response of ships during collision. However, one of the major challenges in modeling the collapse of naval structures is the formulation of an adequate failure criterion which conciliates the micro-scale physical aspects associated to crack initiation in ductile materials with the mandatory use of large shell element sizes in the large-scale naval structure models. The purpose of this paper is to present a review on failure criteria used in finite element modeling of ship collision events. Failure criteria based on a limiting value of the equivalent plastic strain is the most commonly used in ship collision modeling, but some criteria based on stresses state, forming limit diagram, strain energy, fracture mechanics among others are also disclosed in this review. Special attention is focused on the limitations of the failure criteria, as well their development, validation and practical application in numerical modeling. Numerical modeling of crack propagation and welded joints in naval structures subjected to impact loads are also reviewed.

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1. Introduction

Oil spills continue to occur despite of the global efforts to prevent ship accidents. The risk of oil spill has been increased together with the growth of the global ship fleet. Oil tankers represent nearly half of the world fleet and they are the maritime segment with the largest ships ever made. These large sizes vessels are very efficient in oil transport but, at the same time, pose serious risk of oil leakage in a possible collision event (Darbra and Casal, 2004).

The main causes of oil spill are ship collision and grounding (ITOPF, 2011) with the majority of accidents occurring near seaports and sea-lanes between the main ports. Ship accidents can not only provoke oil spill and permanent ship structure damage but also degradation of the marine environment, human losses and ships traffic blocking (Fig. 1). Due to recent improvements in ship safety procedures, human qualification and new ship design, the number of large oil spills decreased significantly during the last years.

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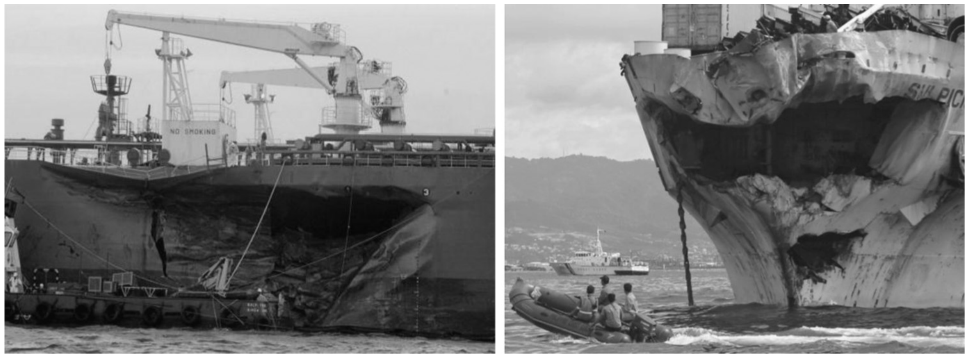

Fig. 1. Collapsed structures after ship to ship collision accidents occurred in the Singapore Strait (2010) and in waters of Talisay City, Phillipines (2013).

Major ship accidents often promoted remarkable improvements in worldwide ship safety. The International Convention for the Safety of Life at Sea (SOLAS) was created after the Titanic passenger liner foundering in 1914. The environmental disaster caused by Exxon Valdez oil tanker in the coast of Alaska in 1989 is considered the largest oil spill catastrophe, with the destruction of hundreds of kilometers of ecosystems in a virgin coastline of Alaska. Three years later, rigid regulations were imposed by the International Maritime Organization (IMO) to prevent oil spill, such as the imposition of a schedule for the gradual conversion from single to double hull oil tankers.

The design of tanker structures against accident scenarios requires various approaches, broadly divided in experimental and numerical analyses. Large-scale experiments of ship collision events are clearly too expensive and risky to be executed. The first efforts to model ship collision employed simplified analytical methods based on plastic mechanism analyses of basic structures. The ship structure is decomposed into simple components such as plates, stiffeners, web frames, panels etc, with each component contributing to the global mechanical response of the entire structure. Until recently, these simplified analytical methods were considered the most appropriated technique to evaluate structural performance of ships in events of collision and grounding (Hong, 2008). Indeed, until early 1990s, the advantage of finite element analyses was rather limited compared to these simplified analytical approaches. Due to the poor memory capability and processing power of the computers, finite element models were restricted to coarse geometry models. In the last years though, finite element modeling of ship collision events became practicable due to the rapid development on computational processing power. More complex geometries and diverse non-linear material models could be taken into account, yielding reasonable results. Even so, given the thin thickness of shipbuilding plates when compared with the large scale size of actual oil tankers, shell element type continue to be practically of mandatory use in the finite element meshing of ship models which impair the use of more sophisticate material failure models based on three dimensional stress and strain fields. Hence, the numerical modeling of rupture and tearing is still nowadays the most challenging task in the naval structural crashworthy analysis.

Assessment of structural failure in ship collision events is a very complex process influenced by diverse factors as the mechanical properties of the shipbuilding materials, geometry of the various ship components, loading and boundary conditions, manufacturing defects, among others. The numerical simulation of ship collision requires the adoption of a correctly established failure criterion because of its strong influence on the global structural energy absorption, the amount of fractured ship substructures and the reproduction of the global structural collapse modes, which includes membrane stretching, crushing, folding and tearing of plates. However, ship collision deals also, in contradiction with these large scale global modes of failure, with small scale phenomena like crack initiation, welding failure and stress concentration. So the major challenge when performing a complete analysis of ship collision is to take into account these different aspects at local and global levels. Indeed, given the large dimensions of ship structures, it is rather impeditive the use of fine meshes to model crack propagation. One should remember that most current failure criteria applied in ship collision modeling remove the shell elements which met a given crack initiation criterion. Given the imposed large sizes of the shell elements employed to model ship structures, once one element is removed to mimic an actual crack formation, considerable errors in stress and strain states in the new formed crack region occurs due to the new discrete crack geometry. For all these reasons, the modeling of failure in ship collision events is a topic under intensive research.

Accordingly, the aim of this work is to review the main failure criteria used in finite element modeling of the structural behavior of ships in a collision scenario. The review is organized in three principal sections: failure criteria, crack propagation modeling and weld failure criteria. The failure criteria section (Section 2) deals with the crack initiation models adopted for ship collision modeling so including failure models based on accumulated strain, triaxial stress state dependence, forming limit diagram, fracture, plastic energy among others. Section 3 reviews the scientific efforts to model crack growth in ship structures. Weld failure criteria is presented in Section 4, with the numerical formulations adopted to model the failure in fillet welds of ship structures implemented in finite elements codes. Section 5 presents a general discussion, following the conclusions.

2. Failure criteria

2.1. Strain based failure criteria

The most common failure criterion used in ship collision numerical modeling is the equivalent plastic strain criterion. Local material rupture is assumed to occur when the equivalent plastic strain reaches a critical value, sometimes called maximum plastic strain or rupture strain, usually obtained from uniaxial tensile tests. A wide range of maximum plastic strain values for shipbuilding steel has been reported. In the finite element modeling of ship collision, the maximum equivalent plastic strain ranges from 10% to 70%. It should be observed that the numerical modeling of a ship structure when subjected to a collision event is very sensitive to the adopted rupture strain value. Indeed, it has been demonstrated that the definition of the failure criterion and their parameters is the most important key point for a correct prediction of a realistic structural collapse mode and an acceptable