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Reliability-based design of stiffened plates in ship structures subject to wheel patch loading

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ABSTRACT

Reliability-based design methods are among the engineering tools for design of structures considering uncertainties in the design variables such as loads, material properties, manufacturing tolerances, etc. In design of stiffened plates of ship structures, there are some sources for uncertainties regarding the loads due to the highly nonlinear environment of the ocean. In addition to the environmental uncertainties, internal forces decrease the reliability of design due to the vagueness of items, which are included in the deadweight. Cargos with patch loading pattern like wheel and steel coil are common type of loading in some ships. These cargos are usually transferred by ferries, general cargo ships and bulk carriers. The application of reliability method in design of such structures against this local loading pattern has not been studied so far. Therefore, in this paper, the stochastic method and plastic formulas have been explained in designing steel panels subject to the patch loading. As a case study, stiffened plate structure of the ships subject to the truck wheel was investigated considering all design parameters as random variables. Bound theorem model for the patch loads is used to calculate the plastic load carrying capacity of the plate. First Order Second Moment (FOSM), First Order Reliability Method (FORM) and Importance Sampling method have been employed in the analyses. Both probability of failure and reliability index are calculated for different axel load distribution functions. The total failure probability was determined based on the rule of total probability. Sensitivity analyses for all parameters were carried out and the effects of coefficient of the variation of dominant variables were studied.

1. Introduction

1.1. Statement of the problem

Ships' structures are subjected to different loading conditions, so that the uncertainties in their estimation are the causes of overloading and structural failures. Patch loading is a regular loading pattern for various types of ships such as ferries, general cargo ships and bulk carriers. As a result of overloading, structural damages might endanger safety of the vessel. Fig. 1(a) shows the deformed deck plate of a landing craft due to the overloaded trailers, while Fig. 1(b) exhibits dented tank top plating in a hold of a general cargo ship carrying steel coils. Such permanent deformations might affect the ultimate strength of the plate as discussed by Paik [1]. In addition, trapped water in these areas can become a source of corrosion. Prevention of such damages is important since repairing might be complex and costly. It should be noted that aging process as a result of overloading, corrosion etc. causes structural failures; therefore, the assessment of these structures is of great importance which was discussed in details in [2].

Generally, deterministic approaches that are applied in design of these types of vessels are not as precise as the probabilistic methods; however, they are convenient to apply. In order to control the survivability of the structure, stochastic methods such as reliability-based design approaches are to be implemented. Reliability-Based Design (RBD) methods apply to contend with the uncertainties of design variables.

1.2. Previous works

Reliability methods have been applied in various sections of ship design process in recent years. These applications vary from structural design to safety matters and stability. One of the earliest attempts to include the reliability approach in design of structure in classification rules is the Joint Tanker Project in which three major classification societies developed a set of international rules for designing oil tankers (CSR Oil Tankers) as a part of International Maritime Organization (IMO) Goal Based Design. Application of the reliability methods to estimate the design loads (including wave induced moments) and hull

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Nomenclature

A	Tire contact area
a	Length of plate
b	Width of plate
COV	Coefficient of variation
E_i	Event i
$f_y(y)$	Joint probability density function of random variables
g(Y)	Limit-state function
h	Width of patch load
ls	Hinged length
N	Numbers of events
P_f	Probability of failure
P_c	Nominal plastic capacitysubject to a uniform load
P_p	Plate load capacitysubject to a patch load
P(Failure)	Total failure probability
$P(E_i)$	Probability of occurrence of E_i
$P(\text{Failure} \mid E_i)$	Probability of failure given that E_i has occurred
r_1 & r_2	Models' responses
T_L	Tire load
T_P	Tire inflation pressure
t	Plate thickness
x^{rv}	Random variables
x^{dv}	Decision variables
y	Vector of random variables
β	Reliability index
δ	Plate deflection
σ_y	Yield strength


(a) (b)

Fig. 1. (a) Deformed deck plate of a landing craft due to the overloaded trailers, (b) deformed structure of tank top of a general cargo ship.

girder strength for various types of vessels such as ultra large container ships, oil tankers and bulk carriers have been the subject of extensive researches that are available in the literature.

The mentioned approach implemented in alternative design and arrangement for fire safety (The International Convention for the Safety of Life at Sea (SOLAS) II.2/17), alternative design for oil tankers (The International Convention for the Prevention of Pollution from Ships (MARPOL), Annex I-4/19), evacuation assessment of passenger ships and other international rules and regulations, however the application of reliability and risk methods in ship design are not as common as other engineering fields. Detailed information about the application and history of RBD in ship design is presented in Soares et al. [3].

Reliability methods are also used in the assessment of survivability of damaged vessels and the residual strength of collided or grounded ships. In this regard, contributions made by Hogström and Ringsberg [4], Rodrigues et al. [5], Fang and Das [6], Saydam and Frangopol [7], Papanikolaou and Eliopoulou [8], Luís et al. [9] may be observed.

Due to the fact that the reliability of a ship structure is deeply dependent to its aging, researchers including Akpan et al. [10,11], Sun and Bai [12], Elhanafi et al. [13] and Soares and Garbatov [14] focused on the different aging problems such as corrosion and fatigue and also their effects on the reliability of ship structure.

Yang et al. [15] investigated the application of reliability methods in design of top-hat stiffened composite panels under in-plane loading employing stochastic method. Simplified analytical methods were used to assess the reliability of ultimate compressive strength of top-hat stiffened laminated panels. The sensitivity analysis of random variables was done and some recommendations were provided for application purposes. Gaspar et al. [16] applied reliability analysis for bottom stiffened panel system of an oil tanker by using nonlinear finite element along with Monte Carlo and response surface methods. They assessed the capacity of the system by considering in-plane loading and lateral pressure. Zheng and Das [17] conducted a research in order to improve the reliability methods for designing stiffened plates. Elhanafi et al. [13] assessed the reliability index of longitudinal deck and bottom Y-shape stiffeners considering the effect of corrosion. Fatigue reliability design of stiffened plates is also assessed by researchers such as Mahmoud and Riveros [18] and Feng et al. [19].

Patch loads are predictable in various types of structures. In marine structures, patch loading pattern can occur as a result of ice load, vehicle axel load, steel coil etc. Among these loading patterns, ice load has been studied more than others in previous researches. International Association of Classification Societies (IACS) developed a series of formulations to assess the structures in polar region [20] in which the ice load is simulated as patch load. Plate behavior (such as deflection) subjected to patch load has been analytically explained in shell and plate design references [21]; in addition, several empirical formulations have been proposed in literature. Different formulation, as it is described in detail in subsection 2.2, were proposed by Hong and Amdahl [22], and Nyseth and Holtsmark [23] to predict the plastic capacity of plate under patch loading based on various folding pattern. Other than analytical approach, some other researchers implemented nonlinear FEM analysis to investigate the effect of patch loading on the strength of plate. For instance, Cerik [24] evaluated the effect of local lateral patch on ultimate longitudinal compressive strength of steel plates. He concluded that the damages caused by patch loads have dramatic reduction effect on plate strength. Ultimate strength of frames and grillage was experimentally investigated by Daley et al. [25]. They investigated various panel sizes and concluded that there are relationships between overall plastic collapse and buckling.

In design of girders especially for civil structures such as bridges and overhead cranes, web plate is to be designed by considering in-plane patch loads, thus; it was fully studied in previous studies. Mijušković et al. [26] analyzed buckling of rectangular plate girder subjected to