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Performance-based design of blast resistant offshore topsides, Part II: Modelling and design

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Abstract

A simplified analytical model for deck plates of offshore topsides structures is proposed. Based on the theory of virtual work and an assumed deformed shape function in Cartesian coordinates, a set of equilibrium equations in terms of energy are developed. The equations are formed as a static case and a dynamic case with unsolved variables defined as generalized coordinates. When these equations are re-arranged, they are equivalent to a modal analysis, which can be solved using Lagrange's equation method. The generalized coordinates in the static case can be solved manually while in the dynamic case, the ordinary differential equations are solved numerically by developing a computer program using a symbolic software package, MAPLE. The proposed method is comparable with finite element analysis results up to a certain threshold at which development of membrane strain and plasticity modes become dominant. When comparing the results to the reported experimental data, the proposed shape functions for deformations in the lateral directions are modified in order to accommodate the observed behaviour. The results compare favourably with test data and finite element analysis as a control case.

Despite inconsistent ductility ratios between the proposed method and the finite element analysis at very high overpressures, the method shows good correlation of results at practical design values. Hence, the proposed method would be a useful tool for preliminary appraisal methods especially for design engineers involved in evaluating the performance of deck plating subjected to a range of hydrocarbon explosion scenarios.

Keywords: Ductility ratio; Overpressure; Performance level; Finite element; Static yield limit; First fundamental period

1. Introduction

Deck plates on topsides of offshore installations which are typically fabricated from mild steel, not only serve as deck flooring but are also used for protection against weather, the overspill of liquid and as demarcation of hazardous areas. The plates are laid on top of supporting beams and continuous fillet welds are applied at the interfaces between the bottom deck plates and top flanges of the beams. With these connections, the boundary conditions of the deck plates can be regarded as fixed supports. The welded connections also improve the lateral stability by integrating the structural components at the deck level as one large panel which is needed for resisting skew loads during pre-service operations such as lifting and sea transportation.

Possessing a larger surface area compared to other structural members on a topside, the deck plates are highly likely to be the first structural components pounded by a blast load due to the ignition of a hydrocarbon release. This scenario certainly provides an advantage to the structural system because of the behaviour of plate systems. With the right boundary conditions, it allows large deformations to develop that result in less energy being transferred to other main structural members which are supporting permanent loads. Consequently, this will potentially reduce damage to primary joints and other structural members.

The study of plate behaviour is a well-researched field and only key aspects are highlighted in this introduction. Historically, engineers had their own rules of thumb for determining load carrying capacities of plates before the first mathematical expression on membrane action was introduced by Euler in 1766. This was followed by other mathematicians/engineers whom had associated the plate response with governing criteria such as aspect ratio, slenderness ratio, shape and boundary conditions. Szilard [1] and Timoshenko and Krieger [2] provide some classical solutions for estimating maximum deformation under static and linear elastic conditions

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with various boundary conditions while the Biggs [3] method, idealizes the plate with load history to an equivalent system (single degree of freedom) using transformation factors for maximum response. Nurick et al. [4] reviewed and summarized the development of the plate studies subjected to impulsive load by others and concluded that incorporating transverse and lateral displacements would result in closer approximation with experimental data. Schleyer et al. [5,6] conducted tests on mild steel clamped plates subjected to pulse pressure and proposed an elastic–plastic analytical method with pre-determined nonlinear spring at the plate edges. Amdahl [7] developed a simpler model based on the assumption of rigid plastic behaviour and combined a portion of the plate with T-stiffener as an equivalent asymmetrical I beam profile. While the method is acceptable for assessment of the support, it is slightly conservative in design as the middle deformation of the plate is being ignored.

Although a number of methods have been proposed [1–8] with some complex formulations for plates subjected to pressure loads, very few have looked into their practical uses in industry where the deck plates should be regarded as structural components that hold important roles in reducing damage from spreading to other structural components as well as for protection of nonstructural components. A Performance-Based methodology is one of the approaches that can be used to satisfy this dual purpose.

The primary objective of the present study is to simplify the analysis method which although currently looks complicated, is in fact straightforward with relatively simple formulae. Although sophisticated software is available such as finite elements and high-tech computer systems which definitely make calculations easier and fast, they are costly and require experienced users. In the proposed method, by considering a simple deformed shape function for a plate which any shape of deformed function can be chosen as long as they meet the kinematic boundary conditions, basic parameters such as the first fundamental period, the static and dynamic displacements, and the static displacement at yield can easily be evaluated and become useful tools for preliminary sizing of deck plates.

The present study on the fixed supported plate employs an energy method which is based on the proposed simplified nonlinear method for a simply supported plate by Louca and Wadee [9]. Then the solutions to the derived partial differential equations are solved numerically by simple programming codes using a symbolic software package, called Maple.

2. The plate boundary conditions and selected deformed functions

Consider a rectangular flat plate with dimensions $2a$ by $2b$, density of R, Young's modulus E, plate flexural rigidity $D(Et_p/[12(1-\nu^2)])$ and thickness of t_p. The kinematics boundary conditions for the plate with fixed supports as shown in Fig. 1 can be written as follows:

$$\text{when } x = \pm a, \quad u, w \text{ and } \frac{\partial w}{\partial x} = 0 \tag{1}$$

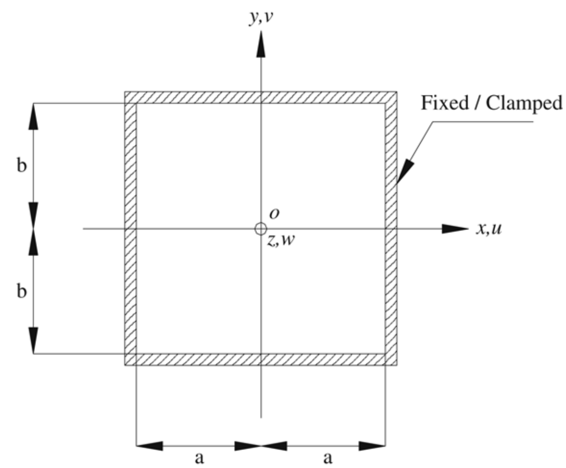

Fig. 1. A fixed rectangular plate and the notations used ($a \geq b$).

$$y = \pm b, \quad v, w \text{ and } \frac{\partial w}{\partial y} = 0. \tag{2}$$

The three selected shapes of the generalized deformed functions u, v and w which are time-dependent, simple, straightforward for generation of derivatives and integrals; are introduced in the x-, y-, z-directions respectively. They are given by Eqs. (3)–(5) which satisfy the boundary conditions given by Eqs. (1) and (2) as well.

Several analyses were performed at the early stages of the model development using an increasing number of time-dependent variables for determining the efficiency of the proposed functions. However the analyses became quite complicated and the result showed only a marginal improvement, less than 5% in displacement. In order to keep the model simple such that it is of value for preliminary design, it was decided only 3 variables were necessary i.e $\phi_1(t)$, $\phi_2(t)$ and $\phi_3(t)$.

$$w(x, y, t) = (a^2 - x^2)^2(b^2 - y^2)^2\phi_1(t) \tag{3}$$

$$u(x, y, t) = x(a^2 - x^2)(b^2 - y^2)\phi_2(t) \tag{4}$$

$$v(x, y, t) = y(a^2 - x^2)(b^2 - y^2)\phi_3(t) \tag{5}$$

where

$\phi_1(t)$ = time-dependent generalized coordinates out-plane displacement in w-direction

$\phi_2(t)$ = time-dependent generalized coordinates in-plane displacement in x-direction

$\phi_3(t)$ = time-dependent generalized coordinates in-plane displacement in y-direction.

The first two terms for w in Eq. (3) are even function which will vanish at supports as well as its first derivatives, while the first two terms for u and v in Eqs. (4) and (5) are odd functions, which will also vanish at supports.

In order to find the approximate solutions for u, v and w, the concept of virtual work is adopted. This states that the change in internal strain energy must equal to the work done by external forces during virtual distortion on the plate. The equation for