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Dynamic structural response of perforated plates subjected to water impact load

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ABSTRACT

The objective of the present work is to investigate the dynamic structural response of perforated plates subjected to water impact load. A fully coupled ALE/FEM method, is used to simulate the fluid–structure coupling problem. The deformations of the plate and of the water are coupled through the hydrodynamic pressure subjected by the water on the plate, and the velocities of the structural particles affecting the deformation of the water. Considering plates with various numbers of openings resulting in a different degree of opening intensity, the structural deformations around the plate are analysed. The effects of the number, degree and location of the openings on the maximum distortion and recovering rate of the plate are analysed. The predictions of the plates' distortions at two typical time moments during the impact loading are estimated by the proposed mathematical equations.

1. Introduction

Under the extreme sea states, offshore structures are subjected to complex and severe load combinations. Structural members in the splash zone are subjected to the maximum deterioration due to the increased and repetitive concentration of wave forces. In order to reduce the direct wave impact, coastal and offshore structures are often constructed with one or more perforated layers.

Breakwaters with perforated members are classical examples of such kind. Encapsulating the members with a perforated cylinder cover will not only enhance their service life, but also reduce the hydrodynamic forces caused by the direct wave impact [11,32,28]. The presence of outer perforated cover alters the water particle kinematics significantly and eventually this remains the reason for the force reduction mechanism. A horizontally composite type of structure, containing a central circular pile encircled by a perforated caisson can be considered for force reduction on the load-bearing pile and for scour reduction around the bottom of the pile [19,21,3]. Partially damaged piles can be encircled by a caisson with suitable porosity in order to utilise the pile for a long span of time [20].

Wash plates are usually constructed in a tank of a ship hull to minimise the impact of sloshing, lighten the structural weight or to provide access [13]. A horizontal plate with suitable porosity can effectively reduce the reflection coefficient and wave run-up on a vertical coastline surface [40,15,16].

Such applications of interest have motivated many researchers to investigate the wave induced force and water surface fluctuations on offshore structures that are constructed with perforated members [39,41,29,14,16]. There is still a scarcely investigation of the transient response of the outer perforated structures subjected to water induced load. The objective of this work is to start studying the effect of perforations by considering the dynamic response of a perforated plate due to direct water impact loads. It is believed that this work can provide new insight into other applications of perforated components.

The initial investigations to estimate the water impact loads and the related responses of ship structures were performed by simplified approaches. The loading was calculated without considering the effects of the elastic response, and then the structural responses due to the quasi-rigid loads were predicted [2,10,24]. Their results were consistent with the experimental data of Ramos et al. [25] and Luo et al. [18], which proved that the approach provided satisfactory assessments for the overall response of ship structures. The water impact loads on marine structures were also well predicted by numerical solutions [23,30,34,35].

If the plate thickness is relatively small, or the entry velocity is very high, the hydroelasticity becomes a problem even for bodies with moderate deadrise angle, as stated by Lu et al. [17]. In these cases, more advanced models with considering the hydroelasticity should be used. It has been studied, theoretically and experimentally for slamming problems by Faltinsen [7,8]. Their work showed

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that the hydroelasticity was related to the relationship of the material and geometric properties of the structure, the impact velocity and the relative angle between the water and the structural surface. Lu et al. [17] demonstrates a fully coupled FEM/BEM analysis of the elastic wedges impacting with water. A fully coupled simulation of an elastic wedge entering into water was studied by Stenius et al. [26] using an explicit finite element method. By using the commercial code LS-DYNA, Wang and Guedes Soares [36] studied the hydroelastic responses of a flexible wedge impacting with water, and the results were in good agreement with Lu et al. [17], and Wang et al. [37,38] investigated the transient vibration of a horizontal elastic plate due to longitudinal compression during water impact.

During the water impact, the distortion of the perforated plates is an important issue in the strength analysis. When a ship travels in various waves, the loading conditions for the ship components are complex. During the sloshing of tanks, the wave impact loads on the perforated plates may lead to plastic deformation and collapse of the structure. Meanwhile, the perforated plates may also be subjected not only to lateral but also to axial loading including bending, shear and torsion. When the strengths of the offshore or ship structures are assessed, the wave induced deflections of the related perforated shell/wall are of great significance. It has been indicated that the important information to be considered in the structural analysis is rather the trend of the shape than the plate particularities [5].

Instead of the actual imperfect plate, more filtered and smoothed data are required for general applications in finite element analysis to solve the problem of the distortion mesh due to existent incompatibilities. One solution is to obtain the mathematical model of structural deformations by a surface fitting technique before importing the model data in the finite element modelling. In terms of surface fitting models, the polynomial, Fourier series and alternative customized mathematical formula are widely used. Polynomial fitting is commonly used to decompose observations on a spatially distributed variable into a component associated with any regional trends [6]. It was concluded that the plate's imperfections can be described with a double Fourier series by Kmiecik et al. [12]. By using the Least Square Method (LSM), Chen et al. [4] proposed a function to represent the complex continuous surface. The global displacement of the plate was represented by the linear terms, while the irregular surface was modelled as trigonometric functions.

For the water impact of a perforated plate, which is discussed in the present work, the plate enters into the calm water horizontally, which may induce very high water impact loads. The analysed plates are with different numbers of openings which results in large deformations. Therefore, it is considered that a fully-coupled method should be applied to this problem. Further, with a complicated configuration, the dynamic responses of a perforated plate cannot be easily solved by general plate theory. In this work, the hydroelastic water impact of a perforated plate is investigated by using the commercial explicit finite element code LS-DYNA. The objectives are to study the structural responses due to the water impact loads, and to investigate the effects of the openings on the structural response. Besides, the deflections of the perforated plates are analysed by proposed mathematical models, based on the numerical predictions of the plates' deformation.

2. Perforated plate configurations

The boundary condition of the analysed plates is shown in Fig. 1, where L and l are the plate length and width. The applied boundary conditions, where one edge is totally free, without any restraints, are chosen due to the fact that the wash plate is of a depth less than the one of the tank. The structural deflections and pressure due to the water impact will be studied for the marked points A, B and C. To present the degree of opening intensity of the perforated plates, a parameter *DOO* (degree of opening) is introduced in Eq. (1), which represents the percentage of the opened surface area to the intact plate surface area.

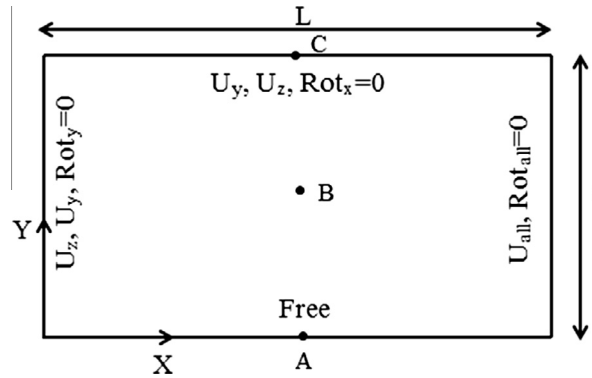

Fig. 1. Boundary conditions of the plates.

$$DOO = \frac{1}{Ll}\sum_{i=1}^{n}\pi r^2 100\% \tag{1}$$

where n is the number of openings of the plate and r is the radius of the opening. It should be noted that the openings in one plate are uniform. As can be seen in Fig. 2, different types of perforated plates are studied in this work. With the different number of openings, the plate configurations are determined by different parameters (a–g), while the plate length L and width l are the same for all studied cases. Various plates (entitled as P1, P2,... P10) with a thickness of 4 mm are studied in this work as plotted in Table 1 which includes the values of the degree of opening intensity (*DOO*) calculated by Eq. (1). It should be noted that, P8 means the plate with central openings and P11 represent the one with asymmetrical openings.

3. Finite element modelling

The numerical modelling of this water impact problem is conducted by the explicit finite element scheme in LS-DYNA. The fluid is assumed incompressible and inviscid, and the free surface is initially at rest. The finite element analysis is based on the Arbitrary Lagrangian–Eulerian (ALE) formulation and a penalty coupling algorithm. The Lagrangian formulation is used to describe plane-strain deformations of the plate, while the multi-material Eulerian formulation is used to analyse the fluids, including the water and the air. The deformations of the plate and of the water are coupled through the hydrodynamic pressure exerted by water on the hull, and the velocity of particles on the wetted surface affecting deformations of the water. The continuity of the surface tractions and the inter-penetrability of water into the hull are satisfied by using a penalty method, which was explained by Aquelet et al. [1].

In Arbitrary Lagrangian–Eulerian (ALE) formulation, a reference coordinate which is not the Lagrangian coordinate and Eulerian coordinate is induced. The differential quotient for material with respect to the reference coordinate is described as

$$\frac{\partial f(\overrightarrow{X},t)}{\partial t} = \frac{\partial f(\vec{x},t)}{\partial t} + \vec{w}\frac{\partial f(\vec{x},t)}{\partial x}, \tag{2}$$

where $\overrightarrow{X}$ is Lagrangian coordinate, $\vec{x}$ is Eulerian coordinate, and $\vec{w}$ is relative velocity between the particle velocity $\vec{v}$ and the velocity of the reference coordinate $\vec{u}$. The Arbitrary Lagrangian–Eulerian