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Influence of load shape on dynamic response of cross-stiffened deck subjected to in-plane impact

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ABSTRACT

Under severe sagging condition or wave slamming, ship deck is dynamically loaded in nature with impact type load. Based on the nonlinear explicit finite element method, the paper aims at studying influence of load shape on dynamic response of a cross-stiffened deck subjected to in-plane impact, accounting for strain rate effect, strain hardening, and potential contact of compressive components. Axial residual displacement of the impacted end is selected as main detected dynamic response of the deck. Four parameters depicting load shape are considered; they are impact duration, peak load, the decaying type after reaching the peak load (here refers to second order derivative of the load), ratio between rise time of the load and total impact duration. The first three load shape parameters, impact duration, peak load and decaying type, are related to impulse. The longer the impact duration, the larger the peak load, the slower the decaying of the load, which can result in the larger impulse. The larger the impulse is, the larger the dynamic response of the impacted deck is, on the condition that the impact duration is finite with the order of milliseconds. While the fourth load shape parameter, ratio of rise time and impact duration, although it is not related to impulse, it is also an important influential factor on dynamic response of the impacted deck. The smaller the ratio of rise time and impact duration is, the larger the dynamic response of the impacted deck is; if the impact duration is longer, the effect is more significant. So the parameter, ratio of rise time and impact duration, deserves more concern in future research.

1. Introduction

Load carrying capacity of the ship deck subjected to in-plane compression has an important impact on the safety of the ship hull. There are two kinds of load carrying capacity of the deck subjected to in-plane compression; they are, ultimate strength under static or quasi-static loading, and dynamic buckling or collapse strength applied by impacting load under severe sagging condition or wave slamming.

As for ultimate strength of stiffened plate, many researchers have presented predicting formulas and collapse modes, such as Paik and Zhang [1,2]. In these formulas, influence factors are slenderness of plate between stiffeners and slenderness of combination of stiffener and attached plating. Collapse modes include plate buckling, stiffener buckling (also called tripping), and overall stiffened plate buckling. These collapse modes are neither excluding nor independent; several of them probably occur simultaneously. By controlling applied displacement with very slow velocity, such as 0.05 mm/s which can be considered as static or quasi-static loading regardless inertia effect, ultimate strength of stiffened plate can be obtained once reacting load reaches maximum value, followed by a decline process of the reacting load.

As for dynamic buckling or collapse strength of the stiffened plate, due to time-dependant load, the subject is more complicated than ultimate strength. In this condition, there are some additional issues required to be considered, such as inertia effect and dynamic constitutive equation of the material. Some research works have been investigated, such as, plate applied uniform in-plane velocity [3], plate or stiffened plate subjected to in-plane half sine wave impact [4–7], stiffened plate subjected to axial crushing by moving mass [8,9], as well as axial crushing of prismatic plated structures in ship collision or grounding [1,10]. A series of dynamic collapse tests were carried out on steel plates under axial compressive loads by Paik [3], with loading speeds varying from 0.05 mm/s to 400 mm/s. Experiments showed that the dynamic ultimate strength of steel plates gets larger with the increase of the loading velocity. A fluid–solid impact experiment was carried out by Li [6] for a plate falling on water from an over-water slamming tower. Results showed that fluid–solid impact load has the millisecond order duration and a half sine wave shape. According to the equivalent strain of a measuring point near the impacting end of the plate, three critical criteria were

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Nomenclature

t_p	impact duration
T	first order vibration period of the deck
P_m	peak load
$P(t)$	impact load $P(t)=P_m f(t)$
$f(t)$	shape function of the impact load
$f''(t)$	second order derivative of the $f(t)$, reflecting the type of decaying after reaching the peak load
e_t	ratio of rise time of the load and total impact duration
u_x	axial displacement of the impacted end of the deck
u_r	residual axial displacement of the impacted end of the deck, the value of u_x at the impact duration, reflecting dynamic response of the deck
P_0	ultimate strength of the deck subjected axial compression
u_0	applied axial displacement corresponding to ultimate strength P_0
I	impulse $I=\int_0^{t_p} P(t)dt$

used to define the critical loads of dynamic buckling, dynamic plasticity and dynamic collapse. However, the position of the measuring point is somewhat arbitrary, which will result in uncertainty. Fluid–solid impact on stiffened plate was not investigated in Li's research. Cui did similar experiments and numerical simulations, and presented similar conclusions [4,7] compared to Li's research. In Cui's numerical simulation, the half-sine loads with millisecond order duration were applied on the plate to investigate dynamic buckling. The dynamic buckling is observed during the loading process, which is different from high velocity impact, such as explosion, where the dynamic buckling happens after loading. The strain hardening is considered whereas the strain rate effects were not taken into account [4]. According to Budiansky–Roth criterion, Zhang presented elastic dynamic buckling of stiffened plates under in-plane impact by a sudden increase of the deflection of the center of stiffened plate [5]. However, the plasticity of the material was not considered in Zhang's research. In ship collision or grounding, the stiffened plate of the ship is progressively folded; two methods termed as intersect unit method (IUM) and plate unit method (PUM) to predict the mean crushing load of the crushed structure are used widely [1,10]. The mean crushing load is derived by energy dissipated in one fold process divided by effective crushing distance. However, the fold mode and crushing distance will change with the load shape dramatically, which is the subject discussed in the paper. Buckling loads and absorbed energy of thin metallic plates stamped with V-grooves are investigated by using dynamic-explicit FEM code [8,9], where the plates were subjected to a mass with various impact velocities. However their loading conditions are different from that of ship deck under severe sagging condition or waves slamming.

The paper aims at studying influence of load shape on dynamic response of a cross-stiffened deck subjected to in-plane impact loading, using Abaqus/explicit FEM code, considering strain rate effect, strain hardening, potential contact of compressive components. Four parameters of load shape are considered; they are peak load, impact duration, the type of decaying after reaching the peak load, and ratio between rise time of the load and total impact duration. The former three are relative to impulse, while the forth one is not. Initial imperfection of the deck is not considered in the paper, which has been considered in another paper [13]. Axial residual displacement of the impacted end is selected as main detected dynamic response of the deck. Typical collapse modes after impact are also presented in the paper.

2. The finite element model of the cross-stiffened deck

The finite element model of the cross-stiffened deck subjected to axial impact is summarized in this section. The geometric dimensions, meshing strategy, material properties, analysis type, and boundary conditions are illustrated as follows.

2.1. Geometric dimensions and meshing strategy

The geometric dimensions, meshing strategy of the cross-stiffened deck is as same as the one in static ultimate strength analysis [11], shown in Fig. 1, and mesh convergence analysis has been considered in [11]. The deck is modeled by 4 nodes reduced integration quadrilateral shell element S4R in Abaqus FEM code, which can account for elastic, plastic and large membrane and bending behavior.

2.2. Material properties

The steel properties with the elastic modulus $E=210$ GPa, Poisson's ratio $\upsilon=0.3$, initial yield stress $\sigma_y=355$ MPa and material density 7800 kg/m^3 is used for the deck. A bi-linear elastic–plastic model is employed to describe the nonlinear property of the material. The elastic hardening modulus is assumed as $E_h=1.18$ GPa after the initial yield. The material is assumed to

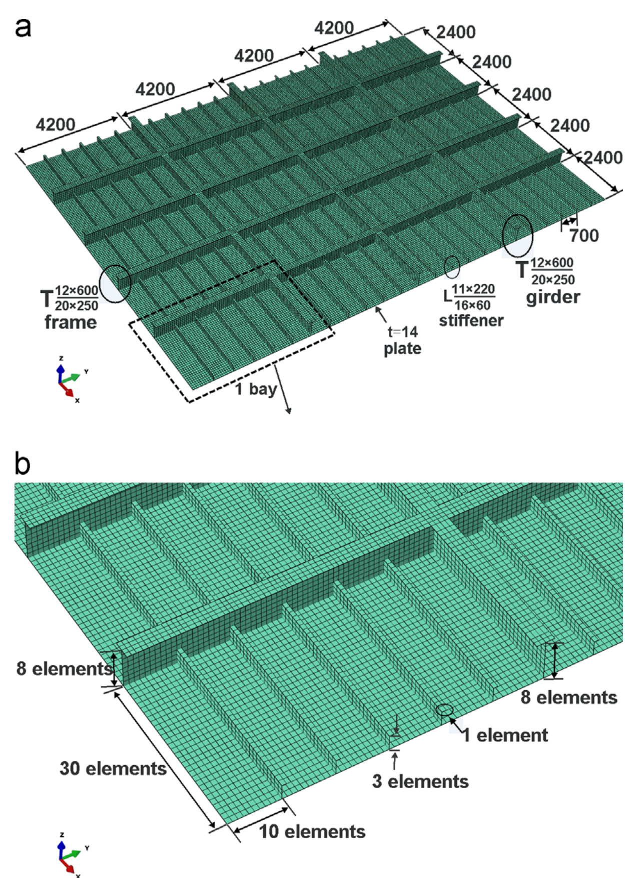

Fig. 1. Finite element model of the cross-stiffened deck.