Accumulation of Permanent Deflection of Steel Plates Subjected to Repeated Slamming Impact Loadings

Dac Dung Truong, Van Vu Huynh, Sang-Rai Cho, Xuan-Phương Dang, and Hao Dinh Duong

Abstract Slamming phenomenon unavoidably occurs on marine structures while in service. The extreme slamming events induced repeated impact pressures can cause damage to the structures and possible crew and compartment casualties. This paper presents investigations of accumulated damages of steel plates subjected to such repeated loadings. The numerical analysis model was developed, in which the load input was as the impulse-triangular profile simplified from the test slamming pressure time history data. The developed analysis model was validated by a comparison with test data. Subsequently, a parametric study on steel plates with actual scantlings used in marine applications was performed. Key parameters in estimating the permanent set of marine plates due to repeated impact pressures were then identified. Accumulation of the plate's permanent deflection under repeated slamming loads was evaluated accordingly.

Keywords Slamming · Repeated impact pressures · Steel plate · Permanent deflection · Numerical simulation

1 Introduction

During their service, marine structures are frequently subjected to repeated impact pressures induced by slamming. Such loads can damage the structures which was reported in Cho et al. [1].

Several studies on the structural response to slamming loads were reported in the literature. However, these studies considered only single pulse which is different from

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the loads come from slamming events. Besides, simple structure models were only used to study damage extents under such loads through various approaches (experimental, theoretical, numerical). For example, Weinig [2] investigated the effects of the elasticity of the impacted structure on the impulsive pressure due to slamming. Khedmati and Pedram [3] numerically investigated large deformations of stiffened aluminum plates due to single slamming pressure, and some design recommendations regarding loads and geometry were provided. Recently, the large deformation of aluminum plates due to water impact has also been studied by Abrahamsen et al. [4] by wet drop tests. It is apparent that less structural responses could be certainly observed when only considering single impulsive loading.

Regarding the repeated slamming loads, there are some experimental and numerical studies on the effect of such loads [5–11]. Mori [5] carried out several wet drop tests to investigate the response of aluminum-alloy plates of high-speed crafts to slamming loads. Caridis and Stefanou [6] numerically studied the response of steel plates under several impacts. The accumulation of plastic deflection after repeated impacts was reported. Shin et al. [7] and Seo et al. [8] investigated the accumulation of the deformation of plates by several repeated wet drop tests on steel plates with zero and 10° dead-rise angles. The results showed the accumulation of deflections was unnegotiable when the plate was subjected to repeated impact pressures. Besides, the simplified method is also preferable in the early design stage because of its simplicity. Recently, Truong et al. [9–11] developed the empirical formulae to predict the permanent set evolution of aluminum and steel plates subjected to repeated slamming pressures.

This study aims at developing a numerical analysis model for predicting the permanent deflection of steel plates due to repeated impact slamming pressures. The numerical model is validated by comparing with the test data. A parametric study for actual plates used for marine structures is performed, and effect of key parameters on the structural response is investigated.

2 Brief Description of Wet Drop Tests

To investigate the damage extents of structures due to repeated impact pressures, a series repeated wet drop tests was conducted using the drop testing machine; the machine consists of a guide rail system, an electromagnetic system and a water tank, as shown in Fig. 2a; drop height (*h*) can be varied from 1.0 to 2.0 m. Different nominal thicknesses were used to fabricate six plate models in which the thickness's each two plate models is identical, while the size of the plate was fixed as L × B = 2000 mm × 1200 mm; all the plate models were also supported by the 5-mm thick surrounding-plate walls with H = 277 mm. The plate body model is shown in Fig. 2b. To measure the water pressure and strain, several pressure sensors and strain gauges were used.

Several impacts with the same drop height *h* were performed for each model. A deflection measuring device was used to record the permanent deflection after each

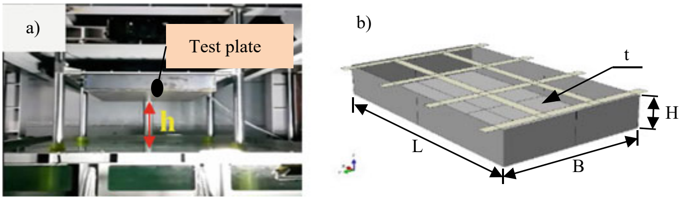

Fig. 2 **a** Set up for wet drop test, **b** geometry of the test plate model

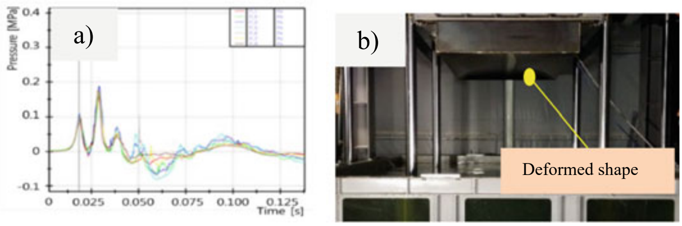

Fig. 3 **a** Pressure recorded, **b** deformed shape of plate after several pressure impacts

impact. Detailed experimental work can be found in Shin et al. [7]. Figure 3 shows the water impact pressure time history recorded during the tests and the deformed shape of the 8-mm thick plate model after several impacts. From the pressure time histories obtained, the peak pressure, and its duration were determined to be applied for the numerical as a load input. The permanent deflection test results of the 8-mm thick plate model for four impacts are utilized for the validation, as in the following sections.

3 Numerical Modeling and Validation

3.1 Finite Element (FE) Model

The numerical computations are established using the FE software package ABAQUS/Explicit. A quarter FE model consisting of the plate model and the supporting part, was considered to reduce the required computation time, as shown in Fig. 4.

The plate model and the supporting part are meshed with the four-node shell element S4R. Five integration points through the plate's thickness are used and the hourglass controls were used as default. After performing mesh convergence tests, the optimum mesh size of the model was determined as roughly twice times the plate's thickness.

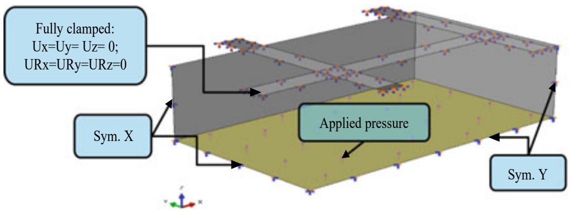

Fig. 4 Quarter FE model of test model

In order to represent the material of the test plate models, the relevant material properties which are available in Seo et al. [8], were used herein. The true stresses and strains are determined to be used in the numerical simulation. The hardening expression for a true stress–strain relation which was proposed by Cho et al. [12], are employed. To consider the strain rate effect, the Cowper-Symonds equation [13] is used. Details of the material constitutive equations and its confirmation can be found in Refs. [14–16].

In the numerical model, a damping model value is also applied to cause the impacted plate quickly approaches a static equilibrium state where the next impact load can be simulated. The simulation duration for each impact is set as 0.4 s.

3.2 Verification of FE Model

Figure 5 shows a comparison between the obtained numerically permanent deflection and test results. A good agreement between the predictions and the test results is achieved. The percentage difference between the test and numerical results is less than 5%. It is evident that the deflection of the plates numerically obtained increased with the number of impacts, and its increment was generally reduced. Besides, as seen that the numerical model gives an underestimation except for the first impact.

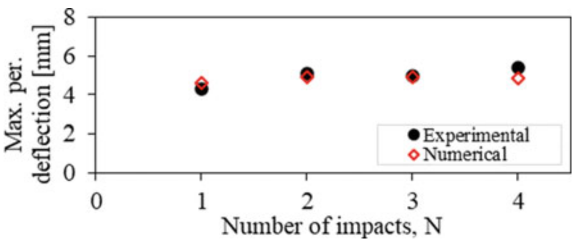

Fig. 5 Comparison of prediction and test results for permanent deflection

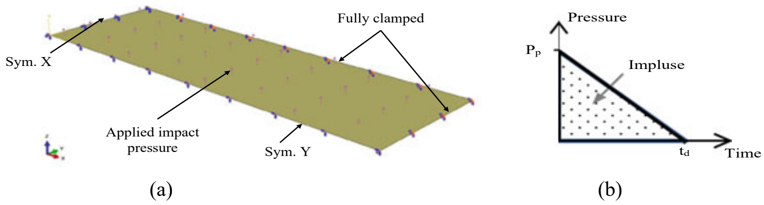

Fig. 6 **a** ¼ FE model of a plate model and **b** impulsive load profile

4 Parametric Study

4.1 FE Plate Models and Material Properties

Based on typical stiffener spacings of marine-steel structures, the plate model is selected as 800 mm in breadth (b), and its lengths (a) are of 2400, 3200, 4000, and 4800 mm. The thicknesses of the plate (t) are 10, 15, and 20 mm. The typical values of the aspect ratios, α (a/b) and plate slenderness ratios, β ($b\sqrt{\sigma_Y/E}/t$), are then generated.

The mild steel ($\sigma_Y = 235$ MPa) is adopted. A similar simulation methodology described in Sect. 2 is used herein. The plate is fully clamped at its edges. The ¼ FE model is shown in Fig. 6a. The simulation duration is set as 0.5 s.

4.2 Definition of Impact Pressure Loads

The impulse charactered by a peak pressure (P_p) and a duration (t_d), as shown in Fig. 6b, is adopted. The peak pressure ratio (P_p/P_c) is 3.0 as a typical value; P_c is the static collapse pressure [13]. Note that the P_p value is selected to sufficiently cause the plate deforms in plastic (w_p/t within a range of 1 to 4, without any fractures). It is assumed that the plate is uniformly loaded by the impulse, and 8 identical impacts are analyzed. The t_d/T_n is selected as 0.6, where T_n ($1/f$) is the fundamental period of a clamped plate. Note that f is the fundamental frequency of a clamped plate considering submersion effects, and it can be determined by using the modified formulations taken from [17].

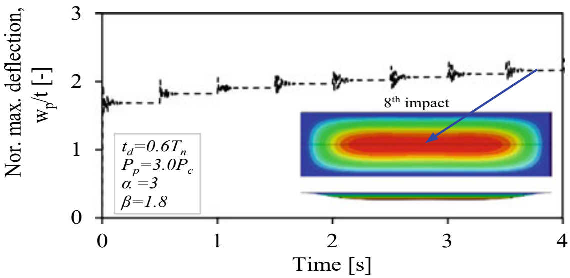

Fig. 7 Typical deflection time history and deformed shape of the plate after 8^{th} impact

5 Results and Discussion

5.1 Effect of Load Repetition

Figure 7 shows the deflection time history at the plate's center for eight impacts. A deformed shape at the last impact is presented to show the typical profile of plate under impulsive loadings.

As seen that the permanent deflection get an increase with the impact numbers N. After 1st impact, the plate deformes significantly, while with consecutive impacts, the deformation increases gradually. In the following sections, the plot of w_p/t for 8 impacts is presented for evaluating the response of the various plates subjected to repeated impacts.

5.2 Effect of Plate Slenderness Ratio and Aspect Ratio

The effect of β on the permanent deflection accumulation of the plates is presented in Fig. 8a. As seen that w_p/t increases gradually when β is increased regardless of N. However, the increment of the deflection is identical for various β, which is line with the observation of Truong et al. [9–11]. In addition, for the large β the permanent deflection evolution is somewhat greater for the eight impacts.

Figure 8b indicates accumulation of w_p/t for various α with N. It is evident that the deflection gradually decreased when increasing α, regardless N; however, the deflection is negligibly decreased and approaches a certain value when α is greater than 5.

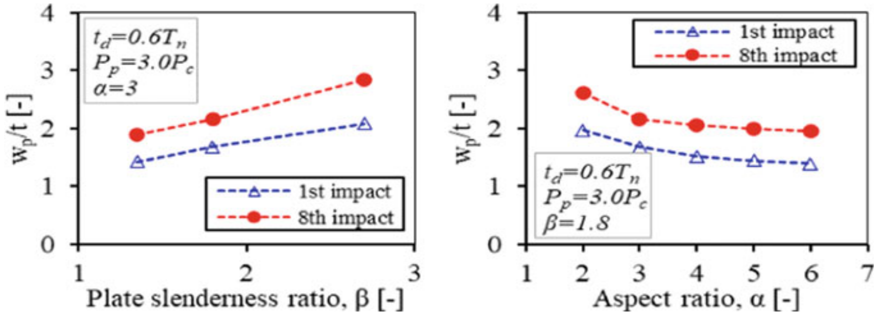

Fig. 8 Variation in normalized residual deflection of plate for different **a** β and **b** α

6 Conclusions

This study developed the numerical analysis model for estimating the permanent deflection accumulation of steel plates under repeated impact pressures induced by slamming. A parametric study was performed for various actual scantlings of marine plates to assess the structural response to repeated impact loadings. It was found that the steel plates undergo a significant deflection after the first impact, and subsequently it experiences the accumulation of deflection following by several consecutive impacts regardless of α and β. In addition, the permanent deflection of the plates was gradually increased and decreased when increasing β and α, respectively regardless of N. It was also found that when plate is subjected to repeated impact pressures, its deflection was almost unchanged for the case of α greater than 5.

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