EFFECTS OF IMPACT LOCATION ON THE DYNAMIC RESPONSE OF REPEATEDLY IMPACTED ALUMINUM ALLOY PLATES

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ABSTRACT

This paper presents a numerical investigation of the effects of impact location on the dynamic response of aluminum alloy plates to repeated mass impacts. The numerical model was developed and validated against relevant test data. In the simulation, the strain hardening was adopted using existing published equations. A parametric study was performed by considering different impact locations while keeping impact energy (mass and velocity) identically for each impact. The results showed that the plate was deformed progressively, and the resulting impact forces increased, while its duration decreased when the plate was impacted repeatedly. While changing in impact location after each impact remarkably affected the response of impacted plates, i.e., less damage was observed. The study results are expected to be helpful for the design of marine structures including fishing boats subjected to repeated impacts arising from collisions or dropped objects.

Keywords: *Numerical simulation, aluminum alloy plate, repeated impacts, residual deformation.*

I. INTRODUCTION

Marine structures can be damaged due to repeated mass impacts arising from contact with floating objects, ice floes, and/or dropped objects while in service. Such damages could cause danger to crews and even economic loss. However, the effect of repeatedly impacted responses of the structures is still not explicitly considered in relevant classification rules.

In addition to traditional materials such as steel and composite, aluminum alloys are widely applied in fabricating marine vessels, such as high-speed vessels or fisheries supporting tools and fishing boats, thanks to their lightweight and corrosive resistance advantages [1]. This material has a high energy absorption capacity, i.e., high plastic deformation to fail. Therefore, to fully characterize the resistance features of the aluminum alloy structures for the development of reliable design tools, it is required to thoroughly understand the behavior of the material subjected to various loading conditions, such as the impact repetition and impacting locations.

Regarding the single mass impact conditions, many studies on the response of the structural components made of aluminum alloys have been reported [1-9]. In those studies, the dynamic response and failure patterns of the aluminum beam/plate due to single impact loading that may differ from actual impact scenarios, were explored. For the repeated impact loadings, although there are extensive investigations on the behavior of steel beams and plates [10-22], few studies for aluminum structures have been investigated yet [10,11,19,23]. Zhu and Faulkner [10] studied several repeated impact tests on mild steel and aluminum plates to investigate the response of the repeatedly impacted plates. Huang et al. [11] examined the pseudo-shakedown behavior of the clamped aluminum and steel plates through repeated impact tests. It was concluded that the membrane force remarkably affects the pseudo-shakedown state of plates. He and Guedes Soares [19] also investigated the pseudo-shakedown state experimentally for aluminum alloy beams subjected to repeated mass impacts, and concluded that it could be obtained when the beam is subjected to a small impact force (small impact energy); however, in practice, marine structures are often subjected to much larger impact energies, so this state will often be very unlikely, this statement was also verified in Ref. [10]. Recently, Truong et al. [23] numerically investigated the dynamic response of aluminum alloy plates to repeated mass impacts for various impact energies.

From a survey, it is apparent that those studies only focussed on either the simple models or the applied impact loadings at the center of the model, while the impact location in reality would be different for each impact event.

Since difficulties in experiments and thanks to the developments of computational tools, a nonlinear finite element analysis method has become preferable to be used alternately. However, prior to such a numerical method can be used for structural designs, its reliability and accuracy must be confirmed through comparison with test data and/or theoretical/analytical methods. Many studies have successfully adopted the numerical method in the assessment of structural responses to various loading conditions, especially for the repeated mass impacts problem, for example, Refs. [12-22].

In this study, a numerical analysis model is established using the finite element (FE) software ABAQUS/Explicit to investigate the response of aluminum alloy plates used in marine vessels to repeated impacts. The developed FE impact model is validated against existing relevant test results. The practical aluminum alloy type, namely 5083-H116, which is usually used in marine applications, is adopted in this study. The strain hardening model with no strain rate consideration is introduced in the FE plate model. Effects of the impact (or contact) location on the dynamic response are examined by performing a parametric study. Discussion on the dynamic response results is provided.

II. FINITE ELEMENT MODELING

In this study, the numerical analysis model was established using the FE analysis software ABAQUS/Explicit [24] to study the repeated impact response of the aluminum alloy plate, considering different impact locations. The FE model contains two parts: the plate and the striker, as displayed in Fig. 1.

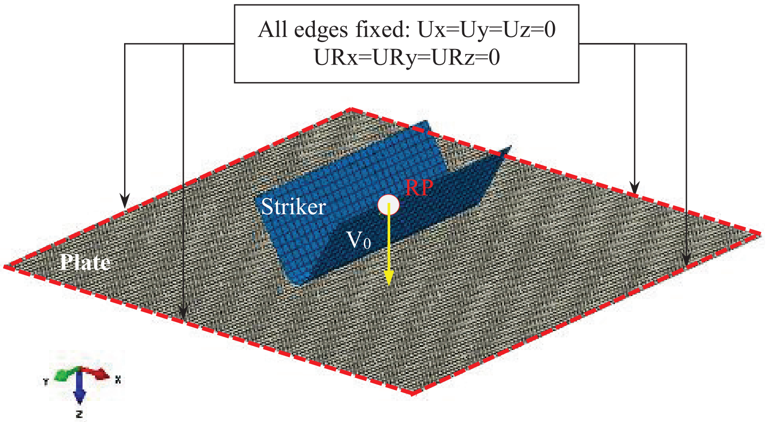

Figure 1. FE model of a plate model.

1. Plate model

A square unstiffened plate with a side length of 560 mm, and thickness of 3 mm was used herein. The plate was modeled by four-node doubly-curved shell elements with a reduced integration scheme (S4R). To consider the simulation's efficience and accuracy, a mesh convergence test was performed. Then, an optimum mesh size was selected as approximately twice times the thickness of the plate, i.e., 6 mm × 6 mm.

In marine applications, aluminum alloys with grade 5083, for example, AA5083-H116 (the special temper H116 is used to strengthen non-corrosive properties), are usually used for plating parts of high-speed vessels thanks to its lightweight and non-corrosive properties. Therefore, for practice, AA5083-H116 was considered in this study. The structural response involving large deformation is strongly dependent on the definition of plastic behavior by strain hardening models. Here, a power law model defined by Gao et al. [25] for the relationship between true stress σ and plastic strain ε_p, as in equation (1), was utilized, in which Young modulus E = 70,000 MPa, yield strength σ_0 = 192 MPa and N = 0.17. The true stress-strain curve applied to the FE plate model is shown in Fig. 2, which was implemented in ABAQUS/Explicit as tabulated data.

$$\varepsilon_{\mathrm{p}} = \frac{\sigma_0}{E}\left(\frac{\sigma}{\sigma_0}\right)^{1/N} \qquad (1)$$

In this study, because only the plastic deformation mode was considered, no fracture criterion was defined. No strain-rate sensitivity was necessarily defined for the plate model since aluminum is insensitive. The boundary conditions of the plates were assumed as a full clamp.

2. Striker

The striker was a knife-edge shape having a header length of 280 mm with a radius of 17 mm, as illustrated in Fig. 1, which can represent the impacts from contacts with edges of objects in practice, for example, the ice floes, and luggage. The striker was modeled as a discrete rigid surface by the four-node 3-D bilinear rigid quadrilateral element (R3D4); its mesh size was roughly of 10 mm × 10 mm, resembling the striker's curvature head shape and ensure sufficient contact between the striker and plate, thus providing a more realistic simulation of the contact area.

The striker was only kept free in the vertical translation. The initial impact velocity (V_0) and the mass of the striker were assigned to the referent point (RP), as indicated in figure 1. The contact between the striker and the plate was defined using the contact algorithm "General contact". In the contact card, the friction coefficient was assumed as 0.3, following Ref. [15], and the "Hard contact" was also adopted in the "Normal behavior" option [24].

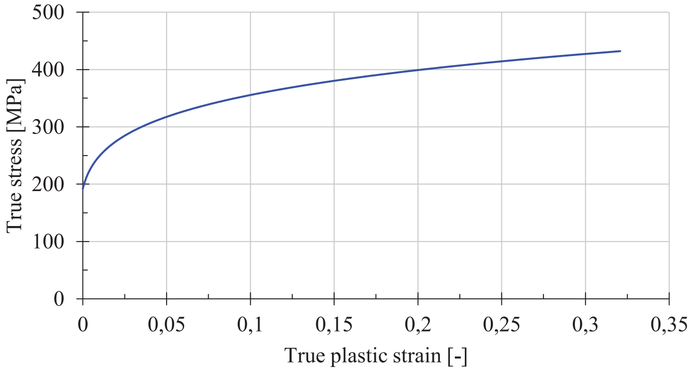

Figure 2. True stress-plastic strain curve adopted in the numerical model.

3. Repeated impact scenarios

To investigate the response of the plate to repeated mass impacts at different impact locations, a case with striker mass M of 42 kg and initial impact velocity V_0 of 4.852 m/s (corresponding to 1.2 m of the strike's drop height) was simulated. The repeated impacts were simulated by performing the calculations repeatedly. The identical impact energy was applied to each impact. After the first impact finished and the vibration of the impacted plate was overcome, the same impact energy was assigned to the striker for the later impact simulation, and the subsequent impact simulation was started again. The residual deformed shape, stress and strain of the plate caused by the previous impacts were preserved as the initial state for the currently restarted analyses. Note that no damping was introduced in the FE plate model in order to avoid any reduction of numerical damage extent results. The simulation duration time of each impact was set as 0.025 s, sufficient to capture the peak and the permanent deflection of the impacted plate.

4. Validation of numerical analysis

Prior to performing further simulations, the validation for the FE analysis model should first be carried out, in which relevant experiment data and/or theoretical methods were usually preferred for this perpose. Several relevant impact test data reported in Ref. [1] were utilized for validation in this study. The FE modelling techniques introduced herein have satisfactorily predicted the damage extent of the fully fixed unstiffened aluminum plates under repeated mass impact provided in Ref. [23]. Details on the comparison of the numerical results and test results were given in the previous study [23]. It can thus be concluded that the current numerical model can simulate similar repeated impact problems on aluminum alloy plates. In the following section, a parametric study will be performed to examine the effects of the impact location on the dynamic repeated impact response of the plate. The schematic of the study is shown in Fig. 3.

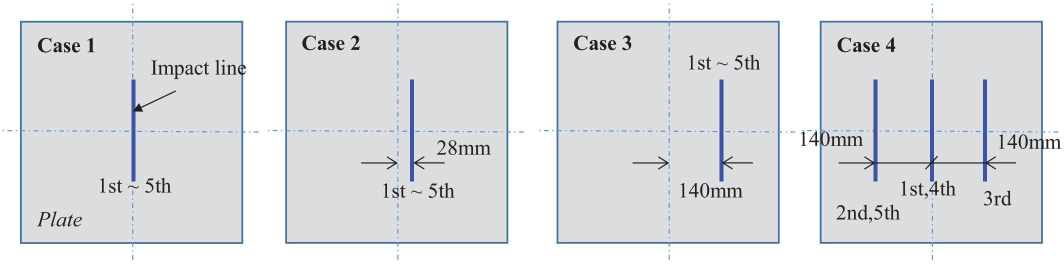

Figure 3. Schematic of impact conditions for parametric study (e.g., Case 1, Case 2 and Case 3 mean the impact is at the center of plate, 28 mm and 140 mm far from plate center, respectively; Case 4 means the 1st , 2nd , 3rd, 4th, and 5th impacts respectively at center, left 140 mm, right 140 mm, center, and left 140 mm far from the plate center).

III. RESULTS AND DISCUSSION

1. General dynamic response

A typical time history of plate center deflection and the impact force during five identical impacts is shown in Fig. 4. It is apparent in Fig. 4a that the deflection of the plate increases with the number of impacts, while its increment reduces accordingly.

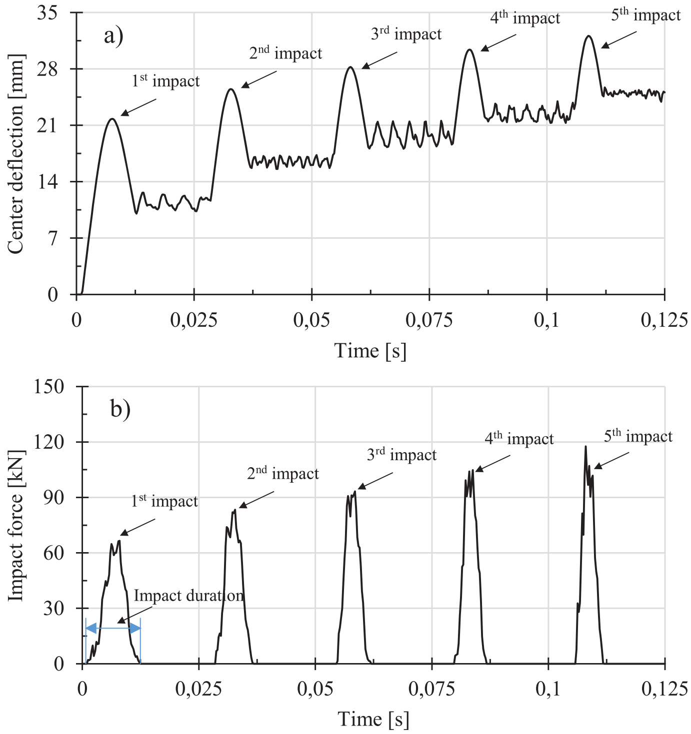

Figure 4. Typical time histories of (a) the center deflection of the plate and (b) impact force throughout five impacts.

The features of the response of plates under repeated impacts are revealed in the figure. In particular, during each impact event, the plate experiences three stages (i) peak deformation, (ii) elastic spring-back (rebound), and (iii) permanent deformation with the oscillations (release). Note that the oscillations may vanish in reality where the damping is involved. In the first stage, the deflection increases until the maximum value when the impact energy is absorbed by the plate. In the second stage, the striker rebounds due to the release of elastic energy stored by the plate, resulting in the decline of the permanent deflection. In the last stage, the plate oscillates around a certain value after the striker separates from the plate.

The dynamic impact response shown in Fig. 4b corresponds to the deflection process mentioned above. The time response of peak impact force observed in each impact event is the same as that of the maximum deflection, and the increase in impact force causes a larger deflection, as well as a reduction of impact duration is noticed as a decreasing deflection increment, suggesting the plate getting stiffer with the impacts.

2. Effect of impact location

The contact's location effect on the repeated impact response of the aluminum plates is examined numerically. Figure 5 shows the residual deformed profiles after 1st, 3rd, and 5th impacts of Case 4, revealing a progressive deflection at different impact locations. For more information on the impact process and damage extent of the structures, the numerically obtained evolution of the plate's center permanent deflection (w_p) and the impact force results are presented.

Figure 6 shows the variation in the evolution of wp, and impact force history under four cases

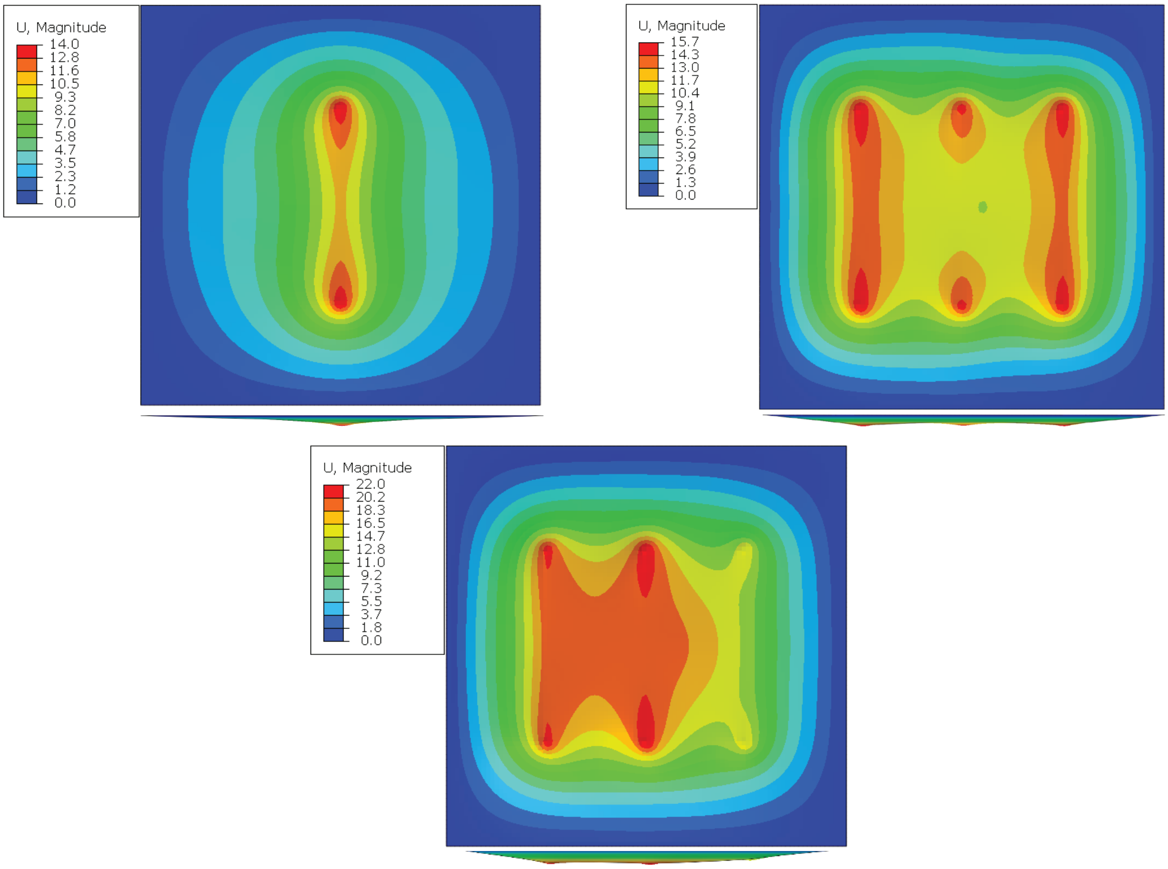

Figure 5. Deformed shapes of the plate for Case 4 after: (a) 1st impact, (b) 3rd impact, and (c) 5th impact. (Unit: mm).

of the impact with the same impact energy (at different locations on the plate); note that, in the figure, "Center impact" denotes Case 1, "28offset" denotes Case 2, Case 3 denotes "140offset", and, "C-L-R-C-L" denotes Case 4 (see figure 3). As seen that the permanent deflection (w_p) accumulates with the number of impacts, regardless of impact locations. For the case of repeatedly impacting at the plate center, w_p is largest throughout impacts, while there are smaller deflections when the impact location is near the supports, i.e., the 140offset case, especially for the last three impacts, as illustrated in Fig. 6a. However, for Case 4, i.e., the impact location varies for each impact event, although the deflection gets increased with impact number, the deflection of the plate reduced significantly, suggesting that the plate under repeated impact with various locations may be safer than when impacts at the same location, which is in line with the observation of Ref. [20].

As for the time histories of impact force shown in Fig. 6b, the location of impacts affects both the peak impact force and the duration time. It was found that the impact duration reduces with the impact number for all the cases. However, at the 1st impact, the time duration is relatively longer in the case of impact at the plate center (Case 1 and Case 4) than those in Case 2 and Case 3, but the impact forces are somewhat the same, indicating there is a difference in impact response (time history) even the total impulse was given the same. Recall that Case 1 and Case 4 have the same impact condition in the first impact, the 1st impact force results of Case 4 are excluded for clear presentation. It can be found that, in repeated impacts, the peak force increases with the impact number regardless of changing the impact location. While the values of the peak forces show some differences, the peak impact forces are lesser in Case 4 than those in the others, which means that changing the impacting location reduces the peak impact force, which results in a less deformation, as mentioned above.

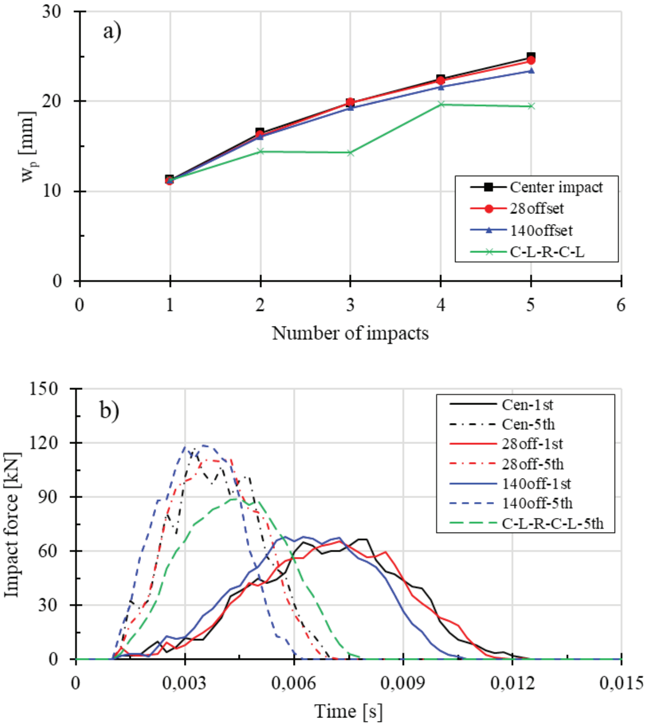

Figure 6. Variation of (a) maximum permanent deflection and (b) impact force response under repeated impacts at different locations.

IV. CONCLUSIONS

This paper presented the numerical investigation of the dynamic response of an aluminum alloy plate to repeated mass impacts induced by multiple contacts between structures and others at various locations. The numerical impact model was validated by comparing it with relevant test data in the literature. The effects of impacting locations on the response of the plates were discussed. It was found that the permanent deflection and peak impact force increase with the impact number, while the defection increment and duration time are reduced accordingly. Owing to the membrane forces generated during impacts, the stiffness of plates increases when the transverse deflections increased. Impacting at different locations for each impact event results in less structural damage than in other cases (i.e., repeatedly impacting at the same location, even if not at the center of the plate). This means that impacting at the same location will be the most severe loading case, which should be considered in the design. However, further investigations on different impact energies and more complicated structure scantlings appear to have provided more comprehensive and reliable data for designing marine structures, including fishing boats under repeated impact conditions.

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