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To cite this article: Peng Ren and Wei Zhang 2014 J. Phys.: Conf. Ser. 500 182034

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Underwater shock response of air-backed thin aluminum alloy plates: An experimental and numerical study

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Abstract. Studies on dynamic response of structures subjected to underwater explosion shock loading are of interest to ship designers. Understanding the deformation and failure mechanism of simple structures plays an important role in designing of a reliable structure under this kind of loading. The objective of this combined experimental and numerical study is to analyze the deformation and failure characteristics of 5A06 aluminum alloy plates under underwater shock loading. Some non-explosive underwater blast loading experiments were carried out on air backed circular plates of 2 mm thickness. The deformation history of the clamped circular plate was recorded using a high speed camera and the deflections of specimens at different radii were measured in order to identify deformation and failure modes. In the finite element simulations, the strength model of 5A06 aluminum alloy is considered using the slightly modified Johnson-cook mode to describe structure deformation. Good agreement between the numerical simulations and the experimental results is found. Detailed computational results of each scenario are offered to understand the deformation and failure mechanism.

1. Introduction

The prediction of damage for Ships and submersibles subjected to an underwater explosion is an important topic for ship designers. Air-backed circular plate is a common structural component of ships [1]. The dynamic response of air-backed plates under underwater shock loading is complicated. Most studies on the dynamic responses and failure modes of ship structures under such conditions are theoretical, but application of a formula to complex structures may be difficult. Hence, methods of accurate analysis to improve shock resistance of structures of ships and submarines have been continuously developed during past decades [2]. Recent reviews described available experimental investigations of the response of loaded plates, accounting for fluid structure interaction, strain rate effects associated to these dynamic events [3-5]. From these studies, it emerges that performance improvements can be achieved through material optimization, such as uniform ductility, improved strength and so on. In fact, the maximum center deflection of plate is inversely proportional to material yield strength [6]. Development of high performance materials can lead to superior shock resistance, Vaziri et al. [7] examined the influence of the material through different material choices. Finnie [8] showed that the impulse per unit deformation was proportional to the thickness of the plate. Smith [9] examined the failure of circular plates by subjecting them to uniformly distributed impulse. This paper

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This work is supported by National Nature Science Foundation under Grant 11372088

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deal with the performance identification of monolithic plates subjected to underwater impulsive loading. First, the non-explosive underwater explosion experiments were carried out on air-backed 5A06 aluminum alloy plates in the plastic range, and high-speed photography is employed to record the dynamic response of target plates. Then, the same experimental model was numerically analyzed using 3D numerical simulation, and the strength model of 5A06 aluminum alloy is considered using the slightly modified Johnson-Cook form to describe structure deformation. Finally, a discussion of experimental results and finite element predictions is provided.

2. Experiment and Results

2.1 Experiment
In order to perform underwater explosive pressure loading as described in Cole [10] in the laboratory, a scaled down non-explosive underwater explosion experimental setup was developed [11]. The experimental setup is schematically shown in figure 1 (a). A projectile is accelerated by a gas gun and impact the water piston. The exponentially-decaying pressure history is produced. The shock waves propagate through the water column and impact the target panel. The pressures depend on the projectile velocity, and the decaying time depends on the projectile and piston mass [11]. Figure 1 (b) shows the typical pressure histories corresponding to three different projectile velocities, as measured by the calibration experiments. Based on the experimental data employ an acoustic approximation, the peak pressure is given by

\[ p_0 = 3.3 \rho_w c_w v, \]

where \( c_w \) is the velocity of sound in water, \( \rho_w \) is the density of water, \( v \) is the velocity of projectile and the constant 3.3 is an empirical value derived from the experiments.

2.2 Test Results
The total 4 test cases, with different projectile velocities, 68.34 m/s, 102.2 m/s, 130.76 m/s and 167.93 m/s were conducted. All of the test results are displayed in table 1, where \( h_1 \), \( h_2 \) and \( \delta_{\text{max}} \) denote projectile thickness, piston thickness and maximum deflection, respectively. The decay time constant is \( t_0 = 43.88 \mu\text{s} \), as determined from experiments. The momentum is given by
\[ I = \int_{0}^{\infty} p \, dt = p_{0}t_{0}. \]  

Table 1. The test records and results.

| NO. | \(v\) (m/s) | \(h_{1}\) (mm) | \(h_{2}\) (mm) | \(I\) (Pa·s) | \(\delta_{\text{max}}\) (mm) | Fracture (yes/no) |
|-----|--------------|----------------|--------------|-------------|----------------|------------------|
| 1   | 68.34        | 10             | 23           | 1486.27     | 8.13           | No               |
| 2   | 102.20       | 10             | 23           | 2222.66     | 12.74          | No               |
| 3   | 130.76       | 10             | 23           | 2843.77     | 17.60          | No               |
| 4   | 167.93       | 10             | 23           | 3652.14     | 23.01          | No               |

Some high-speed camera pictures of the deformation history from a typical test with projectile initial velocity 167.93 m/s are shown in figure 2. The frame times correspond to times after the pressure front reached the target plate surface in the water pressure tube. It is observed that the maximum deflection at the center of the specimen was achieved at about 313 \(\mu\)s and after that the plate merely oscillated with small amplitude due to elastic recovery.

Figure 2. Typical deformation process pictures by high-speed camera (\(v = 167.93\)).

Figure 3 shows the deformation of 5A06 aluminum alloy monolithic panel obtained from postmortem digital photography. It should be noted that the plate slipped between the clamps. Additionally, one can observe the ovalization of the screw holes in the radial direction of the specimen plate. The slipping boundary condition resulted in a deflection larger than the deflection which would have occurred under perfectly fixed boundary conditions.

Figure 3. 5A06 aluminum alloy plate after blast (\(v = 167.93\)).

3. Simulation and results

3.1 Numerical model

Finite element analysis of the underwater impulsive loading experiments was conducted using the code ANSYS-AUTODYN. According to the above experimental observations, a three dimensional coupled Eulerian and Lagrangian technique was used to simulate the fluid-structure interaction. The water was modelled by Eulerian elements. The projectile, piston, anvil tube and target plate were modelled by Lagrangian elements. The projectile is prescribed with an initial velocity \(v\). The geometry of non-explosive underwater blast loading experimental set-up and target plates in the numerical models was identical to that used in the experimental tests. Figure 4 shows a side-view of the quarter symmetry finite element model with mesh refinement at the interfaces.
3.2 Material behavior

To be able to describe the various phenomena taking place during the impact process, it is necessary to characterize the material behaviour of target plates under high strain rates. Thus, a series of material tests were performed on 5A06 aluminum alloy specimens. The true stress-strain curves of 5A06 aluminum alloy obtained from quasi-static and high strain rate compressive tests are presented in figure 5. It indicates that increasing dynamic strain rates tends to mildly increase the flow stress of specimens. Details regarding the mechanical properties tests, results and calibration procedure can refer to [12].

Here, only the main results are showed. A slightly modified Johnson-cook strength mode is used to describe the hardening, strain rate effects. It reads

\[
\sigma = (A + Be^n)(1 + f(\dot{\varepsilon}^*)\ln(\dot{\varepsilon}^*)(1 - T^s)) ,
\]

where \(\dot{\varepsilon}^*\) is the dimensionless strain rate, \(T^* = (T - T_i)/(T_m - T_i)\) is the homologous temperature. And \(f(\dot{\varepsilon})\) reads

\[
f(\dot{\varepsilon}) = 10^{-5} \dot{\varepsilon}^{0.6}.
\]

The related material parameters of 5A06 aluminum alloy are listed in table 2.

| Table 2 Material constants for 5A06 aluminum alloy. |
|----------------------------------------------------|
| E (Gpa) | \(\rho\) (kg/m3) | \(A\) (MPa) | \(B\) (MPa) | \(n\) | \(m\) | \(T_i\) (K) | \(T_m\) (K) |
|----------------|-----------------|-------------|-------------|------|------|-------------|-------------|
| 69.30        | 2830            | 168.4       | 950.5       | 0.71 | 1.08 | 293         | 853         |

3.3 Simulation results

Figure 6 shows the deformation process of target plate as predicted by the numerical simulation, the initial velocity of projectile is 167.93 m/s. As seen, the deformation process is similar to the high-speed camera pictures in figure 2. The equivalent strains at the plate exposed to the water blast pressure obtained by FEM. The simulation results give an equivalent strain at the center of the plate, about 22%. It is larger than that in other regions. The target plates exhibited a deformation pattern consistent with biaxial tension. The final deflection profiles obtained from experimental postmortem are plotted and compared to numerical simulation in figure 7. It reveals a very good agreement, indicating the modified Johnson-cook strength mode successfully predicts the dynamic response of the 5A06 aluminum alloy under underwater shock loading conditions. Furthermore, the study reveals that 5A06 aluminum plate can sustain higher impulse prior to failure.
Figure 6. Out of plane configuration of specimen as measured by numerical simulation.

Figure 7. Comparison between experimentally measured and simulated specimen final deflections.

Figure 8 summarized the maximum deflection responses vs. impulse for all four specimens both from experiments and numerical simulations. The simulated performance of the 5A06 aluminum alloy plates agrees very well with the experimental results. The results indicate that, the relationship between maximum deflection and impulse is linear. For the no. 4 specimen, a slight deviation from the original linear deflection-impulse relationship is observed in the high range of impulses preceding plate failure. The resultant deflection obtained by the simulation and experimental accounting for the extra deflection due to sliding is shown in figures 3 and 7.

Figure 8. The maximum deflection responses vs. impulse for all three specimens, which collapse into a single linear relationship.

4. Conclusion
The performance of monolithic aluminum alloy plates subjected to underwater impulsive loading was investigated by lab-scale underwater shock loading test and finite element simulation. The deformation history of target plate was observed. The 3D numerical simulations using ANSYS-AUTODYN combined with material performance testing for the experimental configuration showed good agreement with the experimental results. Calculations show the distinct strain response regimes of the structures. The detailed of computational results extracted in simulations have proven that the tension stress state is the most major reason that leads to target plates failure. The relationship between maximum deflection and impulse is linear prior to target plate fracture. The insight gained here provides guidelines for the design of structures for which response to underwater shock loading is an important consideration.
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