A NUMERICAL SIMULATION OF A RECTANGULAR PLATE RESULTING FROM CLOSE-IN UNDERWATER EXPLOSION SHOCK

Hai-Anh Nguyen[1,a] Nguyen Ngoc Kien[2,b] Tien Dat Hoang [3,c]

[1]Department of Mechanical Engineering, National Chiao Tung University

[2]Department of Mechanical Engineering, Hanoi University of Science and Technology

[3]Faculty of International Training, Thai Nguyen University of Technology

[a]haianh.me04g@nctu.edu.tw, [b]kien.nguyenngoc@hust.edu.vn, [c]hoangdat@tnut.edu.vn

ABSTRACT In this paper, numerical simulation was carried out on the rectangular plate using ABAQUS 6.11 for the experimental results of paper [K.Ramajeyathilagam (2004)]. The deformation and rupture of a rectangular plate are conducted, and the results are close to the failure modes shown in experiments. This investigation develops a procedure that couples the finite element method with Acoustic structure coupling (ASC) method and Cole's empirical UNDEX loading formula to study the problem of transient responses of a structure subjected to an underwater explosion shock. All of these results can be a valuable reference for designing underwater structures to resist UNDEX.

1. INTRODUCTION

During underwater explosion (UNDEX), the sudden release of energy from a conventional high-explosive or nuclear weapon generates a shockwave and forms a superheated, highly compressed gas bubble in the surrounding water [1]. For example, approximately 53% of the total energy released from a 1500-lb (680.39-kg) Trinitrotoluene (TNT) UNDEX is applied to the shockwave and 47% is applied to bubble pulsation. Most of these cases demonstrate that the damage caused to marine structures, such as on the surface of ships and submarines, occurs early and is caused by primary shockwaves. This research considers only the effects of the shock waves. The primary concern in naval engineering and offshore structure research is predicting how submerged structures are damaged by UNDEX. Accurately predicting how submerged structures are damaged by underwater explosions is of priority concern in naval engineering and offshore structure research. Recently, numerical methods for analyzing the dynamic response of submerged structures exposed to UNDEX shock wave loadings have been successfully developed. For example, R.Rajendran (2000) investigated dynamic deformation and fracture evaluation of 4 mm High Strength Low Alloy (HSLA) steel plate subjected to underwater explosion for circular and rectangular geometries [2]. Ramajeyathilagam (2004) presented experiments that using a model box set-up under air-backed conditions in a shock tank employing small explosive charges of PEK-I and numerical investigations on thin rectangular plates subjected to underwater explosion loading using the CSA/GENSA [DYNA3D] [3]. Liang (2006) presented a preliminary study of the transient responses of a 2000 ton patrol boat under shock loading using the finite element method coupled with DAA2 [4]. Hung (2009) investigated dynamic responses of three cylindrical shell structures subjected to underwater explosion [5]. Shin (2004) presented numerical simulations of Ship shock analyses using finite element based coupled ship and simulation for far-field underwater explosion [6]. Wang (2014) examined the dynamic response of ship structures with the combined effect of shock wave load and bubble pulsation subjected to close-in non-contact UNDEX [7].

In the aforementioned literature, the UNDEX response the detailed failure mechanisms of submerged structures subjected to UNDEX are not very clear. Furthermore, there is shortage of the experimental records of ship structures subjected to close-in non-contact UNDEX shock wave integrated loadings. This study aims to develop a procedure to investigate the shock response of submerged structures exposed to UNDEX with the incident pressure from the explosive charge determined by the Cole's empirical equation [1]. Numerical analysis for the experimental model by using ABAQUS software and the calculated results were compared with the experimental data.

2. THEORETICAL BACKGROUND

2.1 Empirical Formulation for Shock Wave

An explosion is a chemical reaction that converts the initial material into a gas at an extremely high temperature and pressure; the process occurs with extreme rapidity and emits a substantial amount of heat. The temperature in the product gases is approximately 3000°C, and the pressure is 50,000 atm. Empirical equations were determined to define the profile of the shock wave and can be expressed as follows [1]:

$$P_{\max} = K_1\left(\frac{W^{1/3}}{R}\right)^{A_1} \text{ (1)}; \qquad \lambda = K_2 W^{1/3}\left(\frac{W^{1/3}}{R}\right)^{A_2} \text{ (2)}$$

$$P(t) = P_{max} e^{-t/\lambda} \qquad (3)$$

K1, A1, K2 and A2 are constants depending on various explosive charge types (Table 1)

Other variables in the equations are:

W: the weight of the explosive charge (Kg)

R: the distance between explosive charge and target (m)

P(t): the pressure profile of the shock wave (MPa)

Pmax: the peak of the pressure of the wave (MPa)

λ: the shock wave decay constant (millisecond, ms)

Table 1 Shockwave constants [1]

	HBX-1	TNT	PETN	Nuclear
K1	53.44	52.2	53.59	1.07×104
A1	1.144	1.18	1.194	1.13
K2	0.092	0.0894	0.086	3.627
A2	-0.247	-0.185	-0.257	-0.22

2.2 Acoustic-Structure Coupling (ASC) method

For the numerical simulation of the interaction between a shock wave and structure, the acoustic-structural coupling method from the ABAQUS software was applied [8]. An acoustic element was introduced into the flow field, and its size was selected according to the literature [8], as shown in Fig.1. The primary principle and theoretical formula of the acoustic-structural coupling method are described in the ABAQUS software manual.

Acoustic fields are highly dependent on the conditions at the boundary of the acoustic medium. This boundary can be divided into subregions *S*. Consider a cylinder floating on a free surface, as shown in Fig.1. The boundary of this model is S_{fp} , where the value of the acoustic pressure *p* is prescribed; S_{ft} is the normal derivative of the acoustic medium; S_{fr} is the reactive acoustic boundary where a prescribed linear relationship exits between the fluid acoustic pressure and its normal derivative; S_{fi} is the radiating acoustic boundary, and S_{fs} shows the motion of an acoustic medium directly coupled to the motion of a solid; S_{frs} is the acoustic-structural boundary where the displacements are linearly coupled but not necessarily identically equal because of the presence of a compliant or reactive intervening layer. S_{ft} is a boundary between acoustic fluids of possibly differing material properties [9]. The equation of the structure equilibrium in the fluid field was solved. The structure and acoustic medium were discretized using the Finite Element Method (FEM), and the surface on which the pressure was applied was defined. The pressure load from the UNDEX in Geers and Hunter's model (2002) [9] was exerted on the discretized surfaces. Hence, the response of the structure and the pressure propagation in the fluid field was obtained from literature [8]. Equations were solved using ABAQUS. The surface-based interaction embedded in ABAQUS was used and is described in this paper.

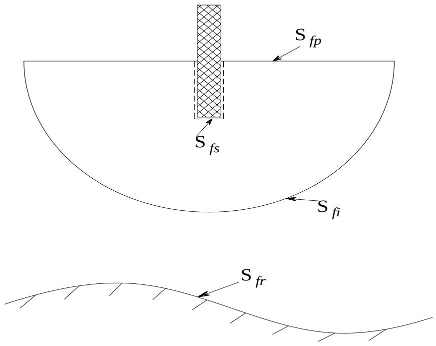


Fig. 1 Fluid domain and boundary

3. NUMERICAL SIMULATION

3.1 Model Description

The experiments by Ramajeyathilagam and Vendhan [3] were conducted in a shock tank, and the experimental set-up is shown in Fig.2. A rectangular box was submerged in water with air-backed condition. The exposed area of the experimental plates was 0.3 × 0.25 m2, and the thickness of the plates was 0.002 m. The explosive charges of PEK-I (1.17 × TNT) were located 0.15 m on the normal line passing through the center of the plate. The experiments were carried out using charge weights of 0.01-0.08 kg in steps of 0.01 kg. Detail of all the Shock Factor (SF) tests carried out in Table 2. Engineering properties of the plate material are provided in Table 3 (the linear elastic material model is adopted to describe the mechanical property of the material).

Fig. 2 Experiment setup [3]

Table 2 Shock factor test [3]

Case	Charge weight (W-kg)	Stand-off distance (R-m)	Shock Factor (SF) ($0.45\times W^{1/2}/R$)
No.1	0.01	0.15	0.3
No.2	0.02	0.15	0.424
No.3	0.03	0.15	0.52
No.4	0.04	0.15	0.6
No.5	0.05	0.15	0.671
No.6	0.06	0.15	0.735
No.7	0.07	0.15	0.794
No.8	0.08	0.15	0.849

Table 3 Engineering properties of the plate material [3]

Property	Value	Unit
Elastic modulus	210×10^{9}	Pa
Poison's ratio	0.3	-
Mass density	7860	kg/m^3
Static yield stress	300×10^{6}	Pa
Ultimate tensile stress	380×10^{6}	Pa
Rupture strain	0.36	-

To simulate the dynamic responses of the plate subjected to underwater shock, the finite element models of the plates and the flow field were created, as shown in Fig.3. The finite element model of the panel was based on nonlinear (i.e., material and geometric) formulations. Fig.4 provides the sketch of the boundary conditions of the finite element model. Fig.4 shows that the outer surface of the fluid domain was set to be non-reflecting; however the top surface of the panel was not. Therefore, the infinite flow field and the air-backed condition were modeled. The finite element model of the plate consisted of 672 S4R elements (a clamped four-edge condition was assumed). The finite element model of the flow field consisted of 129,545 AC3D4 elements. The time step used in this simulation was 10^{-6} s.

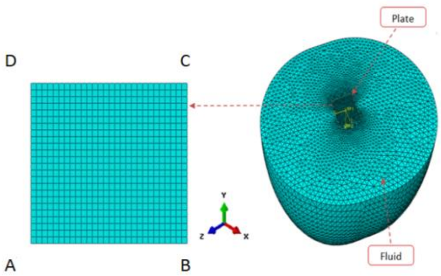


Fig. 3 Finite element model

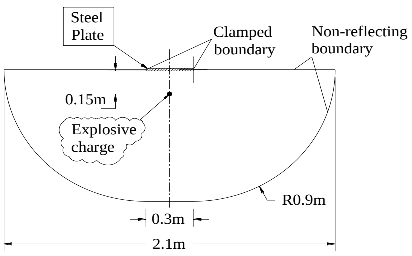


Fig. 4 Sketch of boundary conditions

4. RESULTS AND DISCUSSION

Table 4 shows pictures of experiments and numerical simulations in eight cases (Case No.3 is missing a figure). In Case No.4, partial tearing occurred in the experiment. The numerical method adopted in the simulations was sufficiently accurate in terms of the complex UNDEX process.

Permanent deformation of profiles of the plate along the centerline for both longitudinal (line AD in Fig.3) and transverse directions (line AB in Fig.3) from the finite element model and the experiments are compared in Table 5. The numerical prediction is found to be very low near the edges and crosses to the other side. The permanent set predicted at the center of the plate is found to be lower than the experimental values for all cases.

Table 4 Comparison deformation of plate between experiment [3] and numerical simulation

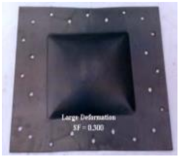
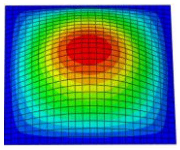
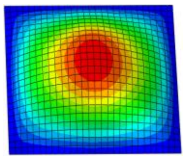
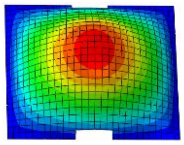
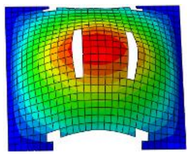
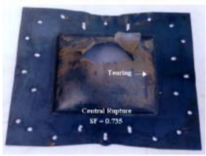
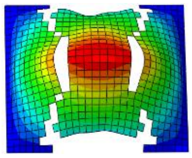
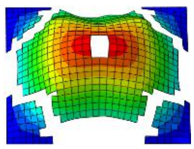
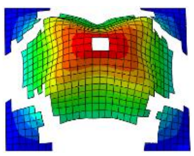
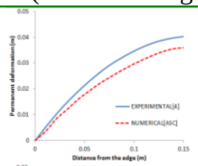
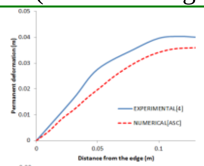
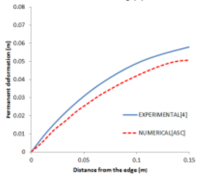
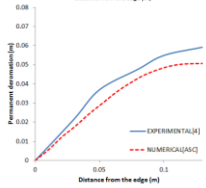
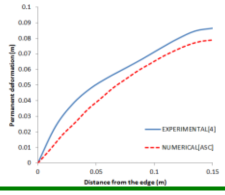
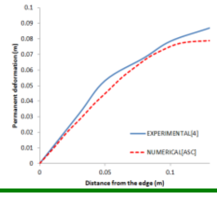
Case	Experiment [3]	Numerical simulation
No.1		
No.2		
No.3	No data	
No.4		
No.5		
No.6		
No.7		
No.8		

Table 5 Comparison of deformation profile (longitudinal and transverse directions)

Case	Longitudinal (line AD in Fig.3)	Transverse (line AB in Fig.3)
No-1		
No-2		
No-3	No data	
No-4		

CONCLUSION

This paper focus on the UNDEX (underwater explosion) formula compared with the experimental data. Numerical simulations of the experimental of a cylinder were performed using ABAQUS software. The results are summarized in the following:

(1) Demonstrate the possibility of using Cole's formula is an effective tool to solve the response of the structure subjected to UNDEX.

(2) ABAQUS/Explicit provides an efficient means to evaluate the transient response of structural-acoustic systems loaded by external acoustic sources.

(3) The analysis of a submerged plate acted upon by a shock wave generated by an underwater explosion is performed. Deformation of the plate obtained from experimental, and numerical analyses were in good agreement.

For further study, we will continue to combine the remaining factors are bubble-pulse loading, bulk cavitation and the formation of water jet in underwater explosion environment.

REFERENCES

[1] Cole, R.H. Underwater explosion. Princeton University Press. Princeton, NJ. 1948.

[2]R. Rajendran, K. Narasimhan. Performance Evaluation of HSLA Steel Subjected to Underwater Explosion. Journal of Materials Engineering and Performance 2001; 10:66-74.

[3] K. Ramajeyathilagam, C.P. Vendhan. Deformation and rupture of thin rectangular plates subjected to underwater shock. International Journal of Impact Engineering 2004; 30:699-719.

[4] Cho-Chung Liang, Yuh-Shiou Tai. Shock response of a surface ship subjected to noncontact underwater explosions. Ocean Engineering 2006; 33:748-772.

[5] C.F.Hung, B.J.Lin, J.J.Hwang-Fuu, P.Y.Hsu. Dynamic response of cylindrical shell structures subjected to underwater explosion. Ocean Engineering 2009; 36(8):564-577.

[6] Shin, Young S., Ship shock modeling and simulation for far-field underwater explosion. Computer & Structures, 82, 2004:2211-2219.

[7] Hao Wang, Xi Zhu, Yuan Sheng Cheng, Jun Lin. Experimental and numerical investigation of ship structure subjected to close-in underwater shock wave and following gas bubble pulse. Marine Structures, 39, 2014:90–117.

[8] ABAQUS Analysis User's Manual and Abaqus Theory Manual, version 6.11.1 Dassault Systèmes, RI, USA 2011.

[9] Geers, T. L., Hunter, K. S. "An integrated wave-effects model for an underwater explosion bubble" J Acoust Soc Am, 111 (4), 2002：1584–1601.

Hai-Anh Nguyen received the B.E. degree from Hanoi University of Science and Technology (2013), M.S. degree from Dayeh University (2015) in Mechanical Engineering. Currently, he is a PhD student from the Mechanical Engineering Department, National Chiao Tung University. His current interests include Additive Manufacturing, Numerical simulation, ABAQUS.

Nguyen Ngoc Kien received the B.E. (2003), M.S. (2006), and D.E. (2013) degrees in Mechanical Engineering from Hanoi University of Science and Technology University. Currently, he is deputy-head department Manufacturing Technology at HUST.

Tien Dat Hoang received the B.E. (2010) from Thai Nguyen University of Technology (TNUT), M.S. (2015) degree from National Chiao Tung University (NCTU) with the first rank in mechanical engineering department. Currently, he is working as a lecturer at TNUT. His research areas include finite element analysis, rotor bearing systems, ANSYS. In 2015, he received the certificate of the Phi Tau Phi scholastic honor society, Taiwan.