NUMERICAL INVESTIGATION OF SHOCK IMPACTS ON COMPOSITE MARINE STRUCTURES

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Abstract

The objective of this work is to apply a coupled Eulerian-Lagrangian approach for the modeling of shock impacts on composite marine structures. This type of problems are difficult for conventional analysis methods due to the complex physics, which includes strong shock propagation, transient fluid cavitation, significant structural deformation, and anisotropic and inhomogenous material behavior. To model the complex multiphase fluid dynamics, a multiphase compressible Eulerian solver equipped with a one-fluid cavitation model is employed. To model the solid deformation and stress fields, a general Lagrangian solid solver (ABAQUS/Explicit) is employed. The fluid and solid solvers are strongly coupled via the use of user subroutines in ABAQUS/Explicit. An overview of the numerical model is presented, One-dimensional (1D) analytical and experimental validation studies are shown.

1 Introduction

Underwater explosion (UNDEX) near structures is an important topic for marine structures, which can be subjected to strong underwater shock loads and cavitation reloads. Understanding of UNDEX threats require detailed information of the fluid behavior and the structural response due to the UNDEX shock-structure interaction and the subsequent cavitation reloads. Some experimental and numerical studies have focused on investigation of the response of an isotropic plate subjected to an underwater explosion [1, 2]. Compared to isotropic metallic materials like steel and aluminum, composite materials can help to increase paid load (due to weight reduction) and improve survivability (due to the higher specific strength and stiffness). A number of recent studies have examined the shock response of sandwich plates subjected to blast loads using an acoustic fluid approximation and finite element solid analysis [3-5]. Although these works improved the understanding of the response of composite structural subjected to blast loads, additional studies are still required, particularly in the areas of shock-bubble-fluid-structure interaction.

The authors have applied an Eulerian-Lagrangian coupling multiphase model to simulate 1D interaction between compressible fluid and elastic structure [6]. To include the effect of cavitation reloads, an isentropic cavitation model [7] was also coupled into the multiphase model. In this work, this multiphase model will be further modified and applied to model the response of composite plates subjected to UNDEX loads, where the fluid is simulated using an Eulerian solver and the solid is simulated using the commercial ABAQUS finite element code. The fluid solver and the solid solver are strongly coupled via user-defined subroutines.

2.1 Eulerian Fluid solver

The conservative form of the Eulerian equations for inviscid and compressible gas, water, or bubbly flow can be expressed as

$$\frac{\partial U}{\partial t}+\frac{\partial F(U)}{\partial x}+\frac{\partial G(U)}{\partial y}=S \qquad (2.1)$$

and

$$p=p(e,\rho) \qquad (2.2)$$

where

$$U=[\rho,\rho u,\rho v,E]^T$$
$$F(U)=\left[\rho u,\rho u^2+p,\rho uv,(E+p)u\right]^T$$
$$G(U)=\left[\rho v,\rho uv,\rho v^2+p,(E+p)v\right]^T$$

where ρ is the gas flow density, p is the pressure, u and v are the flow velocities in the x and y directions, and E *is* the total energy and is given as $E=\rho e+0.5\rho(u^2+v^2)$. e is the internal energy per unit mass. U is the vector of conservative variables. $F(U)$ and $G(U)$ are the vectors of flux terms. Equation (2.2) is the equation of state (EOS) for closure of the Eulerian System (2.1). In this work, the γ -law of a perfect gas is adopted

$$p = (\gamma_g - 1)\rho e \qquad (2.3)$$

where γ_g is the ratio of specific heat for gas and is set to be 1.4 except for the explosive gas where γ_g is set to be 2.0.

Two types of equation of states are employed for the water. The bilinear equation of state

$$p = p_0 + (\rho - \rho_0)c_f^2 \qquad (2.4)$$

is adopted for weakly compressible water in problems involving plane wave-structure interaction and the Tait equation of state

$$p = B(\rho/\rho_0)^{\gamma_l} - B + A \qquad (2.5)$$

is adopted for fully compressible water in UNDEX problems. p_0 and ρ_0 are the reference pressure and density, and are equal to be $10^5\,Pa$ and $1000\,kg/m^3$, respectively. c_f is the sound speed of weakly compressible fluid. B , A and γ_l are constants and are set equal to $3.31\times10^8\,Pa$, $10^5\,Pa$ and 7.0, respectively.

The one-fluid model has been shown to be efficient to capture unsteady cavitation [7, 8]. If all flow phases are treated as compressible and the cavitation mixture is assumed to be homogeneous and isentropic, the isentropic one-fluid cavitation model can be expressed as

$$\frac{\alpha}{1-\alpha} = K\frac{(\bar{p}/\bar{p}_{cav})^{1/\gamma_l}}{(p/p_{cav})^{1/\gamma_g}} \qquad (2.6)$$

and

$$\rho = \frac{K\rho_g^{cav} + \rho_l^{cav}}{\left(\frac{\bar{p}}{\bar{p}_{cav}}\right)^{-1/\gamma_l} + K\left(\frac{p}{p_{cav}}\right)^{-1/\gamma_g}} \qquad (2.7)$$

where K is a model constant and is determined using $K = \alpha_0/(1-\alpha_0)$, and α_0 is the known void fraction of the mixture density at p_{cav} . ρ_g^{cav} and ρ_l^{cav} are the associated gas and liquid densities, respectively, at the cavitation pressure p_{cav} . $\bar{p} = p + \bar{B}$, $\bar{p}_{cav} = p_{cav} + \bar{B}$ and $\bar{B} = B - A$. K is equal to 0.9 in this work. The cavitation pressure can be iterated from the void fraction (α) or density (ρ) using Equation (2.6) or (2.7).

2.2 Lagrangian solid solver

The discrete equation of motion for a solid structure can be written as follows:

$$\mathbf{M}\ddot{\delta} + \mathbf{K}\delta = \mathbf{F}\,, \qquad (2.8)$$

where δ is the unknown material displacement vector, and **M**, **K**, and **F** are the structural mass matrix, stiffness matrix, and forcing vector, respectively. In the current work, the effect of structural damping is ignored. The commercial FEM package ABAQUS/explicit is used to model the solid domain (ABAQUS Manual).

2.3 Eulerian-Lagrangian Coupling

Consider an interface separates a compressible fluid at the left side of interface and a solid structure at the right side of the interface, as shown in Fig. 1, the nonlinear characteristic equation (2.9)

$$\frac{dp_I}{dt} + \rho_{IL}c_{IL}\frac{du_I}{dt} = 0\,, \qquad (2.9)$$

and the equation of motion (2.8) can be solved simultaneously to obtain the interface pressure and velocity.

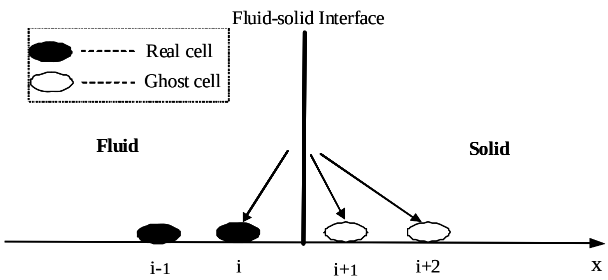

Fig. 1 Eulerian-Lagrangian coupling

The fluid-solid interface motion are given by the solid solver. To avoid re-meshing of the Eulerian fluid solver, the fluid-solid interface is treated as internal boundary, where the characteristic equation is solved to obtain the interface pressure and velocity. The predicted interface pressure and velocity are extrapolated across the fluid-solid interface to define ghost fluids, which imposes an accurate boundary condition on the interface. By doing so, the computation can be conducted in one fluid medium on a fixed Eulerian grid with a high-order high-resolution numerical scheme.

3 Results

In this computation, the stability condition is constrained by

$$\Delta t = \min(\Delta t_f, \Delta t_s) \qquad (3.1)$$

where

$$\Delta t_f = CFL \frac{\Delta x}{\max\limits_{i,j}\left(\left|u_{i,j}\right| + c_{i,j}\right)} \qquad (3.2a)$$

and

$$\Delta t_s \approx \frac{L_{\min}}{C_d}, \quad C_d = \sqrt{\frac{\hat{\lambda} + 2\hat{\mu}}{\rho}}, \qquad (3.3b)$$

$$\hat{\lambda} = \frac{E\nu}{(1+\nu)(1-2\nu)}, \quad \hat{\mu} = \frac{E}{2(1+\nu)}$$

where CFL is the Courant number and is set to be 0.9 in the current work. L_{min} is the smallest element dimension in the grid; C_d is the dilatational wave speed; $\hat{\lambda}$ and $\hat{\mu}$ are the Lame's constants; ν is Poisson's ratio.

3.1 Validations

To validate the Eulerian-Lagrangian fluid-structure interaction (FSI) solver, analytical validation study is shown for the case of a planar shock wave impacting on a single air-backed mass system. Detailed descriptions of the problem can be found in [6, 10]. The schematic diagram is shown in Fig. 2. The computational domain is (-10m, 0.145m) with the initial location of the fluid-solid surface at x=0.0. The initial maximum pressure is 7.15*bar* and the mass of the mass1 is 5.46 *kg*. The histories of the velocity and cavitation region are recorded as shown in Figs. 3 and 4. Figure 3 shows that the velocity histories of the mass with/without cavitation model. The current Eulerian-Lagrangian method (fig.3a) compares fairly well with the analytical model in [10] (fig.3b). Figure 4 shows the cavitation region captured by the current approach (fig.4a) is very close to the analytical solution (fig.4b). The small deviation is due to different cavitation models used. In our work, a conservative one-fluid cavitation model is applied while in [10] the cavitation pressure is set to be zero.

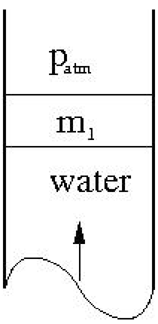

Fig. 2 Schematic diagram

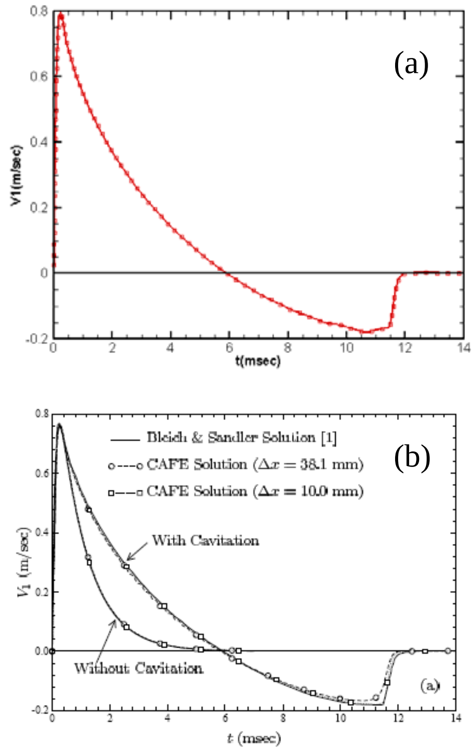

Fig.3 Velocity history (analytical and CAFÉ solution from [11])

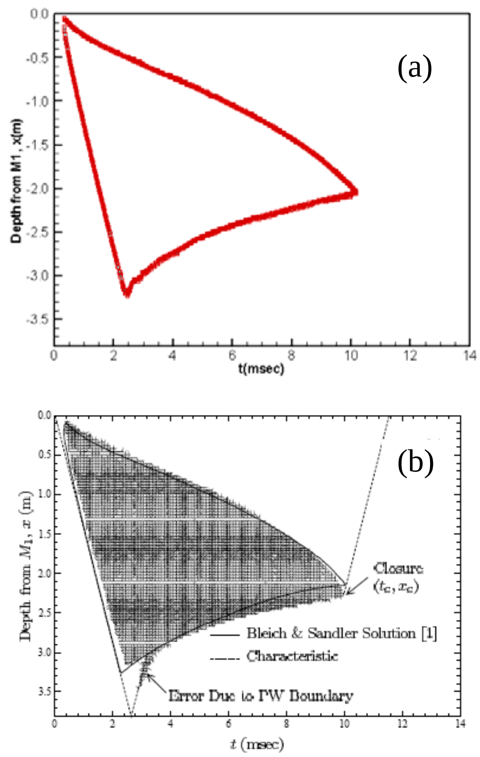

Fig.4 Cavitation history analytical and CAFÉ solution from [11])

To demonstrate the capability of the coupled Eulerian-Lagrangian approach in modeling shock impacts on composite structures, experimental validation studies are shown for the case of a planar shock impact on a three layer composite plate. The composite plate consists of two steel face sheets and an in-between metal form core. The computational set-up is shown in Fig. 5. Details about the experiment can be found in [5]. The length of the fluid column is 1.4m with an initial density $\rho_0 = 1000 kg/m^3$ and sound speed $a = 1400 m/s$. The incoming pressure wave ($p(t) = p_{\max} e^{-t/\theta}$) is imposed at the left end of the fluid column, where $p_{\max}$ is the peak pressure and θ is the characteristic decay time. The parameters for the steel face sheets are $t_{face} = 6mm, 12mm$ (thickness of the steel faces), $\rho_{face} = 8000 kg/m^3$ and $E_{face} = 210 GP_a$. The form core has a thickness of $t_c = 25mm$.

Two different boundary conditions were simulated for the composite plate: free-sliding and supported at the rear steel face. The difference between these two conditions is that the fixed rear support prevents the structure from sliding and thus the structure will experience much more compression, leading to a higher core compression (see fig.7). The predicted plastic core compressions against the shock impulse are shown in Figs. 6 and 7. Current numerical results are compared with the numerical and experimental results from [5], and the "coupled" indicates the current Eulerian-Lagrangian approach while "decoupled" indicates the method which treats the front face as free-standing plate and neglecting the constraints from the rear structures. Good agreement can be observed for the current approach and experimental results [5]. The deviation between coupled approach and decoupled approach is much more significant for case with supported rear face is because the rear constraint increases the core compression significantly.

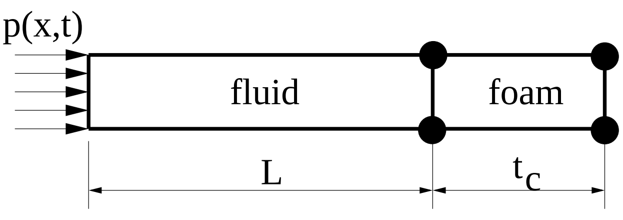

Fig.5 Computational diagram for fluid-composite plate interaction

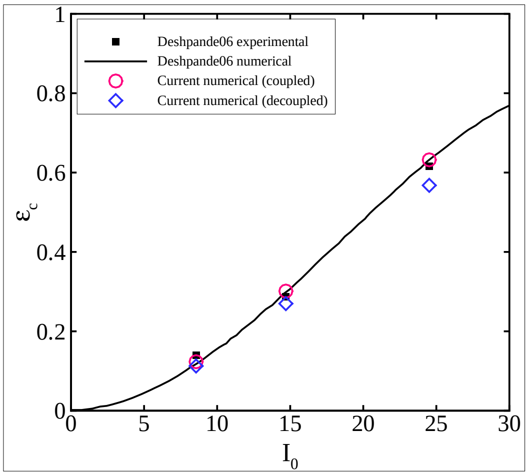

Fig.6 Plastic core compression for the free-sliding sandwich plate

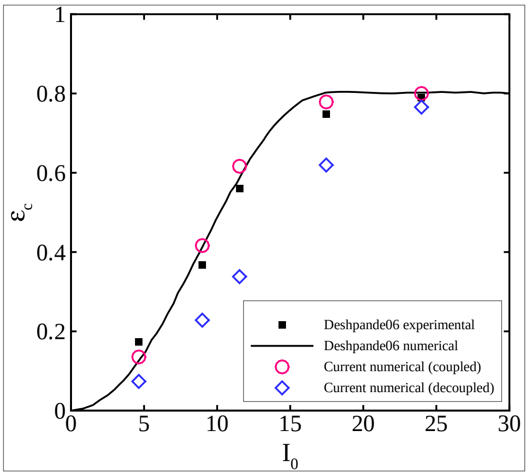

Fig.7 Plastic core compression for the supported sandwich plate

4 Conclusion

In this work, an Eulerian-Lagrangian approach is presented and validated. Applications of this approach to shock impacting on the composite structures are shown. Results shows that this approach is able to efficiently capture the solid deformation and unsteady cavitation evolution. In addition, the approach can be easily used to analyze the response of composite structures subject to pressure loads, and thus to evaluate the deformation and damage for composite structures. Such finding can be used to provide a guide to design shock mitigation strategies for marine structures to resist the high blast loads.

The current work has important relevance to other projects carried out in our group. For example, how to develop new shock mitigation strategies to help the design and optimization of composite propellers subject to shock and impact loads. Due to time limations, 2D results are not yet available. However, during the conference, we will show results of 2D shock impact on composite structures and discuss the findings.

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