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Application of Arbitrary Lagrangian-Eulerian Technique for Air Explosion Structural Analysis for Naval Ships Using LS-DYNA

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Abstract

Survivability improvement method for naval ship design has been continually developed. In order to design naval ships considering survivability, it is demanded that designers should establish reasonable damage conditions by air explosion. Explosion may induce local damage as well as global collapse to the ship. Therefore possible damage conditions should be realistically estimated in the design stage. In this study the authors used ALE technique, one of the structure-fluid interaction techniques, to simulate air explosion and investigated survival capability of damaged naval ships. Lagrangian-Eulerian coupling algorithm, equation of the state for explosive and air, and simple calculation method for explosive loading were also reviewed. It is shown that air explosion analysis using ALE technique can evaluate structural damage after being attacked. This procedure can be applied to the real structural design quantitatively by calculating surviving time and probability.

Keywords: naval ships, survivability, TM5-1300, structure-fluid interaction techniques, ALE(Arbitrary Lagrangian-Eulerian), air explosion

1 Introduction

The numerical simulations of collision have been achieved in automobile field early along with experiments, and the complex analysis of structure-fluid interaction problem was begun to achieve in the codes of LS-DYNA (Hallquist 1999), MSC/DYTRAN (MSC. Software Corporation 1999) etc.. These codes are the explicit hydro-codes with fast development of computer environment from the mid-90s specially. These codes using structure-fluid interaction techniques have been used for air-bag analysis and tire water-film analysis in automobile field, for the bird-striking problem in aircraft field and for sloshing analysis (Kim et al 1994) in shipbuilding field.

Within the country, as the underwater explosion and shock response analysis have been performed in the 1990s, structure-fluid interaction techniques are regularly applied to the ship building field (Chung et al 1992, Chung et al 1997, Lee et al 2001). In the field of naval architecture and ocean engineering, the structure-fluid interaction techniques have been recently developed for the survivability design of naval ships and ocean plants like FPSO by estimating explosion loadings. Figure 1 shows the various application examples of structure-fluid interaction techniques (Hallquist 1999, MSC.Software Corporation 1999).

The naval ship has to ensure the safety from the enemy attacks and damages so that it must be able to accomplish a given task. This ability of the naval ships is expressed in ability of the security for the survivability, and the survivability especially can be expressed the relationship of susceptibility, vulnerability and recoverability (Kim et al 2002). There are many attack weapons to surface naval ship as figure 2 shows the anti-shipping threat weapons and the mechanism of the ship damages (Said 1995).

Therefore, it is important for modern naval ships, especially combat naval ships, to establish countermeasure of vulnerability for survivability. It is known that the countermeasure of vulnerability is to establish the double hull structure, box girder, blast hardened bulkhead, protection wall against fragments and so on, and it must be decided within possible design conditions.

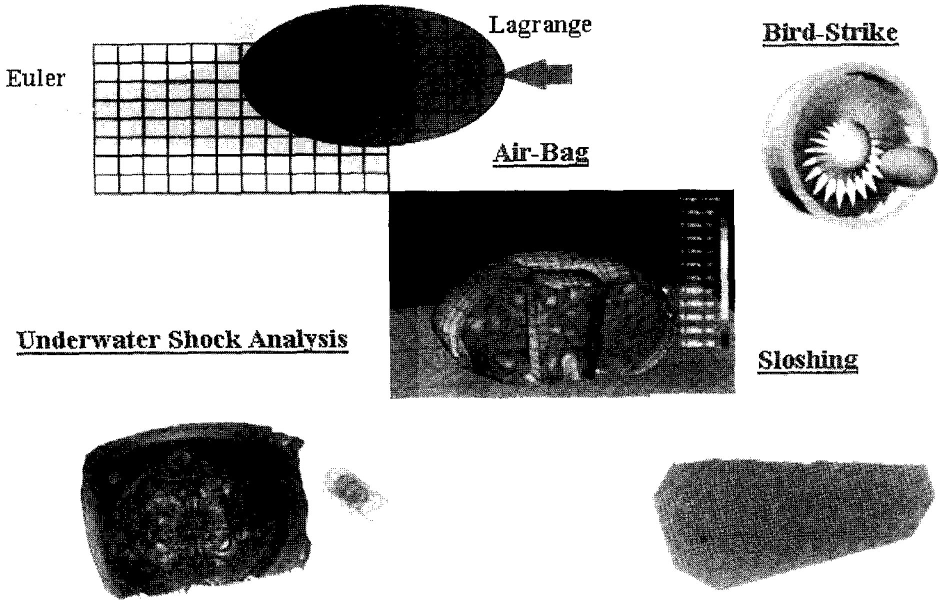


Figure 1: Application examples of structure-fluid interaction techniques

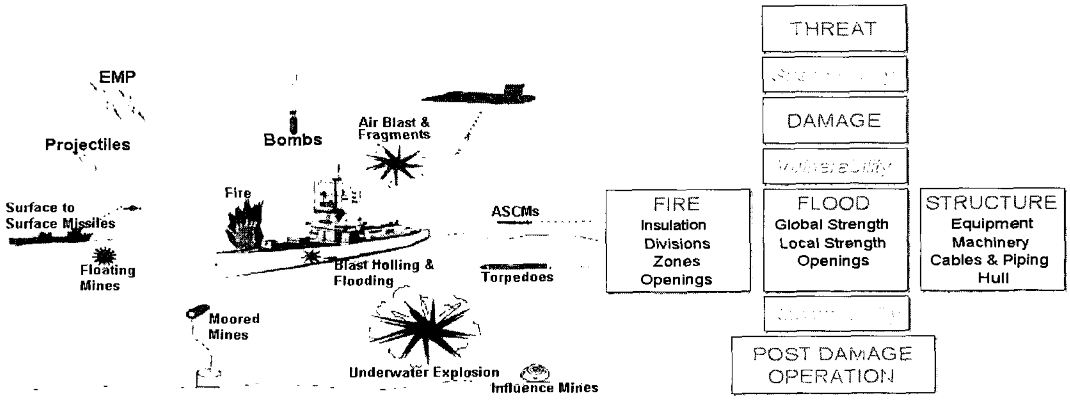


Figure 2: Anti-shipping threat weapons and mechanism of the ship damages

In order to design naval ship considering survivability, it is demanded that designers should establish the reasonable attack scenarios, which generally are divided into external and internal explosions to the ship. Explosion may induce local damage as well as global collapse to the ship. Therefore possible damage conditions should be realistically estimated in the design stage. In this study, the authors used the explicit dynamic software, LS-DYNA by Arbitrary Lagrangian-Eulerian (ALE) technique to simulate explosion analysis and investigated survival capability of damaged naval ships.

2 Structure-fluid interaction technique

The structure-fluid interaction technique can be applied to air explosion analysis by means of direct modeling explosive and air with fluid element and hull structures with structure element. To solve the structure-fluid interaction problem, establishment and load search technique of contact surface are important, and ALE technique is applied to simulate the interaction between the pressure of fluid by structure and the force of structure by fluids. A solving scheme of structure-fluid interaction problem is as following.

Structure

Governing equations including large deformation, material non-linearity
=> F.E.M. (space domain), F.D.M. (time domain)
=> Displacement, velocity, acceleration and stress

Fluid

Equation of state, conservation of energy
=> F.V.M. or B.E.M. (space domain), F.D.M. (time domain)
=> Pressure, density, internal energy and velocity

Interface of structure-fluid

Setting up coupling interface and calculating coupling force
=> Pressure (fluid -> structure), velocity (structure -> fluid)
=> Arbitrary Lagrangian-Eulerian

When Lagrangian part hits Eulerian or ALE parts, it is called 'coupling'. On the other hand, when Lagrangian part hits Lagrangian parts, it is called 'contact'. The code as LS-DYNA or MSC/DYTRAN searches for the intersections between the Lagrangian parts and Eulerian (or ALE) parts. If an intersection is detected inside an Eulerian element, it marks the Lagrangian-Eulerian common coupling points on this interface at previous time step. It tracks the independent motion of the 2 materials over time interval Δt. Then compute the penetration distance. The coupling forces are computed based on this penetration and re-distributed back onto both meshes.

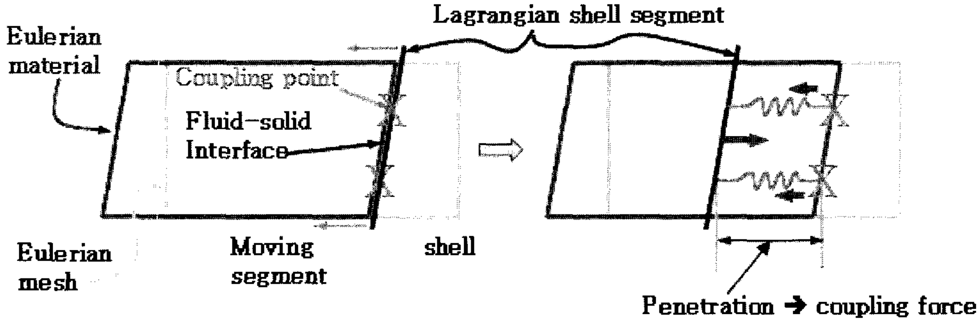


Figure 3: Setting up coupling interface and calculating coupling force

In ALE technique explosive and air are supposed to fluid behavior and the relation between pressure, density and internal energy is defined by equation of the state using the constitutive models for structure materials as follows.

The equation of state for explosive

The equation of state of JWL (Johnson-Wilkinson and Lee), equation (1) is adapted to explosive with exponential function form. Table 1 shows material constants of JWL equation for T.N.T. explosive material (Carleone 1993).

$$p = A(1-\frac{\omega}{R_1 V})e^{-R_1 V} + B(1-\frac{\omega}{R_2 V})e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

Where A, B, R_1, R_2, ω = material constant by experiment

E = internal energy per unit volume

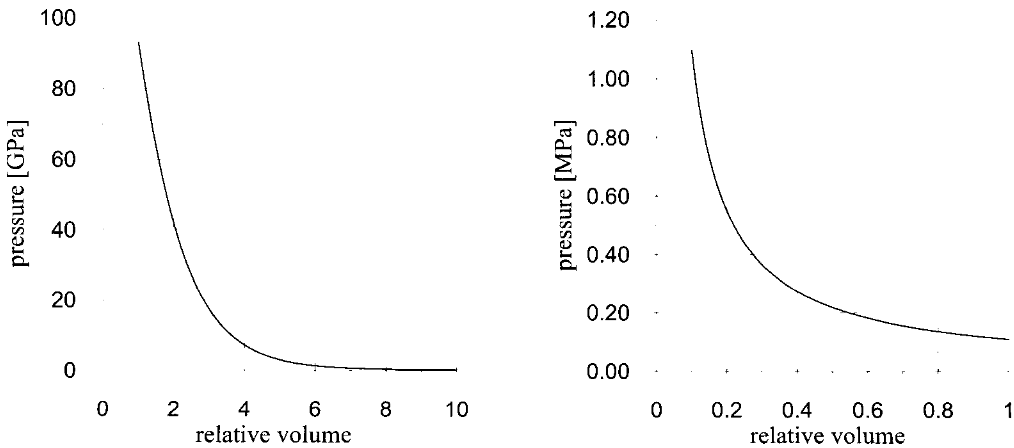
V = relative volume = $\frac{1}{\eta} = \frac{\rho_0}{\rho} = \frac{v}{v_0}$

(η = relative density, ρ_0, v_0 = initial density and volume)

Table 1: Material constants for JWL equation

Material constant	ρ	A	B	ω	R1	R2	d	E
Unit	[kg/m3]	[Pa]	[Pa]				[m/sec]	[J/m3]
T.N.T.	1,630	3.712×10^{11}	3.231×10^{11}	0.3	4.15	0.95	6,930	7.00×10^{9}

And by equation (1), we can find the relation between relative density and pressure and relative volume. Figure 4(a) shows the relation between relative volume and pressure for T.N.T. explosion.



(a) T.N.T explosion (b) air

Figure 4: Pressure versus relative volume

The equation of state for air
The equation of state of Gamma law, equation (2) is adapted to air.

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E \qquad (2)$$

Where γ is the ratio of specific heat (C_p) at constant pressure and specific heat (C_v) at constant volume, i.e. $\gamma = C_p/C_v$. For air, γ is 1.4 and ρ is 1.28 kg/m^3 and E is 2.7404×10^5 J/m^3 (Van Wylen 1985). And by equation (2), we can find the relation between relative density and pressure and relative volume. Figure 4(b) shows the relation between relative volume and pressure for air.

3 Comparison with results of numerical simulation

Simple calculation method for explosive loading: TM5-1300
Numerical analysis by ALE technique has been developed recently that is verified as quantitative in some degree; however there are difficulties and complexity in initial design step. TM5-1300 method which was developed from the results of experiment by US Navy from middle of 1960 years can be applied simply in initial design step (Joint Departments 1990).

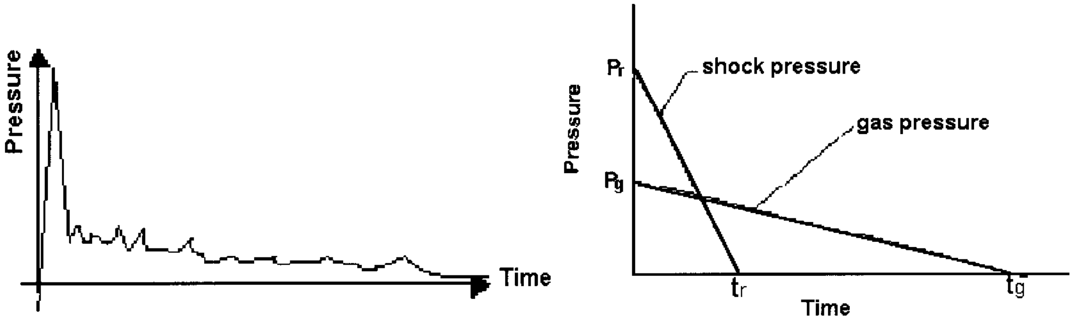


Figure 5: Typical blast pressure time history

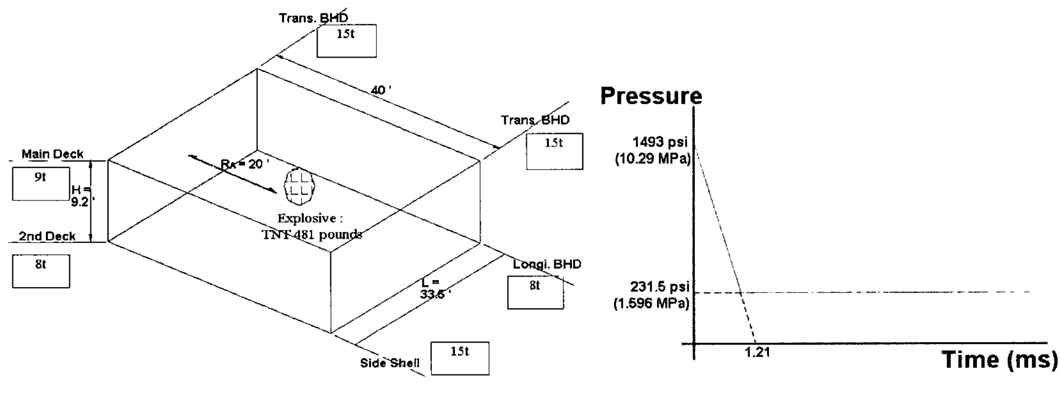
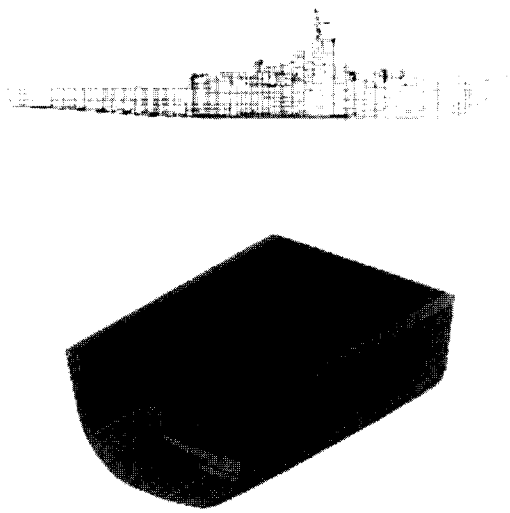


Figure 6: Example of loading calculation by TM5-1300

The detonation of a threat weapon produces two pressure phases. First phase is the initial shock pressures of high intensity and short duration. This is followed by a quasi static phase resulting from the gas pressures produced by the explosive material in the warhead and by the heat released of the detonation process. These gas pressures are much lower than the peak pressures produced by the initial blast where their decay rate is much longer. For most cases it is conservative to treat these gas pressure values as static pressure acting uniformly on all surfaces of a compartment. Final output is a pressure-time history curve and it is applied as a load function in LS-DYNA to analyze response in the modeled structure without fluid modeling. The pressure-time history curve is an approximation combining the separate calculations for shock and gas as shown in figure 5. And figure 6 shows the simple example that "Kim et al(2003)" calculates the load.

Finite element model for analysis

To simulate explosion analysis by ALE method, an assumed naval ship is modeled. Figure 7 shows the F.E. model for analysis



Displacement	7,000 ton
Length of the ship (Lbp)	120 m
Breadth of the ship (B)	18 m
Depth of the ship (D)	12 m
Draft of the ship (d)	6 m

Figure 7: F.E. model for analysis and principal dimensions of the model

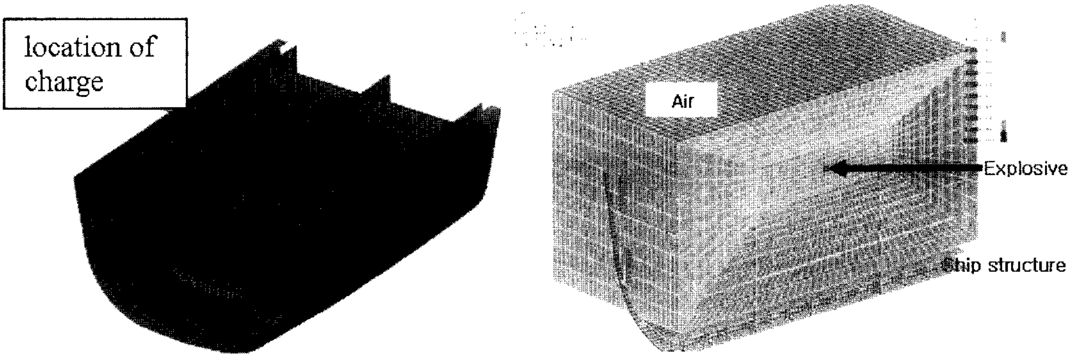


Figure 8: Design attack scenarios and ALE modeling for explosion analysis

Design attack scenarios and ALE modeling

This analysis is based on assumed threats because of lacking specific threat definitions at this moment. The assumed design attack scenario is shown as following. The hit locations are as shown in figure 8 and hit location is in the middle of each compartment. The charge weight is 481 pounds (TNT equivalent) and the hit location which explosion occurs at is the center of the port side room under upper deck. The ship structures are modeled with Lagrangian element and also the air and the explosive are modeled with Euler element. The F.E. model with fluid mesh for ALE technique is also shown in figure 8.

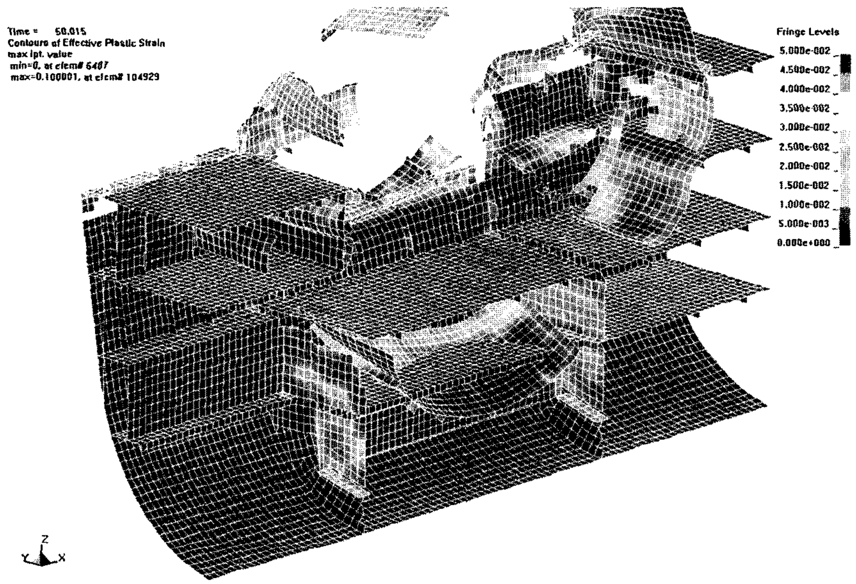


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Figure 9: Effective plastic strain contour of the ship model by TM5-1300 method

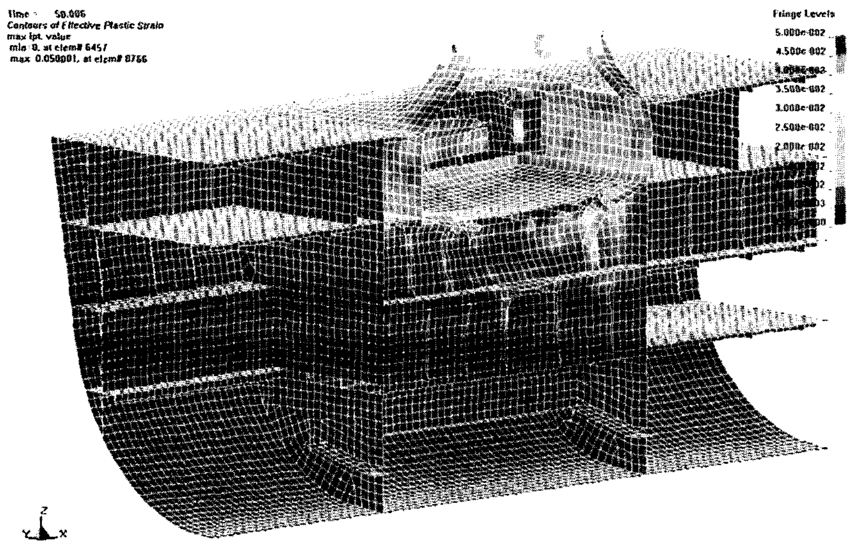

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Figure 10: Effective plastic strain contour of the ship model by ALE method

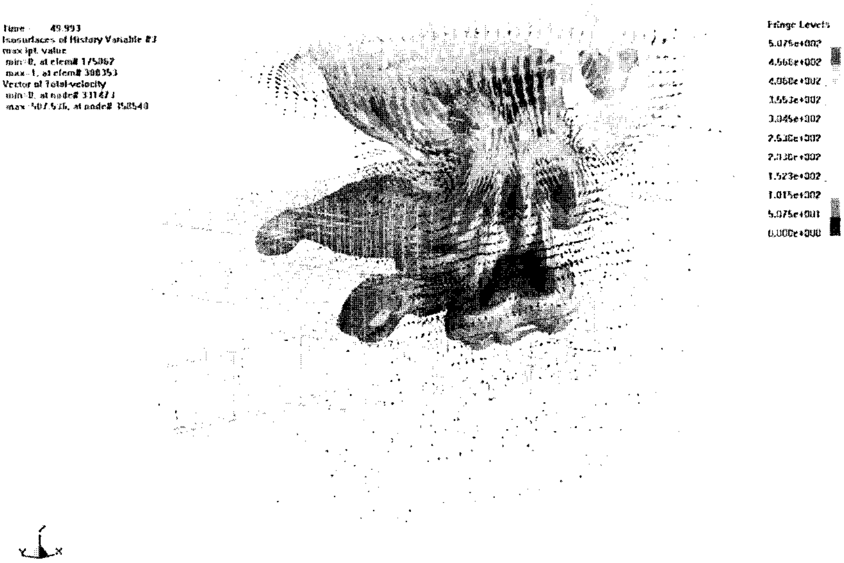

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Figure 11: Mass density contour and outflow velocity vector of the ship model by ALE method

Comparison results with TM5-1300 and ALE method

To compare with results of simple and ALE method, we have performed explosive analysis by TM5-1300 and ALE method about ship model in figure 7. And figure 9 and figure 10 show the deformation and the equivalent plastic strain results for ship model by TM5-1300 and ALE method, respectively. Figure 11 shows the mass density contour and outflow velocity vector of the ship model by ALE method.

In this analysis, we applied the failure strain 5% from the viewpoint of conservative evaluation. In case of TM5-1300 method as shown in figure 9, we can see that even some of the side shell plates far from the explosive as well as deck plates near the explosive exceed failure strain 5% and it seems to take place the excessive collapse. However, in case of ALE method as shown in figure 10, only deck plates near the explosive are failed. And also as shown in figure 11, we can find that after explosion, most gas pressures are vented out the hull through the failed deck plates. It means that explosion gas will not affect on side shell and then the side shell plates far from the explosive will not be failed. So comparing the results of two methods, it seems ALE method can simulate more real explosive phenomena than TM5-1300 method.

By numerical analysis using ALE technique, we can know the behaviors that get up in the ship structure after explosion, and reflect to naval ship design on the basis of this. We need the calculation of surviving time for damaged structure to decide the survivability of target ship, and may reflect the analysis result as design basis. We can refer the study by Kim et al(2003) as an example method for calculating the surviving time and probability after attack.

4 Conclusions and further studies

This study investigated structure-fluid interaction technique's concept, and applied ALE technique to an example of numerical explosion analysis to improve naval ship's survivability design. From this study, following conclusions were obtained.

- The ALE technique, one of the structure-fluid interaction techniques, can be applied to air explosion analysis by means of direct modeling explosive and air with fluid element and ship structures with structure element.
- US navy's simple calculation method is one of the explosion analysis methods, but this method has difficulty reflecting real phenomena. On the other hand, the method using ALE technique can represent the structural behavior realistically.
- Explosion analysis using ALE technique can examine structural damage after being attacked. On the basis of this result, we can apply this procedure to real structural design quantitatively by calculating surviving time and probability.

Further research topics are as follows:

- Numerical analysis using ALE technique to embody real phenomena qualitatively and to verify those quantitatively including effect of fluid mesh size in the near explosive region.
- Evaluation of numerical analysis results, to set up specific failure criteria and exactness of surviving time calculation.

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