대한조선학회논문집
Journal of the Society of Naval Architects of Korea
Vol. 48, No. 6, pp. 552-559, December 2011
http://dx.doi.org/10.3744/SNAK.2011.48.6.552

자유낙하식 구명정의 가속도 응답 추정을 위한 LS-DYNA 에서의 다중물질 ALE 와 단일물질 ALE의 비교

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Comparisons of Multi Material ALE and Single Material ALE in LS-DYNA for Estimation of Acceleration Response of Free-fall Lifeboat

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Abstract

An interest in Arbitrary Lagrangian Eulerian (ALE) finite element methods has been increased due to more accurate responses in Fluid-Structure Interaction(FSI) problems. The multi-material ALE approach was applied to the prediction of the acceleration response of free-fall lifeboat, and its responses were compared to those of the single-material ALE one. It could be found that even though there was no big difference in the simulation responses of two methods, the single-material and multi-material ALE ones, the latter multi-material ALE method showed a little bit more close response to those of experimental results compared to the former single-material ALE one, especially in the x- and z-direction acceleration responses. Through this study, it could be found that several parameters in the ALE algorithms have to be examined more carefully for a good structural safety assessment of FSI problems.

Keywords : Free-fall lifeboat (자유낙하식 구명정), Acceleration response (가속도 응답), Multi material ALE (다중물질 ALE), Single material ALE (단일물질 ALE)

1. Introduction

During the launch of free-fall lifeboat, there are two primary concerns. The first one is the motion of the lifeboat which is affected by the change in hull shape, weight distribution and initial conditions.

The second one is the acceleration responses to which the occupant in the lifeboat is subjected. Harmful accelerations may occur in the free-fall lifeboat when it impacts on the water. The hydrodynamic impact of boat during water entry is a complex problem and makes the establishment of the numerical analysis be a challenging task.

Lagrangian method is usually used for the structural analysis and occasionally for the fluid one. Its computational cost could depend on the mesh size and deformation. If large deformations occurred, the mesh would be high distorted and the calculation could be terminated. Remesh process is necessary for the continuous calculation. Since the fluid part is extremely distorted during the launch of free-fall lifeboat in the water, the Lagrangian method is not suitable for the fluid model.

Since the material part is treated differently from the geometric mesh in Arbitrary Lagrangian Eulerian (ALE) finite element method contrary to the Lagrangian one, while the lifeboat structure hit the water surface, the fluid element will be deformed largely. This phenomenon will make the time step changed to a very small value for explicit calculations. The ALE methods or rezoning are used to create a new undistorted mesh for the fluid domain, which allows the calculations to continue.

The ALE method has been applied to many Fluid-Structure Interaction (FSI) problems, such as slamming (Lee, et al., 2008a,b, 2010) and sloshing (Lee, et al., 2010), and it is recommended that their simulation responses should be verified by the experimental ones. These FSI problems

접수일 : 2011년 2월 11일 | 1차 수정일 : 2011년 10월 13일 | 게재확정일 : 2011년 11월 7일
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could be conveniently simulated using Arbitrary Lagrangian Eulerian (ALE) formulation and Euler-Lagrange coupling algorithm of LS-DYNA code (LSTC, 2009). Volume of Fluid (VOF) method is adopted for solving a broad range of nonlinear free surface problems and coupling algorithm is more suitable for the FSI problems with very complicated structure, where fluid grid can overlap the structural mesh (Aquelet, et al., 2003, 2006; Souli, et al., 2000).

The single material ALE approach was applied to the prediction of the acceleration response of free-fall lifeboat (Bae et al, 2010). In this paper, the Multi Material ALE method was adopted for the same FSI problem and its responses were compared to those of the single-material ALE one.

2. Arbitrary Lagrangian Eulerian (ALE) Method in LS-DYNA

The ALE method in LS-DYNA code is the computational algorithm that applies the conservation equations in the finite element method. Energy, mass, and momentum are conserved and advected from element to element. LS-DYNA uses a split operator technique to solve the conservation equations using Eulerian formulation and ALE one. The conservation of mass, momentum and energy are given by the following equations:

$$\frac{\partial \rho}{\partial t} = (-\rho) \div (v) - (v_i - u_i)\frac{\partial \rho}{\partial x_i} \tag{1}$$

$$\rho \frac{\partial v_i}{\partial t} = \sigma_{i,j} - \rho (v_i - u_i)\frac{\partial v_i}{\partial x_j} \tag{2}$$

$$\rho \frac{\partial e}{\partial t} = \sigma_{ij}\epsilon_{ij} - \rho (v_i - u_i)\frac{\partial e}{\partial x_j} \tag{3}$$

where, ρ is the material density, ν is the material velocity, σ is stress tensor, ϵ is the strain tensor, e is internal energy and u is the mesh velocity.

While the fluid element has extremely distorted during the analysis, mesh rezoning algorithms are used to maintain the fluid mesh, and computational time does not increase. While a non uniform mesh is transformed into an uniform mesh in the rezoning method, a non uniform mesh, reversely into an uniform mesh in the equipotential algorithm. The latter equipotential algorithm maintains the location of the boundary nodes at their Lagrangian location and iterates the internal nodes to converge to an uniform mesh by solving equipotential equation for nodal displacement.

There are two approaches to implement the ALE equations, such as the solution of the fully coupled equations for computational fluid mechanics handling a single material in an element and reference of an operator split for each time step into two phases with the first Lagrangian phase and the second advection phase. In the advection phase, transport of mass, internal energy and momentum across cell boundaries are computed. This might be thought of as remapping the displaced mesh at the Lagrangian phase back to its original or arbitrary position element. The VOF method is attractive because of being applicable to solve broadly non-linear problems in fluid and solid mechanics. The method allows arbitrary large deformations and enables free surfaces to evolve (Aquelet, et al., 2003, 2006; Souli, et al., 2000).

3. Multi Material ALE

The multi-material ALE formulation uses the same governing equations as the single-material ALE formulation except that the calculations are performed iteratively for each material group in the element. For material group i, the strain rate is ε_i, and the internal energy is Ei. The deviatoric or shear stress is τ_i, and pressure from the equation of state is P_i. Then the stress is given by the following equation (4).

$$\sigma_i = -P_i + \tau_i \tag{4}$$

The internal nodal force is calculated by the equation (5).

$$F = \alpha_i \cdot \int_V B_i^T \sigma_i \tag{5}$$

where, B_i is the strain-displacement matrix. α_i is the volume fraction in the element and has the following requirement;

$$\sum_{i=1}^{Ngroups} \alpha_i = 1 \tag{6}$$

where, Ngroups is the number of different materials in the element. The volume fractions need to be recomputed using a pressure relaxation in each element. The pressure relaxation is given as follows;

$$P_1 - K_1 \frac{\partial V_1}{V_1} = P_2 - K_2 \frac{\partial V_2}{V_2} \quad (7)$$

$$\delta V_1 + \delta V_2 = \delta V \quad (8)$$

where, δV is the amount of material (volume) flux in the element after the Lagrangian calculation and the subscripts refer to adjacent elements. The amount of total material to be advected can now be calculated. The volume of fraction is used to determine whether the way of materials in the element are advected or not. The rules of advection in LS-DYNA as follow;

Rule 1:

Material common to both neighboring elements is transported in proportion to the volume of the acceptor element, with the restriction that no more than the total donor element volume may be transported.

Rule 2:

If there is no remaining material common to both elements, the remaining transport volume is proportional to the remaining donor volume.

The process is repeated for each material at every time step. As the number of materials to be tracked in each element increases, the computational expense will increase.

4. Multi Material ALE Modeling

The free-fall lifeboat launching were simulated by ALE3D option of LS-DYNA code using single-material ALE approach. The outer surface of the lifeboat modeling was modeled using 4,805 rigid quadrilateral shell elements. Since the main objective of this study is to predict the acceleration response, the rigid lifeboat model could be acceptable. The penalty method was adopted for solving the contact problem between the lifeboat and skid.

The fluid model consists of two parts, such as air and water, using 674500 hexagonal Eulerian elements, whose dimensions are 42.7 × 15.1 × 32.0m for the air and 42.7 × 15.1 × 13.0m for the water domain, respectively, as shown in Fig. 1. The mesh size of the fluid are 0.3 × 0.3 × 0.3m around at the surface, and is increased proportionally to vertical upward and downward directions with 20% bias. The principal dimension of lifeboat is summarized in Table 1.

Table 1 Principal dimension of free-fall lifeboat

Length	7950 mm
Breadth	3070 mm
Draught	1550 mm
Weight	5112 kg
Max Occupant	35 person
LCG	50% From AP

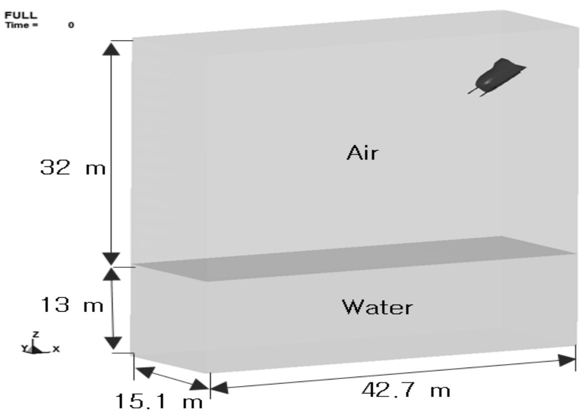


Fig. 1 Configuration of F.E. model of free-fall lifeboat with Multi Material ALE

There are several commands and options for the fluid modeling and coupling algorithm using FSI analysis technique of LS-DYNA code in addition to the element is usually considered with ELFORM 11 for the multi-material ALE in SECTION_SOLID command, contrary to the case of single-material ALE with ELFORM 12.

For the fluid material description, MAT_NULL command and Equation of State (EOS) have to be defined (LSTC, 2009). Since this study is not concerned with tracking the propagation of energy and pressure in water and air. EOS linear polynomial was used for the properties of water and air, the property of EOS linear polynomial of fluid model is shown in Table 2.

Several parameters are very sensitive to the coupling between the fluid and structure in CONSTRAINED_LAGRANGE_IN_SOLID command. Coupling leakage and penalty forces, etc., are affected by the penalty factor, the number of quadrature coupling points on a Lagrangian segment and the mesh size ratio of the structure mesh to fluid. Following this conditions, the default values are used for the penalty factor and the number of quadrature coupling points. Additionally, continuum treatment and advection method can be selected in CONTROL_ALE command.

Table 2 EOS linear polynomial of fluid model

Item	Water	Air
density (kg/m3)	1025	1.225
C0 (Pa)	0	0
C1 (Pa)	2.002e9	0
C2 (Pa)	8.436e9	0
C3 (Pa)	8.010e9	0
C4	0.4394	0.4
C5	1.3937	0.4
C6	0	0
E0 (Pa)	2.086e5	2.5e5
V0	1	1

The boundary condition of fluid model and constraint condition of structure are also important to the acceleration responses of free-fall lifeboat water entry on to the water. The following assumptions are considered as follows:

1. Only gravitational external load is applied to the whole system using a load curve for the gravitational acceleration time history.
2. Top, side and bottom boundaries of the fluid are fixed to the normal directions.
3. Initial velocity of lifeboat is set to zero.

5. Sensitivity of FE Model in FSI Analysis

In this FSI analysis, lifeboat was modeled by Lagrangian shell elements, and fluid, by Eulerian solid elements. In general, it is known that the coupling algorithm is usually sensitive to the relative mesh size between Lagrangian and Eulerian elements. For the investigation of the sensitivity of their relative mesh size, three mesh sizes were considered, such as 0.2 mm (model I), 0.3 mm (model II) and 0.5 mm (model III), where mesh size of lifeboat was 0.1 mm.

Fig. 2 shows the acceleration response in X axis direction according to fluid mesh size. It could be found that the response of model II was the most close to that of experiment, as shown in Fig. 2. Much leakage occurred in models II and III compared to model I. From this study, the relative mesh size between the lifeboat Lagrangian and fluid Eulerian elements should be determined for the reasonable response with less leakage.

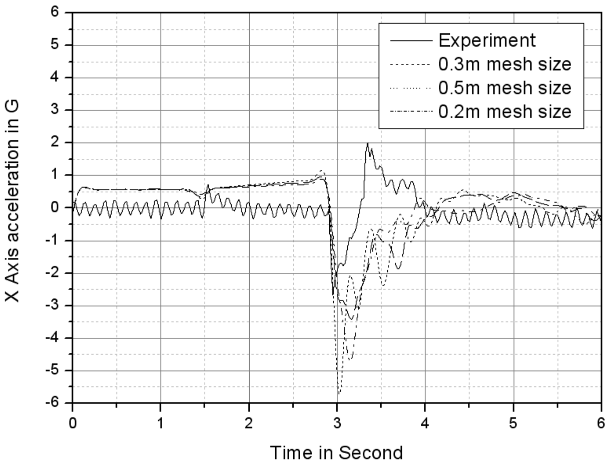


Fig. 2 Acceleration response in x-axis direction according to fluid mesh size

6. Comparison Multi Material ALE to Single ALE

The numerical simulations were carried out using LS-DYNA Version 9.71 R4.2 with single precision. Based on the computational time, the case of multi material ALE took longer than that of single material ALE, as shown in Table 3. This can be explained that multi material ALE needs more computational procedure, since the computation is regarding to the interaction of a lifeboat with the water and the air.

Table 3 Computational time in each case

Method	Computational time
Multi Material ALE	8 hrs 41 mins
Single Material ALE	2 hrs 49 mins

The acceleration response of lifeboat was used for the assessment of the occupant injury potential. Since the experiment data was taken at the data record frequency 2500 Hz and filtered with Butterworth low pass filter 20 Hz, simulation results with frequency scale 1000 Hz were filtered using a Butterworth digital 8.0 Hz low pass filter. The acceleration responses of simulation for the x-axis, y-axis and z-axis directions are compared with those of experiment, as shown in Figs. 3~6, according to loading conditions, such as full, 50% forward, 50% backward and empty loading conditions, respectively. Their peak values are also summarized in Table 4~6.

Based on the experimental results, it was found that the most severe responses were obtained from 50% backward loading condition, which could be explained that the CG of loading condition was shifted to the backward. While the shift of CG to 50% backward caused the righting moment arms to be increased and also led to increase the severity of slamming phase, the situations were conversed by its shift to 50% forward.

Regarding the characteristics of the longitudinal (x-axis direction) acceleration responses, the multi material ALE case in 50% backward loading condition was better than the single material ALE case, as shown in Figs. 3~6(a) and Table 4. From the experimental responses, it can be found the bow entry into the water at the vicinity of 3.0 sec and then its rebounce from the water at 0.4 sec later.

Table 4 Maximum x-axis acceleration

Loading Condition	x-axis acceleration in G		
	EXP	Single ALE	Multi ALE
Full (100%)	2.671	3.415	3.221
50% Forward	2.752	3.642	3.566
50% Backward	2.041	3.246	2.239
Empty	3.481	4.929	4.516

However, this rebounding phenomenon could not still be found in the multi material ALE analysis. Even though the peak values of both methods shows relatively larger than those of experiment results, these values are still acceptable because of much lower peak values in X-direction compared to IMO standards, 15g (IMO, 2003).

As can be seen in Figs. 3~6(b) and Table 5, the transverse (y-axis direction) acceleration responses were shown to be very small in the experimental results, while just a small track of bow impact was shown at the vicinity of 3.0 sec in the case of full loading condition, as shown in Fig. 3(b).

Relatively very small tracks of bow impact also appeared at the vicinity of 3.0 sec in the all loading conditions of both simulation results. It could be found that there was no significant difference between simulation results of two methods in the y-axis direction acceleration responses due to very small responses.

It could be also found, as shown in Figs. 3~6(c) and Table 6, that the characteristics of vertical (z-axis direction) acceleration responses of the multi material ALE could show a little bit more close to those of experimental ones compared to the single material ALE case. The first large peak response might be caused by the bow impact to the water at the vicinity 3.0 sec.

Table 5 Maximum y-axis acceleration

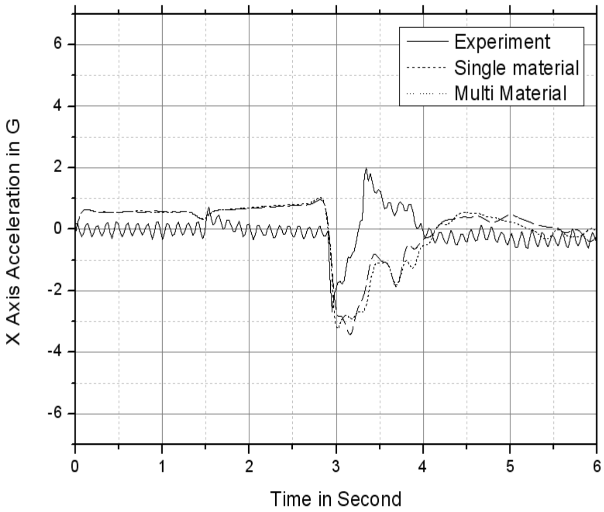
Loading Condition	y-axis acceleration in G		
	EXP	Single ALE	Multi ALE
Full (100%)	0.871	0.411	0.394
50% Forward	0.525	0.442	0.436
50% Backward	0.295	0.397	0.531
Empty	0.402	0.603	0.552

Their peak values and the interval time of the second ones might depend on their CG positions according to the loading conditions, and their entry depths into the water due to their weights. Although the second peak responses were not be found in the both method of simulation results, the simulation results are still reliable as the reference of lifeboat performance, because their peak values are still below the IMO standards in X-Axis acceleration below 15g, and the other direction one below 7g (IMO, 2003).

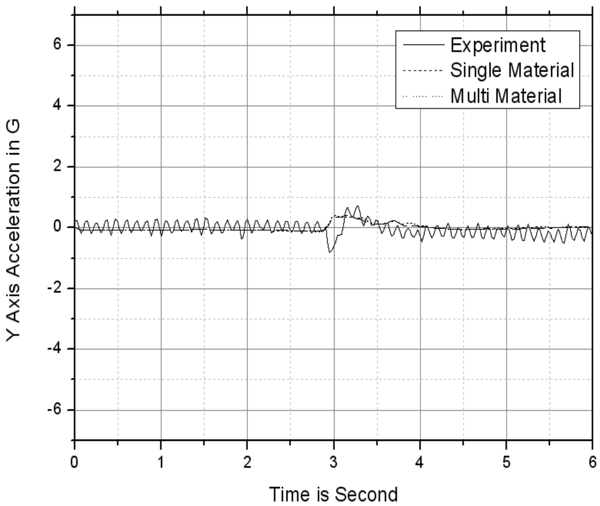
Table 6 Maximum z-axis acceleration

Loading Condition	z-axis acceleration in G		
	EXP	Single ALE	Multi ALE
Full (100%)	3.963	4.641	3.555
50% Forward	3.340	2.971	3.482
50% Backward	4.502	4.592	4.536
Empty	3.778	3.031	3.829

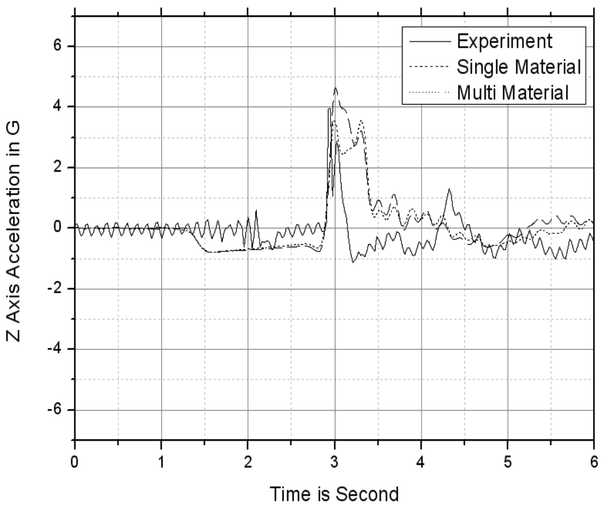
Even though there was no big difference in the simulation responses of two methods, the single-material and multi-material ALE ones, the latter multi-material ALE method showed a little bit more close peak values to those of experimental results compared to the former single-material ALE one, especially in the x- and z-direction acceleration responses. CAR Indexes in all loading conditions of experimental and simulation results were also found to be accepted by the IMO standards with less than 1.0 (IMO, 2003), as shown in table 7.



(a) x-axis direction

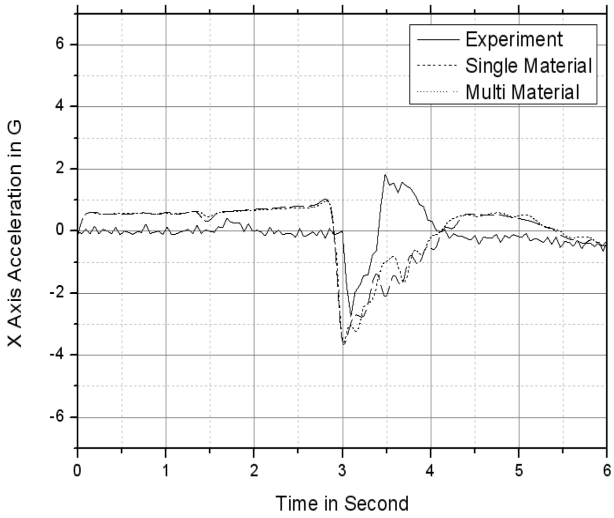


(b) y-axis direction

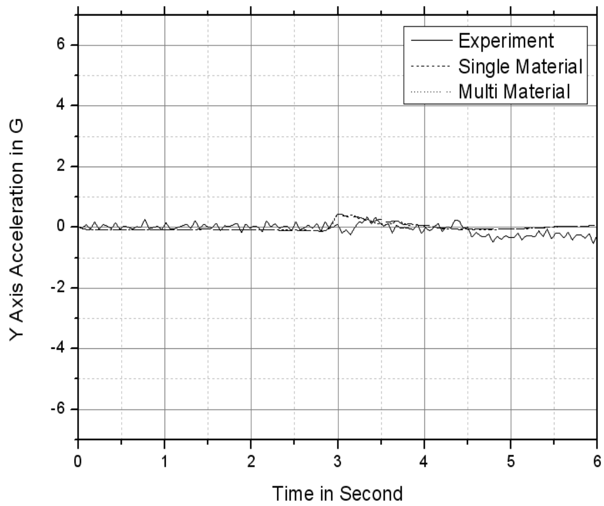


(c) z-axis direction

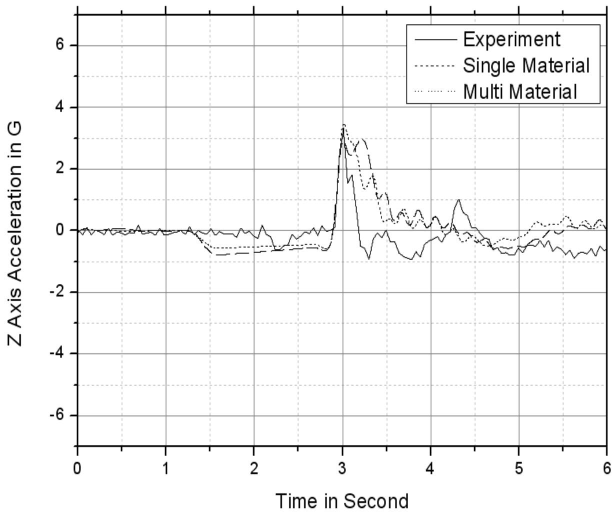
Fig. 3 Acceleration response in full loading condition



(a) x-axis direction

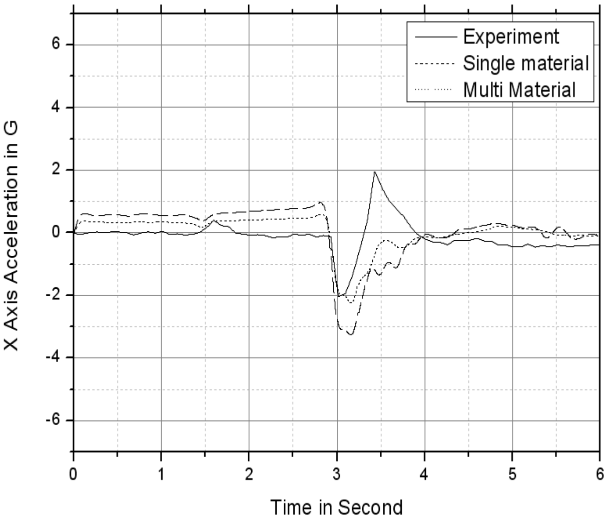


(b) y-axis direction

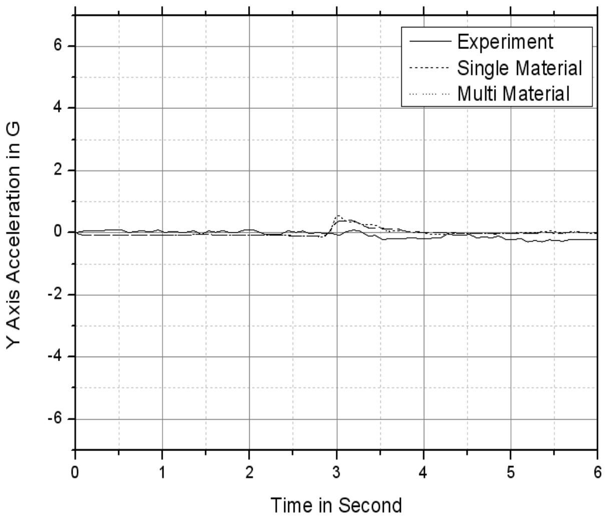


(c) z-axis direction

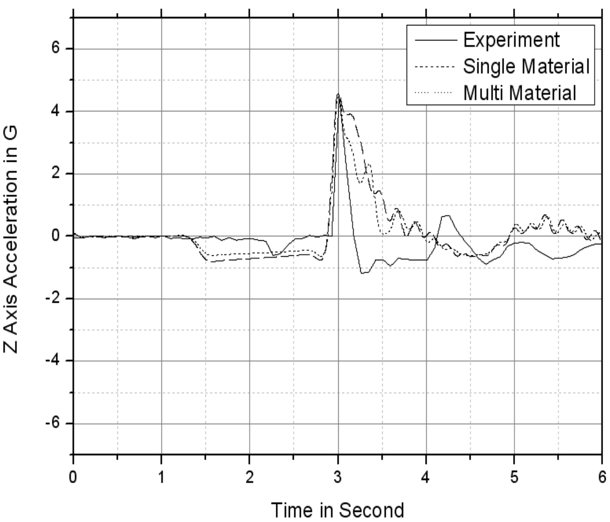
Fig. 4 Acceleration response in 50% forward loading condition



(a) x-axis direction

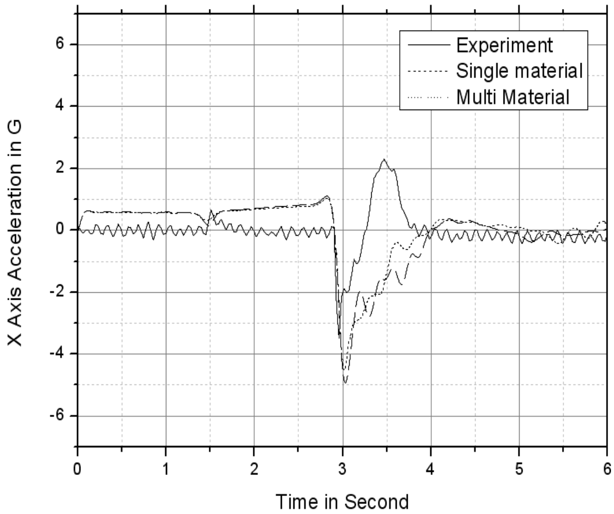


(b) y-axis direction

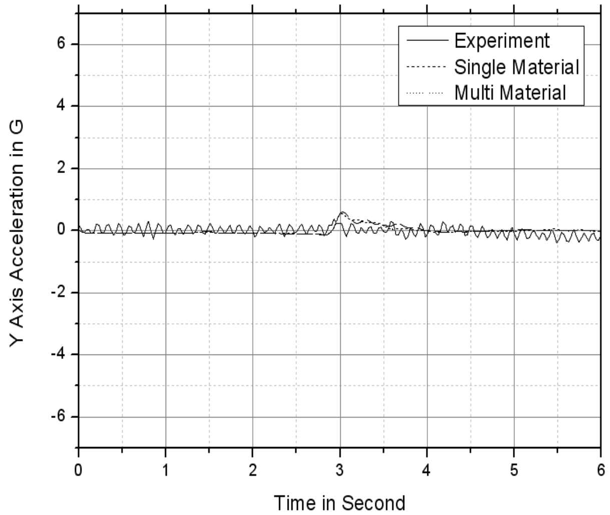


(c) z-axis direction

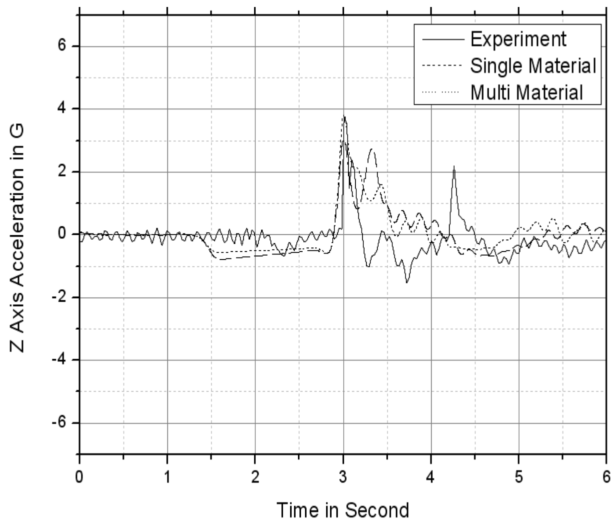
Fig. 5 Acceleration response in 50% backward loading condition



(a) x-axis direction



(b) y-axis direction



(c) z-axis direction

Fig. 6 Acceleration response in empty loading condition

Table 7 Combined acceleration ratio index

Loading Condition	CAR Index		
	EXP	Single ALE	Multi ALE
Full (100%)	0.606	0.703	0.554
50% Forward	0.517	0.463	0.555
50% Backward	0.659	0.693	0.667
Empty	0.590	0.550	0.629

7. Conclusions

The multi material ALE approach was applied to the prediction of the acceleration responses of 1/5 scaled 35 persons free-fall lifeboat model using FSI analysis technique of LS-DYNA code, and its responses were also compared to those of the single-material ALE one. It was found that even though there was no big difference in the simulation responses of two methods, the single-material and multi-material ALE ones, the latter multi-material ALE method showed a little bit more close peak values to those of experimental results compared to the former single-material ALE one, especially in the x- and z-direction acceleration responses.

Through this study, it could be found that several parameters in the ALE algorithms have to be examined more carefully for a good structural safety assessment of FSI problems.

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