Structural Analysis of a Conceptual Submarine SMR against Underwater Explosion

Tae-Yong Kim [a], Jun-Young Kim [a] and Yoon-Suk Chang [a*]
[a]*Dept. of Nuclear Engineering, Kyung Hee University, 1732 Deokyoungdae-ro, Yongin, Kyunggi, 446-701, Korea*
[*]*Corresponding author: yschang@khu.ac.kr*

1. Introduction

The most of NPPs (Nuclear Power Plants) are designed for high energy production, typical ones are not suitable for city-states requiring less energy. Recently, SMR (Small Modular Reactor) has been considered as an alternative about this issue. The reactor has various forms depending on the operating environment. Among them, flexblue® supplying 160 MWe is futuristic reactor operated under the sea. The model can supply a suitable amount of energy to the city-state, a prototype has been currently proposed [1].

In general, SMR adopts simple protection system due to its inherent features. For instance, an only simple exterior wall made of carbon steel is being considered in the SMR contrast to larger typical commercial NPPs with multiple ones. Questions have been raised about the safety of the SMR and torpedo explosion was assumed as a severe human-induced accident in structural analysis.

In this study, the analysis considering the underwater explosion was conducted to assess the structural integrity of SMR. JWL (Jones-Wilkins-Lee) EOS (Equation Of State) was applied for explosion load and postulated flexblue® model was used. Explosion analysis was implemented using the commercial program LS-DYNA [2]. As results, effective plastic strain and pressure of SMR were derived.

2. Analysis Methods

2.1 JWL EOS

JWL EOS, shown in Eq. (1), is adopted for demonstrating TNT (TriNitroToluence) explosion in LS-DYNA.

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

where P is the pressure caused by the explosion, A, B, R_1, R_2, and ω are material constants by experiment, E is the internal energy per unit volume, and V is the initial relative volume. Table I shows the material constants of the JWL for TNT explosives. As shown in Fig. 1, the relationship between relative volume and pressure is depicted.

Table I: Constants of JWL EOS used in this study [3]

A(GPa)	371.2
B(GPa)	323.1
R_1	4.15
R_2	0.95
ω	0.3
E(GJ/m^3)	7

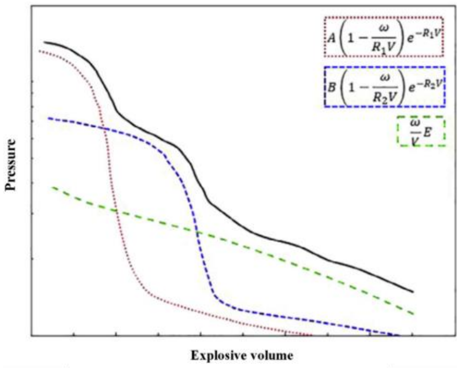

Fig. 1. Pressure-explosive volume histories [3]

2.2 Grüneisen EOS

Grüneisen EOS, shown in Eq. (2), is used to calculate the internal characteristics of seawater. It handles shockwave propagation in an underwater explosion by incorporating a non-linear shock velocity – particle velocity relationship [4].

$$P = \frac{c_0^2 \rho_0 \eta}{(1-s\eta)^2}\left(1-\frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m \quad (2)$$

where ρ_0 is initial density, E_m is internal energy per unit mass, η is nominal volumetric compressive strain by $\eta = 1 - \rho_0/\rho$. Table II shows the material property of water used in the analysis.

Table II: Material property of water [5]

Density (kg/m^3), ρ_0	1,000
Dynamic viscosity (N·s/m^2), μ	0.0089
Speed of sound (m/s), c_0	1,483
Fitting constants, s	1.75
Grüneisen constant, Γ_0	0.28

3. Explosion Analysis

3.1 Numerical Models

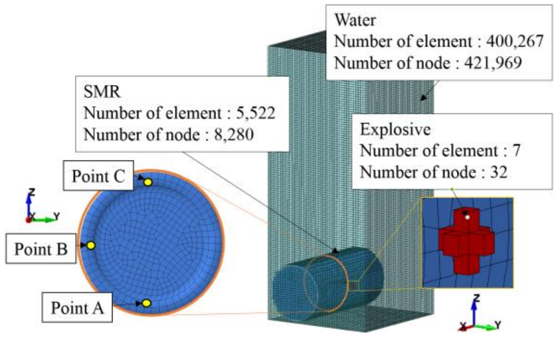

Fig. 2. FE model of explosive and water

The FE (Finite Element) model used in explosion analysis and its mesh information was shown in Fig. 2. SMR, water and explosive are made of solid elements. According to the SMR operating condition, the water depth was set to 70 m. Points A, B and C, shown in Fig. 2, were set to measure the internal pressure of SMR during the explosion.

3.2 Analysis Conditions

To consider the failure of SMR's exterior wall, the erosion option was set to 0.24 for failure strain [6]. If effective plastic strain exceeds the criterion, the SMR's elements are deleted.

The explosive was in contact with SMR to derive conservative analysis results. The outer surface of the water was fully fixed as boundary condition and gravity was applied to simulate water pressure.

4. Analysis Results

4.1 Variation of Pressures

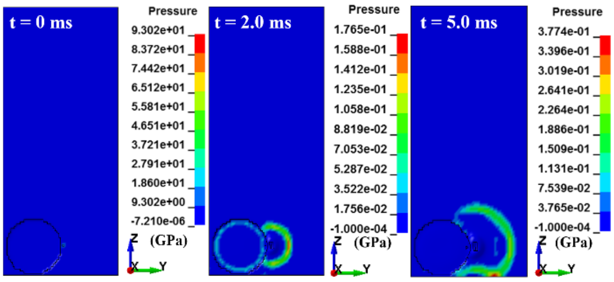

Fig. 3. Snapshots of pressure propagation

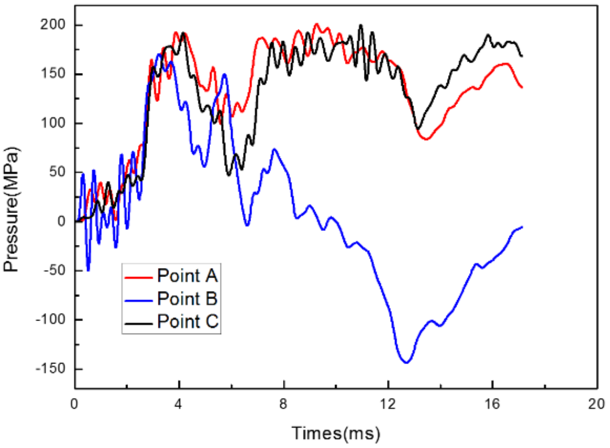

Fig. 4. Pressure - time histories at points A, B and C

Fig. 3 shows contours of water pressure following the explosion. Over time, the pressure contours spread in a spherical shape. When t = 5.0 ms, contours were reflected from the bottom.

The pressure - time histories at points A, B, C were shown in Fig. 4. In points A and C, The maximum pressure was about 200 MPa at 4 ms following explosion.

4.2 Variation of Strains

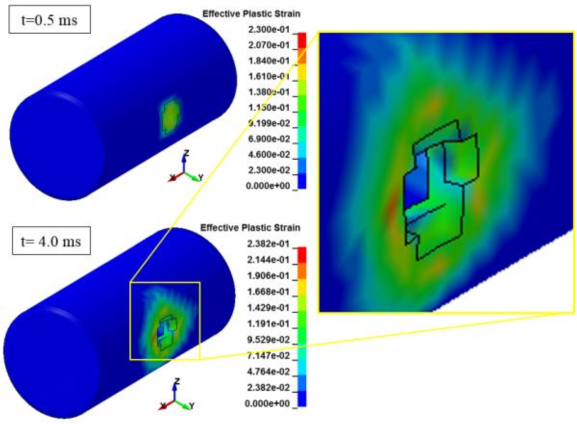

Fig. 5. Effective plastic strain contours

Fig. 5 represents an effective plastic strain of the SMR at each time. Elements exceeding the failure strain began to be deleted after 0.5 ms and the number of deleted elements increased until 4 ms. Partial failure of the outer walls was observed.

5. Summaries

In this study, underwater explosion analysis of a conceptual submarine SMR was performed and the following results were derived.

(1) The water pressure propagated in a spherical shape. After the explosion, the pressure at points A and C were increased up to 200 MPa.
(2) Strains of the conceptual SMR, near the explosion location, exceeded the failure criterion of 0.24. Thereby, an optimum protection system is being conceived based detailed numerical analysis.

REFERENCES

[1] M. Santinello, M. E. Ricotti, H. Ninokata, G. Haratyk, J. J. Ingremeau, V. Gourmel, "External heat transfer capability of a submerged SMR containment: The Flexblue case", Progress in Nuclear Energy 96, pp 62-75, 2017.
[2] Livermore Software Technology Corporation, "LS-DYNA Keyword User's Manual 971", 2007.
[3] Kim, S. H., Chang, Y. S., and Cho, Y. J., 2017, "Parametric analyses of major nuclear components and reinforced concrete structures under FCI-induced explosive condition," Nuclear Engineering and Design, Vol. 322, pp. 148-158.
[4] J. H. Kim, H. C. Shin, "Application of the ALE technique for underwater explosion analysis of a submarine liquefied oxygen tank", Ocean Engineering, Volume 35, pp. 812-822, 2008.
[5] S. S. Shin, D. Hahm, T. H. Park, "Shock vibration and damage responses of primary auxiliary buildings from aircraft impact", Nuclear Engineering and Design 310, pp. 57-68, 2016.
[6] L. Gardner, R. Cruis, "Life cycle costing of metallic structures", Engineering Sustainability, Engineering Sustainability 160, pp. 167-177, 2007.