ZULFAQAR Journal of Defence Science, Engineering & Technology
e-ISSN: 2773-5281
Vol. 8, Issue 2 (2025)
DOI: https://doi.org/10.58247/jdset-2025-0802-15
Journal homepage: https://zulfaqarjdset.upnm.edu.my

UNDERWATER EXPLOSION OF STEEL PLATE: A NUMERICAL SIMULATION ANALYSIS VALIDATION STUDY

Mohd Zaid Othman[a*], Abdul Azim Mohamad[a], Tan Kean Sheng[a], Amir Radzi Ab Ghani[b]

[a] Department of Mechanical Engineering, Faculty of Engineering, National Defence University of Malaysia, Sg. Besi Camp, 57000 Kuala Lumpur, Malaysia
[b] College of Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia

ARTICLE INFO

ARTICLE HISTORY
Received: 30-06-2025
Revised: 31-10-2025
Accepted: 26-11-2025
Published: 30-11-2025

KEYWORDS
Numerical simulation
Underwater explosion
Steel plate
ALE
Hydrodynamic effects

ABSTRACT

This research presents the development and validation of a numerical simulation analysis program aimed at predicting the deformation of square steel plates subjected to underwater explosions. Utilizing the LS-PREPOST and LS-DYNA software packages, a comprehensive numerical model is constructed to simulate the complex interactions between explosive forces, hydrodynamic effects, and structural response in an underwater environment. The Arbitrary Lagrangian Eulerian (ALE) methodology was used for this research since it has the tools to best simulate the phase changing behaviour of air and explosive and their interactions with the surroundings. The ALE method was employed to model the dynamics of seawater, explosive charges, and air-backed target plates in three-dimensional space. The simulation program was rigorously validated against published experimental data, ensuring its reliability and accuracy in predicting plate deformations. By refining simulation parameters and methodologies, the program demonstrates its capability to accurately simulate blast-related phenomena and provides valuable insights into the behaviour of steel plates under underwater explosion conditions. This research contributes a valuable tool for engineers and researchers to assess blast loading effects on marine structures, informing the design and mitigation strategies for enhanced safety and resilience in maritime environments.

1.0 INTRODUCTION

In today's expanding maritime industry, the threat of underwater explosions poses a critical challenge to the safety and resilience of marine infrastructure. These explosions, whether accidental, deliberate, or military in nature, generate complex hydrodynamic effects and high intensity loading conditions that can cause severe damage to steel structures submerged in water. Despite advancements in computational modelling and experimental techniques, there are still significant gaps in our understanding of how steel plates respond to underwater explosions. This research aims to bridge this gap through a comprehensive numerical validation study, leveraging advanced simulation methods and experimental data to enhance our understanding of blast loading effects on steel plates. Comprehensive research on the dynamic response of steel plates subjected to underwater explosions is still necessary, despite advances in numerical simulation techniques and our understanding of blast loading events. While designing blast-resistant structures for marine environments, engineers face a variety of difficult issues due to the interplay between explosive forces, hydrodynamic effects, and structural behaviour. The transient response of a ship segment exposed to underwater blast was studied by using the numerical simulation analysis methodology in order to obtain the influence of mass proportional damping factor on the velocity feedback [1-3].

Investigations were conducted to examine the consequences of shock waves from the detonation of 2.5 g of TNT on ships and it was found that the relations of different types of loads and different types of

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

constraints produced unique water jets characteristics; vertically upward, opposite directions and downwardly directions [4-6]. In another research [7-8], the response of a two layered cylindrical shells where water was placed between the shells loaded against underwater blast was studied via the experimental and numerical methods. The experimental tests showed that fracture and large deformations of the outer skin of the two layered cylindrical shells due to the incoming bubbles produced bubbles in the location of the in between water medium. Another type of numerical simulation analysis methodology i.e., the smooth particle hydrodynamic (SPH) method was utilized to model large deformations of manufacturing like forgings and metal stampings [9-10]. It was observed that the shaped charge jets' velocity and length were the highest and could lead to larger impact depth. One dimensional underwater blast response of double-walled hulls consisting of two plates with a water medium in the middle was studied by using the experimental laboratory size fluid-structure interaction and finite element analysis simulations [11-12]. It was found that water filled double-walled hulls managed to mitigate the underwater blast loading and water thickness did not have any major contributions towards the reduction of the blast loadings. Simplified hull girder subjected to underwater explosion was much more complex to analyse based on the performed numerical simulation analysis [13-14] and based from the predicted results of the simulations, two main deformed patterns were highlighted i.e. the M-deformed pattern and the W-deformed pattern.

The dynamic performances and deformations patterns of reinforced concrete beams plie wharfs structures i.e. vertical piles against inclined piles against underwater explosions were studied both experimentally and by numerical simulation analysis methodologies [15-16]. The study found that inclined pile wharfs suffered more damages which include cracks, spalling and brittle shear than vertical pile wharfs due to underwater explosions. The goal of this research is to close this gap by analysing the behaviour of steel plates under underwater explosion conditions using a rigorous numerical validation analysis. By integrating advanced finite element analysis with experimental validation, this research seeks to enhance our understanding of blast wave propagation, deformation mechanisms, failure modes, and energy absorption characteristics in steel plates. The findings of this study are expected to contribute valuable insights to the development of robust design guidelines and mitigation strategies for protecting underwater structures against explosive threats.

2.0 METHODS AND MATERIAL

The process used to create and run the numerical simulation analysis programme for forecasting the deformation of square steel plates exposed to underwater explosions is described in this section. This section describes the procedures used to build numerical models, parameterize simulation settings, verify simulation outcomes, and examine how steel plates behave when subjected to underwater blast loading. This study ensures the accuracy, consistency, and reliability of the simulation program and its results by following a structured approach. The methodology comprises multiple crucial stages, such as creating numerical models with LS-DYNA and LS-PREPOST software, creating intricate geometric and material representations of the target plate and its surroundings, and calibrating simulation parameters to precisely depict blast-related phenomena. Subsequent phases involve the validation of simulation results against published experimental data to assess the program's predictive capabilities and the analysis of simulation outputs to gain insights into the deformation patterns. ALE technique was used to model and simulate the explosion of steel plate in this paper as compared to other solvers; for example, Smoothed Particle Hydrodynamics (SPH), Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) (CFD-FEM hybrid) due to its capability to model and account for the changing of phases of the progressions of the explosive, i.e., from solid explosive to liquid phase and finally to vapour. CFD-FEM hybrid was not chosen for this project since UPNM does not have the solver license to process the program while the SPH method was not chosen because this method is more suitable for large Langrangian deformation phenomenon and does not account for changes in phases of the materials.

2.1 Geometrics and Mesh-Elements Preparations

The geometry and mesh generation for steel plate were created using LS-PREPOST, which is pre-processing software for LS-DYNA. The geometry of the steel plate was created, specifying dimensions such as length, width, and thickness, along with any required geometry for the explosive charge. Boundary and loading conditions were determined when modelling the plate. These boundaries simulate supports or fixtures that hold the steel plate in place. Nodes at the boundary were restricted from moving in one or more directions. For instance, if a plate is clamped at its edges, the displacement of the nodes along those edges would be

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

set to zero in all directions. Then, the displacement was set up for output parameter for crucial understanding the deformation behaviour of the steel plate under blast loading. The model was executed to the LS-DYNA simulation by running the keyword file through the LS-DYNA solver. After the simulation was completed, results were imported into LS-PREPOST for post-processing to analyse the result and evaluate the deformation of the steel plate. Validation of obtained deformation from the simulation process was compared against the data from the experimental test [17-18] and the accuracy of the predictions was evaluated by comparing the deformation patterns.

Figure 1. The three-dimensional physical experimental assembly of the underwater explosion test [17]

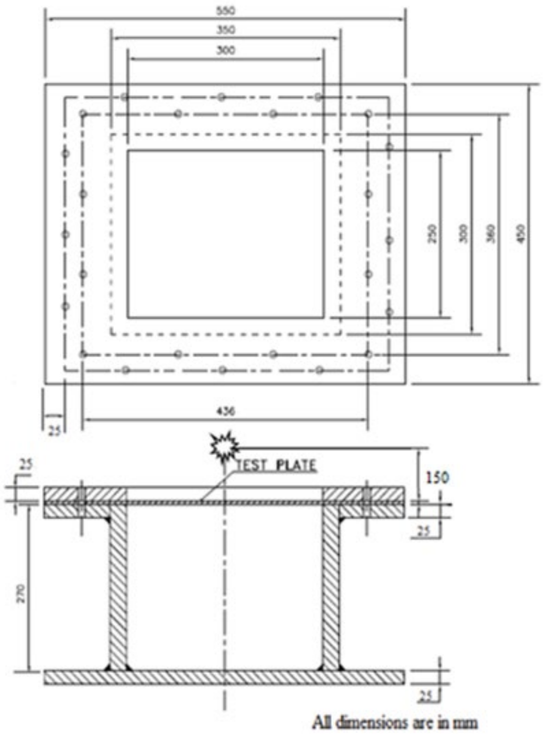

Figure 2. The experimental assembly of the underwater explosion test; the plan view of the assembly (above), the cross-sectional view of the assembly (below) [17]

In this section, the experimental tests were carried out by [17-18] who described and utilized it as the main validation process for this simulation project. The underwater explosion experiments were conducted using an underwater Explosion Bulge Test (EBT) fixture specifically designed to securely hold 1.2 mm and 2.2 mm thick mild steel test plates under air-backed conditions (see Figure 1 and Figure 2). The fixture was immersed in a large water tank with dimensions of 10 m × 12 m × 10 m to minimize surface, boundary, and bottom reflections. The EBT fixture featured a cavity measuring 300 mm (width) × 250 mm

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

(length) × 270 mm (depth), with a top flange and top cover plate both sized at 550 mm × 450 mm × 25 mm, ensuring effective accommodation of the test plates. Small explosive charges, 10 g, were positioned at a standoff distance of 150 mm from the centre of the plates to generate shock waves. The water depth was maintained at 2 m from the free surface, enabling effective shock wave transmission while mitigating reflections that could interfere with the results. The steel plate that had an exposed area of 300 mm x 250 mm was modelled in the z, y planes and the explosive mass that was equivalent 10 g of TNT was positioned in the x-axis which is 150 mm stand-off distance from the centre of the plate so that the deformation of the steel plate could be observed in the x-axis direction (see Figure 3). The steel plate was rigidly fixed around four of its outer edges, i.e., the nodes were fully constrained in all the x, y, z translation directions and around the x, y, z rotational directions. The steel plate was assigned a plate thickness of 1.2 mm by using the *SECTION_SHELL keyword.

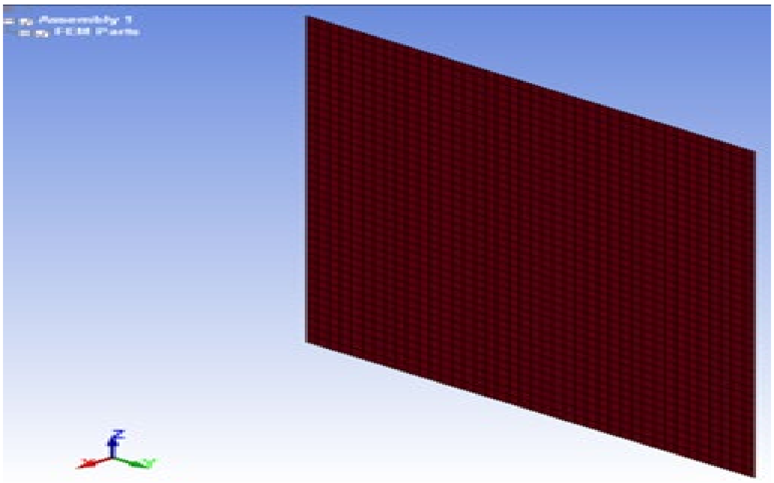

Figure 3. The steel test plate as modelled in LS-PREPOST

Using the element generation command, the edge of the plate was selected to propagate the shell along the x-axis about 270 mm to create fixture for air-backed conditions, and the purpose of this fixture is a structure that holds the steel plate in place prior to the underwater blast test (see Figure 4). To complete the fixture, the same dimensions as the plate were applied at the back using the shape mesher command. The fixture that was propagated and the shell that was created to close the fixture at the back were combined to become one part model.

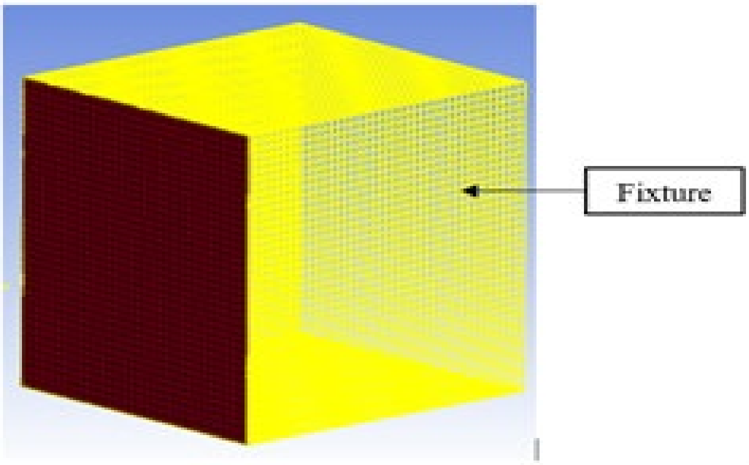

Figure 3. Modelling the fixture for air-backed conditions

The following step is to create a water region part using box solid by using the shape mesher command. An appropriate medium was used to make sure the simulation runs smoothly without error as shown in Figure 5.

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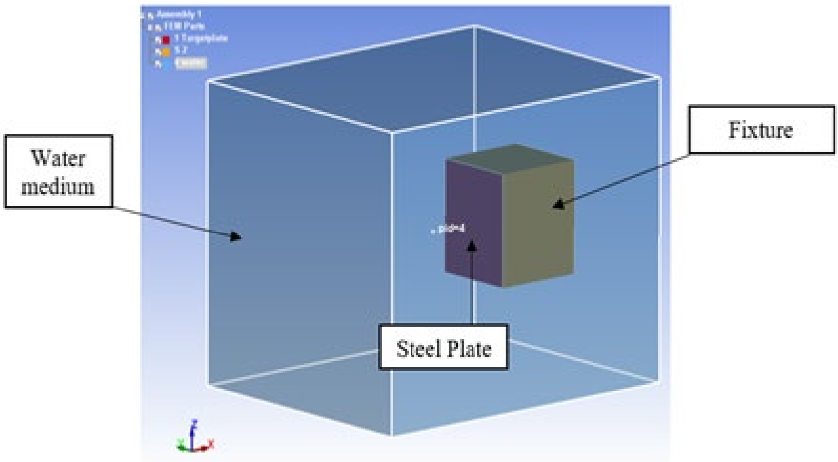


Figure 4. The steel plate with the fixture modelled inside a water medium

2.2 Material Properties

The material of the plate was defined using the *MAT_024_PIECEWISE_LINEAR_PLASTICITY keyword, consistent with the material properties that were used in the experiments as in Table 1. In the ALE modelling, the equations of states for the water, air and explosive utilized in the simulations are as shown in Table 2, Table 3, Table 4, respectively.

Table 1. Material properties of the steel plate [17]

Property	Values	
	1.2 mm plate	2 mm plate
Elastic modulus (E), MPa	2.1×10^5	2.1×10^5
Mass density (ρ), kg/m^3	7869	7860
Poisson's ratio (γ)	0.3	0.3
Static yield stress (σ_γ)	280	300
Ultimate tensile stress (σ_{ult}), MPa	350	380
Rupture strain (ε_{rup})	0.33	0.36

Table 2. Gruneisen equation of state for the water [17]

C(m/s)	S_1	S_2	S_3	γ_o	A	E/MPa
1480	2.56	-1.986	0.2268	0.4834	0	0.2054

Table 3. Linear polynomial equation of state for the air [17]

Description of parameter	C_0	C_1	C_2	C_3	C_4	C_5	C_6
Value	0	0	0	0	0.4	0.4	0

Table 4. JWL equation of state for the explosive [17]

Description of parameter	A (GPa)	B (GPa)	R_1	R_2	ω	E (kJ/kg)
Value	371.2	3.23	4.15	0.95	0.3	7

2.3 ALE Methodology

The *ALE_MULTI-MATERIAL_GROUP keyword was utilized to define and manage multiple materials within the same ALE domain, including the explosive, water, and air are as shown in Figure 6. This approach allows the simulation to handle interactions between different materials seamlessly, enabling accurate modelling of shock wave propagation and material behaviour under dynamic loading. Each material within the group was assigned specific properties, including its equation of state and material parameters as mentioned before to ensure realistic representation of the fluid-structure interaction in the simulation. The initial volume fraction geometry was defined to specify the distribution of materials within the ALE domain. This setup ensures accurate initialization of the explosive, water, and air regions in the simulation. The *INITIAL_VOLUME_FRACTION_GEOMETRY keyword was used to assign the respective volume fractions to each material, based on the experimental configuration. This approach allows for a precise representation

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

of the initial material layout, ensuring correct interaction between the materials during the explosion and subsequent fluid-structure interaction. Two sets of data were defined in the simulation under the *INITIAL_VOLUME_FRACTION_GEOMETRY keyword. The first set represented the water medium and TNT, while the second set modelled the water medium and the air-backed region as shown in Figure 6. The dimensions of the TNT were defined using this keyword to precisely simulate the effects of a 10 g TNT explosion. The TNT was placed at a distance 150 mm from the plate.

The volume inside the fixture was designated as the air-backed region, with the plate and fixture normals aligned in the same direction to ensure proper contact definitions and to prevent nonphysical interactions or numerical instabilities during the simulation. In this simulation, the *SET_MULTI-MATERIAL_GROUP_LIST keyword was utilized to define and manage the interaction between the explosive (TNT), water, and air-backed regions within the ALE domain. This grouping ensures accurate modelling of the material interfaces and facilitates the seamless propagation of shock waves through the different media during the underwater explosion. The *CONSTRAINED_LAGRANGE_IN_SOLID keyword was employed in this simulation to define the coupling between the Lagrangian steel plate and the surrounding ALE elements, including the water, air-backed region, and explosive. This keyword ensures proper force and pressure transfer across the fluid-structure interface, accurately capturing the dynamic interaction between the plate and the surrounding media. By constraining the motion of the Lagrangian nodes to the ALE mesh, this approach prevents penetration and numerical instabilities.

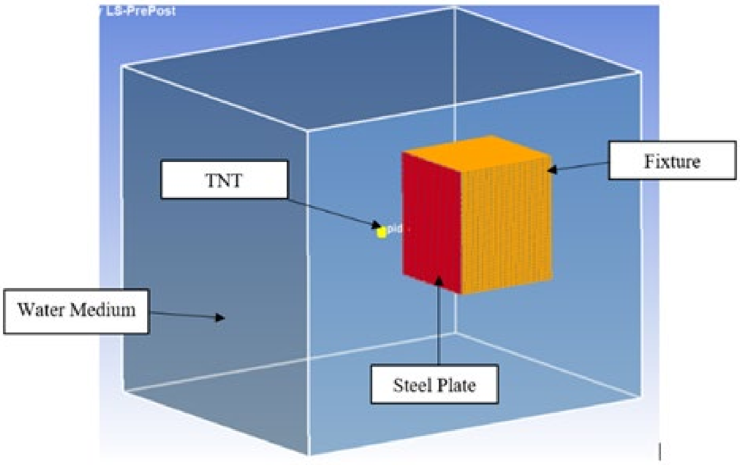


Figure 5. Overview of all parts in the ALE simulation, including the steel plate, fixture, TNT, water medium, and air-backed region

3.0 RESULTS AND DISCUSSION

This section presents the results of the underwater explosion numerical simulation, focusing on the application of ALE methods to model fluid-structure interactions during an underwater explosion. The maximum displacement of the steel plate was analysed and compared with experimental data to validate the simulation. The role of ALE elements in modelling the water and air-backed regions is discussed, highlighting its importance to accurately simulate the plate's deformation under the explosive forces. Insights gained from the plate displacement results are provided, emphasizing the effectiveness of ALE techniques in capturing real-world fluid-structure interaction. The interaction of fluid elements during the underwater explosion in the ALE framework, including the explosion, water medium, and air-backed medium, is illustrated at a time step of 0.001 seconds. A parametric study was conducted to assess the effect of plate thickness and explosive charge on the structural response under underwater explosion conditions. Two plate thicknesses, 1.2 mm and 2 mm, were analysed, each subjected to TNT charges of 10 g, 20 g, and 30 g which produced a total of six number of tests as shown in Table 5. This study aims to evaluate the influence of these parameters on plate deformation while also eliminating the possibility of coincidental results in the simulation. The summary comparison of the simulation towards the experimental tests data [17] is tabulated in Table 5.

By varying these factors, a more comprehensive understanding of the structural behaviour is achieved, improving the confidence in the numerical validation. A total of six simulations tests were modelled and simulated (see Table 5) and compared against the published experimental tests data [17]. It

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

could be observed that the percentage differences between the predicted mid-point deformations experienced by the test plates were around 10.8 % which is quite an acceptable range.

Table 5. Numerical simulation predictions compared against the experimental test results [17]

Test number	Plate thickness (mm)	TNT mass (g)	Experimental test (mm) [8]	Numerical simulation (mm)	% Differences
Z1	1.2	10	53.8	63.4	18.8
Z2	1.2	20	83.7	97.9	16.9
Z3	1.2	30	115	127	10.4
Z4	2.0	10	40	37.3	7.2
Z5	2.0	20	57.8	56.4	2.5
Z6	2.0	30	67.7	73.8	9.0

Figure 7 shows the contoured displacement colours of the steel plate resulting from the underwater explosion from the top view and Figure 8 shows the side view of the deformed steel plate. The progression and the development of the underwater detonation of the explosive impacting the steel plate are shown in Figure 9. Figure 10 shows the three central deformations tests of the 1.2 mm of steel plate from the numerical simulations and Figure 11 shows the three central deformations tests of the 2.0 mm of steel plate from the numerical simulations. The numerical simulation results were compared with the experimental data [17] to evaluate the accuracy of the model in predicting the deformation of the steel plate under underwater explosion conditions. In the experimental setup, the steel plate was held in place using a bolt-clamped fixture, which provided localized constraints at the clamping points while allowing some flexibility in the remaining areas of the plate.

However, in the simulation, all nodes along the plate's boundary were fully constrained to replicate the experimental boundary conditions as closely as possible. This approach aimed to prevent unnecessary movement and ensure the plate deformation behaviour was consistent with the physical experiment. The comparison revealed that the maximum deformation in the simulation was slightly different from the experimental value. The result of the simulation from Test Z1 predicted a maximum displacement of 63.4 mm, while the experimental measurement [17] recorded 53.8 mm. The discrepancy can be attributed to the differences in constraint application, as the bolted fixture in the experiment might allow minor localized movement, whereas the fully constrained simulation restrict all boundary displacements. Additionally, material imperfections and slight variations in explosive positioning in the physical test may have contributed to the difference in results. Despite these minor differences, the overall deformation pattern and response trend observed in the simulation closely matched the experimental findings. This validates the effectiveness of the numerical model in capturing the fluid-structure interaction and blast effects on the steel plate. Further refinement of the constraint conditions, such as simulating a bolted clamping mechanism instead of full node constraints, may help improve the accuracy of future simulations.

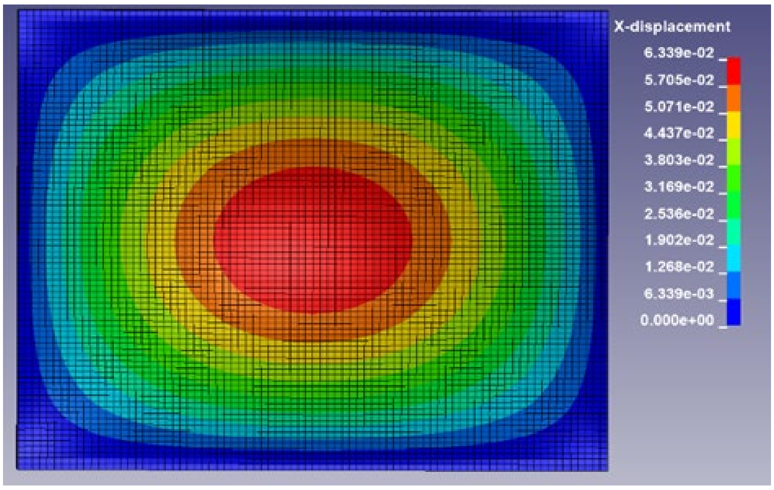


Figure 6. Numerical simulation analysis displacement contour of deformed steel plate

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

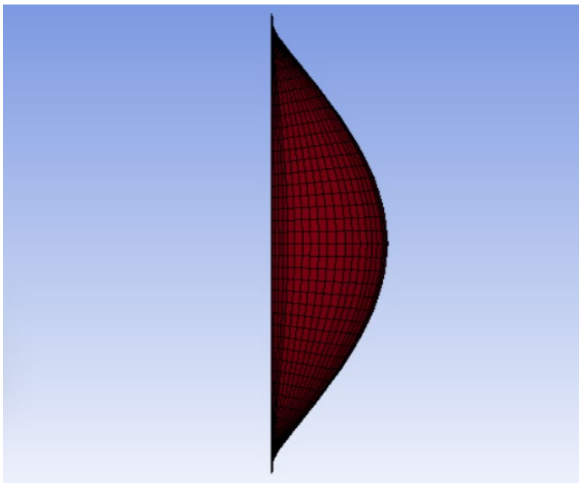


Figure 7. Side view of numerical simulation analysis of deformed steel plate

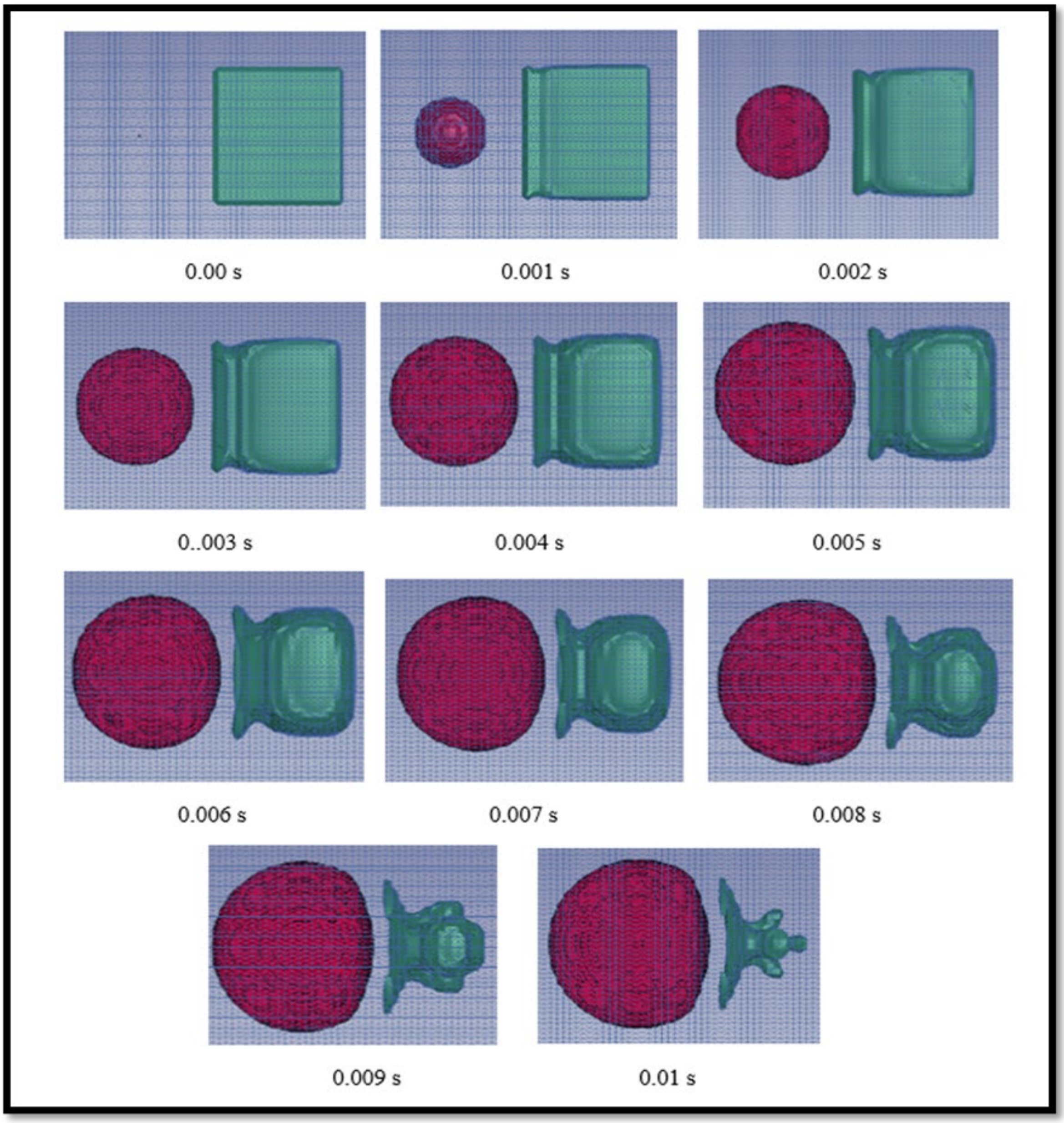


Figure 8. Progression of explosive, water and air medium as produced by ALE numerical simulation analysis methodology

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

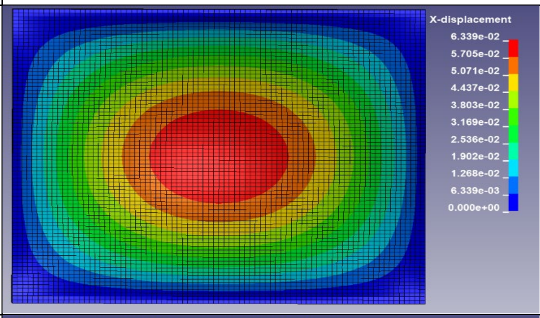
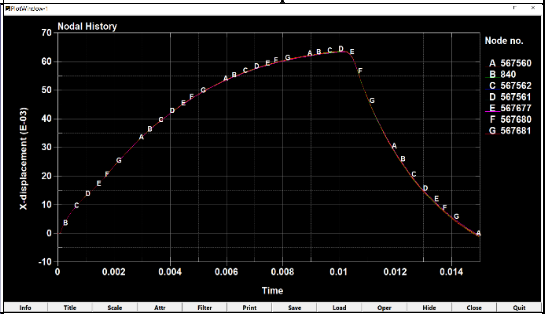
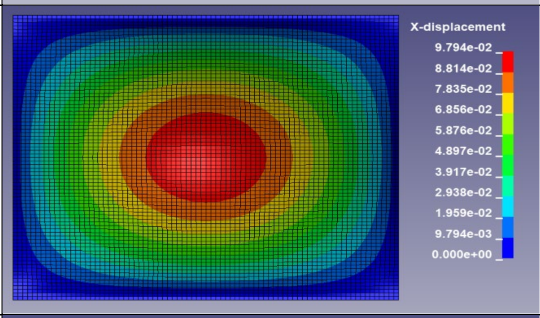
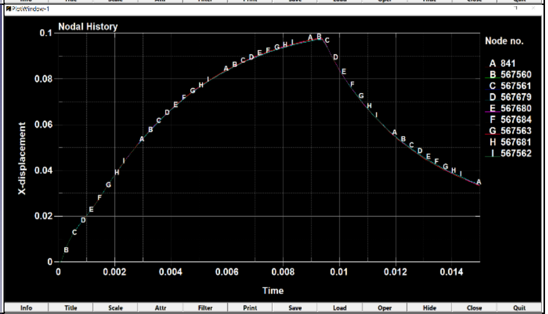
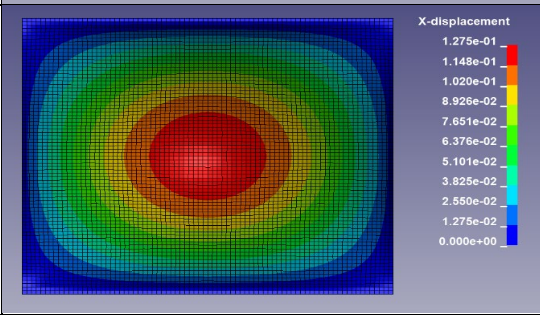
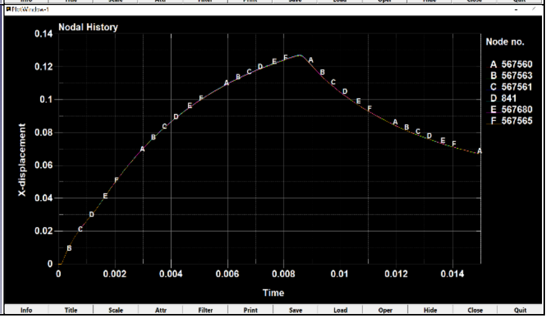
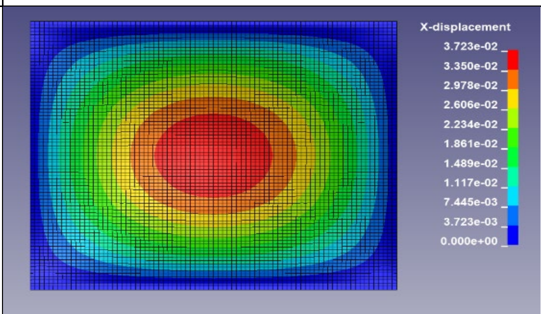
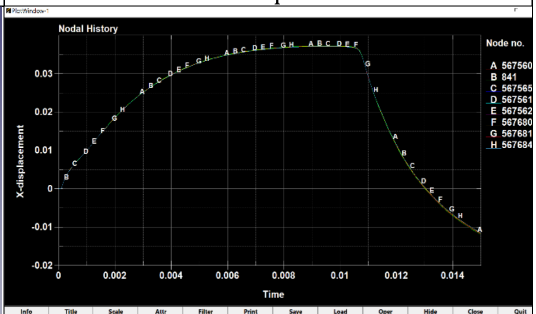
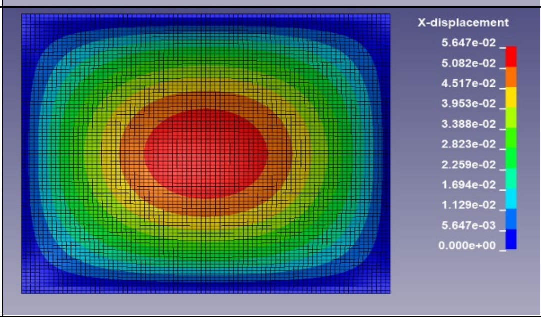
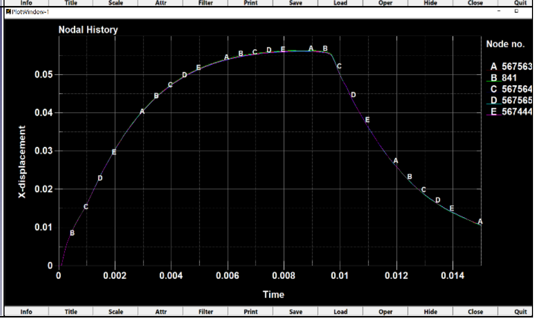
TNT	Plate deformation contour	Graph
10g		
20g		
30g		

Figure 9. Central deformation magnitude from numerical simulation analysis for 1.2 mm thick steel test plates (a) mode of deformations (left), (b) displacement vs time deformations' graphs (right)

TNT	Plate deformation contour	Graph
10g		
20g		

*Corresponding Author | Othman, M. Z. | zaid002@gmail.com

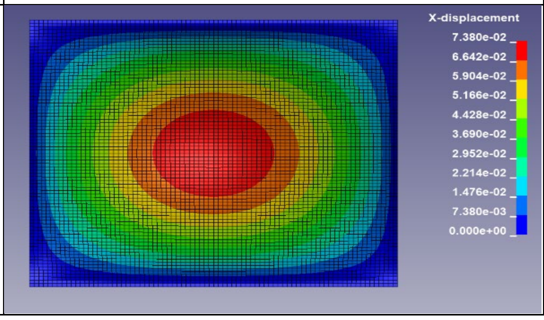
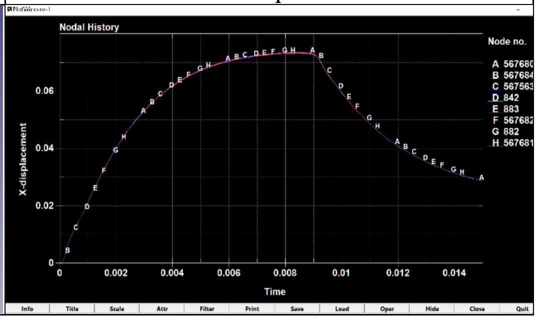
TNT	Plate deformation contour	Graph
30g		

Figure 10. Central deformation magnitude from numerical simulation analysis for 2 mm thick steel test plates (a) mode of deformations (left), (b) displacement vs time deformations' graphs (right)

4.0 CONCLUSIONS

This study has successfully developed and validated a numerical simulation model to analyse the deformation of steel plates subjected to underwater explosions. When an explosive explodes underwater, it produces spherical shockwaves together with pulsations of water bubbles, collapses of water bubbles, creation of water jets and the production of local cavitation [19-20]. These side effects arising from the underwater explosion phenomenon will have consequences on ship structure, ship stability and probable damages to ship structure due to the shock waves and bubbles pulsations. Using LS-DYNA with the ALE method, the interaction between explosive shock waves, water, and the steel plate was effectively simulated. The results demonstrate that the maximum deformation occurred at the centre of the plate, aligning closely with experimental data, though minor discrepancies were observed. These variations highlight the challenges in precisely modelling material properties, boundary conditions, and fluid-structure interactions. Despite some differences between numerical and experimental results, the findings confirm that ALE-based simulations can provide valuable insights into blast wave propagation and structural response in underwater environments. The study emphasizes the importance of accurate material properties, refined mesh resolution, and appropriate Equation of State (EOS) models in improving simulation reliability. Additionally, further experimental validation is recommended to enhance the accuracy of future studies. Overall, this research contributes to the understanding of underwater explosion effects on steel plates, providing a foundation for improved design and safety measures in marine structures. By refining simulation techniques and integrating high-quality experimental data, future studies can further enhance the predictive capability of numerical models, ensuring better protection against underwater blast threats.

5.0 CONFLICT OF INTEREST

The authors declare no conflicts of interest.

6.0 AUTHORS CONTRIBUTION

Othman, M. Z. (Supervision, Writing - review & editing)
Mohamad, A. A. (Writing - original draft, Methodology, Validation, Numerical Simulation Analysis)
Tan, K. S. (Numerical Simulation Analysis)
Ab Ghani, A. R. (Project administration)

7.0 ACKNOWLEDGEMENTS

The authors fully acknowledged Ministry of Higher Education (MOHE) and National Defence University of Malaysia (NDUM) for their support in making this research feasible.

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*Corresponding Author | Othman, M. Z. | zaid002@gmail.com