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Su Altı Patlama Yüküne Maruz Sandviç Kompozit Panellerin Nümerik Analizi

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ÖZET

Su altı patlamaları, yüzer yapılar ve içerisindeki insan yaşamı için son derece tehlikelidir. Hava patlamaları ile karşılaştırıldığında, su altı patlaması, sıvı ortamının etkisiyle çok daha zorlayıcıdır. Bu sebeple su altı patlamasına karşı dayanımı yüksek deniz yapılarının tasarımı önemli olduğu kadar zor bir konudur. Malzeme teknolojisinin hızla ilerlemesiyle birlikte kompozit malzemeler, düşük yoğunluklu, yüksek elastikiyete ve yüksek mukavemete sahip olmaları nedeniyle deniz ve savunma alanlarında metallere göre yaygın olarak tercih edilmektedirler. Bu çalışmada, yumuşak çekirdekli bir sandviç panel, sonlu elemanlar yöntemi kullanılarak modellenmiş ve su altı patlama yükü altında dinamik davranışı incelenmiştir. Model ve yöntemin doğrulama çalışmasında ilk olarak, su altı patlama yüküne maruz karbon epoksi kompozit plak yapısının dinamik tepkileri literatürde mevcut olan sonuçlarla doğrulanmıştır. Bu bölümde, plağın dinamik tepkisini analiz etmek için ALE (Arbitrary Lagrangian-Eulerian) ve Load_SSA (Sub-Sea Analysis) yöntemleri kullanılmış ve ALE yöntemi kullanılarak iyi bir uyum elde edildiği gözlenmiştir. Ardından, yumuşak çekirdekli (köpük) kompozit sandviç paneller sonlu eleman tabanlı ALE yöntemi ile incelenmiştir. Son olarak, parametrik çalışmalarla birlikte plak yapısının su altı patlama yükleri altında maksimum deformasyon sonuçları irdelenmiştir. Artan çekirdek katman kalınlığı, aynı patlama şartlarında plak orta nokta çökmesinin azalmasına ve patlama sonrası salınım frekansının artmasına sebep olduğu görülmüştür.

Anahtar kelimeler: Su altı patlamaları, Kompozit malzemeler, Sonlu elemanlar yöntemi, ALE yöntemi

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Research Article

Numerical Analysis of Composite Sandwich Panels Subjected to Underwater Blast Load

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ABSTRACT

Underwater explosions are tremendously hazardous for floating structures and human life inside. When compared to an air blast, an underwater blast is more effective due to the effect of the fluid domain. Therefore, the design of marine structures with high strength to underwater explosions is a difficult subject as well as important. With the rapid progression of material technology, composite materials are widely preferred over metals in fields of marine and defense industries due to low density, high elasticity and high strength in their nature. In this study, a sandwich panel with a soft-core was modelled using the finite element method, and the dynamic behavior of the panel subjected to an underwater blast load is investigated. In the validation study of the model and method, firstly, the dynamic responses of the carbon epoxy composite plate structure subjected to underwater explosion load were confirmed with the results available in the literature. In this part, ALE (Arbitrary Lagrangian-Eulerian) and Load_SSA (Sub Sea Analysis) methods were used to simulate the dynamic response of the plate and a very good agreement was observed by using the ALE method. Then, the composite sandwich panels with a soft-core (foam) were investigated by the finite element-based ALE method. Finally, the maximum deflection results of the plate structure subjected to underwater explosion loads were examined with parametric studies. Increasing core layer thickness caused a decrease in plate deflections and an increase in post-explosion oscillation frequency under the same blast conditions.

Keywords: Underwater blast, Composite materials, Finite element method, ALE method

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1. Introduction

Underwater shock phenomena pose a significant risk to human life while sailing aboard a vessel. It also causes irretrievable damage to the vessels. Commercial ships, as much as warships, can be targets of an assault. Thus, underwater shock assessments should be considered at a large extent while designing a ship.

An underwater blast is far more dangerous than an air blast because it has a much larger effect radius. This is primarily due to the fact that, unlike air, water is an incompressible fluid, allowing a blast wave to propagate towards it without losing magnitude. In addition, the velocity of sound in water is nearly 4.5 times that of air.

With the rapid progression of material technology, composite materials are widely preferred over metals due to their low density, high elasticity and high strength. Also, soft-core or viscoelastic materials can be used between the composite face layers as a core layer because they have a great amount of resilience, so they can absorb a vast amount of shock energies.

The finite element method is way more advantageous for detailed structural systems than analytical methods. Because mainly, some semi-analytical methods such as Navier or Levy methods can only be applied to certain problems with certain types of boundary conditions. Ls-Dyna is a finite element simulation program recently merged into ANSYS Corporation and can perform a great deal of analyses. There are several methods in the program in which shock analyses can be performed. For instance, air and underwater blast loadings can be made by using LOAD_BLAST_ENHANCED and LOAD_SSA (Sub Sea Analysis) control cards, respectively. In addition, the ALE (Arbitrary Lagrangian-Eulerian) method is highly preferable for more accurate results.

Isotropic materials are accepted as conventional materials in structural mechanics and thus, it has been the subject of numerous studies over the years. Ramajeyathilagam et al. (2000), and Ramajeyathilagam and Vendhan (2004) did several numerical analyses by validating the results with experimental ones. Air-backed conditions were applied. In their studies, 3 different steel specimens were used under different shock factors by arranging TNT (trinitrotoluene) weight as charge amount and distance between the charge and the specimen. For the strain-rate dependent material model, Cowper-Symonds parameters were utilized. They emphasized the importance of the strain rate effects on plastic-kinematic material models.

Rajendran (2009), and Rajendran and Narasimhan (2001) performed numerical and experimental shock analyses. Different shock variables were examined in relation to TNT charge weight and charge distance. They proposed an assumption for the numerical studies, supposing that the velocity of the plate should be multiplied by two in order to validate the results, and they pointed out that this assumption has less errors for large displacement instances.

It has been a really troublesome problem to model experimental procedures numerically, especially for the boundary conditions. Theoretically, a clamped boundary condition means restricting all the 6 degrees of freedom. However, Nurick et al. (1996) investigated several clamped boundary conditions and their effects on the blast specimen for the deformation analyses.

Composite materials are accepted as advanced structural materials carrying features of lightweight and high strength. The finite element approach is often utilized in the computational modeling and analysis of underwater blast incidents. Wei et al. (2013) developed a new fluid structure interaction mechanism by including strain rate effects for monolithic and sandwich composite materials. Different failure mechanisms, such as Hashin's fiber and modified Tsai-Wu were used. It was found that lightweight, high performance foam core material improve the panel performance by mitigating the impulse which is transmitted to the back side of the panel. In their other study (Wei et al., 2013), they investigated the prediction of dynamic response of the sandwich beams subjected to shock loading. They concentrated on the significance of inter-lamina delamination, shear-off mechanism, brittle behavior of composite materials, spring back for monolithic materials after unloading the structure, and core crushing. Matos et al. (2018) conducted an experimental and computational research to evaluate the dynamic response of weathered biaxial composite plates subjected to near-field explosive/blast loadings. The composite plates were clamped to an air-backed cage within an underwater blast facility for the experiments. An RP-503 explosive was submerged and exploded behind the composite specimen. Submersion in 65 C° saltwater for 35 and 70 days accelerated the aging of the composites. The results demonstrate that water diffusion into the composite material causes a more pronounced blast response as well as mechanical property deterioration. A coupled Eulerian–Lagrangian finite element simulation was conducted to complement the experimental findings.

For static analyses, it's known that as the curvature of the plate increases, the deformation under load decreases. However, Kumar et al. (2013) showed that with the increasing value of the curvature, the plate is witnessed to be more open to deformation for underwater blast loading.

Hammond and Grzebieta (2000) did underwater blast experiments on far-field air-backed steel plates. They used Ls-Dyna software for finite element analyses for comparison of the peak deflection results of the plate center, and excellent agreement was shown. Karbhari and Zhang (2003) used two and four layered E-Glass/Vinylester composite specimens from uniaxial, biaxial and triaxial, non-woven and fabric materials for experimental analyses in order to observe damage and failure behavior. In addition, hydrothermal degradation was taken into consideration. It was seen that most of the damage took place through the interface debonding as well as cracking and fiber pitting. Schiffer and Tagarielli (2015) presented a new experimental technique in order to perform laboratory-scaled investigations on underwater blast loadings on circular plates. Quasi-isotropic glass/vinylester and wowen carbon composite plates were studied. They also performed explicit finite element analysis for comparison of the results and good agreement was found.

There are several studies made on ship structures to investigate the dynamic response of the structures subjected to underwater blast loads. Aman et al. (2011) concluded that the response of the structure is affected most severely by the bubble pulse. Both integrated and non-integrated analyses utilized. Also, the response changes with the attack angle and water depth. Zhang et al. (2014) also supports this conclusion of the global response of the ship's structure by using the Double Asymptotic Approximation method. Qiankun and Gangyi (2011) used a section of a ship as a structure for their work. A non-contact underwater explosion was studied, pointing out the importance of the fluid mesh.

2. Underwater Blast Phenomena

Underwater explosions can be investigated using two distinct fluid scenarios. The first scenario is both water-fronted and backed domain, the second is water-fronted and air-backed. Because of the dissipation effects of the water, the structure acts differently in both scenarios. In water-fronted and air-backed scenario has investigated in this study in order to mimic a real-time naval vessel instance.

Underwater explosion incidents can be classified in three regimes:

The first regime is known as the primary shock wave which immediately follows the explosive reaction, resulting in a pressure profile that causes significant structural damage. Water travels with the shock wave and deforms the structure during the main shock regime.

The second and third regimes are usually named as bubble pulses, which occur when the displacements, thus the velocity of the structure's motion is brought to rest when the movement is over. Momentum caused by water results in backwards compression due to the absolute vacuum caused by the full empty volume domain right after the spherical movement of water. The major impact of this regime is cavitation effects. In the present work, mainly the first regime is studied.

Cole (1948) has investigated the phenomena of underwater explosions and formulated the physical problem in extensive detail. The value of the incident pressure reaches its maximum value at around 100 nanoseconds, then it decreases. This behavior is exponential and dissipation factor dependent, as follows:

$$P(x,y,t) = \begin{cases} P_{\max}(x,y)e^{\frac{-(t-t_d)}{\theta(x,y)}} & t \geq t_d(x,y) \\ 0 & t < t_d(x,y) \end{cases} \tag{1}$$

$$t_d(x,y) = \frac{R(x,y)-R_0}{c_f} \tag{2}$$

Where c_f is the velocity of the sound in the water, $t_d(x,y)$ is the arrival time of incident pressure on the structure, and R_0 and $R(x,y)$ show the minimum distance and any distance from the charge to the structure, respectively. The coordinate system of the plate and explosive location is given in Figure 1.

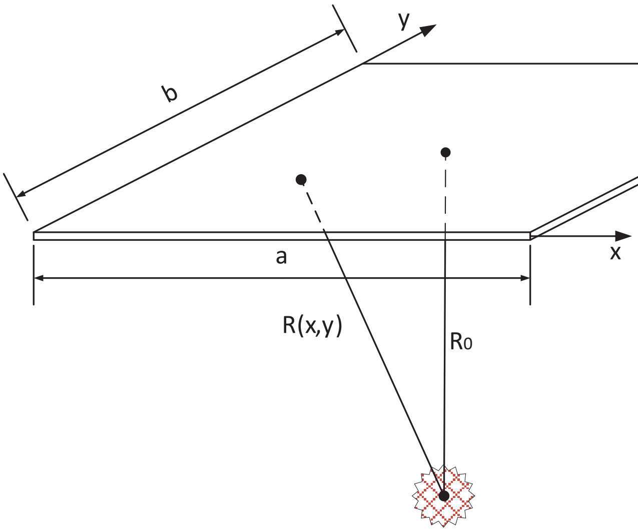


Figure 1. Plate geometry and location of the explosive

P_{max} and the dissipation factor θ are calculated by the charge parameters, the mass of the charge and the distance between the structure and the charge. The values of the equation parameters below are listed in Table 1 and Table 2 in Section 0.

$$P_{\max}(x,y) = K_1\left(\frac{W^{1/3}}{R(x,y)}\right)^{A_1} \tag{3a}$$

$$\theta(x,y) = K_2 W^{1/3} \left(\frac{W^{1/3}}{R(x,y)}\right)^{A_2} \tag{3b}$$

By using the formulation above, free field incident pressure is reproduced from Ramajeyathilagam et al. (2000) in Figure 2. It depicts the pressure data for a 70 gr TNT charge with a stand-off distance of 16 cm.

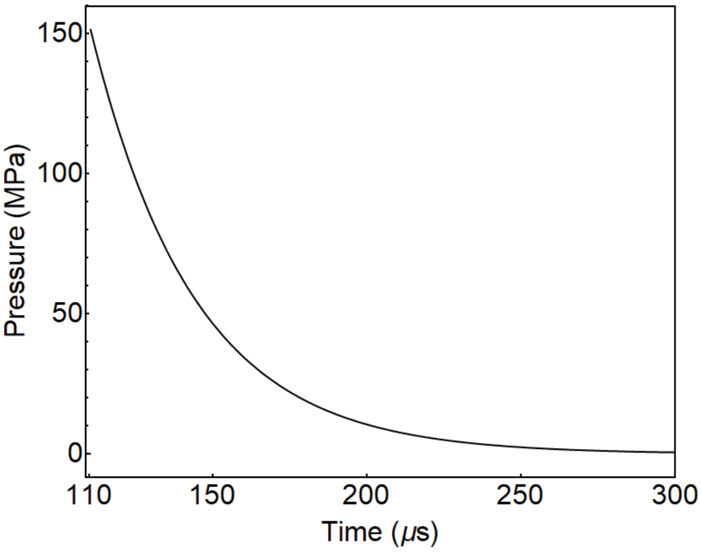


Figure 2. Example of free field pressure time history

Equation of motion of a submerged plate is

$$(m + m_a)\ddot{d} + kd = 2P(x,y,t) - \rho_f c_f \dot{d} \tag{4}$$

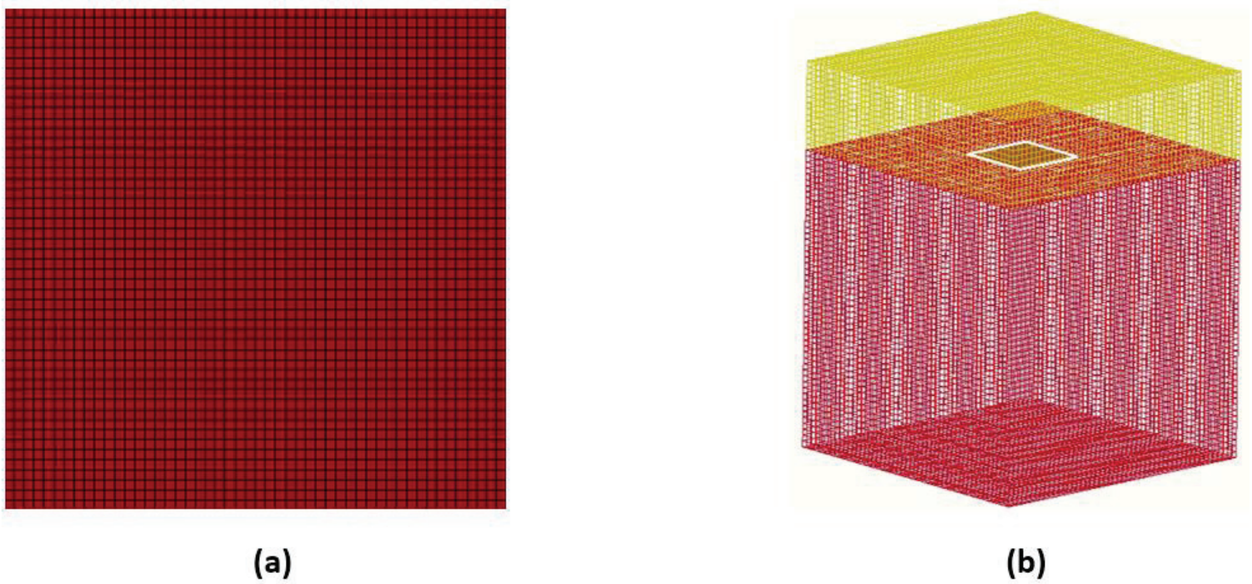
Where m and m_a are the structural mass and the added mass from the surrounding water; ρ_f is the density of the fluid; $\ddot{d}, \dot{d}$ and d are the acceleration, the velocity and the displacement of the plate, respectively. The shell structure reflects the pressure wave to the fluid, which doubles the incident pressure. The effect of the shock wave initiates the motion of the plate and the surrounding water. The velocity of the water particles around the plate is equal to the velocity of the plate. The latter term in the right-hand side of Equation 4 is called rarefaction pressure, which is caused by plate motion.

3. Modelling, Mesh Convergence and Validation

Ls-Dyna is an explicit dynamic finite element solver. It is widely utilized in a variety of industries, including automotive, marine, aerospace, and defense. For underwater blast analyses, LOAD_SSA (Sub-Sea Analysis) control card can be used as well as the ALE (Arbitrary Lagrangian-Eulerian) method. For this study, both the ALE method and LOAD_SSA card were used separately.

LOAD_SSA card uses Taylor’s Flat Plate Theory (Taylor, 1963) for fluid-structure interactions. The incident pressure is obtained by Eq. 1-3. The advantage of this method is that there is no need to model the water domain. The rarefaction pressure due to water movement is calculated according to the velocity of the plate according to Taylor's theory. On the other hand, although modeling of water and explosives is necessary in the ALE technique, water-induced damped motion is taken into consideration.

The validation process of the study is based on the experimental and numerical studies of Matos et al. (2018). Data digitalization has been used to acquire the results from the respected article. All models chosen in the article are non-weathered composite specimens. All blast scenarios have 1.5 grams of equivalent TNT as charge and a 0.152 m. distance between the plate and the charge. Four layers of a carbon-epoxy composite structure are used. 40,000 shell elements with square geometry (200×200), shown in Figure 3(a), were chosen for the plate geometry and all four layers are identified in each element. Figure 3(b) represents the ALE model with the water and air domains represented by the red and yellow colors, respectively. White lines represent the edges of the shell model. Totally, 125,000 elements constitute the water domain, while 37,500 constitute the air domain. In both domains, elements are cubic and have 2 cm edge length.


(a)

(b)

Figure 3. Finite element model a) 2D shell structure model, b) ALE model

In the first case, four layers have material angles of 45/-45/-45/45 respectively. In the second case, four composite layers have material angles of 0/90/90/0, respectively. Each layer has a thickness of 0.315 mm, composing a final laminate with 1.26 mm of total thickness comprised by 4 plies (layers). The plate is a square of 25.4 mm edge length. Different from the experimental setup of the validation study (Matos et al., 2018), the plate is modeled with only having the exposed area, which is the blue area shown in Figure 4. The clamped edges, which form the yellow area shown in Figure 4 mounted on the rigid supports are not additionally modeled. The assumption of not restricting in-plane axial and translational movement is applied in the same manner as in the validation study.

However, the material model has been chosen as MAT_LAMINATED_COMPOSITE_FABRIC (MAT58) instead of MAT_COMPOSITE_DAMAGE (MAT22) as in the validation article due to the damage criteria found out such as delamination and cracks etc. No damage criteria is applied to the model. For detailed material properties, the article can be seen (Matos et al., 2018). Also, shell elements are used in the validation study instead of 3D solid elements.

The stand-off distance between the charge and the plate center is 0.152 meters, and the amount of the charge is 1.5 grams of TNT equivalent. LOAD_SSA control card has been utilized for shock case parameters. The properties of the TNT are shown in Table 1 and Table 2, respectively.

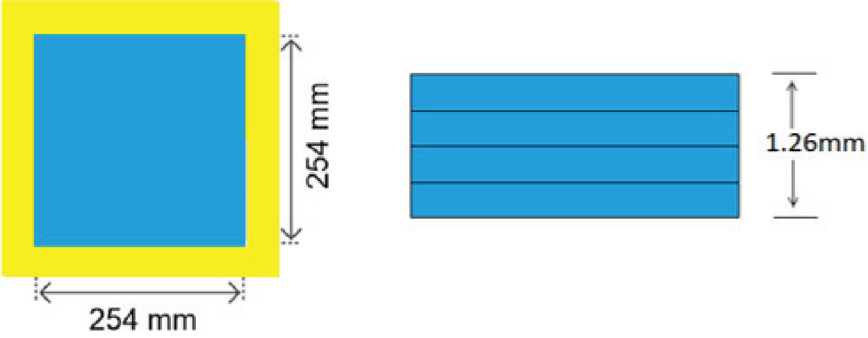


Figure 4. Front and side view of the specimen

Table 1. TNT properties (Ramajeyathilagam et al., 2000)

ρ	1650 kg/m^3
K_1	52.2e6 Pa
K_2	92.5e-6 s
A_1	1.13
A_2	-0.22

Table 2. JWL EOS TNT properties (Dobratz, 1972)

A	491 GPa
B	9 GPa
R_1	4.4
R_2	1.1
ω	0.3
E_0	8 GPa

ρ is the density and K_i, A_i are the constant parameters of TNT in Table 1, and A, B, R_i, ω and E_0 are the constant parameters of Jones-Wilkins-Lee equation of state for Pentoline explosive which consists of 50% TNT and 50% PETN given in Table 2. The Gruneisen and Linear Plynominal EOS parameters are the same as the ones in the article by Matos et al. (2018). The values are valid for the MKS (meter-kilogram-second) units.

Table 3. Mesh convergence results

Number of Elements	Max. Deflection (mm)
1,600	23.39
6,400	22.53
14,400	21.86
25,600	21.61
40,000	21.53
57,600	21.47

Mesh converge study is conducted using LOAD_SSA card for six cases to confirm the maximum deflection value of the plate center. The four layer composite stacking sequence is chosen 0/90/90/0 in the study and results are given in Figure 5 and Table 3.

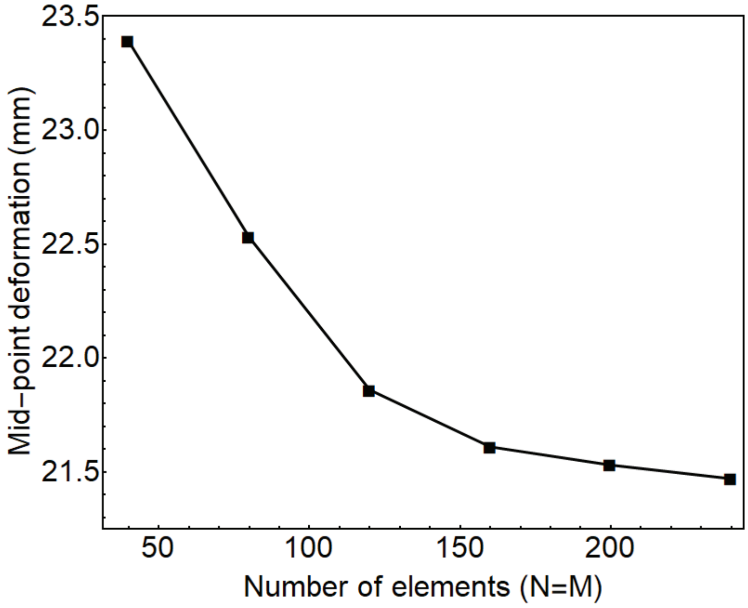


Figure 5. Mesh convergence graph

The maximum deflection of the plate center is given in Table 4. The results of LOAD_SSA and ALE methods are compared with the experimental and numerical results from the literature.

Table 4. Maximum deflection results of the validation study

Material Orientation	(Matos et al., 2018)(Experiment)	(Matos et al., 2018)(Numerical)	LOAD_SSA	ALE Method
0/90/90/0	21.4 mm	-	21.5 mm	26.5 mm
45/-45/-45/45	19.2 mm	22.5 mm	16.3 mm	22.8 mm

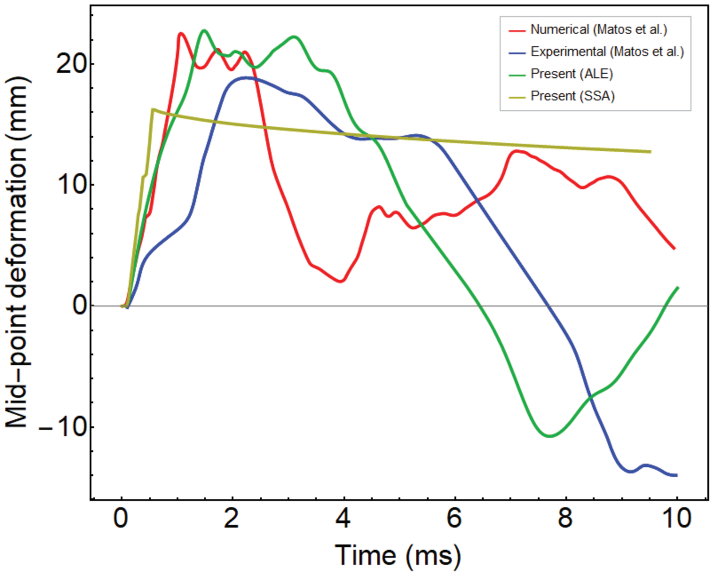


Figure 6. Validation study (Matos et al., 2018) for 45/-45/-45/45 layup

Figure 6 represents the material orientation of 45/-45/-45/45 layup configuration, while Figure 7 represents the material orientation of 0/90/90/0 layup configuration.

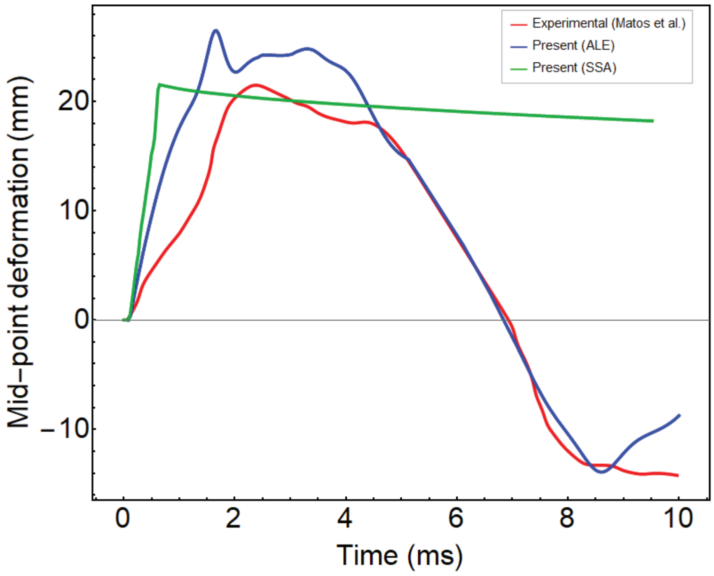


Figure 7. Validation study (Matos et al., 2018) for 0/90/90/0 layup

It is clearly seen in Figure 6 and 7 that the ALE method is more accurate results than the LOAD_SSA in terms of deformation trend in time, and elastic behavior of the plate compared to the experiments made in the respected article.

4. Parametric Study for Soft-Core Sandwich Composite Plate

As seen in the Section 0, the results obtained by the ALE method are more accurate than the ones with LOAD_SSA card, so parametric studies have been carried out using the ALE method. In the present section, soft foam core is added between composite face layers in order to investigate dynamic response of the sandwich plate. For parametric analysis, a soft-core having three different thickness values is added. Soft-core material parameters have been taken from the study (Taskin et al., 2019) and are shown in Table 5.

Table 5. Material Properties of Soft-core (Foam Core) (Taskin et al., 2019)

E	6.895 MPa
ρ	94.195 kg/m^3
ν	0

E, ρ and ν represent the elasticity modulus, the density and Poisson’s ratio, respectively. The values listed in Table 6 are for MAT_LAMINATED_COMPOSITE_FABRIC (MAT58) for composite material in Ls-Dyna. No damage criteria were applied in the parametric studies as well as the validation studies.

E_{ij}, G_{ij} and ν_{ij} represents the elasticity modulus, the shear modulus and Poisson’s ratio of the laminate respectively. As mentioned in the previous section, four unidirectional fabric plies of laminate having 45/-45/-45 /45 material orientation angles have a total thickness of 1.26 mm, each of the plies having a 0.315 mm thickness. In this study, four different parametric studies are conducted. In the first case, no soft-core material is used. Foam material is chosen as MAT_ELASTIC (MAT1) in the Ls-Dyna pre-post. The laminate comprises of 5 plies with a material orientation of 45/-45/soft-core/-45/45 when the soft-core is added in the middle. Then the effect of the foam core is investigated. In the second case, soft-core material is added in the middle of the 4 plies, which means on the front face 2 composite plies with a thickness of h= 0.63 mm, in the middle foam core material with a thickness of 5h= 3.15 mm, and on the back face 2 composite plies with a thickness of h= 0.63 mm are used, forming a 4.41 mm thickness value in total, as can be seen in Figure 8. A soft-core material having a 10h and 15h thickness is used between the unidirectional composite face layers for the third and fourth cases, respectively. Distance between the explosive and the midplane of the sandwich plates was taken 16.2 cm.

Table 6. Material Properties of Uni-Directional Carbon – Epoxy Composite Layers (Taskin et al., 2019)

ρ	1420 kg/m^3
E_{11}	131 GPa
E_{22}	10.34 GPa
G_{12}	6.895 GPa
G_{23}	6.895 GPa
G_{13}	6.205 GPa
ν_{12}	0.22

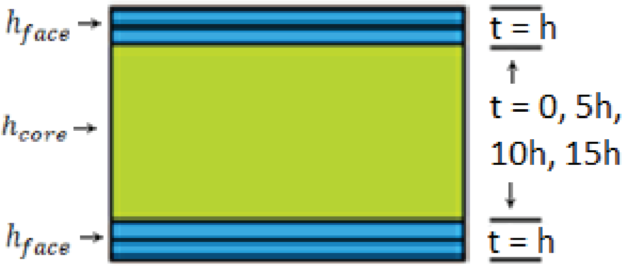


Figure 8. Side view of the sandwich structure with parametric thickness values

In the present work, mainly maximum deformation behavior has been taken into consideration. Table 7 shows the maximum deflection of the center node for all cases.

Table 7. Maximum Deflection Results of Present Study

Cases	Maximum deflection at plate center (ALE_Method)
No Soft-core	17.1 mm
5h Soft-core	14.6 mm
10h Soft-core	12.3 mm
15h Soft-core	9.9 mm

Figure9 represents the deformation contours at the maximum deflection of the plate mid-point by the ALE method. The upper limit of the deformation fringe chart is set at 20 mm. Figure 9.a is the case with no foam core; b, c, and d are the cases with foam cores having 5h, 10h, and 15h thicknesses, respectively. From the results, it is observed that with increasing foam core thickness, maximum deflection of the plate decreases.

Figure 10 represents the solution with the ALE method for 4 different core cases. It is clearly seen that as the thickness of the soft-core material employed in the sandwich structure increases, deflection values for the same shock factor (same stand-off distance and charge mass) decrease. However, the oscillation frequency increases due to the structure's increased mass and inertia. A transient trend can be clearly seen as well.

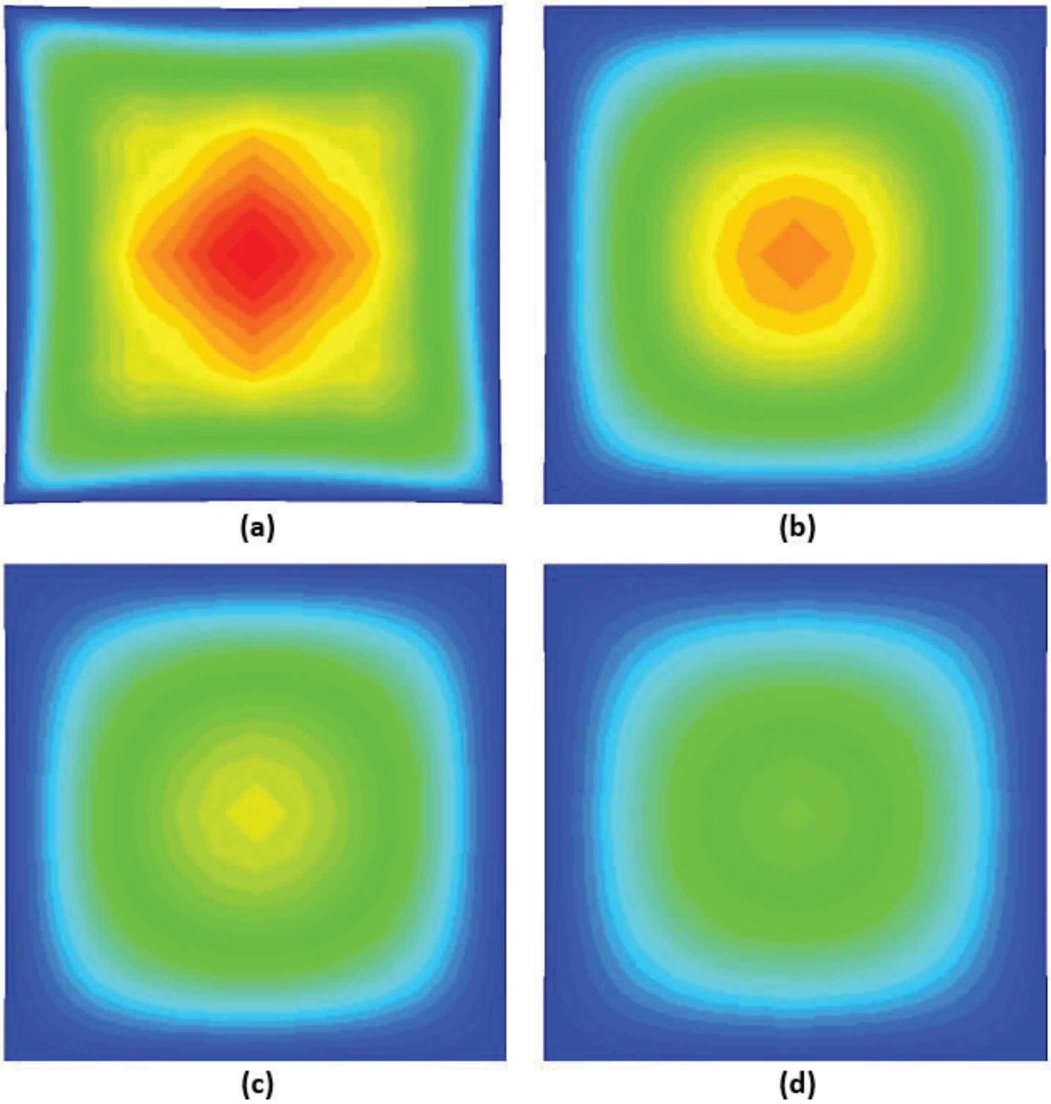


Figure 9. Deformation gradient of the plate with ALE method a) No soft-core, b) 5h, c) 10h, d) 15h

5. Conclusion

In this study, underwater explosion analyses have been investigated using a piece of the commercial finite element codes, Ls-Dyna. ALE method and LOAD_SSA (Sub Sea Analysis) control card have been used to analyze the underwater explosion phenomena. Then, parametric studies have been carried out using the ALE method due to the fact that it is a more accurate method than LOAD_SSA. In addition to composite laminated plate analyses, a soft-core (foam) material has been placed in the middle of the laminate to have a sandwich composite structure. It is clearly seen that with the increasing thickness of the soft-core material used in the sandwich structure, displacements for the same shock factor (same stand-off distance and same charge mass) decrease, whereas the mass and inertia of the structure and damping oscillation frequency increase. For the further study, numerical analyses of curved composite sandwich panels subjected to underwater explosions can be investigated with semi analytical algorithms, such as Generalized Differential Quadrature Method.

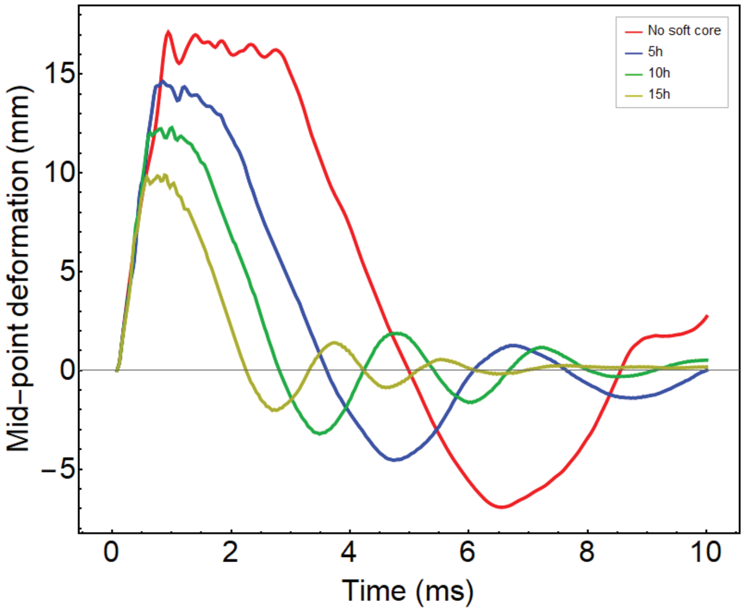


Figure 10. Deflection of the plate mid-point for all cases with ALE method

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