ORIGINAL RESEARCH (AR)
DOI: 10.4274/jems.2023.82713

Journal of ETA Maritime Science 2023;11(2):79-85

Simulation of Shockwave Effects on a Ship-like Structure due to Underwater Explosions

Alpaslan Tatlısuluoğlu[1], Serdar Beji[2]

[1]Exercise Brunch Head, OF-5 Allied Maritime Command (MARCOM) Northwood, United Kingdom
[2]İstanbul Technical University Faculty of Naval Architecture and Ocean Engineering, İstanbul, Türkiye

Abstract

Underwater explosions that threaten the hull integrity and proper operation of navy ships' systems and subsystems are considered from the viewpoint of damage estimation. The commercial code LS-DYNA with the Arbitrary Lagrangian-Eulerian numerical technique is used to analyze the shock effects on structural components of a ship-like form for three different scenarios. Computed maximum permanent deformations are matched with the corresponding keel shock factor (KSF) values for searching a functional relationship of a linear form. Although observed for limited simulations and therefore should be viewed with caution, the linear dependency of the maximum permanent deformations on the KSF values implies that the KSF may be a simple indicator for estimating the extent of damage due to underwater blasts.

Keywords: Underwater explosion, High-pressure shock waves, Ship-hull damage simulations, Keel shock factor

1. Introduction

An underwater explosion (UNDEX) creates a greatly compressed gas bubble, which in turn generates a shock wave [1]. Such a shock wave travels considerably faster than the speed of sound in water with a steep front and causes a very high peak pressure value that decays nearly exponentially. The expansion of the gas bubble decreases the pressure and reverses the pattern to a contraction with a pressure increase. The cycles of expansion and contraction repeat a few times, diminishing the pulse pressure values further each time. Meanwhile, the bubble rises toward the surface due to the hydrostatic lifting force. In explosions occurring at relatively close quarters of a surface ship or a submarine, the peak pressure value of the shock wave is the crucial parameter determining the safety of personnel and equipment.

Powerful underwater blasts that endanger the combat survivability of the navy ships or submarines are a major security concern. The impact of a shock wave on a sea vessel can result in severe structural and equipment damage besides personnel injuries and casualties. Therefore, naval ships must be shock-hardened as possible to ensure combat survivability for both personnel and equipment. The most reliable way of testing a ship for survivability is to conduct shock trials; however, with extensive planning and coordination, such a trial may take a year or more. Furthermore, environmental lawsuits can cause delay or even cancelation of the trials, and an actual trial involving an UNDEX can destroy the tested military vessel completely. For all these reasons, realistic combat testing of military vessels is quite difficult. On the other hand, predicting the structural response of a submerged or surface vessel to underwater shock waves is a research topic whose outcome is much sought by naval engineers. To this end, numerical simulations provide an alternative for studying structural responses and assessing the effects of underwater blasts.

Within the last few decades, commensurate with advancing computational facilities, quite several numerical studies

Address for Correspondence: Serdar Beji, İstanbul Technical University Faculty of Naval Architecture and Ocean Engineering, İstanbul, Türkiye
E-mail: sbeji@itu.edu.tr
ORCID ID: orcid.org/0000-0002-1927-9262

Received: 26.12.2022
Last Revision Received: 14.03.2023
Accepted: 22.03.2023

To cite this article: A. Tatlısuluoğlu, and S. Beji. "Simulation of Shockwave Effects on a Ship-like Structure due to Underwater Explosions." *Journal of ETA Maritime Science*, vol. 11(2), pp. 79-85, 2023.

for analyzing the dynamic response of structures exposed to UNDEX shock wave loadings have been conducted. Shin [2] used the doubly asymptotic approximation coupled with finite-element modeling of the structure to perform numerical ship shock analyses, which were compared with test data. Using the energy method, the ultimate capacity of a warship's bulkhead to a UNDEX was investigated by Peng et al. [3] who derived a formula for the total deflections. Quite in line with the present study, Gan et al. [4] used a box-like floating model to experimentally and numerically investigate the damage due to a spherical charge. Zhao et al. [5] performed a numerical study for simulating TNT explosions by adopting the ghost fluid method. Li et al. [6] recently presented an extensive review of the measurements of UNDEX loads, highlighting the advantages and disadvantages of different methods and emphasizing the need for measurements with large equivalent-weight charges.

The current studies use the commercial code LS-DYNA with Arbitrary Lagrangian-Eulerian (ALE) numerical technique for structural deformation simulations of a ship-like surface vessel with dimensions adopted from a real navy ship for three different scenarios of explosive configurations. Structural deformations observed from the hydrocode simulations are correlated with the corresponding KSF values for formulating a simple expression to estimate the extent of damage quantitatively.

2. Simulation Technique, Relevant Parameters, and Details for a Ship-like Structure Subject to Underwater Blasts

Conducting actual ship shock tests is the most reliable way for evaluating the structural response to an underwater blast. Nevertheless, besides the high-cost demands of shock trials, which may easily exceed $50 million per trial, the legal procedures and significant time spent in all these make numerical simulations a very affordable and valuable alternative for studying structural responses and assessing the effects of weapons under simulated combat test conditions. While all these advantages of numerical simulations are undeniable, it must be remarked that experts suggest the use of both approaches in combination as a better choice [7].

2.1. Arbitrary Lagrangian-Eulerian Technique

Besides high-pressure shock waves, UNDEXs generate liquid and gas bursts. Since the surrounding fluid medium elements around the explosive charge deform severely, the Lagrangian-based finite-element meshes in an explosive charge region are not always feasible. To account for the high-deformation rate, an extremely small time step per iteration is required, which in turn results in longer computational times. Also, numerical approximation inaccuracies increase because of large mesh distortions [8]. On the other hand, the Eulerian-based finite-element modeling advances the solution in time on a fixed mesh system using Navier-Stokes equations. Thus, unlike the Lagrangian approach, the Eulerian codes with fixed mesh arrangement avoid mesh distortions. Codes with various techniques such as Lagrangian, Eulerian, Coupled Eulerian-Lagrangian (CEL), and ALE are available. Mair et al. [9] present a thorough review of these different methods in modeling UNDEXs and related structural behavior and concludes that the CEL and Multi-Material ALE are the most versatile among all. The current simulations were performed using LS-DYNA software based on the ALE formulation technique for predicting the structural behavior of a box structure in the vicinity of an UNDEX in three different cases. The effects of shock wave propagation were modeled by the explosive charge modeling of the code in a fluid medium, while the structural response was modeled by the finite-element method.

2.2. Simulation Components

Numerical simulations using the LS-DYNA software require the specifications of definite components. There are four main components of the present simulations, which are briefly described below. Figure 1 shows the fluid and structural domains used in the simulations. The air domain, which surrounds the fluid and structural domains, extends 10 m above the fluid domain but could not be drawn due to overlapping meshing. All the boundaries are specified as open boundaries to avoid the undesirable effects of reflections.

• Explosive model: An UNDEX scenario begins with the selection of an explosive. In this work, a TNT-type spherical explosive is used in the simulations. Since high explosives react quickly and produce gases at high temperatures and pressure from an initial volume, the explosive is determined according to a given initial charge density ρ_C and mass W, which is taken in grams in the simulations. Judging by trial and error, the meshing of the explosive charge is refined to an adequate degree.

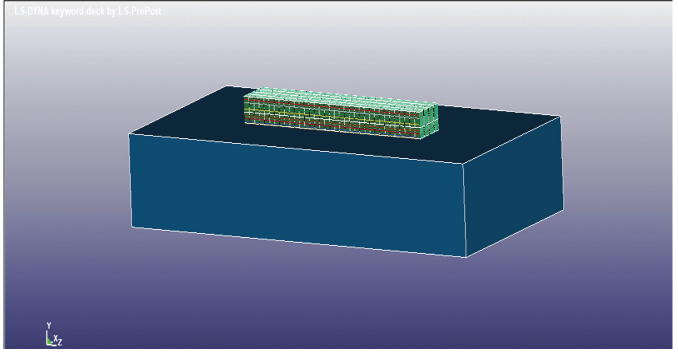

Figure 1. Fluid and structural domains as numerically analyzed

• Fluid model: Once the explosive model is decided, meshing for the fluid region is designed. The meshing of the fluid in the vicinity of the explosive must be performed judiciously. To model the fluid, the null material definition NULL-MAT of LS-DYNA is used. The Gruneisen equation of state is used for the water, which defines the pressure for a compressed material in terms of the density, intercept constant of the shock wave velocity curve, etc. [10]. For the fluid domain, the saltwater mass density is ρ_f=1025 kg/m^3 and the average mesh dimensions are in the range of 50 cm with a total of 404271 nodes for the present simulations.

• Air model: Following the specifications concerning the fluid model, the meshing of the air domain is constructed using NULL-MAT like the fluid material specification. For the air domain, the air mass density is ρ_f = 1025 kg/m^3 and the average mesh dimensions are in the range of 50 cm with a total of 156492 nodes for the present simulations.

• Structural model: The ship-like geometry is modeled as a barge in the shape of a rectangular prism of length L=42 m and width B=8.75 m with appropriate longitudinal and transverse structural components and two bulkheads. The total weight of the structure is represented by three lumped masses evenly placed along the keel line, ensuring that the center of gravity corresponded to the amidships. Shell plating is specified as 0.2% C-hardened steel of h=7 mm thickness, ρ_s=7870 kg/m^3 mass density, E=210 GPa Young's modulus, v=0.3 Poisson's ratio, and σ_y=315 MPa yielding stress for higher tensile steel. The structural steel parameters used in the simulations correspond to the steel commercially called DH-36. Mechanical and thermo-mechanical tests were performed on DH-36 with true strains exceeding 60% over a wide range of strain rates 0.001-000 s^{-1} and temperatures 77°K-1000°K. It has been reported that DH-36 has good ductility and plasticity even at low temperatures and high strain rates without observable micro-cracks [11]. Table 1 gives all the main parameters of the barge and its shell plating.

2.3. Preliminary Arrangements

The barge's main dimensions of are based on an actual military ship with L = 42 m, B = 8.75 m, T = 5.75 m, Δ = 480 tons (loaded). Figure 2 shows a simulation layout sketch, showing the barge and the explosive with relevant distances.

The most important part of the simulation is determining the distance between the barge and the explosive, R, and

Table 1. *Barge dimension and shell plating parameters*

Barge dimensions	L=42 m B=8.75 m T=5.75 m Δ=480 tons
Shell plating	H=7 mm ρ_s=7870 kg/m^3 E=210 GPa σ_y=315 MPa ν=0.3

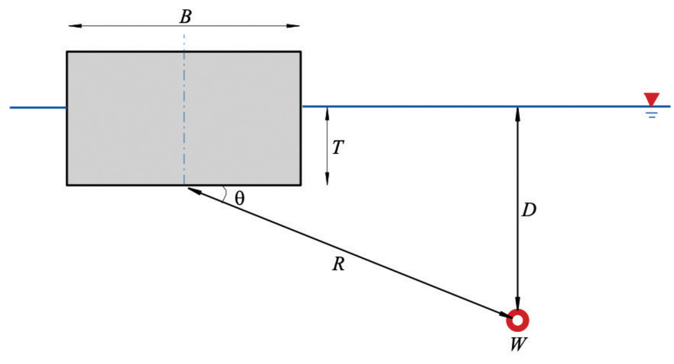

Figure 2. *Sketch of the simulation layout*

the amount of explosive, W, because the extent of damage to the barge depends on these parameters. At this stage, we use a simple empirical relationship, the hull shock factor HSF = $W^{1/2}/R$ or its slightly different form the keel shock factor (KSF), which includes the shock wave's angle of incidence [1]. The KSF is a simple but reliable formula for a quantitative estimate of the relative severity of an UNDEX as experienced by a ship at a given standoff from the explosive:

$$KSF = \frac{W^{1/2}}{R}\left(\frac{1+\sin\theta}{2}\right) \quad (1)$$

where W is the mass of charge, R the distance between the charge and the keel of the ship, and θ the angle between a horizontal reference line parallel to the sea surface and the line connecting the keel to the charge, as shown in Figure 2. Typically, a keel shock factor equal to or greater than unity, KSF ≥ 1 indicates a severe or damaging explosion to the ship.

Three different simulations were carried out using the set of parameters listed in Table 2. The charge mass W and angle θ were varied so that the charge mass was doubled first, increasing KSF from 0.71 to 1.00; subsequently, sin θ was made unity by placing the explosive directly under the ship, thus making KSF = HSF = 1.37.

Meshing for the simulations was prepared using the commercial TrueGrid software. TrueGrid translates the generated finite-element model into the LS-DYNA keyword format for numerical simulation. Figure 3 shows the meshing of the barge-like structure considered; the actual mesh resolution was higher than that shown here.

Eight specific nodes on the bottom of the model were selected to observe certain locations on the hull. The node

Table 2. *Charges and distances used in numerical simulations*

Simulation number	Charge mass W (kg)	Standoff R (m)	Depth D (m)	Angle sin θ	KSF
1	500	23.1	16.50	0.465	0.71
2	1000	23.1	16.50	0.465	1.00
3	1000	23.1	28.85	1.000	1.37
KSF: Keel shock factor					

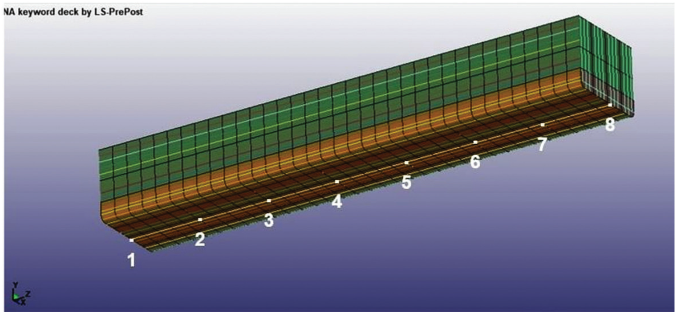

Figure 3. *The meshing of ship-like (barge) structure with control nodes 1-8*

numbers are 8042545, 8042704, 8043382, 8043589, 8044020, 8044076, 8044218, and 8044290, which are marked as 1-8 in the given order, as shown in Figure 3. At these eight nodes, the simulation data were recorded using the DATABASE-HISTORY-NODE command. This particular feature is crucial in obtaining the structural displacements, velocities, and accelerations at selected locations.

Five different types of beam elements were used. Three different sizes of stiffeners, 40×4 T, 50×5 T, and 60×6 T, were placed in the middle deck, upper and lower boards, and bottom. Plates of size 60×6 T were used as transverse elements and size 80×8 T as longitudinal elements. Finally, steel plates of 5 mm (deck) and 7 mm (all the rest) thickness were used as shell elements covering the box-like form. Figure 4 shows a perspective view showing the longitudinal cross-section of the structure with longitudinal and transverse beam elements.

3. Structural Response Results of Ship-like Form Exposed to Underwater Explosions

Since the amount of explosive specified was relatively large [12], the finite-element model was run for 30 ms with a time step scale factor of 0.67. Initially, several trial computations with different mesh sizes and time steps were performed for Simulation 1 and the differences in results were examined until it was ensured that the finally used time and mesh resolutions were reliable. For every 200 μs, the binary data

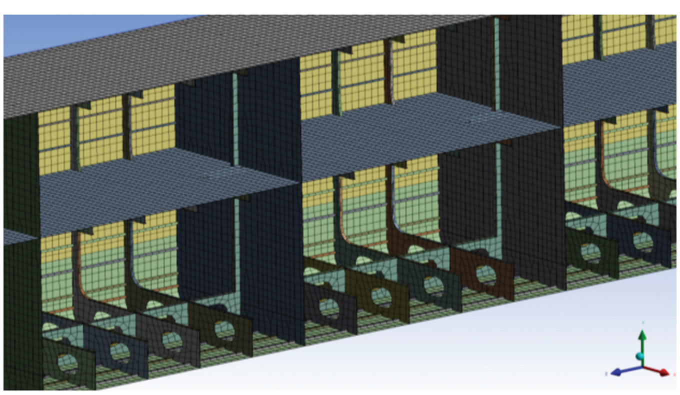

Figure 4. *Longitudinal cross-section of ship-like (barge) structure*

file recorded the finite-element response information of the model. Thus, a single simulation run of 104 μs time interval produced 50 subsequent states of computation.

Three-dimensional response visualization was accomplished by LS-POST of LS-DYNA [13]. LS-POST rendered the displacement, velocity, acceleration, and pressure data display as well as allowing the user to observe the shock wave propagation through the fluid medium. LS-POST also has the capability of extracting ASCII solution data and saving it to a separate ASCII file for later evaluation.

Simulation 1: The first simulation was performed with W = 500 kg TNT-equivalent explosives and R = 23.1 m standoff as measured between the charge and the keel of the barge. The angle was selected as θ = 27.7° which gave $\sin\theta = 0.465$ and KSF ≈ 0.71. The maximum displacement value averaged for all control nodes for Simulation 1 was computed as approximately 37.8 cm. Figure 5 shows the time histories of displacements (left) and velocities (right) for Simulation 1 for all the selected nodes. Unlike the time histories of displacements, velocities fluctuate about a mean for all nodes. This is probably in accord with the propagation of the shock wave over different nodes. Acceleration graphs, though not included here, show that initially all the nodes are greatly accelerated in the burst-like fashion of the shock, but these large accelerations die out within fractions of a second. An important detail concerns the continuing increase observed in displacements at the time (0.3 s) the simulations stopped. The displacements measured are absolute displacements, which include both the plastic shell deformations and the bodily motion of the barge. To estimate the structural plastic displacements, the simulation must be terminated at a time before the bodily motion takes place. This time was judged by monitoring the velocity and more importantly acceleration fluctuations, and when these fluctuations visibly settled the simulation was terminated. This is a subjective method relying on an accurate estimate of the time lag of bodily motion, but the lack of a better option necessarily forced this approach. Therefore, the displacements given contain some uncertainties and must be viewed with caution.

Simulation 2: The second simulation was carried out for W = 1000 kg TNT-equivalent explosives and R = 23.1 m standoff as measured between the charge and the keel of the ship. The angle θ = 27.7° hence sin θ = 0.465 so that KSF ≈ 1.00, which was aimed purposely as this particular simulation corresponded to an actual physical test at sea. The computed maximum permanent deflection for Simulation 2 was approximately 56.6 cm, which agreed reasonably well with the measured maximum displacement in a physical test done under similar conditions, but open comparisons were impossible as details and the measured values of these trials are withheld due to confidentiality issues. Despite this observed agreement, it is emphasized once more that the computed values may be regarded as only estimates due to the estimated termination time of simulations.

Simulation 3: The third simulation was carried out for W = 1000 kg TNT-equivalent explosive and R = 23.1 m standoff as measured between the charge and the keel of the barge. The angle was taken as θ = 90.0° θ = 1.0 so that KSF ≈ 1.37, which, the charge is placed directly underneath the vessel, corresponded to KSF = HSF. All the conditions being equal with Simulation 2, the present one differs only in one aspect, that is, θ. Specifically, this simulation was planned to observe the effect of angle θ on the extent of permanent damage to a vessel. Figure 6 shows the time histories of displacements (left) and velocities (right) for Simulation 3 for all the nodes. The maximum displacement values averaged for the eight control nodes for Simulations 1, 2, and 3 were found to be approximately 37.8 cm, 56.6 cm, and 90.8 cm, respectively. The computed deformations for Simulation 3 are obviously quite large, as can be visually observed from Figure 7, which depicts the structure before (upper) and after (lower) the explosion.

In Table 3, the KSF values are given against the corresponding maximum deformations computed from the simulations. The least-square approach is used to establish a linear relationship between the KSF values and the computed deflections for this structure to assess the reliability of KSF as a measure of potential damage level. Accordingly, a proportionality factor of 3/5 was obtained so that

$$\delta = \frac{3}{5}\frac{W^{1/2}}{R}\left(\frac{1+\sin\theta}{2}\right) \tag{2}$$

where δ is in meters, W the charge mass in kg, R the standoff in meters, and θ the angle as shown in Figure 2.

Figure 8 shows KSF values versus corresponding maximum deformations and the plot of equation (2). It should be emphasized that equation (2) with the given constant is valid strictly for the structural form used here, and more simulations are required to establish the linear relationship

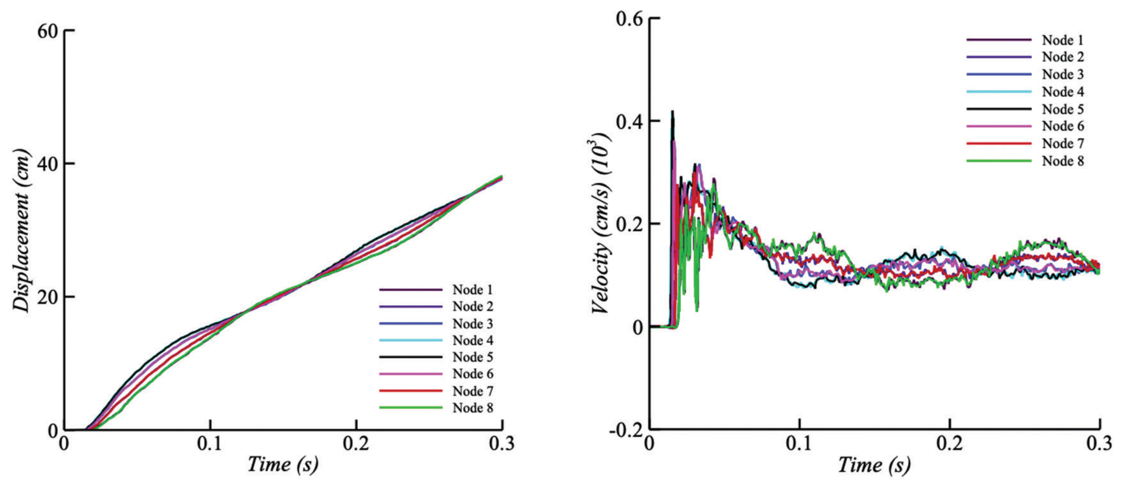

Figure 5. *Simulation 1: Time variations of displacements (left), and velocities (right)*

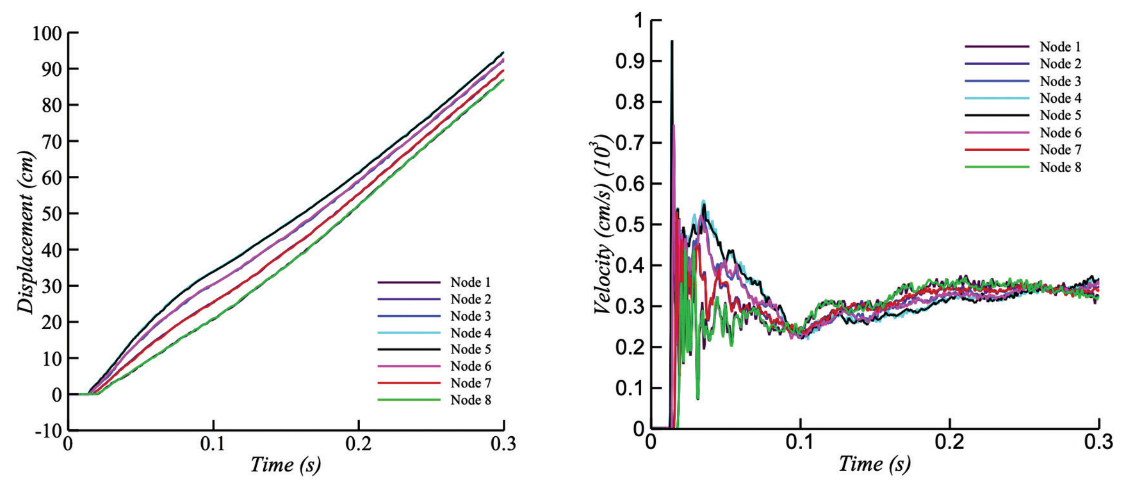

Figure 6. *Simulation 3: Time variations of displacements (left), and velocities (right)*

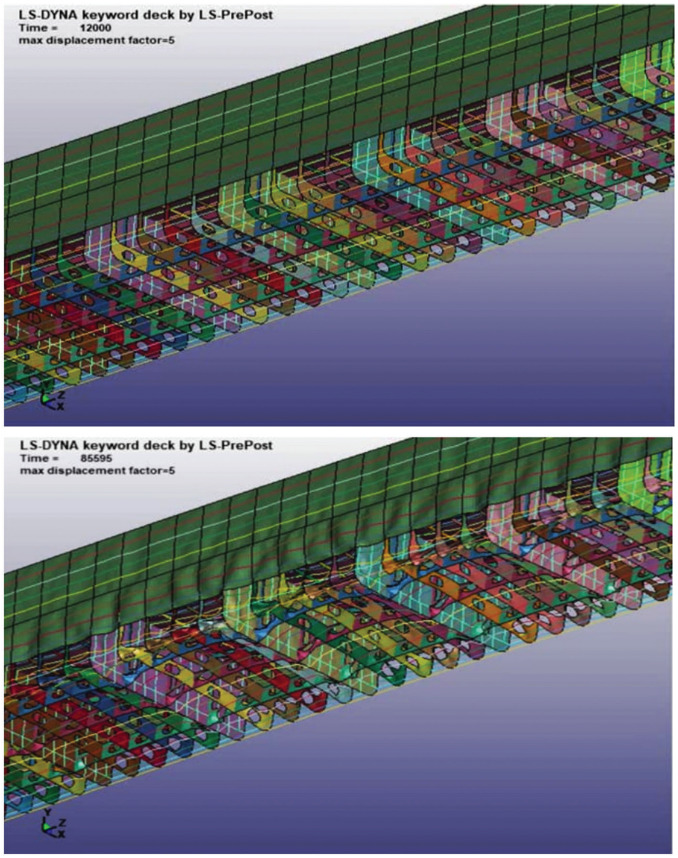

Figure 7. *Intact (upper) and deformed (lower) structures before and after the explosion for Simulation 3*

Table 3. *KSF values and corresponding maximum permanent deformations, velocities, and accelerations*

Simulation number	KSF	Max. Def. (cm)	Max. Vel. (cm/s)	Max. Acc. (cm/s^2)
1	0.71	37.8	0.42	0.44
2	1.00	56.6	0.57	0.59
3	1.37	90.8	0.94	1.15
KSF: Keel shock factor				

with confidence. Furthermore, the multiplying factor, 3/5 for the present case, must depend on the effective plate thickness of the structure and material yielding stress values. Therefore, Figure 8 or equation (2) should only be considered as a speculative indication of a possible relationship between maximum displacement and KSF. Equation (2) then serves just as a hint to connect KSF to the extent of damage, hence, attempts in this direction may be expected to yield a simple and useful practical formula for estimating probable damage. A separate project for establishing such a sound relationship is in progress.

4. Conclusion

The effects of a three-dimensional UNDEX on a ship-like structure modeled as a barge, which represents a ship

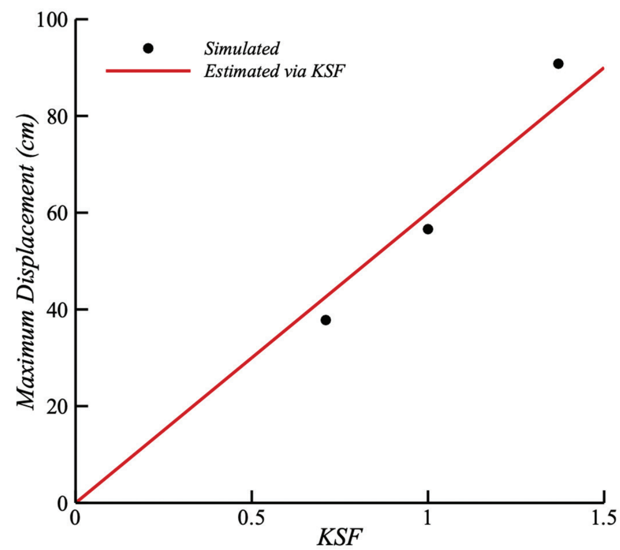

Figure 8. *Keel shock factor values versus corresponding simulated maximum displacements and equation (2)*

KSF: Keel shock factor

beam are investigated through numerical simulations by using the LS-DYNA software with the ALE approach. Three different simulations were performed to examine the effects of different KSF values. The second simulation designed for KSF ≈ 1 represents a case similar to the one for which the field measurements were available though not open to the general use. Although the computed maximum permanent deformation for the second case is found to be quite close to the measured value, the computed values should be viewed only as estimates obtained by judging a suitable simulation time to exclude the bodily motion of the barge. This is an unavoidable but significant drawback of this study. Furthermore, with the use of limited simulation data, a linear relation between the maximum deformations and the corresponding KSF values is sought for the specific structure considered here. This simple relationship, which provides a good first estimate of permanent deformations, is only an indicator that maximum permanent deformations and KSF may in some way be related though not necessarily linearly. Therefore, it may be expected that future work can produce a better established and more general formula for ship structures with different structural properties. Research project in this direction is in progress. Finally, in view of the calculated kick-off velocities, for KSF ≈ 1 serious and for KSF > 1 fatal damage to ship structures appears certain.

Acknowledgment

This work was produced from a part of the doctoral dissertation of the first author at İstanbul Technical

University, Faculty of Naval Architecture and Ocean Engineering.

Peer-review: Externally peer-reviewed.

Authorship Contributions

Concept design: A. Tatlısuluoğlu, S. Beji, Data Collection or Processing: A. Tatlısuluoğlu, Analysis or Interpretation: A. Tatlısuluoğlu, S. Beji, Literature Review: A. Tatlısuluoğlu, Writing, Reviewing and Editing: A. Tatlısuluoğlu, S. Beji.

Funding: The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

[1] W. D. Reid, "The response of surface ships to underwater explosions," Ship Structures and Materials Division, Aeronautical and Maritime Research Laboratory, Melbourne, Victoria, Australia, DSTO-GD-0109, 1996.

[2] Y. S. Shin, "Ship shock modeling and simulation for far-field underwater explosion," *Computers and Structures*, vol. 82, pp. 2211-2219, Sep-Oct 2004.

[3] X. Peng, W. Nie, and B. Yan, "Capacity of surface warship's protective bulkhead subjected to blast loading," *Journal of Marine Science and Application* vol. 8, pp. 13-17, March 2009.

[4] N. Gan, L. T. Liu, X. L. Yao, J. X. Wang, and W. B. Wu, "Experimental and numerical investigation on the dynamic response of a simplified open floating slender structure subjected to underwater explosion bubble," *Ocean Engineering* vol. 219, pp. 108308, June 2021.

[5] Z. Zhao, J. Rong, and S. Zhang, "A numerical study of underwater explosions based on the ghost fluid method," *Ocean Engineering*, vol. 247, pp. 109796, March 2022.

[6] G. Li, D. Shi, L. Wang, and K. Zhao, "Measurement technology of underwater explosion load: A review," *Ocean Engineering*, vol. 254, pp. 111383, June 2022.

[7] H. U. Mair, R. M. Reese, and K. Hartsough, "Simulated ship shock tests-trials?" Feb 1998.

[8] J. E. Chisum, "Simulation of the dynamic behavior of explosion gas bubbles in a compressible fluid medium," Ph.D. dissertation, Naval Postgraduate School, Monterey, CA, USA, 1996.

[9] H. U. Mair, R. M. Reese, and K. Hartsough, "Review: Hydrocodes for structural response to underwater explosions," *Shock and Vibration*, vol. 6, pp. 81-96, 1999.

[10] *LS-DYNA Theoretical Manual*, Livermore Software Technology Corporation, Livermore, CA, USA, 1998.

[11] S. Nemat-Nasser, and W. G. Guo, "Thermomechanical response of DH-36 structural steel over a wide range of strain rates and temperatures," *Mechanics of Materials*, vol. 35, pp. 1023-1047, 2003.

[12] *LS-DYNA Keyword User's Manual*, Livermore Software Technology Corporation, Livermore, CA, USA, 1999.

[13] *A New Post Processor for LS-DYNA*, Livermore Software Technology Corporation, Livermore, CA, USA, 1999.