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Structure Analysis of Marine Pipes under the Effect of Water Explosion Force (Wave)

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Abstract

Underwater explosion is a subject that has been paid attention to by many researchers. In this study the underwater explosion phenomena under shockwave loading is explored by numerical method. For this purpose, by modeling a marine pipe buried in the water by ABAQUS software, the effect of the shock wave and the damages were assessed. Then using the laboratorial results, the fluid-structure interaction and shock wave loading and its results were analysed. Finally, it was concluded from numerical modeling that the highest levels of strain on the pipe buried in the water under underwater explosion and shock wave loading occur in the ending parts of the pipe in both sides and away from explosion field.

Keywords: Underwater Explosion; Marine Pipes; Shock Wave; Interaction; ABAQUS.

1. Introduction

Underwater explosion which is abbreviated as UNDEX is a subject that has been continuously paid attention by researchers and is about 151 years old. The importance and the determining role of marine forces and marine battles in wars has been the main factor for studies about underwater explosions and even nowadays, the most equipped research facilities and the most prominent scholars are usually related to and under the support of military. On the other hand, how under sea structures are destructed under wave force of the explosion is among the concerns of sea engineers and researchers of offshore structures. Analysis of underwater explosion is one of the very important, new and complex issues and is among the main design considerations for sea structures such as platforms. The endurance and control of these structures against shock waves of explosion, accurate loading mechanism and obtaining a comprehensive method for the response of these structures against these types of loads is the current subject of many research centers in the world and hence the subject of this paper. Underwater explosion includes two main phenomena namely shock wave and air bubbles; and dynamic loading on the structure is the results of these. The methods for studying underwater explosion includes laboratory, analytical and numerical methods and in this study, the numerical method is mainly discussed. Therefore this paper aims to study the effect of shock wave on marine pipes and the damages on the pipes. Depending on the conditions including the type and the amount of the explosive material and its distance to structure and water surface, the initial pulse (shock wave) can result in a major part or a fraction of the structure response. Thus, the pipe and the surrounding fluid with non-reflective boundaries are subject to explosion of a certain amount of an explosive material and the analysis is done involving and taking into consideration the effects of structure and fluid interaction.

2. Review of the Literature

The initial studies include the works of Mind Lin and Haywood that studied low modes and the approximation of initial times [1, 2]. The first paper was published by Geers in 1969 and 1972 in which time history diagram related to

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displacements, strains and surface pressure had been analysed [3, 4]. In 1979, Haung explored the interaction of wave and shell with two coaxial spherical shells and two coaxial cylindrical shells that had been filled with the same fluid inside and outside [5]. The model used for the two modes was placed in sand bed. In 2006 and 2007, Iakovlev studied the interaction between the shell and shock wave. The liquid inside and outside of the pipe were the sam [6, 7]. And then in 2008, he studied the effect of shock wave on empty submerged pipe [8.]. Hung et al (2009) investigated the dynamic linear and non-linear response of shock wave on three submerged cylinders. The three cylinders were non-tempered, tempered from inside and tempered from outside. Experiments were conducted for different distances between explosion and the cylinder. For close distances, the change in plastic forms of the cylinder was clearly observed [9]. Panahi et al. (2011) studied the dynamic response of a cylinder with foam core to the shock force of the wave. The fluid had been assumed as non-viscous and compressible. Also, the effect of changing the type of the cylinder's core on surrounding tensions was studied. Pressure distribution in fluid range and the change in the shape of the cylinder were measured [10]. Considering the conducted studies, the studies that have recently been conducted on wave-shell interaction have been either focused on structure aspects that have the aim of calculating the critical estimations required for initial design of ships or submarines such as the maximum of tensions and the bending of the structure, or focused on shell and fluid interaction for a state in which the fluid inside and outside of the shell are the same. In this study the interaction between fluid and the shell ate completely and systematically studied. Zare et al. (2011), first provided a brief explanation about underwater explosion and then modelled the process of bubble formation resulted from it in Dytran. As a result, the ability to see the effects of the bubbles resulted from underwater explosion more accurately compared to other modeling software is obtained. In this modeling, important issues related to the bubbles resulted from underwater explosion such as the change in bubble form, turning into loop form, it's ascending and its maximum speed and density in each expansion-concentration-density-return cycle were calculated and observed. Amirifar et al. (2008) stimulated underwater explosion phenomenon in two-dimensional form. Euler equations were used for describing the fluid behavior and ideal gas equations were used for bubbles containing gas and surrounding water mixture. Also, Schmidt's modified state equation was used for simulating cavitation phenomenon. The numerical method used for solving the flow, is second order ALE method and for creating the network without structure, Delaunay algorithm has been used. For increasing the accuracy and better capture of the physics of the flow and accelerating the solution process, network adaptation technique has been applied and for avoiding numerical instabilities on the boundary of separation of the two fluid phases and modifying the resulted fluctuations, a least squares smoother has been used [12].

Explosion is a chemical reaction during which the main material turn into gas with very high pressure and temperature in a very short time and a major heat exchange. The resulted gas temperature is about 3000 Celsius degrees and the pressure is 5000 atmosphere. This reaction can begin by application of enough energy in some points of the explosive material. This can be done by detonator or hitting.

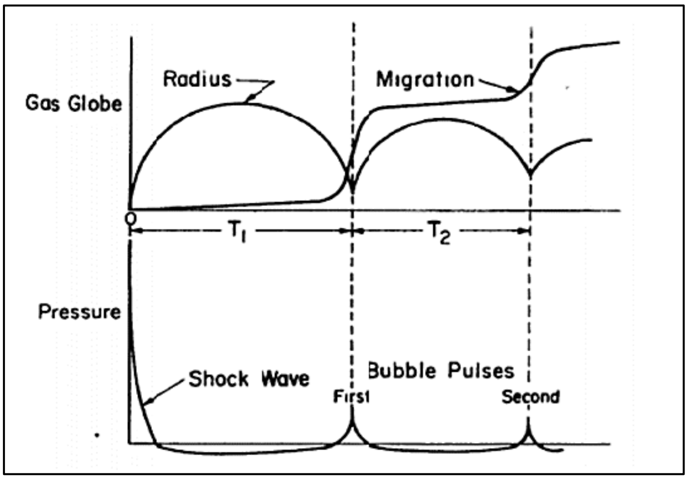

Figure 1. Schematic representation of the process of underwater explosion [13]

The underwater explosion phenomenon can be studied in near time range and distant time ranges. In near time, the first shock wave is formed and spread in the water. And in distant time, the oscillation of the bubble and the effect of reflection of waves from the rigid and free surface boundaries appear. The combustion of the explosive material begins from one or several points inside the explosive material called detonation points and turns the explosive material into high-pressured gas with a speed called detonation speed. After full combustion of the explosive material, the gas products begin expanding and affect the surrounding environment. If the environment is ground, a hole (explosion funnel) is formed. In water, gas bubbles are formed and an explosion wave is dispersed into the air. In water environment, the formed gas bubble creates a shock wave. In distant time range, the formed bubble fluctuates around equilibrium radius and the simplest assumption for the movement of the bubble is oscillation in fixed depth and without transmission movement towards up. Also, in studying underwater explosion, different areas can be defined in terms of place and the equations governing each area are in a specific form. These areas are shown in the figure [14].

The observable effects resulted from the underwater explosion are severely dependent on the explosion depth. In relatively low depths, the effects are observable and tangible. With the increase in the explosion depth, the observation of these effects in the surface of the water is nearly intangible and difficult and we need sensitive measurement tools for recording them. Separation of the observable effects in the surface of the water resulted from underwater explosion id difficult due to the high speed of their occurrence. However, they can be divided into three main parts [15].

a. The effect resulted from the initial shock reaching the surface of the water
b. The effect resulted from gas bubbles reaching the surface of the water
c. The effect resulted from bursting of the bubble and emission of the gases of the explosion to the atmosphere.

The moving shock results in inducing speed to the fluid. Thus, when the initial shock reaches near the surface of the water, takes water with in its positive phase in proportion to its power. As the pressure of the atmosphere is insignificant compared with shock pressure, a reflective wave is produced as the result of the shock hitting the interface between water and atmosphere, and it moves towards the depth of the water. The shock wave resulted from the explosion is one of the main explosion products that can affect the structures. The pressure of the shock wave reaching the water boundary is the first oscillation resulted from the explosion. This pressure that is nearly equal to 2/10 ib/in for TNT, appears in the form of a big pressure wave and the movement of the water. The high volume of the gas resulted from the explosion or burning begins spreading and the pressure of the water declines quickly. The shock wave that is resulted from the underwater explosion is added to the existing hydrostatic pressure [14].

3. Modeling and Calculations

The numerical model in this paper is through ABAQUS software. This model is based on an experiment that was conducted by Kwon et al [15], an experiment in which an experimental submerged pipe was exposed to a shock wave pressure with 60 IB-HBXI produced explosion pressure. Kwon and Fox described this experiment with a set of selected experimental results.

The aim of this analysis is evaluating the behavior and performance of a structure under underwater explosion shock (wave) loading. The experiment pipe is produced from Aluminium of T6661-T6 type. This pipe is 1.067 mm long, its external diameter is 30.5 mm, its wall thickness is 35.6 mm and it has 5.24 mm thickness for the welds that are at the end of the pipe cover.

The pipe has been placed in a 40 meter deep water test tank horizontally. The 60 Hbx-1 explosive load and the pipe are both placed at the depth of 3.66 meter. The explosive load has been placed in center to center and away from the cylinder side at distance of 7.62 meters from the cylinder side. The hanging depths, the distance of the explosion load and the test time have been selected in a way that the fluid cavitation is not big and significant and bubble pulse does not occur. The strain gauges were placed at different places on external sides of the experiment pipe. As it can be seen from the following picture, the experimental data of the strain gauge are filtered in 2000 HZ. These experimental data provided here are obtained by history of strain curves by Kwon and Fox.

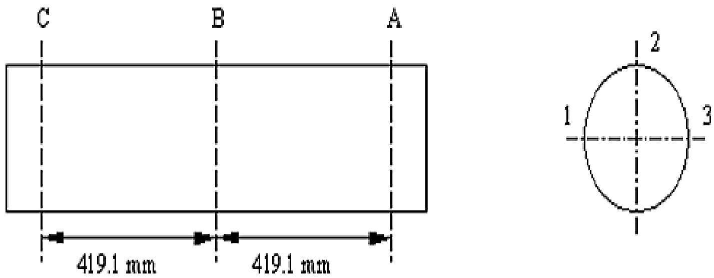

Figure 2. The points where strain gauges are placed [16]

When the behavior of acoustic fluid is linear (i.e. without cavitations) the total acoustic pressure with the fluid includes an input wave and a component of the dispersed wave. For this intended model, the input wave is the shock wave produced by the explosive loading under water (UNDEX).

The dispersed wave is the acoustic field created by the interaction of the input wave and the submerged structure. The nature of the input wave can be determined by the experimental formula or laboratory data that have been described in previous works. Thus, the spherical input shock wave as a passing load and active on the both structure meshes and acoustic meshes, occur on the common sides (the wetted internal sides). Also, the degrees of freedom for the pressure of the external fluid only indicate an uncertain dispersed element of the total acoustic pressure. The type of loading of the input wave is a formulation of a scattered wave or formulation of complete wave.

The formulation of scattered wave that was described before is the presupposed conditions for the analyses of ABAQUS software. Complete formulation is used for instances that non-linear response is expected or the overall acoustic pressure history is in a presupposed boundary condition of acoustic field. During the experiment of underwater explosion, two converters producing pressure were placed at distance of 7.62 meters from explosive load around cylinder and at the same depth with the cylinder. These converters provide an experimental observation for comparing pressure-time history for spherical input shock wave when they move in dot form on the pipe near explosive load (place B1 of strain gauge).

The Figure 3. shows the time history curve for input pressure waves that have been recorded by converters in the laboratory work of Kwon and Fox.

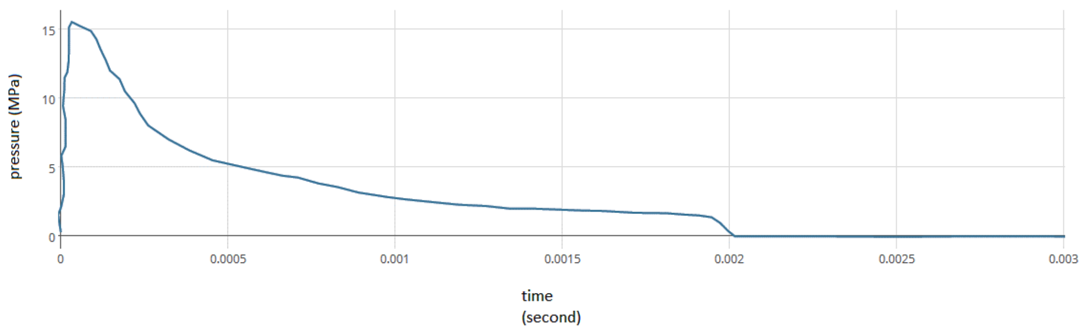

Figure 3. time history curve for input pressure waves [16]

It should be noted that the data including time history curve will be used as range table in defining the input wave loading in ABAQUS software. The following figure shows the mesh of the shell of the limited components of S4R used in representation of the experiment pipe.

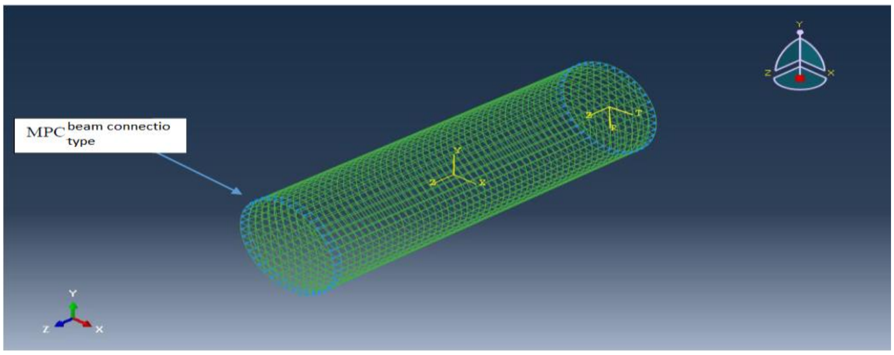

Figure 4. The model of the experiment pipe in the numerical model

The external fluid is meshed with AC3D4 4-node elements that are of acoustic that are of acoustic quadrilateral type. This type of element is used for defining the external fluid as ACED4 is quadrilateral element that can describe the type of acoustic elements. In fact AC3D4 is 4-node linear acoustic quadrilateral element. The external boundary of the external fluid is represented by a cylindrical surface with spherical end. The radius of the external boundary is 0.915 meter. The external boundary should be placed at an important distance from the pipe so that the added mass related to the beam bending modes with low frequency is obtained for the pipe appropriately. The bending modes of the beam corresponds with a sinusoidal transmission of N=1 for the cross section of the pipe in the fluid. To evaluate the impacts of the added mass at the time of using a simple panel of the dependent boundary of wave radiation for the external fluid, the outer boundary for the fluid can be considered as rigid (without radiation). Therefore, an analytical solution for the added mass related to the transmission of a limited radius of the cylinder Ri, placed in the cylinder filled with fluid with radius R0 can be used so that an appropriate characteristic radius is determined for the external fluid. The result obtained through analytical solution by Blevins [17] is shown in the following table.

Table 1. Added mass for transmission mode N=1 in an unlimited cylinder (Fluid between coaxial and centralized cylinders) [17]

Cylinder Radius	Added Mass Ratio
1.5	2.600
2.0	1.667
4.0	1.133
6.0	1.057
8.0	1.032
16.0	1.008
24.0	1.004

The characteristic radius based on the ratio of external boundary radius (R0) to the pipe radius (Ri) with ratio 6 that results in an added mass error of about 6% for limited pipes. When using independent models with improved levels, the place of the external fluid boundary can be at the distance of about half of the distance that is needed for independent model of wave radiation panel.

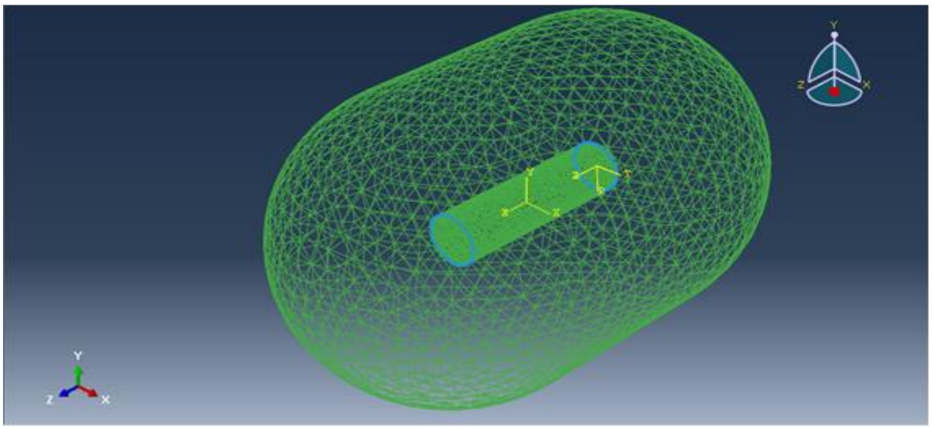

Figure 5. Acoustic meshing of external fluid and the experiment pipe in ABAQUS

4. Results and Discussion

4.1. Fluid-Structure Interaction and Shock Wave Loading

The comparable results for structure response and reaction can be obtained when the boundaries based on the source are placed at half of the distance from the structure. For beam bending modes with low frequency, system losses created by hydrodynamic drag or fluid viscosity force are not considered by acoustic radiations. Therefore, the relative loss of the mass on the meshed experiment pipe is used for approximation of these types of losses. The connection of acoustic structure interaction between acoustic pressure of fluid mesh and structure movements of the experiment pipe in their common surface sides (wetted surfaces has been obtained by the constrain limitation on the surface layer.

Figure 6. shows the surface mesh in wet sides of acoustic structure in relation with the external fluid. As the acoustic mesh is bigger than structure mesh, the surface of the external fluid in the wetted side is designed as the main surface. This correspondence results in a coupling and internal connection between acoustic pressure and structure movements in the experiment pipe in surface nodes and connects the acoustic pressures of the pipe to the mesh of acoustic pressures of the fluid in the wetted sides. The numerical model for this study of underwater explosion under shock wave has 23337 degrees of active freedom overall. Figure 7. is time history for axial movement (U_3) in the center of the nodes at the pipe end cap.

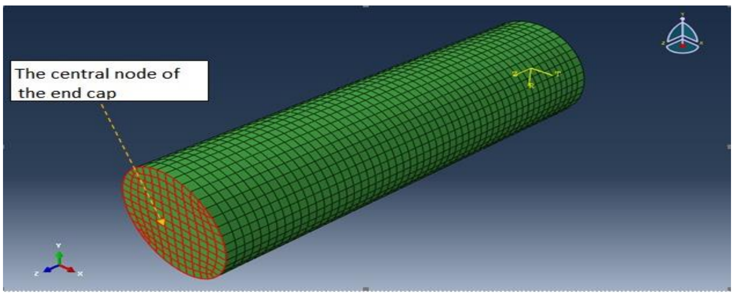

Figure 6. The place of the central node in the end cap of the experiment pipe

Considering the above figure, in the next diagrams the axial U movement in the end of the pipe at the right and left of the cylinder under the loading times at the above place is analysed. These curves clearly indicate the periodic response related to the axial dominant mode for the pipe-end cap.

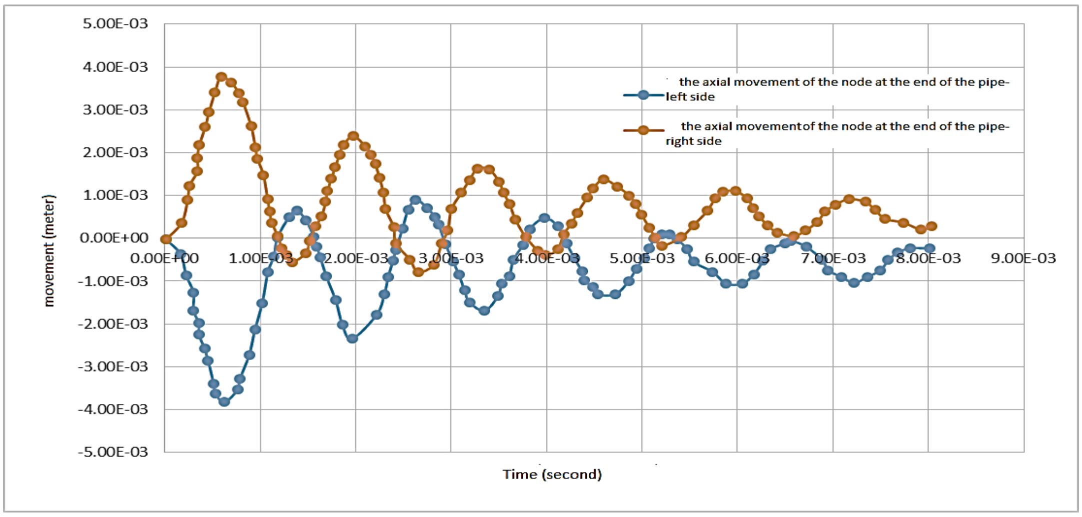

Figure 7. The axial movement U_3 of the nodes at the end of the pipe

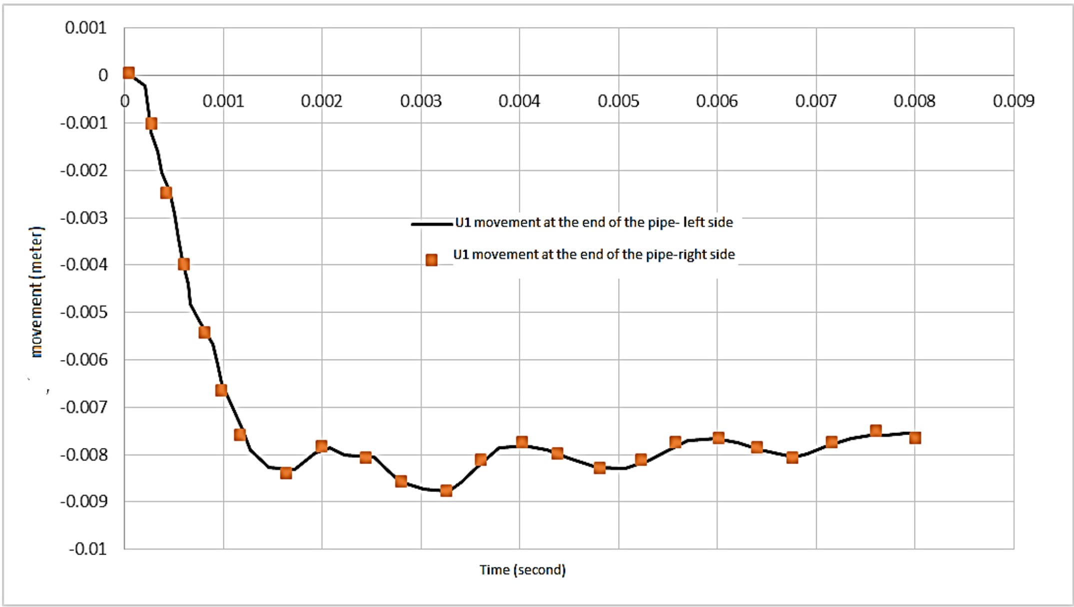

Figure 8. U_1 movement for the central nodes at the end of the pipe

It should be noted that one-way direction of U_1 in the figure is the main direction of the shock wave dispersion. As it can be seen in the figure, the respond curves clearly indicate the time history of the upright movements (U_2) for the nodes at the top and bottom of the middle panel of the experiment pipe. These curves indicate that a dominant vibration model N=2 occurs at 17 HZ frequency. (Based on an approximation periodic cycle of 0.0059 second)

The frequency for the initial mode of the experiment pipe in the external fluid based on the analysis of eigenvalues in ABAQUS is about 330 HZ. This movement in response mode frequency N=2 indicates the effect of the added mass of the external fluid on the response of the submerged experiment pipe.

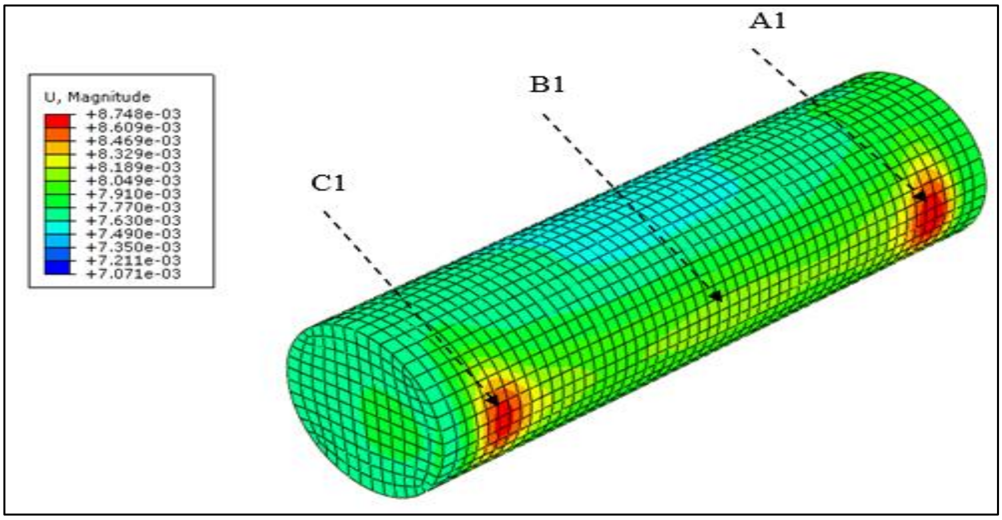

Figure 9. Places of measuring strain and the displacements in the pipe under the explosion in the numerical model

Figure 10. includes the diagrams of the time history of axial strains at place B_1. Place B_1 is the node of the middle and top of the pipe that has been specified in Figure 4-1. and output node was taken from it in ABAQUS. The experimental-numerical analysis (ABAQUS software) in an initial time (prediction of the maximum strain) and the prediction of the frequency of the dominant response of the experiment pipe have a good correlation.

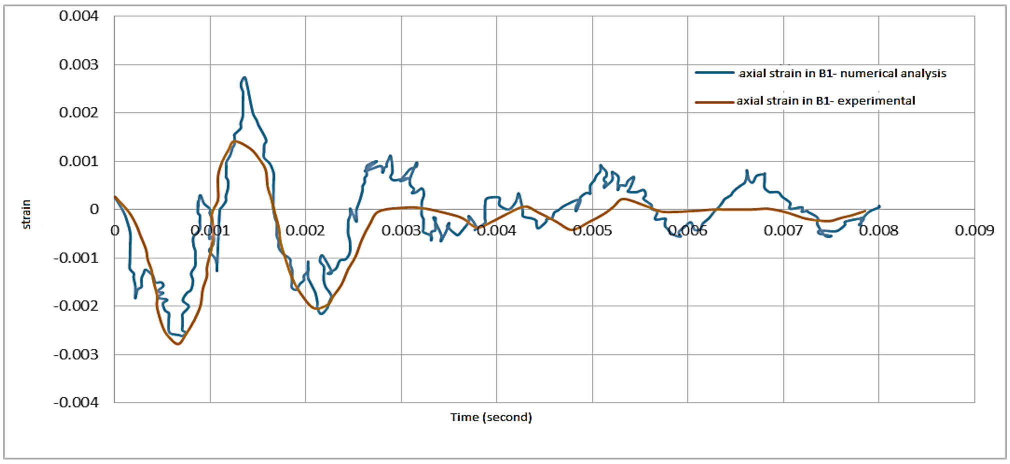

Figure 10. The diagram of time history of axial strains at place B1

Prediction of the fluctuations of strain in longer times results in the modeling of loss in hydrodynamic drag and decline of viscosity by high frequencies response in numerical analysis that has not been provided in laboratorial data and there is not the possibility for comparison. Therefore, fluctuations of strain values such as Figure 10. in short times were provided. This can be resulted from filtering techniques used for experimental data in Kwon et al work. Therefore the above figures which indicate the time history for axial strains indicate that the conducted UNDEX model analysis has a compatible estimation of the maximum response of the pipe and therefore it will be appropriate for more analyses.

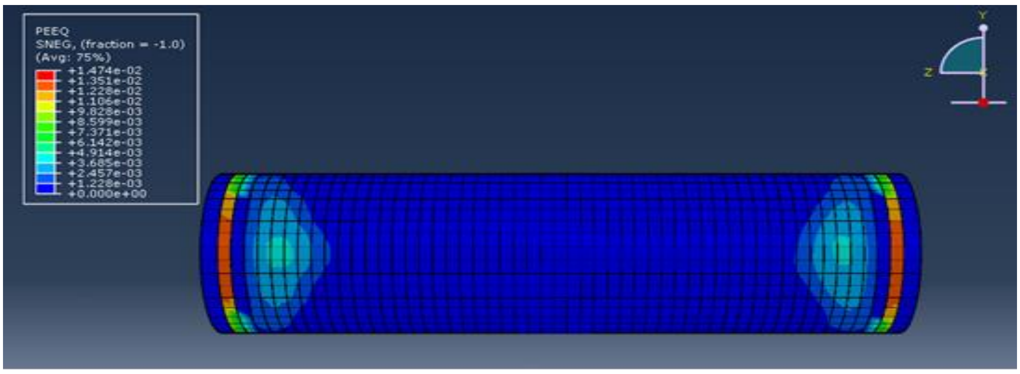

Figure 11. The overall plastic strain on the external surface if the pipe under the explosion

As it is determine from the conducted numerical modeling, the highest levels of strain on the submerged pipes under underwater explosion and shock wave loading occurring the ending sides at the ends of the pipe and away from the field of explosion. These are also observed in the laboratorial work of Kwon et al. [16] and indicate the correctness of the conducted modeling.

5. Conclusion

In this study the numerical simulation of underwater explosion for pipes submerged under loadings of shock wave was analysed. The closeness of the results to the conducted experimental observations in laboratory studies indicates the appropriate accuracy of numerical model for analysing complex issues of underwater explosion in other structures too. In this study the axial strains and stresses in specific locations for the effect of the explosion and the impact of shock wave were measured and analysed. Form the numerical observations and the obtained diagrams it was determined that the highest level of the impact of the explosion on the structure has been in the end of the ending surface of the submerged pipe. This also showed the correctness of laboratory observations too. By studying the published papers it was observed that the fluid and structure interaction has been considered less for the marine pipes that have been under shock loads of the explosion. Thus, the aim of this study has been focusing on this issue and obtaining time history curves resulted from underwater explosion in the studied pipe. For this purpose, the pipe and the surrounding fluid with non-reflective boundaries were subjected to explosion of a certain amount of an explosive material and the analysis was done involving and taking into consideration the effects of structure and fluid interaction.

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