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Bogdan Szturomski*, Radosław Kiciński*

SIMULATION OF THE IMPACT RESISTANCE OF KILO TYPE SUBMARINE LOADED WITH NON-CONTACT MINE EXPLOSION

ABSTRACT

The paper presents simulations of the state of stress and deformation of the Kilo class submarine hull loaded from pressure wave of non-contact mine explosion. To accomplish the task the finite element method was used. Pressure wave was described by T. L. Geers and K. S. Hunter model. The way of modeling the pressure wave using the acoustic medium implemented to CAE programs was shown. To describe the material an elastic-plastic model of Jonson-Cook which takes into account the speed of deformation was used. The paper presents pressure distribution on the Kilo type submarine hull exposed on 100 kg of TNT explosion load in front of the bow of the ship.

Key words:
impact resistance of the structure, model of the pressure wave, underwater explosion of TNT, acoustic medium.

INTRODUCTION

Short-term analysis of the processes such as the impact of the pressure wave of an non-contact underwater explosion on the hull of the ship or other object submerged in the water is a matter of great complexity, and each task must be treated individually [2, 7, 9, 10, 16]. The task is complicated greatly when it take into account the environment interaction with construction. The ship is located in two mediums: water and air. That requires a careful analysis of coupled task which can be done by using a solution such as the finite element method and boundary

* Polish Naval Academy, Faculty of Mechanical and Electrical Engineering, Śmidowicza 69 Str., 81-127 Gdynia, Poland; e-mail: b.szturomski@amw.gdynia.pl; radzio1407@gmail.com

element method. The solution at the boundary of mediums are the loads on construction ,which deforms, which affects on the surrounding medium. Such mutual coupling is repeated *n* times, and at every step of data exchanges it is necessary to obtain adequate convergence. The problem is complicated due to the plurality of non-linearity related to e.g. a plastic material deformation, destruction, etc. By analyzing the strength of the designed object, using simplification it is possible to use a classical analysis of the structure, without solving the coupled problem because, for steel structures, such as ship, adopts that if the hull can withstand the direct impact on the front of the pressure wave, it can also withstand further loads based on the history of the load resulting from the impact of coupled medium, since the first take extreme values.

THE OBJECT OF THE RESEARCH

The object of the research work is a Kilo class submarine (Project 877E) 'Orzeł' which is in Submarine Squadron of 3 Flotilla in Gdynia. She has a double hull structure. External hull is a droplet-shaped, which is covered with a special made of plastic coating. Internal rigid hull have sufficient diameter to use watertight bulkheads and is divided into double deck structure. In the fore part of the upper deck is 6 torpedo tubes caliber of 533.4 mm. At the stern of the ship's compartment is located an engine room. The drive of the ship consists two main combustion engines, the main electric motor and the reserve of the complex movement. They drive through shaft one — six bladed propeller placed behind a pair of depth planes and rudder. Diesel engines type 42DŁ42M are used to move the ship in emerged position and submerged when snorkel are used [4].

Fig. 1. ORP 'Orzeł' during the operations
[http://navalphotos.blogspot.com/2012_01_09_archive.html (access 24.09.2016)]

Tab.1. Basic tactical-technical date of ORP 'Orzeł' [4]

Length	72.6 m
Beam	9.9 m
High	14.5 m
Draft	6.5 m
Displacement surfaced	2460 t
Displacement submerged	3180 t
Speed surfaced	12 w
Speed submerged	17 w
Economic speed	3 w
Depth of hold	300 m
Propulsion 2 diesel-electric motors	42 DŁ42M — 1700 KM each propulsion motor: PG-141 — 5500 KM, 1 x fixed-pitch 6

DESCRIPTION OF THE TASK USING FEM

If the task would be form in a way that we are only interested in that the design can withstand the load from the non-contact explosion or will be destroyed without investigate the details of the destruction evolution, the task can solved by using the finite element method on an explicite solver by analyzing the basic equation of motion in the form of a matrix

$$\mathbf{M\ddot{U}} + \mathbf{C\dot{U}} + \mathbf{KU} = \mathbf{F}, \tag{1}$$

where:

$\mathbf{K}$ — stiffness matrix;
$\mathbf{M}$ — matrix of inertia (density matrix);
$\mathbf{U}, \mathbf{\dot{U}}, \mathbf{\ddot{U}}$ — displacement, velocity and acceleration vector;
$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}$ — damping matrix, where α and β are constant coefficients [3];
$\mathbf{F}$ — load vector.

Analysis of short-term process enforces a certain specificity of modeling this type tasks, which relates to the description of loads caused by incident pressure wave on the construction. It is also necessary to take into account large deformation (displacement) during analysis and large strain with increased strain rate which follows the strengthening of some materials. If in response in construction occurs stresses that exceed the limit of endurance and we intend to analyze the evolution of the destruction the material description should be supplemented by destruction criteria. Reflecting this phenomenon in terms of the FEM requires solving highly nonlinear equations of motion in the form

$$\mathbf{M}(\mathbf{U})\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}(\mathbf{U}, \dot{\boldsymbol{\varepsilon}})\mathbf{U} = \mathbf{F}(t, R, m_{TNT}), \tag{2}$$

where:

$\dot{\boldsymbol{\varepsilon}}$ — strain rate vector;
t — time;
R — distance from epicenter;
m_{TNT} — mass of TNT.

GEOMETRY OF THE TASK

The geometry of the ship has been reflected as a shell in CAD. The most important elements of the ship, such as strong and light hull, superstructure, bulkheads, frames and torpedo launchers, has been modeled. Reinforcements such as girders has been modeled by as beam-rod elements. Geometry has been stripped of all mechanisms replacing them with equivalent point mass applied to the nodes which made the condition of equality of the total weight of the submerged ship's and compatibility of the center of gravity. After discretization model contains 141696 degrees of freedom.

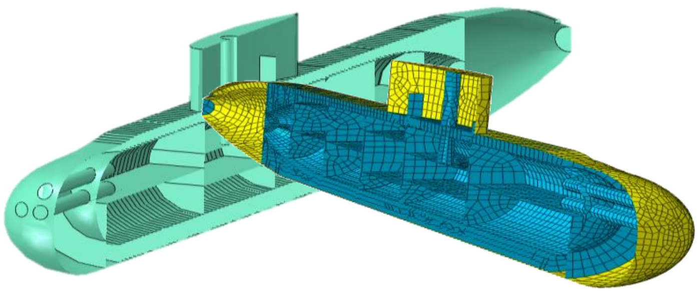

Fig. 2. Geometry and discretization of submarine [own work]

UNDERWATER EXPLOSION

The explosion is the process of rapid burning and pressure increasing occurring of explosives which takes milliseconds [6, 12, 16], which in water generate gas bubble. The overpressure in the epicenter of the explosion depends on type of material and reaches a value about 10 000 MPa (for TNT). The expanding gas bubble interacts with the surrounding water layer forming a spherical shock wave. This wave in the initial stage moves at a speed of $v \approx 5000$ m/s. Then, the water molecules act on the adjacent layer of water and lose speed and travel further on the speed of sound in water, which is approximately $c_o \approx 1500$ m/s. With the arrival of the wave front pressure increases rapidly up to a maximum value called the peak overpressure positive. Then the pressure drops to the initial pressure (fig. 3) [6, 12]. The period of a further drop in pressure and its return to the hydrostatic pressure is called the period of negative phase.

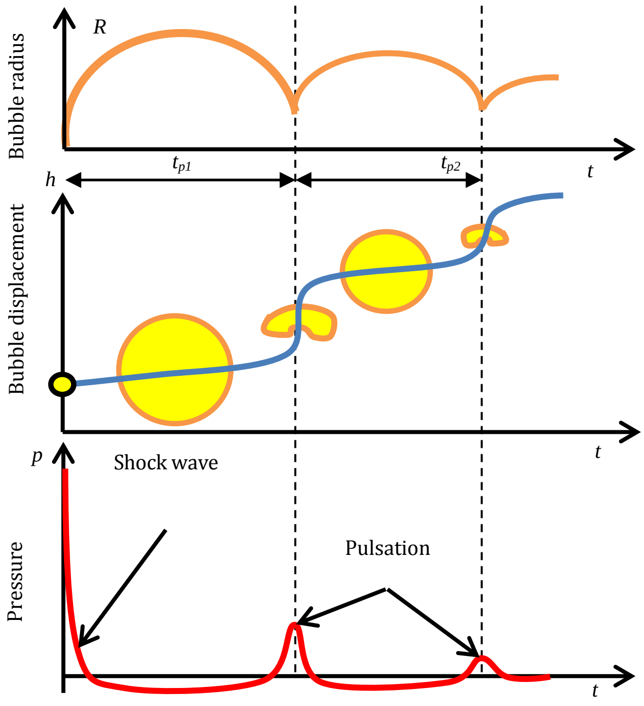

Fig. 3. Diagram of underwater explosion [12]

$$p(t) = 52.3\left(\frac{\sqrt[3]{m}}{R}\right)^{1.13} \cdot e^{C};$$

$$C = \frac{-t \cdot 1000}{0.093 \cdot \sqrt[3]{m}\left(\frac{\sqrt[3]{m}}{R}\right)^{-0.22}}. \tag{3}$$

Profile of the pressure wave, and its value described by many researchers. The main of them is R. H. Cole, who based on experiments conducted gave empirical formulas which describe the pressure in time as a function of distance from the epicenter and detonated weight load [5].The problem of underwater explosion is described also by other authors [8, 14, 15]. In this paper the pressure on the front of the shock wave is described by a function of distance and weight of the TNT gives by T. L. Geers and K. S. Hunter (fig. 4).

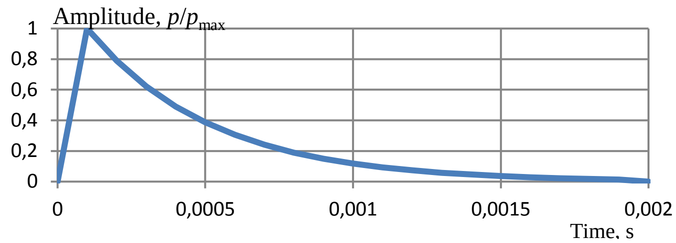

Fig. 4. T. L. Geers and K. S. Hunter pressure wave description [8]

Time appearing in the model is calculated from the time of the wave pressures is given at a point of space and it does not include transit time wave from the epicenter. Thus, setting the load for the structure element, move the time of value t_R, which is:

$$t_R = {}^{R}/_{c_o}; \tag{4}$$

where:

t_R — time of reaching the pressure wave on the element [s];

R — distance between epicenter and element [m];

c_o — speed of sound in medium [m/s].

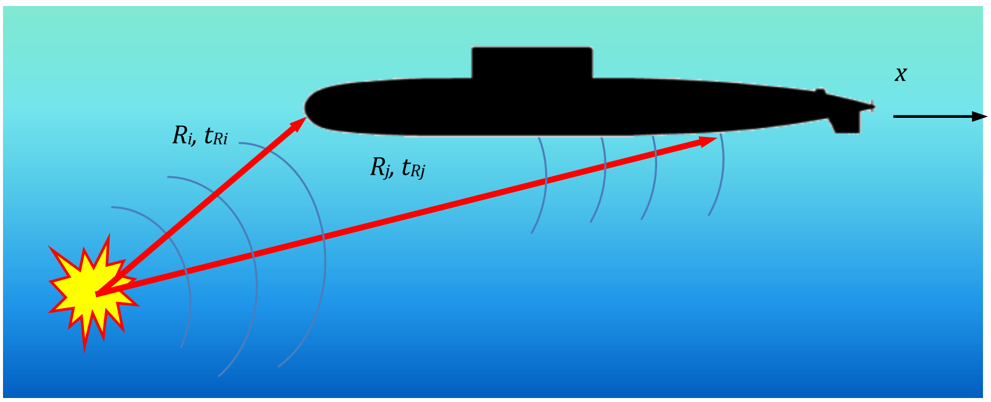

Fig. 5. Distance between elements of hull and epicenter and the wave transition time [10]

Taking into account the velocity of the pressure wave in the water which is approximately 1500 m/s for the Kilo-class submarine the total duration of the load on the structure is 0.048 s. If we consider the detonation charge of 250 kg TNT, detonated at a depth of 15 m with a 20 m ahead the maximum overpressure peak value reaches 11 MPa and decreases along the ship to 2 MPa (fig. 6).

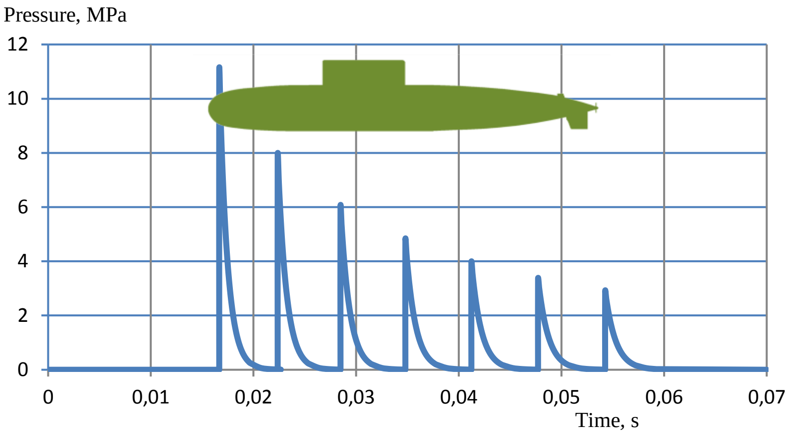

Fig. 6. Pressure wave propagation along the length of the ship, detonation at a distance of 20 m, at a depth of 15 m, weight of TNT 250 kg [own work]

MATERIAL DESCRIPTION

The material in the task was modeled as elastic-plastic including strain ratio. The submarine has two hulls and it was assumed that the rigid hull was made by HY-100 steel, while for the light hull steel HY-80 was used. Plastic part of both characteristics was described using polynomial given by Johnson-Cook [11]:

$$\boldsymbol{\sigma} = (\boldsymbol{A} + \boldsymbol{B}\boldsymbol{\varepsilon}^{\boldsymbol{n}})\left(\mathbf{1} + \boldsymbol{Cln}\left(\frac{\dot{\boldsymbol{\varepsilon}}}{\dot{\boldsymbol{\varepsilon}}_{\mathbf{0}}}\right)\right)\left(\mathbf{1} - \frac{\boldsymbol{T}-\boldsymbol{T}_{\mathbf{0}}}{\boldsymbol{T}_{\boldsymbol{m}}-\boldsymbol{T}_{\mathbf{0}}}\right)^{\boldsymbol{m}}, \tag{5}$$

where:

σ — stresses in material;

A — yield point;

B — strain-hardening coefficient;

ε — effective strain;

n — strain-hardening exponent;

C — the sensitivity coefficient of the material strain rate;

$\dot{\varepsilon}$ — effective strain rate;
$\dot{\varepsilon}_0$ — for steel assumed 1 s^{-1};
T — the temperature at which the material will operate;
T_0 — ambient temperature;
T_m — melting temperature;
m — exponent softening under heat.

The task does not include the temperature parts of J-C equation, assuming that for the non-contact TNT explosion the deformation of the hull will proceed at ambient temperature. For calculations, the following polynomials were accepted for HY-80 steel:

$$\sigma = (672 + 425\varepsilon^{0,36})\left(1 + 0{,}14 ln\left(\frac{\dot{\varepsilon}}{0{,}0001}\right)\right); \quad (6)$$

for HY-100 steel:

$$\sigma = (758 + 402\varepsilon^{0,26})\left(1 + 0{,}11 ln\left(\frac{\dot{\varepsilon}}{0{,}0001}\right)\right). \quad (7)$$

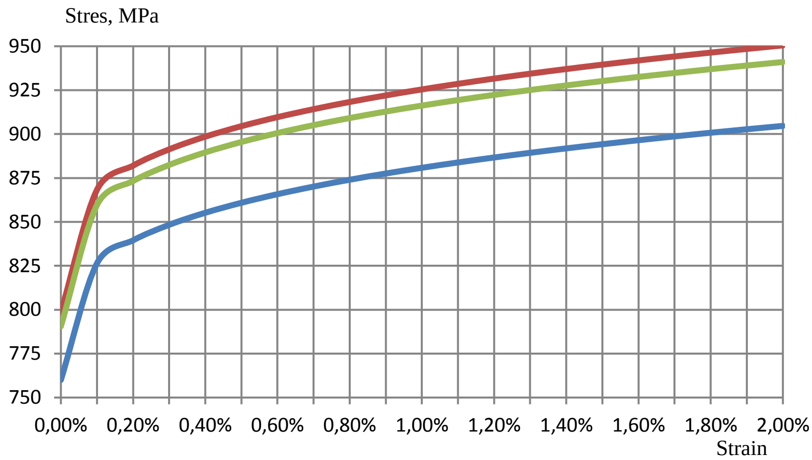

Fig. 7. J-C characteristics for HY-100 steel [own work]

Other properties of both steels are:
- young modulus E = 207 GPa;
- poisson ratio υ = 0,3;
- density ρ = 7746 kg/m^3.

EXPLOSION OF 100 KG TNT ON A FRONT OF A BOW

Submarine has been exposed to the incident pressure wave on the front of the bow. The maximum value in the vicinity of the bow was about 6.3 MPa, while at the superstructure, it decreased to 1.6 MPa. Loading time was 7.1 ms. Acoustic pressure distribution in the water during explosion of charge of 100 kg TNT on the front of the bow at distance 25 m and depth of 20 m in the selected time points is shown in figure 8.

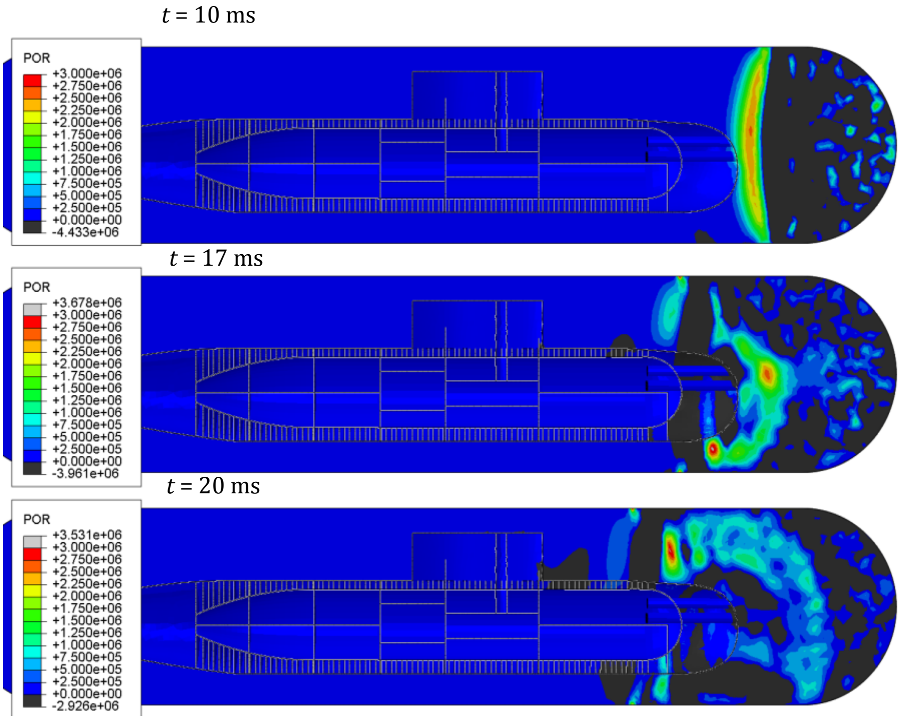

Fig. 8. Acoustic pressure distribution during explosion on a front of a bow [own work]

Reduced stress distribution by hypothesis Huber-Mises-Hencky (HMH) is shown at figure 9. The maximum values, which amounted to 857 MPa, were obtained behind the superstructure. While analyzing generated by the program algorithm mesh concluded that the stress arising because of inaccurate mesh. Accordingly, the highest stresses was recorded on torpedo hatches. Their value was 764 MPa.

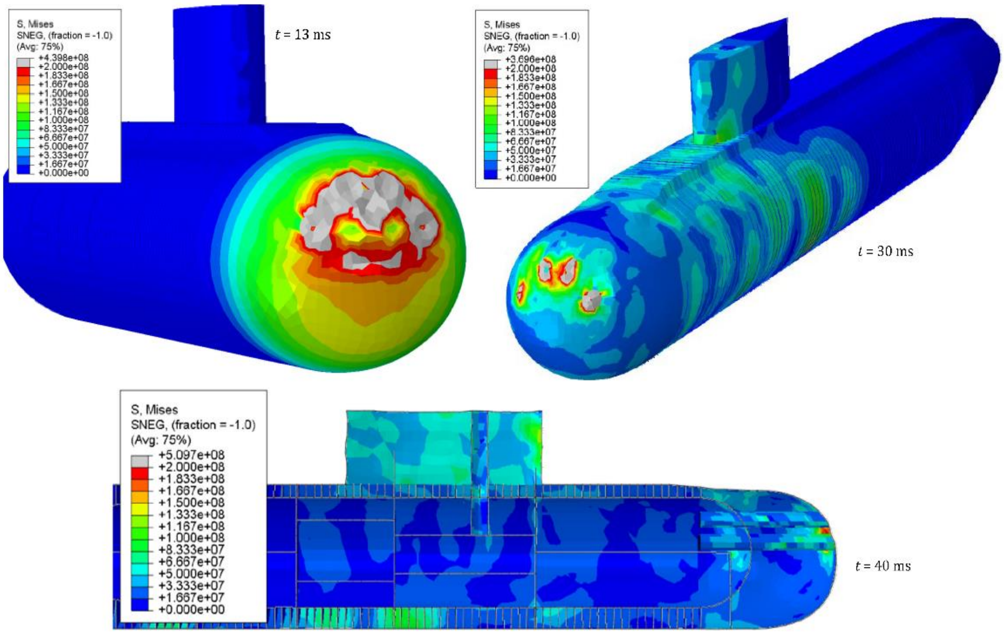

Fig. 9. Reduced HMH stresses at selected time points [own work]

CONCLUSIONS

In the paper impact resistance of the hull of the Kilo type submarine loaded by pressure wave from the non-contact mine explosion using FEM was analyzed. The results of stress distribution on the hull caused by explosion of charge of 100 kg TNT in front of the bow on the basis of which it was found that she should survive the effects of such explosion without major losses. Reduced HMH stresses in the construction of the hull of the ship does not exceed the yield strength. In carrying out numerical simulations, it was found that the acoustic medium in which pressure wave propagated is very sensitive to discretization and element size. Prior to the hull structure stress analysis it have to be carried out simulation of the pressure wave propagation and proper element size must be chosen, to obtain a correct distribution at checkpoints that will be similar to the solutions or analytical experiments.

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SYMULACJA WYTRZYMAŁOŚCI KADŁUBA OKRĘTU PODWODNEGO TYPU KILO OBCIĄŻONEGO FALĄ CIŚNIENIA OD NIEKONTAKTOWEGO WYBUCHU MINY

STRESZCZENIE

W artykule przedstawiono symulacje stanu naprężenia i deformacji kadłuba okrętu podwodnego klasy Kilo obciążonego falą ciśnienia od niekontaktowego wybuchu ładunku TNT. Do rozwiązania zadania wykorzystano metodę elementów skończonych. Fala ciśnienia została opisana wzorami T. L. Geersa i K. S. Huntera. Pokazano sposób modelowania fali ciśnienia przy użyciu ośrodka akustycznego realizowanego w programach CAE. Do opisu materiału użyto modelu elastyczno-plastycznego Jonsona-Cooka, który uwzględniał prędkość odkształcenia. Scharakteryzowano rozkład ciśnienia na kadłubie okrętu podwodnego typu Kilo od wybuchu 100 kg TNT przed dziobem.

Słowa kluczowe:

odporność udarowa konstrukcji, model fali ciśnienia, wybuch TNT w wodzie, ośrodek akustyczny.