Strength Analysis of the Marine Weapon's Construction

Analiza čvrstoće konstrukcije oružja ratne mornarice

Stanisław Milewski
Navigation and Naval Weapons Faculty
Polish Naval Academy
Gdynia
E-mail: s.milewski@amw.gdynia.pl

Bogdan Szturomski
Mechanical and Electrical Engineering
Department, Polish Naval Academy
Gdynia
E-mail: b.szturomski@amw.gdynia.pl

Radosław Kiciński
Mechanical and Electrical Engineering
Department, Polish Naval Academy
Gdynia
E-mail: r.kicinski@amw.gdynia.pl

DOI 10.17818/NM/2021/3.4
UDK 623.8./.9 :621.8
Preliminary communication / *Prethodno priopćenje*
Paper accepted / *Rukopis primljen:* 12. 3. 2021.

Summary

Due to the modernization of warships, it was necessary to carry out strength calculations for the newly assembled devices, for which there were no detailed technical requirements. The authors try to present and harmonize the requirements for naval military structures. The lack of experimental verification of newly built systems was indicated. Therefore the finite element method was used to determine the durability of the critical design elements. There is no explicit reference load in the literature, so the authors present a general solution to one of the worst cases. The work presents the cannon structure elements exposed to damage during the underwater explosion load, using the proposed methodology. The proposed method is sufficient to calculate individual ship cases. However, in the case of hull strength analysis, more complex algorithms should be used.

KEY WORDS

ship
sea cannon
structural analysis
strength and resistance to mechanical damage
underwater explosions

Sažetak

Modernizacijom ratnih brodova pojavila se potreba izračuna čvrstoće novougrađenih uređaja, za koje nije bilo detaljnih tehničkih zahtjeva. Autori ovoga rada pokušali su predstaviti i uskladiti te zahtjeve za strukture u ratnoj mornarici. Ukazano je na nedostatak provedbe eksperimenata koji bi potvrdili valjanost novougrađenih sustava. Stoga je za određivanje trajnosti kritičnih elemenata dizajna upotrebljena metoda konačnih elemenata. U literaturi nema dostatno relevantnih podataka, stoga autori iznose opće rješenje za jedan od najozbiljnijih slučajeva. Rad opisuje elemente topovske strukture izložene oštećenju uslijed podmorske eksplozije, uporabom predložene metodologije. Predložena metoda dostatna je za izračun individualnih slučajeva. Međutim, u slučaju analize čvrstoće trupa, trebalo bi koristiti kompleksnije algoritme.

KLJUČNE RIJEČI

brod
morski top
strukturna analiza
čvrstoća i otpornost na mehaničko oštećenje
podmorske eksplozije

1. INTRODUCTION / *Uvod*

The design and construction of weapons are the subjects of interest and activity of many research and industrial centres worldwide [1]the density of which would be close to the lead density 11.3 Mg/m3. This material should also meet the requirements for ammo bullet cores. In order to check...”,”container-title”:”Advances in Science and Technology. Research Journal”,”DOI”:”10.12913/22998624/115515”,”ISSN”:”2080-4075, 2299-8624”,”issue”:”1”,”journalAbbreviation”:”Adv. Sci. Technol. Res. J.”,”language”:”en glish”,”note”:”publisher: Polish Society of Ecological Engineering (PTIE. For various reasons, it is in the Armed Forces' good to have domestic-made weapons. In Poland, an example of such action is, among others, the prototype of the 35 mm Ship Weapons System (OSU-35), which was designed and built as a result of the implementation of a development project co-financed by the National Center for Research and Development (NCBiR) [2]. Ultimately, the OSU-35 set is dedicated to the Polish Navy as the primary artillery armament of the Kormoran II minehunter. The main purpose of OSU-35 is a direct defence of a ship against lightly armoured air, surface, and shore threats.

The 35 mm Ship Weapon System consists of four autonomous modules: Integrated Tracking Head (ZGS-158M), 35 mm KDA type naval cannon, Multifunctional Operation Console (marked in the system as P-SKO), columns for mounting reserve gun sights - marked in weapon system as R-SKO (Fig. 1). The sea cannon, which is part of the OSU-35, is its primary element and is designed to fire 35 mm FAPDS-T and TP-T artillery shells. The Fire Control System developed the gun settings based on data on target movement location and factors in the primary type of work. Those data are obtained from the ZGS-158M tracking head and other, determining shooting conditions - obtained from a multi-sensor data collection system, included in the system, e.g ., an artillery weather station, an IMU (Inertial Measurement Unit) cannon position sensor or a projectiles counter. The operator controls the system's operation using the console equipment interface (P-SKO) and dedicated software containing, among others, the Fire Control algorithm (KO) and the cannon condition control algorithm.

If a ZGS-158M or P-SKO failure fails, it is possible to operate the defence system in the backup type of work with a preliminary target indication for the ZGS-158M. The guidance and fire control of the 35 mm cannon can also be carried out using the R-SKO operated manually by the operator. The direction of the flow of control signals in both system operation types is illustrated in Fig. 1.

During the project implementation, the ORP KASZUB warship was dedicated and used to test the OSU-35 prototype. It is a missile corvette that has been in the forces of the Polish Navy since 1987. The ship was built at the Northern Shipyard Heroes of Westerplatte in Gdansk. It is designed to search for and destroy submarines. The ship can protect teams of landing ships, transport, and other ships. The ship is adapted to operate in the Baltic Sea and the North Sea's meteorological conditions, with the possibility of sailing on crushed ice [3].

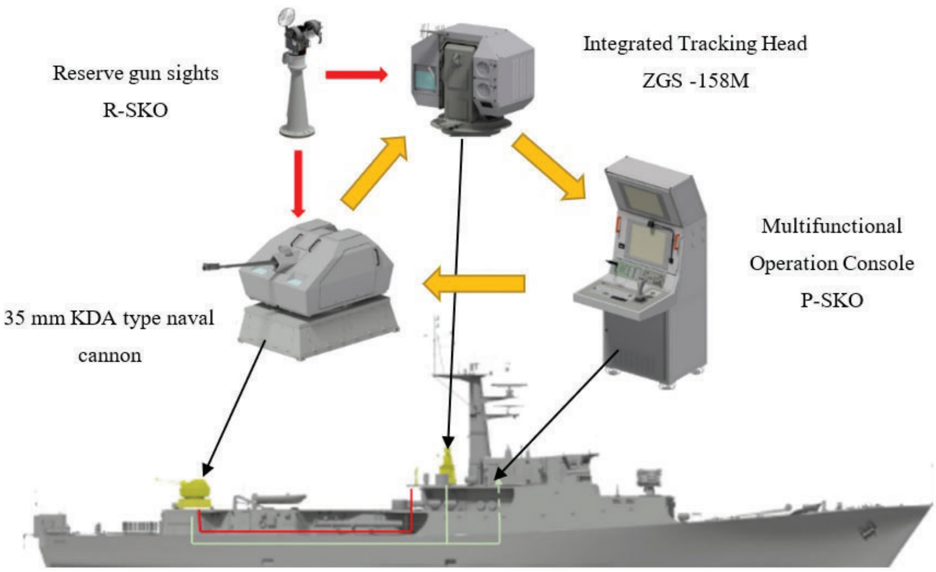

Figure 1 Arrangement of OSU-35 elements on the ORP Kaszub ship and system functionality
Slika 1. Prikaz OSU-35 elemenata na ORP Kaszub brodu i funkcionalnost sustava
Source: Project No. *O ROB 0046 03 001*

The installation and testing of the OSU-35 functionality on the ship confirmed that one of the foremost tactical and technical requirements was met—the requirements related to the designed weapon system's autonomy, modularity, and scalability. As a result, it is possible to adapt it to various ships, both newly built and modernized, with different operating conditions [4].

2. DESIGN OF THE SHIP'S WEAPON SYSTEM / *Dizajn brodskog sustava naoružanja*

Apart from the basic tactical requirements, each weapon system must meet several technical needs resulting from the operating conditions installed onboard the ship. Technical assumptions and standards [5,6]"issued":{"date-parts":[["1976"]]}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} define the permissible values of mass and dimensions parameters and features, ensuring ergonomic and safe operation of the system on a limited area, such as the ship's deck. Due to its large dimensions and significant weight of 675 kg [7], the system's crucial element is the 35 mm KDA gun. The gun was placed on a unique steel structure that uses servos for the gun guidance and control signals developed by the fire control system. Additionally, for operation in the marine environment, the gun has a housing made of composite. Fig. 2 shows a photo of the 35 mm cannon that is part of the OSU-35 prototype mounted on the ORP KASZUB warship.

The gun consists of two primary assemblies: the foundation and the rotating unit (Fig. 3). The foundation is a fixed part of the cannon mounted to the ship's deck in which a power supply and control blocks and safety elements are placed. The top surface of the foundation, on which the monoblock bearing with a toothed ring has been built, constitutes the rotary unit's mounting surface.

The rotary unit structure consists of the upper and lower cradles, which are mounted: a pivot assembly with a cradle, KDA artillery automatic machine, lifting control system, ammunition supply systems, and accessories and actuators enabling maintenance-free and automatic operation of the

Figure 2 35 mm sea cannon mounted on board ORP KASZUB
Slika 2. 35 mm pomorski top montiran na brodu ORP KASZUB

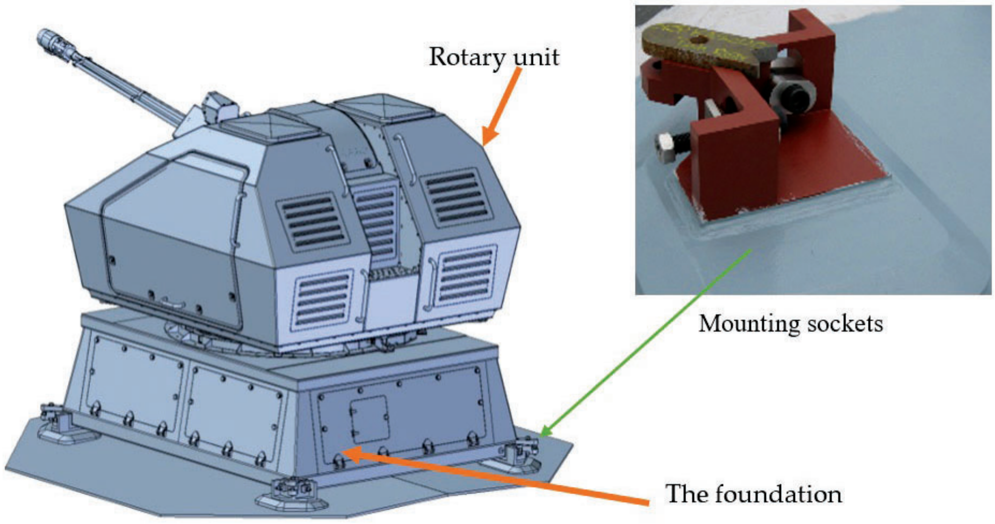

Figure 3 Method of mounting the foundation to the ship's deck
Slika 3. Metoda montiranja podnožja na palubu broda

Source: Project no. *O ROB 0046 03 001*

cannon. For the cannon assembly on the ORP KASZUB ship, the concept of a rotary unit on a foundation was adopted, the corners of which are attached to properly prepared mounting sockets on the deck. The cannon structure must meet several strength requirements under various load conditions. The variety of loads results from the needs of operation at sea and combat operations. All devices installed on the ship are exposed to shock effects caused by, e.g. non-contact explosion of a mine or torpedoes in the water. This approach is also defined by standards [5,6]"issued":{"date-parts":[["1976"]]}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} . Due to the project's prototype nature, the finite element method implemented in CAE programs was used to analyze the strength of the cannon structure.

Since there is no ready solution to mounting the ship's armament system, it was necessary to refer to the technical requirements based on defence standards and regulations of classification societies such as PRS (Polish Register of Shipping), DNV (Det Norske Veritas), etc.

3. DISCRETIZATION OF THE WEAPON SYSTEM STRUCTURE / *Diskretizacija strukture sustava naoružanja*

The task was calculated using the Abaqus CAE software. The problem was solved by loading the gun with inertia forces from the set accelerations (d'Alembert forces), taking into account the materials' plastic characteristics the gun components. Mainly linear quadrilateral 4-node and triangular 3-node triangular elements and 8-node and tetragonal 3-node tetragonal solid elements in critical places were used. In total, the model consisted of 84,459 elements.

For numerical simulation purposes, individual parts of the cannon structure have been represented as shell and solid models [8–11]. During the geometry creation, appropriate geometric simplifications of the details were applied that do not affect the structure's overall strength. These parts were divided into linear triangular and rectangular shell elements and tetragonal and hexagonal solid elements first-order elements. The components prepared in this way, using connectors and interactions, were combined into subassemblies intended for further, comprehensive analysis (Fig. 4).

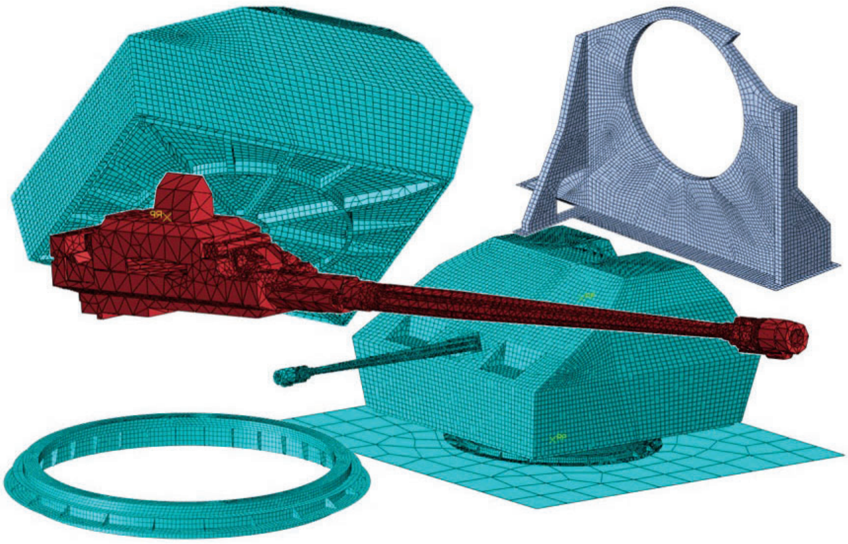

Figure 4 Selected canon elements and their discretization
Slika 4. Odabrani elementi topa i njihova diskretizacija

4. SHIP'S WEAPONS SYSTEM STRUCTURE LOAD / *Opterećenje strukture brodskog sustava naoružanja*

To determine the distribution of reduced stresses in the analysed gun assembly structures, one should refer to a given reference load. When considering marine armaments' operation, one should refer to the worst possible variant: the load caused by a non-contact underwater explosion. [12, 13].

An explosion is a violent combustion process with pressure build-up in fractions of a millisecond [14–17]. The nature of this process is determined by the dynamic conditions in which the explosive mixture is located, particularly the turbulence of the medium. Pressure waves, called shock waves, occurring during an explosion in liquids (underwater explosion) or solids, can reach up to 8000 m / s in the case of detonation. The expanding gas bubble acts on the surrounding water layer creating a spherical shock wave. In the initial phase, during detonation, this wave travels at a speed of v ≈ 5000 - 8000 m / s [18]. Then the water molecules act on the adjacent water layers losing velocity and move further at the speed of sound in the water, which is approximately every ≈ 1500 m / s. Many researchers have described the pressure wave profile and its value. The main one is R.H. Cole, whose publications form the basis of much research on the subject. The problem is also described by other authors [13,19–22]. The criterion for the division of the degree of threat is also blurred, as described in work [23]and thousands of service members and civilians were injured or killed by underwater blast during WWII. The prevalence of underwater blast injuries and occupational blasting needs led to the development of many safety standards to prevent injury or death. Most of these standards were not supported by experimental data or testing. In this review, we describe existing standards, discuss their origins, and we comprehensively compare their prescriptions across standards. Surprisingly, we found that most safety standards had little or no scientific basis, and prescriptions across standards often varied by at least an order of magnitude. Many published standards traced back to a US Navy 500 psi guideline, which was intended to provide a peak pressure at which injuries were likely to occur. This standard itself seems to have been based upon a completely unfounded assertion that has propagated throughout the literature in subsequent years. Based on the limitations of the standards discussed, we outline future directions for underwater blast injury research, such as the compilation of epidemiological data to examine actual injury risk by human beings subjected to underwater blasts.","container-title":"Diving and Hyperbaric Medicine","ISSN":"1833-3516","issue":"3","journalAbbreviation":"Diving Hyperb Med","language": "eng","note":"PMID: 26415071","page":"190-199","source":"PubMed","title":"Underwater blast injury: a review of standards","title-short":"Underwater blast injury","volume":"45","author":[{"family":"Lance","given":"Rachel M."},{"family":"Bass","given":"Cameron R."}],"issued":{"date-parts":[["2015",9]]}}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} . Since the explosion is an unpredictable phenomenon, individual countries refer to the standards [5,6]"issued":{"date-parts":[["1976"]]}}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} . As the explosion acts directly on the ship's hull, it is necessary to apply an equivalent load in the form of a kinematic input to the gun base. The deck on which the gun rests has been modelled as a perfectly stiff body, with appropriate accelerations. In the case of structures intended for use in the Polish Navy, the inputs are the appropriate acceleration values described in [5]. According to the standard, it is assumed that for devices rigidly fixed to the foundation with a mass *m* > 200 kg, the shock acceleration graph has the shape of a full sinusoid or an unsymmetrical sine wave. The maximum acceleration of a symmetrical sinusoidal pulse shall be calculated from the formula:

$$a_{\mathrm{m}} = \frac{2 \cdot \pi \cdot \gamma \cdot v_0}{\tau}, \mathrm{m/s^2} \qquad (1)$$

where

a_m - maximum acceleration

v_0 - initial speed of the base, v_0 = 2,58 m/s

τ - duration of a symmetrical sinusoidal pulse, which should be calculated according to the formula:

$$\tau = 0{,}0028 \cdot m^{0{,}24}, s$$

γ - coefficient calculated according to the formula:

$$\gamma = \begin{cases} 1 & m \le 200 \;\; kg \\ 2{,}2 m^{-0{,}15} & 200 \;\; kg < m < 20000 \;\; kg \\ 0{,}5 & m \ge 20000 \;\; kg \end{cases}$$

m - the mass of the device

Substituting numerical values into formula (1) it takes the form:

$$a_{\mathrm{m}} = 16.2 \frac{\gamma}{\tau}, \mathrm{m/s^2} \qquad (1)$$

Additionally, according to the standard, the following designations of the directions of the coordinate system are assumed:

- x - the direction determined by the intersection of the waterplane plane and the planeship symmetry (along with the ship);
- y - the direction determined by the intersection of the waterplane plane and the midships plane the ship (across the ship);
- z - the direction determined by the intersection of the midships plane and the symmetry plane of the ship (vertically).

However, depending on the place of installation, the device is divided into three groups:

- A - devices at the level of the second bottom and bulkheads near their centre, not closer than 2 m from the side;
- B - devices on the ship's sides and underwater decks as well as on bulkheads within a distance of 2 m from the side;
- C - equipment on decks, platforms, superstructures and masts.

Depending on the device's location and the direction of the impact, the specified acceleration values should be multiplied by an appropriate factor (Tab. 1).

Table 1 Values of the acceleration multiplier for surface ships depending on the direction of the impact

Tablica 1. Vrijednosti multiplikatora ubrzanja za površinske brodove ovisno o smjeru udara

	Load direction		
Device class	x	y	z
A	1/6	1/2	1
B	1/6	1	1
C	1/6	1/2	1/2

The arms inspectorate, based on the standard, determined the parameters which are respectively (Fig. 5):

- a_x = 85 m/s² during 10 ms – along the ship's axis
- a_y = 250 m/s² during 8 ms – transversely to the ship's axis
- a_z = 500 m/s² during 5 ms – vertical

Calculations should be performed in the time interval equal to 0 ÷ 0.04 s (40 ms).

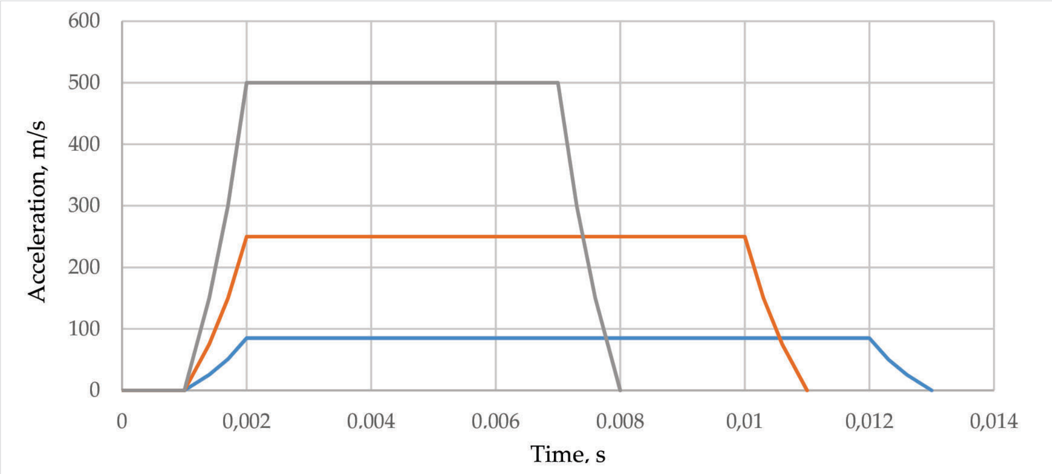

Figure 5 Kinematic load of the OSU-35 gun [5]
Slika 5. Kinematičko opterećenje OSU-35 oružja [5]

5. MECHANICAL PROPERTIES OF OSU-35 CONSTRUCTION MATERIALS / *Mehanička svojstva OSU-35 konstrukcijskih materijala*

The structural elements of the weapon system are made of various materials. These are steels of higher quality, construction steels, non-ferrous metal alloys, plastics, composites, etc.[2]. For CAE strength calculations, it is necessary to know the mechanical properties such as density, Young's modulus, Poisson's ratio, yield point and strength. To obtain those data, a series of static tensile tests were performed. For the simulation, plastic characteristics of materials were determined, which were described by constitutive equations presented by the simplified (neglecting the temperature term and strain rate) Johnson-Cook equation [24]:

$$\sigma_{pl} = A + B\varepsilon_{pl}^{n} \tag{1}$$

where:

A, B, n – material constants;

σ_{pl} – plastic stress;

ε_{pl} – plastic strain.

Due to the project's military (classified) nature, the results of all tests and material models used cannot be presented in this article. An example of the characteristics of one of the materials used (high-quality steel) is shown in Fig. 6.

6. CONSTITUTIVE EQUATION / *Konstitutivna jednadžba*

Under certain operating conditions, the weight of the machines may constitute a dangerous load on the structure. Machine elements always work in the field of gravity. Thus they are loaded with their weight. This load is constant and can be ignored for many static problems. In dynamic situations, where machine elements experience significant acceleration values, mass loads can lead to failure in improperly designed structures. The leading cause of high-value accelerations is shock loads caused by a sudden change in speed resulting from a collision with another object or the impact of a pressure wave generated by an explosion. In the analysed case, the acceleration source is the effect of the pressure wave from the non-contact explosion of an underwater explosive charge, e.g. a sea mine, torpedo, etc. The source of acceleration is rotation. Rotating machine elements, such as the ship's propeller shafts, rotors of electric motors, crankshafts, connecting rods of combustion engines, gas turbines, and many other devices, reach speeds of up to tens of thousands of revolutions per minute. During rotation, machine elements are in the field of centrifugal forces, represented by average acceleration [10]:

$$\begin{gathered} \boldsymbol{a} = \boldsymbol{a_x} + \boldsymbol{a_y} + \boldsymbol{a_z} \\ \boldsymbol{a_n} = \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r}) \end{gathered} \tag{2}$$

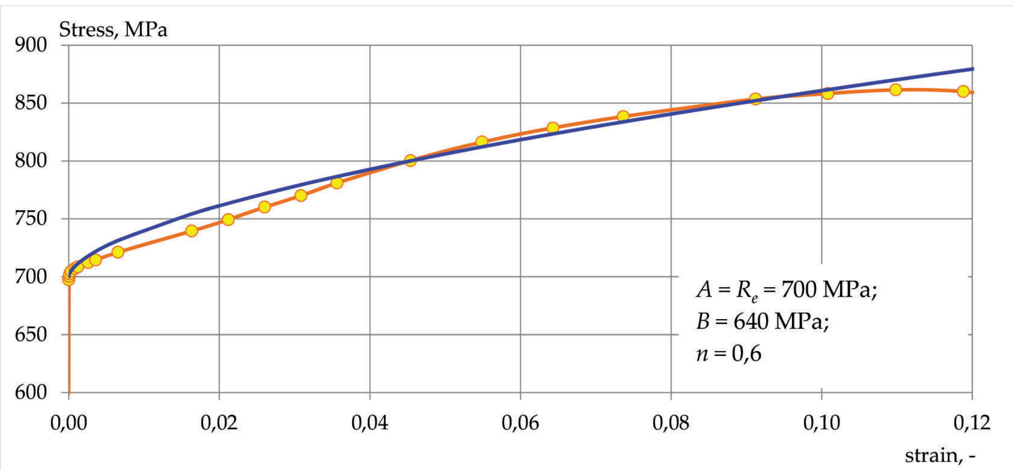

Figure 6 Plastic characteristics of the material given by the machine (red) and the Johnson-Cook model (blue)
Slika 6. Plastične karakteristike materijala koje izbacuje stroj (crveno) i Johnson-Cook model (plavo)

where:

$\boldsymbol{a} = \boldsymbol{a_x} + \boldsymbol{a_y} + \boldsymbol{a_z}$ – components of linear accelerations;

$\boldsymbol{\omega}$ – angular velocity vector;

$\boldsymbol{r}$ – radius vector.

According to the above equation, the mass (centrifugal) loads depend not only on the value of the angular velocity ω, but also on the distance from the axis of rotation r. For this reason, in large-size structures, in elements extremely distant from the axis of rotation, relatively high values of centrifugal acceleration may occur, even at low speeds. Such an object is a ship that heels, heave and pitch due to the sea waves that lead to rotation about all three axes. In practical analyses where the occurring accelerations or the speed of rotating machine elements is constant, especially where the axis of rotation is constant and the rates are fixed in time, a static problem is solved. There is then a complete analogy between fixed rotation and uniform rectilinear motion. The load is, therefore, the mass and centrifugal forces added to the static loads.

Besides, the task considers the plastic characteristics of materials and large deformations, which affect the constitutive equation. The constitutive matrix equation then takes the form [10,12]:

$$\mathbf{K}(\mathbf{U}, \varepsilon_{pl})\mathbf{U} = \mathbf{F} + \mathbf{M}[\boldsymbol{a} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r})] \qquad (3)$$

where:

M – mass matrix;

$\mathbf{K}(\mathbf{U}, \varepsilon_{pl})$ – nonlinear stiffness matrix taking into account plastic properties of materials and deformations;

U – displacement vector;

F – load vector.

7. FEM SIMULATION RESULTS / *Rezultati FEM simulacije*

Several simulations using the explicit dynamic method were carried out following the methodology's load [5]. The states of displacements, strains, stresses, and motion parameters were obtained. The Polish defence standard does not specify precise endurance guidelines. Other standards allowing the use of FEM for the analysis of this type of structure was used. According to the shipbuilding regulations for Bundeswehr 0430 (Schocksicherheit Experimenteller und rechnerischer Nachweis für Überwasserschiffe und Uboote), the stresses due to shock loading must not normally exceed the static yield point. Only where limited plastic deformation of the foundation does not affect the device's efficiency, the theoretical stress may exceed the static yield point. So, the Huber-Mises-Hencky (HMH) reduced stresses [24] is the most crucial parameter. The extreme

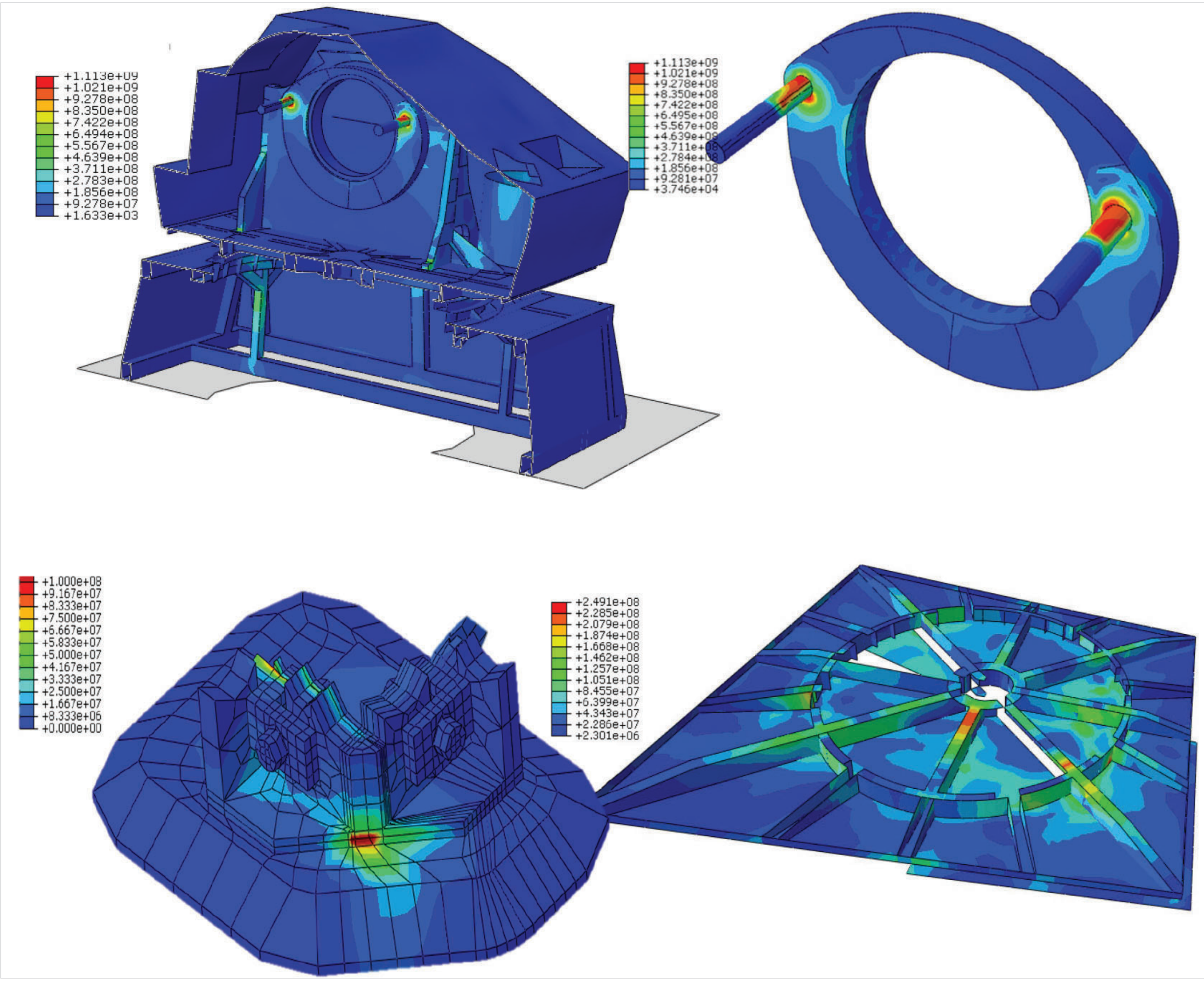

Figure 7 HMH extreme stresses (Pa) in selected elements of the cannon structure

Slika 7. HMH ekstremna naprezanja (Pa) na odabranim elementima strukture topa

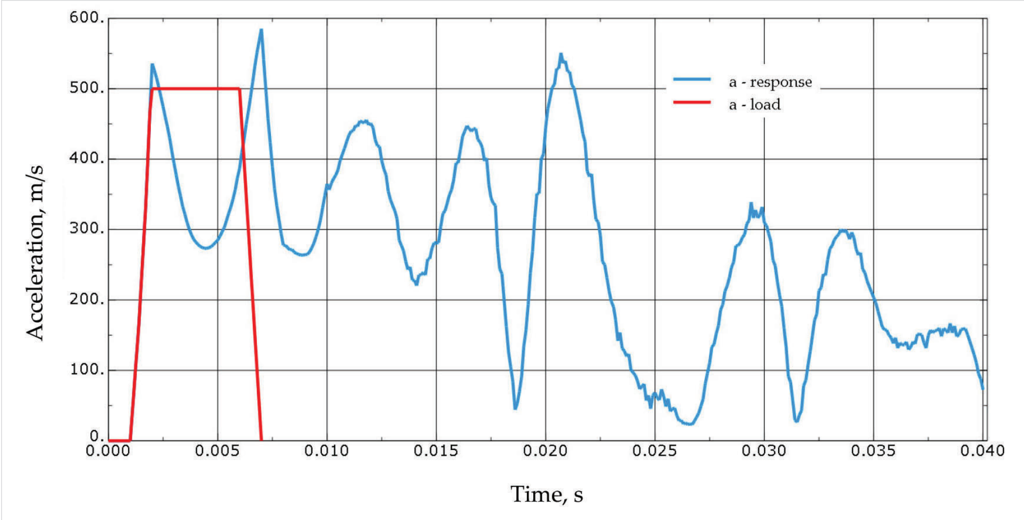

Figure 8 The acceleration values of the model as a reaction to the kinematic load in the gun base
Slika 8. Vrijednosti ubrzanja modela kao reakcija na kinematsko opterećenje u bazi oružja

values of these stresses for selected elements of the OSU-35 structure are shown in Fig. 7.

Based on the simulations, it was found that the geometry was modelled correctly because the load was transferred to all structural elements. Moreover, most elements of the cannon structure can withstand the given load. Particular attention should be paid to the gun bed, as it is exposed to the highest loads. Mounting the cannon to the ship's deck should withstand the designed load. Other observations concerning the cannon construction cannot be disclosed due to the military nature of the work. However, they were used to modernize the cannon structure, making it more resistant to loads caused by the non-contact explosion.

Another important aspect is the acceleration values in the construction of the cannon. The reaction of the model base on the kinematic excitation caused by acceleration is shown in Fig. 8. The figure shows that in the initial phase, the load and the structure response coincide, however, after about 1 ms, the base acceleration decreases, and then its value above the set value increases due to inertia cannon construction. Then the accelerations in the base oscillate according to the vibration theory [25] and approach zero. The acceleration wave in the structure did not manage to return to the bottom in the considered loading time of 40 ms.

From the results of the calculations, it was noticed that in the middle of the height of the armament system, there is an accelerations concentration caused by the kinematic load accumulation from the inertia structural response forces. At this point, the resonance causes the acceleration values to be even several times greater than in the load. The above thesis is also confirmed by the location of the node where the greatest displacements were noticed. Fig. 9 shows the displacements of the base and displacements in the node. The diagram shows that this node moves in the direction opposite to the acceleration in the initial phase, which is the result of the mass inertia of the gun.

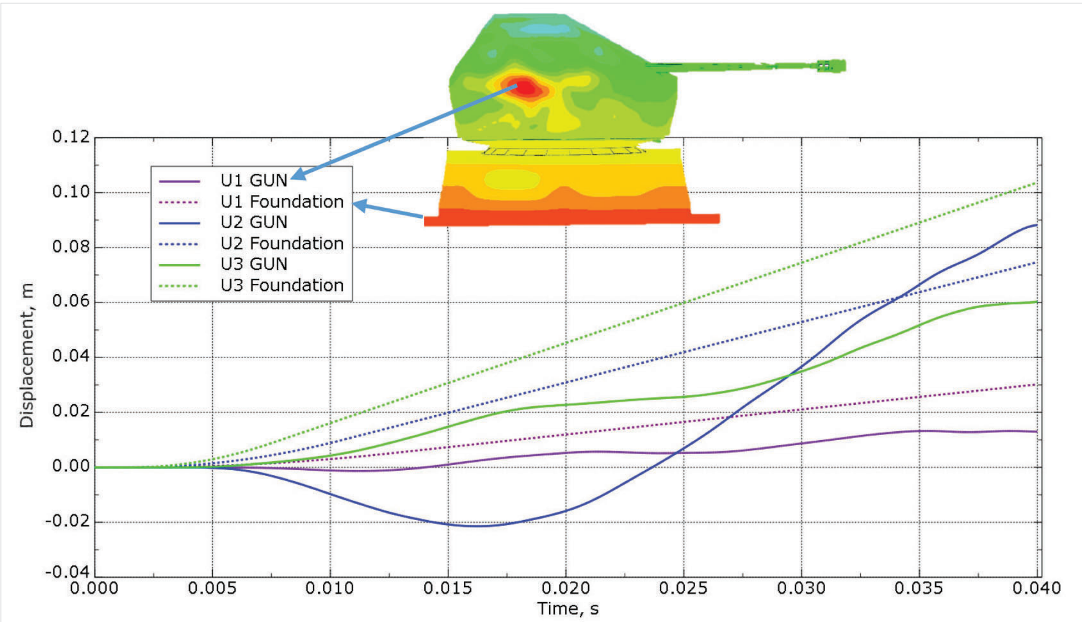

Figure 9 Displacements in the base and in the node where their maximum values occur
Slika 9. Istisnine u bazi i na čvoru gdje se javljaju njihove maksimalne vrijednosti

8. CONCLUSIONS / *Zaključci*

Computer simulations of the impact of the non-contact explosion, set as a kinematic load in the form of an acceleration pulse with parameters included in the methodology [5], enable the assessment of the construction's correctness of the Ship's Weapons System. The obtained results of the HMH stress states in individual elements of the gun structure make it possible to locate the places of maximum stress concentration and to select the gun design points that require additional observation during operation

The cannon will also be subjected to dynamic loads resulting from heeling, heaving, and pitching during regular operational sailing, which will load the ship's structure even if she is not in combat use.

Simulating loads of the entire hull requires a much larger computational task, but it generates more reliable calculation results. In this case, the hull elasticity and errors resulting from the problem of contact of FEM elements should be considered [26]. Another important aspect is the mass loads, which can be the source of a significant multiplication of the load on the tested structure.

The analysis of the features of the OSU-35 system allows for the possibility of using this system as a base for the design and construction of more complex - modular and multi-layer defence systems with the option of application on various types of ships. According to the presented concept, a significant problem in building the ship's defence system is adjusting individual system elements' mass and size parameters to the designed ship each time. Requirements resulting from the class and type of the ship each time require checking the strength of the ship's structure and adjusting the assembly method, fitting the corrosion resistance and stability during the arrangement of individual system components.

Additionally, the proposed methodology refers to an unreal case, which is only the considered structure, without modelling the entire hull. According to the presented description, the further from the rotation's axis, the greater the acceleration values. The construction of the cannon meets the standards' requirements. Still, in reality, the dynamic loads may differ from the loads proposed in the methodology, which should be borne in mind when performing this type of calculations. Material ageing should also be taken into account as it affects the overall strength of the hull.

REFERENCES / *Literatura*

1. Goroch, O.J.; Zbigniew, G.; Leszek, C. Development of Ammunition with Unconventional Applications. *Adv. Sci. Technol. Res. J.* 2020, *14*, 137–144, doi:10.12913/22998624/115515.
2. NCBiR *35 Mm Automatyczna Armata Morska KDA z Zabudowanym Na Okręcie Systemem Kierowania Ogniem Wykorzystującym Zintegrowaną Głowicę Śledzącą AGS-158 Wykonaną w Wersji Morskiej Wraz Ze Stanowiskiem Kierowania Ogniem [35 Mm Automatic KDA Naval Cannon with a Fire Control System Installed on the Ship Using the Integrated AGS-158 Tracking Head Made in the Sea Version with a Fire Control Station - in Polsih]*; Akademia Marynarki Wojennej: Gdynia, 2018.
3. Cieślak J. Dozorowiec ORP Kaszub, Ćwierć Wieku Pod „biało-Czerwoną" [ORP Kaszub, A Quarter of a Century under the "White and Red" - in Polish]. *Morze, statki i okręty* 2012.
4. www.defence24.pl Okrętowy System Uzbrojenia (OSU) 35 Mm Po Certyfikacji [Ship Weapon System (OSU) 35 Mm after Certification - in Polish] Available online: https://www.defence24.pl/okretowy-system-uzbrojenia-osu-35-mm-po-certyfikacji (accessed on 22 September 2020).
5. Inspektorat Uzbrojenia, [Armament Inspectorate] Metodyka Nr 12, Sprawdzenie Wymagań w Zakresie Odporności Na Narażenia Mechaniczne [Methodology No. 12, Checking the Requirements for Resistance to Mechanical Damage - in Polish] 2017.
6. STANAG 4137 (CLASSIFIED) Standard Underwater Explosion Test for Operational Surface Ships and Crafts 1976.
7. Huta Stalowa Wola 35 Mm Automatyczna Armata [35 Mm Automatic Cannon - in Polish] Available online: https://www.hsw.pl/i/fmfiles/kda/hsw-kda.pdf.
8. Abaqus 6.14 *Theory Manual*; Simulia, Dassault Systems, 2014.
9. Kohnke, P. Ansys Theory Reference, Release 5.6 1999.
10. Szturomski, B. *Inżynierskie Zastosowanie MES w Problemach Mechaniki Ciała Stałego Na Przykładzie Programu ABAQUS [Engineering Application of FEM in Problems of Solid Mechanics on the Example of the ABAQUS Program - Available in Polish]*; Wydawnictwo Akademickie AMW: Gdynia, 2013.
11. Gokhale, N.; Deshpande, S.; Bedekar, S.; Thite, A. *Practical Finite Element Analysis*; Maharastra. India, 2008; ISBN 978-81-906195-0-9.
12. Szturomski, B. *Modelowanie Oddziaływania Wybuchu Podwodnego Na Kadłub Okrętu w Ujęciu Numerycznym [Modeling the Effect of the Underwater Explosion to Hull Board in a Numberic Concept - in Polish]*; Akademia Marynarki Wojennej: Gdynia, 2016.
13. Cudny, K.; Powierża, Z. *Wybrane Zagadnienia Odporności Udarowej Okrętów [Selected Issues of Ship Impact Resistance - in Polish]*; Gdynia, 1978.
14. Cole, R.H. *Underwater Explosions*; Princeton University Press: New Jersey, 1948; https://doi.org/10.5962/bhl.title.48411
15. Grządziela, A. Model of Impact Underwater Detonation. *Journal of Kones* 2012, *19*, 191–201. https://doi.org/10.5604/12314005.1137918
16. Grządziela, A. Model Dynamiczny Oddziaływania Wybuchu Podwodnego [Dynamic Model of Underwater Explosion Impact - in Polish]. *Scientific Journal of Polish Naval Academy* 2008.
17. Kiciński, R.; Szturomski, B. Pressure Wave Caused by Trinitrotoluene (TNT) Underwater Explosion—Short Review. *Applied Sciences* 2020, *10*, 3433, doi:10.3390/app10103433.
18. Włodarczyk, E. *Wstęp do mechaniki wybuchu [Introduction to explosion mechanics - in Polish]*; Wydawnictwo Naukowe PWN, 1992
19. Geers, T.L.; Hunter, K.S. *An Integrated Wave-Effects Model for an Underwater Explosion Bubble*; Boulder, 2002; https://doi.org/10.1121/1.1458590
20. Stiepanow, W.C.; Sipilin, P.M.; Nawagin, J.S.; Pankratow, W.P. *Tłoczenie Wybuchowe [Stamping with an Explosion - in Polish]*; Wydawnictwa Naukowo - Techniczne, 1968.
21. Li, J.; Rong, J. Bubble and Free Surface Dynamics in Shallow Underwater Explosion. *Ocean Engineering* 2011, *38*, 1861–1868, doi:10.1016/j.oceaneng.2011.09.031.
22. LeBlanc, J.; Shillings, C.; Gauch, E.; Livolsi, F.; Shukla, A. Near Field Underwater Explosion Response of Polyurea Coated Composite Plates. *Exp Mech* 2016, *56*, 569–581, doi:10.1007/s11340-015-0071-8.
23. Lance, R.M.; Bass, C.R. Underwater Blast Injury: A Review of Standards. *Diving Hyperb Med* 2015, *45*, 190–199.
24. Johnson, G.R.; Cook, W.H. A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates. *Proceedings of the 7th International Symposium on Ballistics* 2009.
25. Dyląg Z.; Jakubowicz A.; Orłoś Z. *Wytrzymałość Materiałów [Strength of Materials - in Polish]*; Wydawnictwo Naukowo Techniczne: Warszawa, 2007; Vol. 1 i 2.
26. Sładkowski, A. Accuracy Analysis of the Solution of Spatial Contact Problem by Means of the FEM. *MECHANIKA* 2005, *3*.