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# Analysis of the possibility of a submarine implosion using finite element method

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**Abstract.** Recently, there have been reports of disasters related to the disappearance of submarines. One of the potential causes of disasters is the ship's descent to the so-called critical depth and its subsequent implosion. However, the occurrence of the submarine implosion phenomenon may be difficult to achieve. This is due to the presence of hydraulic fittings and other more susceptible hull components. The article presents an analysis of the strength of a fragment of the submarine's hull, modelled on Kobben-class ships, to demonstrate the possibility of an implosion. Furthermore, the construction of submarines was presented, and phenomena related to the strength of submarine hulls using FEM were discussed.

## 1. Introduction

A damaged submarine, due to its construction, which is often multi-compartment, remains wholly or partially sealed and settles to the bottom. Its crew can survive several days until the air supply is exhausted. Unfortunately, for decades, in emergencies, the crews of damaged ships were on their own, and their ship became an iron coffin for them. Between 1925 and 1927, the US Navy lost two submarines, USS S-51 and USS S-4, with 73 seamen drowned. Both ships were rammed. The crew of the USS S-4 survived a collision, after which the ship sank to the bottom at a depth of 33 m. The diving team that went to the bottom managed to contact the crew of the torpedo compartment, but at that time, it was not possible to carry out a quick rescue operation that would allow the ship to be lifted from the bottom. As a result of the cold and lack of oxygen, 40 sailors died [1].

The parameter defining the maximum operating depth is the so-called test depth. It is determined by the design office at the ship design stage and verified during post-construction shipbuilding tests at sea. Designers of a new vessel must consider the strength of the rigid hull and all other vessel components exposed to the hydrostatic pressure surrounding the hull [2].

With the development of technology, the test depths achieved by submarines have increased. Currently, the depth record belongs to the Soviet submarine K-278 Komsomolets (NATO: Mike), which on Aug 4, 1989, submerged to a depth of 1027 m [3]. The two-hull, seven-compartment titanium ship 118.4 meters long and 11.1 meters wide displaced 5,680 tons of water in the surface position and 8,500 tons underwater. The above-water draft was 7.4 meters. The OK-650b-3 pressurized water reactor powered the ship with thermal power of 190 MW [2].

Despite the development of technology, safety and rescue procedures, submarine accidents still happen. Since 2000, many accidents have occurred (Table. 1) that have come to light. However, one should be aware that many of them are still shrouded in mystery.

**Table. 1.** List of selected submarine accidents since 2000 [4].

| Date | Navy | Submarine | Category | Loss of Life | Comments |
|---|---|---|---|---|---|
| 2000 Aug-12 | Russia | Kursk (K-141) | At Sea | 118 | Torpedo room explosion |
| 2002 May | US | USS Dolphin | In port | 0 | Fire and flooding |
| 2002 Nov-6 | UK | HMS Trafalgar (S107) | At Sea | 0 | Run aground |
| 2002 Nov-13 | US | USS Oklahoma City (SSN-723) | At Sea | 0 | Periscope collision |
| 2003 May | China | Ming 361 | At Sea | 70 | Carbon monoxide while snorkeling |
| 2003 Oct-25 | US | USS Hartford (SSN-768) | At Sea | 0 | Run aground |
| 2004 Oct-5 | Canada | HMCS Chicoutimi (SSK-879) | At Sea | 1 | Fire |
| 2005 Jan-8 | US | USS San Francisco (SSN-711) | At Sea | 1 | Run aground |
| 2005 Aug-5 | Russia | AS-28 | At Sea | 0 | Stuck on the seafloor, rescued |
| 2005 Sep-5 | US | USS Philadelphia (SSN-690) | At Sea | 0 | Surface collision |
| 2005 Jun-5 | Spain | Mistral (S-73) | At Sea | 0 | Fire |
| 2006 Sep-6 | Russia | Daniil Moskovsky (B-414) | At Sea | 2 | Fire |
| 2007 Jan-8 | US | USS Newport News (SSN-750) | At Sea | 0 | Submerged collision |
| 2008 May-26 | UK | HMS Superb (S109) | At Sea | 0 | Run aground |
| 2008 Nov-8 | Russia | Nerpa (K-152) | At Sea | 20 | Gas leak |
| 2008 Dec-13 | Spain | Tramontana (S-74) | At Sea | 0 | Flooding |
| 2009 Feb | UK / France | HMS Vanguard and Triomphant | At Sea | 0 | Submerged collision |
| 2009 Mar-20 | US | USS Hartford and USS New Orleans | At Sea | 0 | Submerged collision |
| 2010 Feb | India | INS Sindhurakshak (S63) | At Sea | 1 | Battery fire |
| 2010 Oct-10 | UK | HMS Astute (S119) | At Sea | 0 | Run aground |
| 2011 Jun-4 | Canada | HMCS Corner Brook (SSK-878) | At Sea | 0 | Run aground |
| 2011 Dec-29 | Russia | Ekaterinburg (K-84) | Dry Dock | 0 | Fire |
| 2012 Oct-3 | US | USS Montpelier (SSN-765) | At Sea | 0 | Submerged collision |
| 2013 Jan-10 | US | USS Jacksonville (SSN-699) | At Sea | 0 | Periscope collision |
| 2013 Aug-13 | India | INS Sindhurakshak (S63) | In port | 18 | Explosion |
| 2015 Apr | UK | HMS Talent (S92) | At Sea | 0 | Submerged collision, ice |
| 2016 Mar | North Korea | Yono Class | At Sea | ~8 | TBD. Lost. |
| 2016 May-11 | Italy | Scire (S 527) | At Sea | 0 | Periscope collision |
| 2016 Jul-20 | UK | HMS Ambush (S120) | At Sea | 0 | Periscope depth collision |
| 2016 Aug-16 | South Korea | Seagull (SX756) | In port | 1 | Explosion |
| 2017 Feb-Mar | India | INS Arihant (S2) | In port | 0 | Flooding |
| 2017 Nov-15 | Argentina | San Juan (A-42) | At Sea | 44 | TBD |
| 2019 Jul-1 | Russia | Losharik (AS-31} | At Sea | 14 | Battery fire |
| 2020 Jun-12 | France | Perle (S606) | Dry Dock | 0 | Fire |
| 2020 Jul-17 | South Korea | Jang Bogo-class | At Sea | 0 | Surface collision |
| 2021 Feb-8 | Japan | JS Sōryū (SS-501) | At Sea | 0 | Persicope collision |
| 2021 Apr-14 | Indonesia | KRI Nanggala (402) | At Sea | 53 | TBD |

While analyzing Table. 1, it can be seen that the most common cause of accidents is fire, flooding, explosion, and a collision with another object or the bottom. However, some reasons are not fully explained (TBD). The reasons may be known but secret, leading to many conjectures. Especially in the ARA San Juan case, there is speculation about the possibility of an implosion.

## 2. Problem description

An implosion is a sudden collapse of matter in a closed area under the influence of a significant pressure difference. This phenomenon may concern cavitation bubbles [5], gas bubbles caused by an underwater explosion [6,7] or closed tanks loaded with external pressure (e.g. hydrostatic pressure)[8]. For example, if a submarine is sinking to the bottom, increasing weight of water will press against its hull. Higher hydrostatic pressure can cause buckling and, if the safety conditions are exceeded, it causes a sudden (lasting several milliseconds) crushing of the ship's structure. It is an entirely non-linear dynamic process. An implosion similar to an underwater explosion produces a series of pressure pulses that can be noticed by hydrophones.

This does not change the fact that implosion is a relatively difficult phenomenon to achieve. It requires high tightness and a significant pressure difference. There are micro-scale experiments involving implosion of barrels or cans. However, these are simple structures, usually equipped with one or two well-sealed holes. Implosion occurs when the external and internal pressure cannot be equalized in any other way. An example of the difficulties in achieving the implosion phenomenon can be the experiment carried out in the MythBuster program [9]. Even though it is a television show, to achieve the tank implosion, it was necessary to seal it significantly, use advanced vacuum pumps, and locally damage its structure (Figure 1).

**Figure 1.** The tanker used in the MythBuster program, in the lower right corner, damage preparation.

In this manuscript it was decided to analyze the possibility of a submarine implosion, using the example of the Kobben-class submarine. Concerning the subjects' studies, the authors tried to demonstrate the knowledge resulting from service on a submarine. Until 2019, there were four Kobben-class (project 207) submarines in operational use by the Polish Navy. These were (S-306 Skolpen) ORP "Sep", (S-308 Stord) ORP "Sokol", (S-309 Swenner) ORP "Bielik" and (S-319 Kunna) ORP "Kondor" (Figure 2). The fifth submarine (S-318 Kobben) ORP "Jastrzab" is used as a crew training simulator at the Polish Naval Academy. They are the last ships of this series worldwide, the oldest in operational use. In total, 15 such units were built in 1964-67 at the German shipyard Rheinstahl-Nordseewerke to modify the 205 project submarines for Norway's Navy. Five of them were transferred to the Polish Navy in 2002-2003 [10]. These ships end their service in the Polish Navy. Due to the decommissioning, their tactical data can be declassified, and therefore their documentation can be used for scientific purposes. This submarine is adapted to operate in all regions of the world, with the possibility of using the weapon under any conditions. The primary technical data of the Kobben-class submarines is as follows [10–12]:

- Total length 47.24 m
- Height 8.88 m
- Bow draft 3.9 m
- Stern draft 4.8 m
- Displacement surfaced 520 $m^3$
- Displacement Submerged 572 $m^3$
- Periscope depth 11.5 m
- Maximum working depth 186 m
- Maximum testing depth 225 m
- Maximum surfaced speed 12 knots
- Maximum submerged speed 18 knots
- Eight torpedo tubes 533 mm calibre
- Sailing ranges:
  - submerged sailing at a speed of 4.8 knots 280 NM
  - submerged sailing while snoring at a speed of 4.5 knots 5700 NM
- Autonomy 21 days
- Number of crew 26 people

**Figure 2.** Submarines of project 207 in the home port in Gdynia (source: Polish Submarine Squadron).

## 3. CAE model

The first step in numerical analysis was to recreate the hull geometry. Due to the theoretical nature of the work, it was decided to recreate only one of the hull sections. The section was reconstructed based on technical documentation, photos and own measurements. The model is also equipped with a section of the pipeline. This procedure was performed due to the authors' experience, indicating that the most common cause of failure is pipeline cracking and leakage. The model was made of shell elements of different thicknesses (Figure 3).

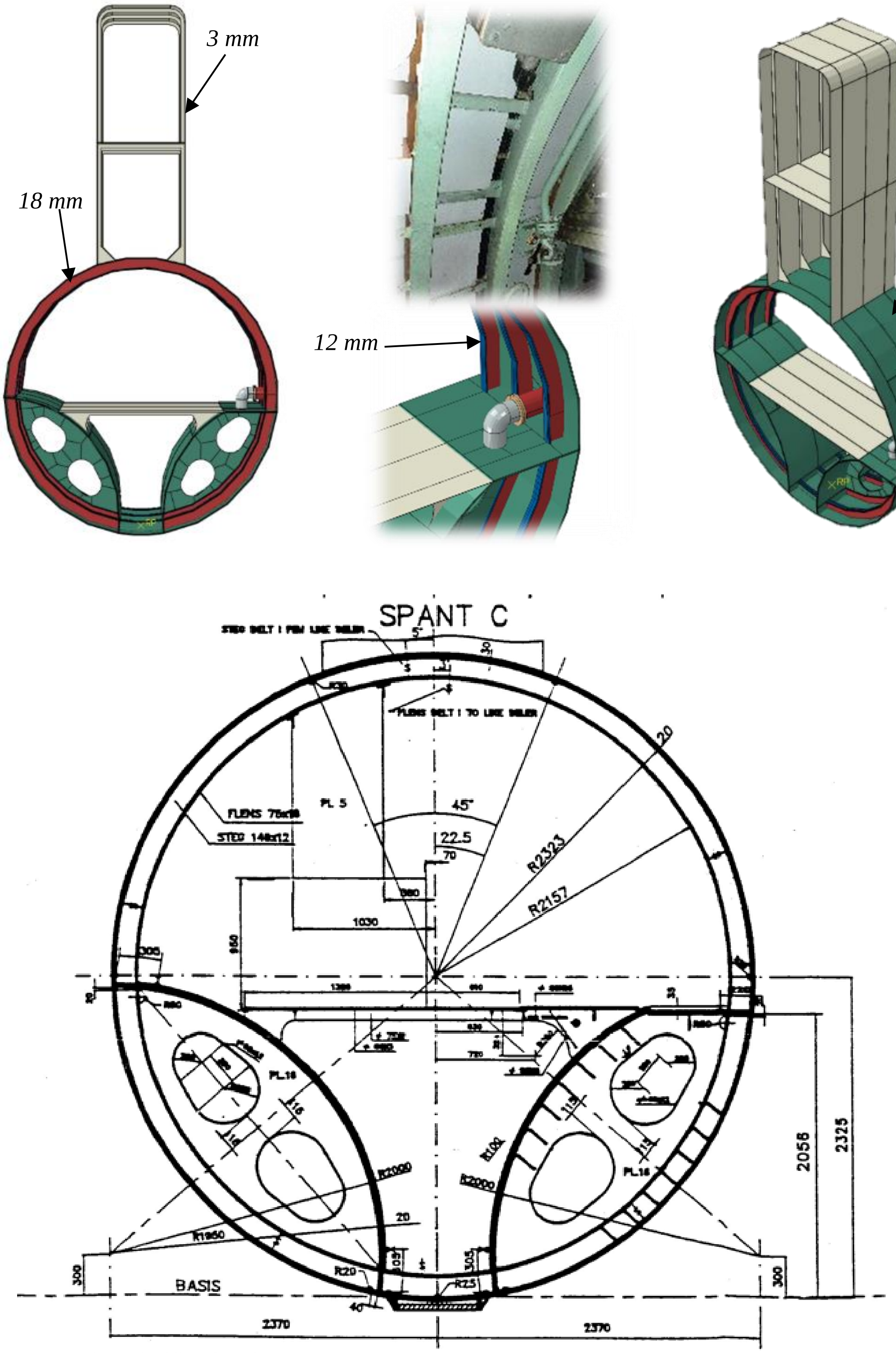


**Figure 3.** Hull geometry, fragments of technical and photographic documentation.

The next stage of the task was assigning material data. These data were obtained owing to the adaptation of ORP "Jastrząb" (S-318 Kobben) as a submarine operation simulator at the Polish Naval Academy in Gdynia, which required numerous hull modifications. Among other things, ventilation and air conditioning openings were cut. In this way, the samples of HY-80 steel for strength tests were obtained (Figure 4).

**Figure 4.** ORP "Jastrząb" (S-318 Kobben), places from which samples for testing were taken.

Standardised samples for material testing were made from the obtained material. Determination of the material characteristics according to [13,14] is a topic for a separate manuscript, and it is presented here [13]. The authors proposed a material model based on the Johnson-Cook equation [14] and appropriate failure parameters [15,16] based on the obtained data. To summarize, the tested HY-80 steel can be described by the following parameters:

$$\sigma_{pl} = (559 + 518 \cdot \varepsilon^{0.379}) \left[1 + 0.0268 \cdot \ln\left(\frac{\dot{\varepsilon}}{0.0001}\right)\right] \left[1 - \left(\frac{\theta - 293.15}{1\,470}\right)^{1.14}\right]$$

$$E = 211\text{ GPa};\; R_e = 559\text{ MPa};\; R_m = 780\text{ MPa}; \tag{1}$$

$$d_{ductile} = 0.414;\; \varepsilon_{failure} = 0.1289;\;\; \eta_{triax} = 0.33.$$

After assigning material data, the research object was discretized into 31,986 linear 4-node elements, 164 linear 3-node elements and 189 linear three-dimensional 8-node elements. The appearance of solid elements results from the intention to use the model for further research on the tightness of the outboard valve connection. The authors intend to describe this issue in more detail in a separate article. The discretization is shown in Figure 5.

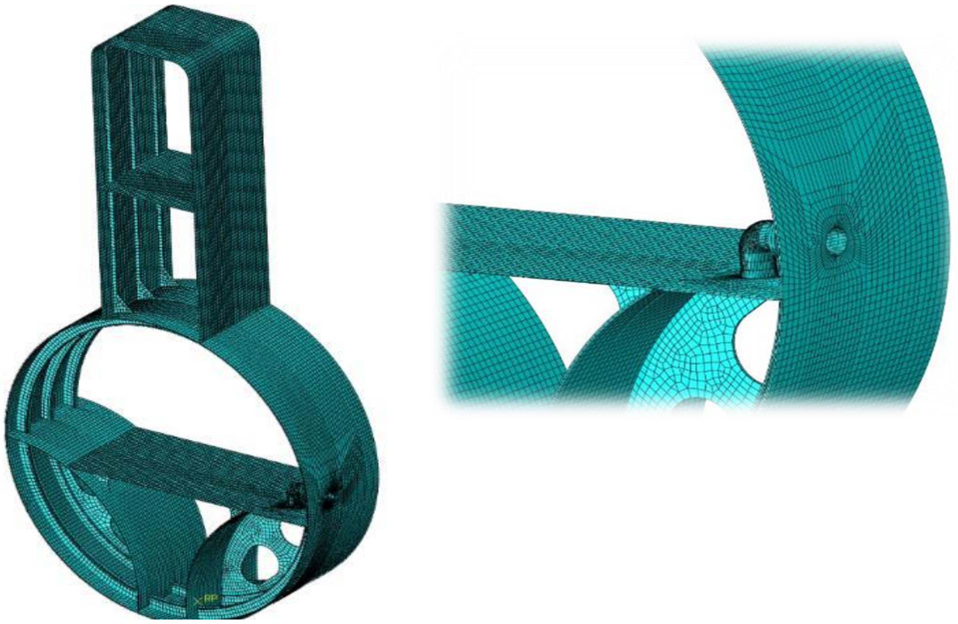

**Figure 5.** Hull section discretization.

## 4. Boundary conditions and loads

The section is assumed to be symmetrical on all sides. This simplification is not entirely consistent with reality, as shown in work [14]. However, the authors of [14] did not consider the specific nature of the work and construction of the submarine. The design of submarines is divided into single-hull and multi-hull. A distinction is made between a light hull (inside which there is water) and a strong hull (resistant to pressure)

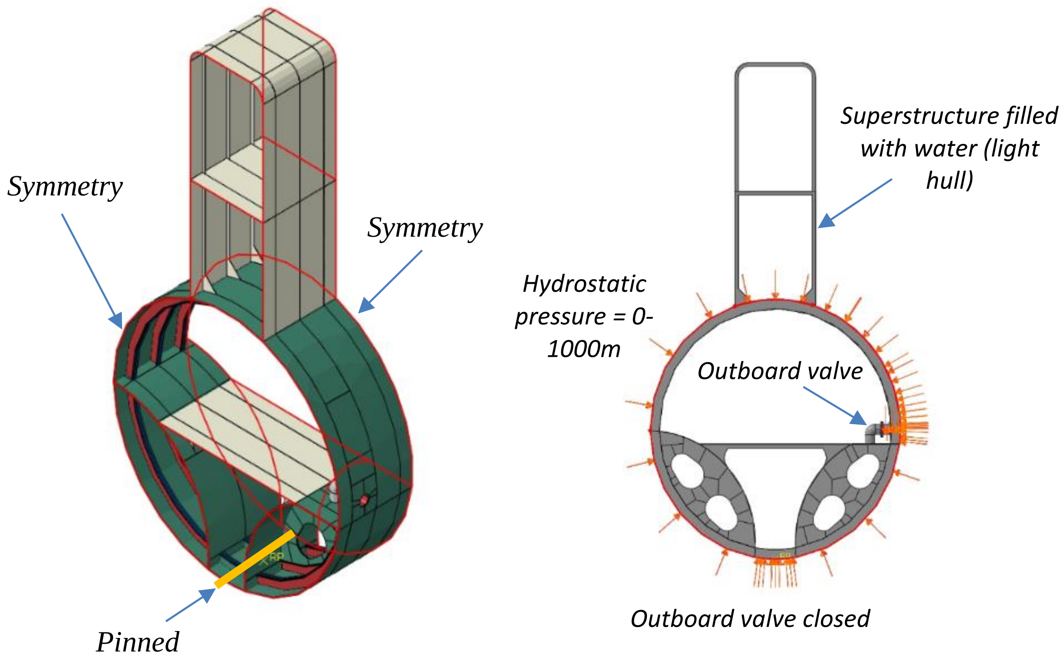


**Figure 6.** Boundary conditions and load. The pressure load is uniform, the heterogeneity of the arrows is due to the discretization and display of the commercial solver.

The light hull includes, for example, a superstructure or ballast tanks. In the quoted study [14], the authors put a load on the ship's outer skin, which is not entirely appropriate. In addition, there are various openings in the ship's shell, which are local deviations from the cylindrical structure of the hull. In addition, there are different types of tanks inside the submarine for balancing the ship and storing water and fuel [2,11,15,16]. It was also assumed that the ship was sunk on an even keel. Considering the above, the following boundary conditions, presented in Figure 6, were assigned to the research object.

Then, the load was applied to the ship's hull. The pressure was applied to both the hull and the outboard valve. It was assumed that the crew saved themselves, drained all the water from the regulating tanks and closed all outboard valves. Thus, hypothetically, this is an ideal situation, conducive to the phenomenon of implosion. The pressure was increased from 0 to about 10 MPa (0-1000 m immersion depth).

## 5. Results

The calculations were carried out, and the results are presented in Figure 8. In postprocessing, the display was set up in such a way as to facilitate the understanding of boundary conditions.

The presented results show that in the range of test depths (up to 225 m), the stresses are concentrated in the area of the outboard valve. It is a place particularly exposed to loads due to shape changes and the occurrence of welds. Such a connection is even more complicated in practice, making the structure more susceptible to damage (Figure 7).

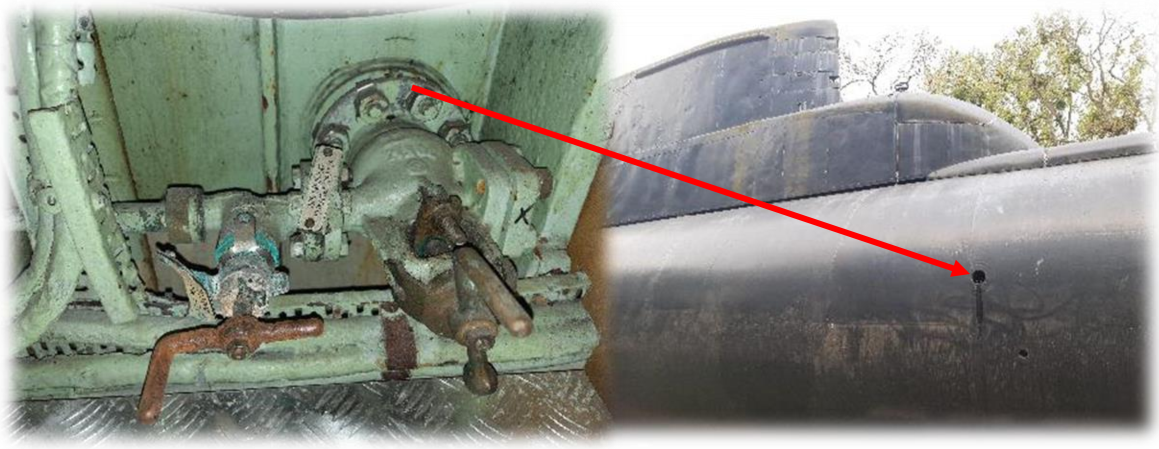

**Figure 7.** Connections of outboard valves with the hull of the submarine.

However, assuming the ship remains watertight, the stress concentration is transferred to the frames. This situation lasts until the ship loses its tightness in the upper part, in the vicinity of the superstructure. In the next time step, a violent rupture along the length occurs, and the ship collapses. Due to the created contacts between the elements, the collisions cause further destruction of the submarine and detachment of the conning tower. This behaviour of the structure is very similar to an underwater explosion [17].

The stresses exceed the yield point at a depth of 230 m. It is also the depth at which, according to the documentation, the ship cannot stay for a long time.

According to the simulation, the ship's hull is able to carry loads until an implosion occurs. After exceeding a depth of 550 m, the hull collapses rapidly within milliseconds.

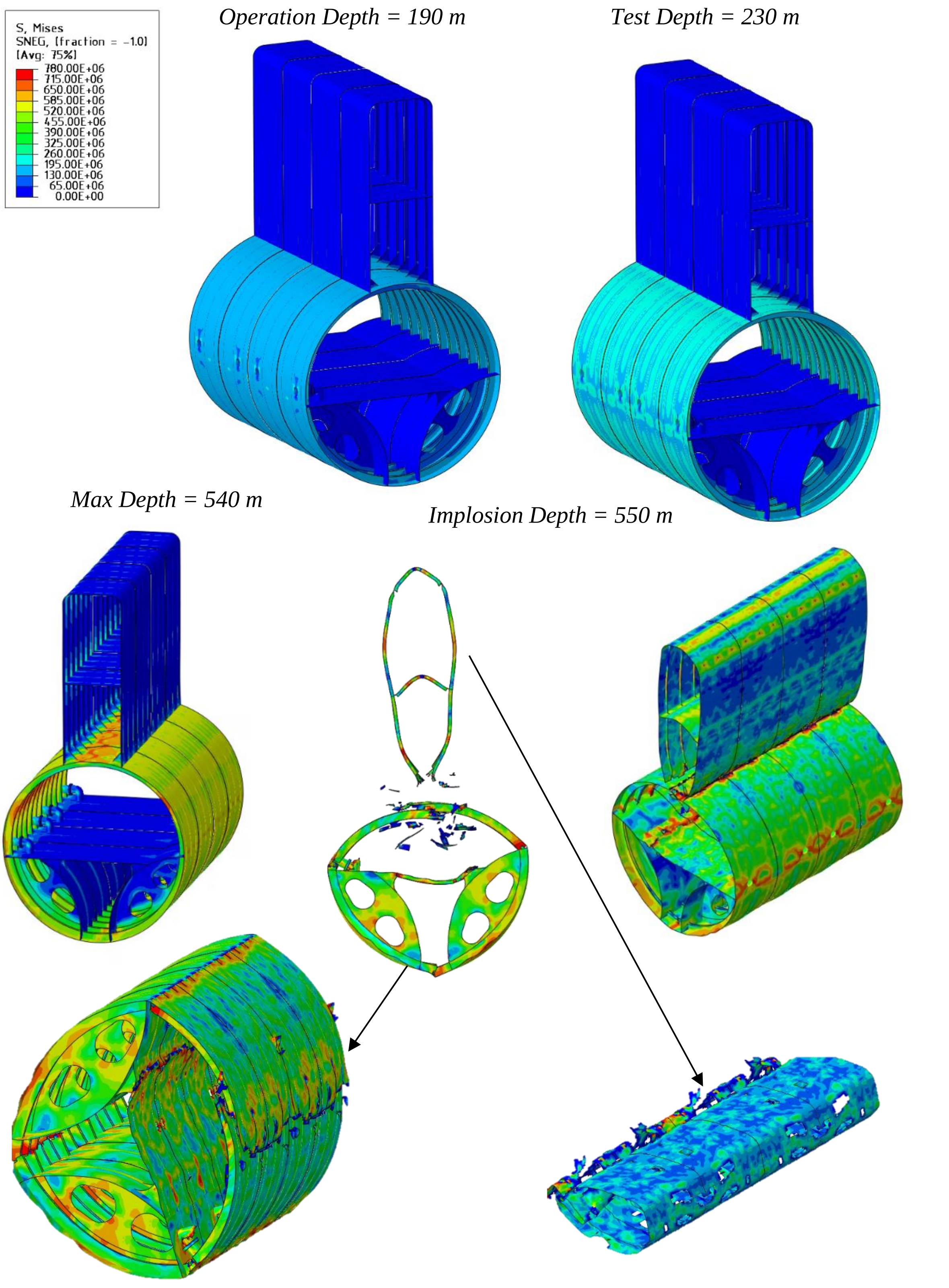


**Figure 8.** Results of numerical calculations for a ship with empty tanks and closed outboard valves.

## 6. Conclusions

A submarine is a device with a very complex structure and a multitude of systems. It is designed to carry high loads generated by the hydrostatic pressure. However, it has several points that cause a local change of shape or heterogeneity of the material, e.g. welded joints. In addition, there are pipelines inside it with much lower strength than the hull.

A higher safety factor characterizes the outboard valves and the hull compared to other marine fittings. The critical place is their connection with gaskets and bolts, where local stresses can reach much higher values.

On the basis of the analysis, it was found that the submarine implosion is possible. However, it would require the tightness of all mechanisms until the implosion depth is reached. In the first leakage, the pressure inside the ship will begin to equalize with the outboard pressure, which will relieve the hull. The presented calculations did not take this phenomenon into account.

The authors' experience and the presented analysis show that the first to be damaged are pipelines or other seals (e.g. masts), which will result in an inflow of water inside and equalization of pressure.

The human factor should also be taken into account. Events such as fire, flooding or carbon monoxide poisoning involve the entire crew, which may not adequately respond to the change in depth. However, in the event of a free fall to the bottom, there is a high probability of the crew's reaction to counteract any kind of failure.

To sum up, the submarine implosion phenomenon is possible. However, due to the inflow of water, the equalization of pressure inside the submarine, in practice, is very difficult to achieve.

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