Design Improvement for a Maritime Training Polygon using 3D Terrestrial Laser Scanning Technology

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Received: 22 August 2023 | Revised: 8 September 2023 and 11 September 2023 | Accepted: 12 September 2023

 DOI: https://doi.org/10.48084/etasr.6306

ABSTRACT

In the current geo-strategic context, the North Atlantic Treaty Organization (NATO) and the International Maritime Organization (IMO) impose increasingly high standards for seafarers' preparation in the ship's vitality training centers (elaborate constructions, designed and equipped specifically for training personnel in scenarios involving flooding and fires that may occur on board ships). The buildings housing these training areas experience considerable mechanical and thermal stress, which, over time, affects their structural integrity. Therefore, repairs and modernization work become necessary. This paper provides a case study on the application of technologies for terrestrial laser scanning of buildings, with a focus on the vitality training polygon. The originality of the approach comes from achieving "as-built" documentation for the vitality polygon using 3D laser scanning technology. This includes both three-dimensional modeling based on digital information from the scanning process, as well as structural analysis using finite element techniques for the buildings where crew training takes place. The study also analyzes the distribution of total deformations and stresses in the walls of exercise compartments for flooding and water fight scenarios. Moreover, temperature distribution in the walls and interior atmosphere of these compartments is examined for fire scenarios and firefighting.

Keywords-3D laser scanning; Building Information Modeling (BIM); finite element methods; mechanical and thermal analysis; flooding and firefighting

I. INTRODUCTION

Risk assessment for personnel involved in maritime transportation [1] is a priority topic and many operators are currently acting to improve their actions to reduce risk exposure. The risks considered are primarily those affecting the safety of the ships, transported goods, or embarked crews. Those who work in the field of marine engineering and navigation are well aware that the International Maritime Organization (IMO), as an entity concerned with sustainable development, has taken on the primary responsibility for the safety and security of maritime transport, including ensuring the ship's vitality. We must not forget the strategies of the North Atlantic Treaty Organization (NATO) which, in the maritime field, has as priorities maritime security, freedom of navigation, and secure maritime trade routes [2]. The vitality of the ship refers to the maintenance of its architectural, functional, and operational characteristics (by ensuring all nautical qualities) in conditions of damage generated by water and fire. The fight to maintain the ship's vitality represents the organized effort of the crew, whether military and/or civilian. They use on-board installations systems and equipment to mitigate the effects of water floods and to extinguish fires generated by various causes. The success of this action depends on the crew's understanding of the ship's construction and characteristics, the functioning of the onboard installation systems and equipment, as well as the appropriate measures to be taken when using them. The level of theoretical and practical training to be demonstrated by the personnel on board ships is regulated at the international level by:

- For military personnel, through NATO operational standards, which refer to the preparation of a compact, efficient, and flexible military force capable of meeting national and international security requirements.
- For civilian crews, through the requirements expressed in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW).

To efficiently train the personnel regarding the ship's vitality, specific arrangements are required, known by the generic name of vitality simulators (or vitality polygons), properly organized and equipped for the fight against flooding and fire situations. In the most general way, vitality polygons must be provided with container modules for the execution of exercises with water and fire, placed and arranged in such a way as to simulate locations and routes possible to be encountered on board a ship. Inside the container modules, all the installations, equipment, and systems necessary for the simulation of the damage (flooding and/or fire) must be provided, as well as equipment for the individual protection of the participants in the simulation exercises (Figure 1). It is therefore imperative that the technical and qualitative level of the simulators for personnel training in the fight to ensure the vitality of the ship matches the level of technical and operational performance of vessels in both military and commercial fleets (characterized by new types of ships, with increasingly diverse and specific functionalities, equipped with sophisticated installations, systems and equipment and which must also meet the most rigorous demands in terms of safety and security).

Fig. 1. Exercises for the fight against flooding (left) and fire (right) situations.

Scientific research concerns regarding the use of 3D laser scanning techniques in the field of marine engineering are reflected in the literature through various publications. It's worth noting that these concerns remain constant, with specialized literature offering interested readers access to articles dating from 1997 to the present. It can also be found, with relative ease, that the field of applicability in marine engineering is extremely wide, starting from modern ships or underwater vehicles dedicated to offshore operations to port facilities. Additionally, this also holds true for domains such as shipbuilding, navigation, operation of offshore platforms or submarine pipelines, reaching as far as marine archaeology. To ensure an appropriate layout of the paper, selected articles related to the content of this work were considered. As the paper is dedicated to a case study, the literature review is brief. However, this does not imply that the topic lacks significance for researchers.

The high values of mechanical and thermal stress to which the buildings of vitality polygons are subjected rapidly erode their structural integrity, thus it is important to know which factors contribute to increasing the rate of deterioration (risk, design, structural components, materials used, quality of workforce) are and what intervention measures can be taken before material, financial and human losses occur [3]. The advantages of using Building Information Modeling (BIM) technology supported by high-performance tools (such as Auto Desk Revit 2020 and Auto Desk Insight 360) allow the creation of complex 3D models but also bi-directional links with different components of documentation (views, sections, plans) thus reducing errors, saving worktime, and maintaining project accuracy [4].

The technology of three-dimensional (3D) laser scanning of buildings is a very efficient tool for drawing up "as-built" documentation. Compared to classical investigation and measurement technologies, laser scanning is fast, safe, does not require multiple work teams and does not involve significant expenses. The high accuracy of measurements and the substantial amount of digital Computer Aided Design (CAD) information that can be achieved with the help of this technology, enable the creation of intricate 3D models, according to the reality on the ground. Once created, the 3D models can be reconfigured into multiple variants and validated by structural analyses (mechanical, thermal, etc.) to justify the choice of the optimal solution and certify the quality and safety of the execution project. For reliable measurement of the structural element deformation caused by various loads (sometimes critical) [5], a new approach is presented to determine and measure the structural displacements, based on a numerical model whose accuracy may be assessed by using the least squares method and which provides more accurate results compared to the existing technologies and instruments of measurement. The use of high-speed laser scanners was highlighted in the literature quite early [6] in various fields, from mechanical engineering to optical engineering and electronics being targeted both hardware and software approaches. In [6], the authors present a three-dimensional image projection system without the use of special viewing glasses. The technology involves the synchronization of laser beams (which determine plane coordinates) with the movement of a helical screen (which establishes the spatial, depth coordinate) thereby generating a true 3D image. Authors in [7] propose methodologies for 3D modeling of complex objects with a high degree of accuracy. They demonstrate the necessity for a hybrid approach that combines photogrammetry with laser scanning techniques. In 2010-2015, there was an increased interest in small, portable scanning tools, whose operational characteristics are similar to those of scanning stations. 3D laser scanners assert their usefulness in quality control and product design in marine engineering, facilitating the creation of new technical documentation in the form of CAD drawings. As a part of Reverse Engineering (RE), 3D scanning can create complex digital libraries and the integration of special software applications can greatly improve the scanning process and shorten modeling time. Authors in [8] propose a solution for transferring both the entire infrastructure (except for the physical measuring machines) and the software information into cloud computing, simplifying the scanning process and accelerating information exchange. A topic of interest is the digitization of existing paper documentation of entities previously built, requiring project modifications. Authors in [9] describe an interesting procedure (which can be extended to other types of entities encountered in marine engineering) for regenerating technical documentation (CAD drawings). By analyzing the shape of real-size vessels or mock-ups, using reverse engineering techniques, 3D modeling is facilitated by digital photogrammetry.

Laser scanning technology can be divided into two categories: static (when the scanner is held in a fixed position during data acquisition) and dynamic (when the scanner is mounted on a mobile platform). The use of dynamic laser scans in marine engineering offers the possibility of collecting information from offshore platforms or with the help of autonomous vehicles. In its contents, authors in [10] present the advantages offered by mobile marine scanning but also pay attention to errors caused by disturbances induced by the navigation environment (geometric characteristics, speed and direction of wave movement as well as the relative positioning of the mobile platform on which the scanner is located in relation to the wave front). Authors in [11] focused on factors affecting the accuracy of 3D laser scanning and highlighted errors concerning the scanned object which may be generated by external environmental disturbances, human intervention (sometimes non-professional) or limitations in measurement methods and instrument defects. Operational principles of terrestrial laser scanning for multi-story buildings (as is the case with the vitality polygon illustrated in the case study of this paper) were examined in [12] addressing both the analytical aspects of numerical modeling and the practical aspects of effective field measurement and scanning. Authors in [13] illustrate, how, with the help of terrestrial laser scanning, it is possible to digitize the already built structures as well as to modify the original project for the purpose of modernization, reconfiguration, or space rearrangement.

II. MATERIALS AND METHODS

3D scanning is often used to produce "as-built" documentation or to carry out the measurements required for the design, construction or upgrading of the buildings, or installations specific to various fields. The "as built" implies the existence of an editable form of the files, that will be updated, according to the requirements. In the absence of the editable form, it is obvious that, first, all the drawings of the project must be redrawn, then the information be updated, resulting in the final form of the execution project. Laser scanning is a technique that involves sampling a surface using laser technology. The information collected can then be used to build 2D representations or 3D models, usable in a wide variety of applications. As mentioned above, laser scanning technology can be divided into two categories: static and dynamic. The advantages of using the static method arise from its high accuracy and relatively dense points cloud. These dynamic laser scanners require additional positioning systems such as Inertial Navigation System (INS) or Global Positioning System (GPS) which make the system more complex and expensive. 3D laser scanning captures thousands of points on the surface to be scanned in a very short time. The result of laser scanning is an organized 3D representation of recorded objects, called a points cloud. The points cloud obtained is subsequently processed in various applications (like Autodesk ReCap or Architecture, Engineering & Construction collection) to obtain accurate and high-precise 2D or 3D CAD representations. The advantages of 3D scanning are: precise and accurate information about the scanned object, scanning can be performed both day and night, outside or indoors, the scanned information can be accessed at any time, without another site visit, speed of measurements (thousands of points measured per second), and the possibility to scan the studied object from a safe distance, which leads to the avoidance of accidents. After 3D scanning, complete information about a building is obtained, allowing a complex analysis of it: facades, walls, floors etc. The analysis can be done starting from a simple study of the positioning and sizing of some elements, up to a complex qualitative analysis of the building in terms of decay, deformations, and possible cracks in the structural elements.

III. CASE STUDIES

An upgrade of an outdated firefighting and flood damage simulator is needed to ensure contemporary training facilities for the crews, students, and other personnel. The main objectives are: to train the skills and aptitudes of the navy categories of personnel in the fire fighting and flood damage onboard ship and to ensure the optimal conditions for the simulation with real scenarios during the practical training sessions. Considering the need for training in the field of ensuring the vitality of the ship to meet the urgency demanded by NATO standards and the requisites of the STCW code for the crews of military vessels, personnel embarked within commercial fleets and for military and civilian students, the project titled Modernization of the Vitality Polygon was proposed at the authors' academic institution. This project was approved for development during the period 2021-2024. The stated goal of the project is to provide modern, safe, and efficient training facilities in order to gain insight, skills and expertise in ensuring the vitality of the ship for the embarked personnel, both military and civilian. The purpose of this paper is to present the results obtained in the first two years of the project. To carry out the project of upgrading the vitality simulator, the following steps were established.

A. Analysis of the Current State of the Vitality Polygon

The vitality polygon within the author's academic institution was put into operation in 1989, and is used for the training of civilian and military students and crews. The vitality polygon has the following structure: building A, intended for training activities in the fight against fire and water (Figure 2), building B, used for training activities involving crew members moving within compartments without visibility (Figure 3), and building C, designed for storing materials used in training activities in the fight against fire and water. At this stage, the deterioration of the equipment was identified, emphasizing the need to modernize the training facilities for the personnel, matching them with the standards of the existing facilities in military and commercial fleets.

B. 3D Scanning of the Vitality Polygon

Scanning of the vitality complex was carried out by use of the Faro Focus 3D-X330 Laser Scanner, a high-speed 3D scanner with the following characteristics: extra-long range, integrated GPS, with a resolution of ± 2 mm and a range between 0.6 m and 330 m with HDR photo coverage. The 3D scanning process was considered for the outside and inside of the three buildings of the vitality polygon. Scanning was performed at a level of minimum accuracy of LOA30 according to the Guide for USIBD [14]. The 3D model complies with the Level of Development Specification 2020 (LOD 300) [15]. Figure 4 illustrates a visual representation of the scanning operations that highlights the positions of the laser beam fixation of the scanning instrument.

Fig. 2. Building A of the vitality polygon.

Fig. 3. Building B of the vitality polygon.

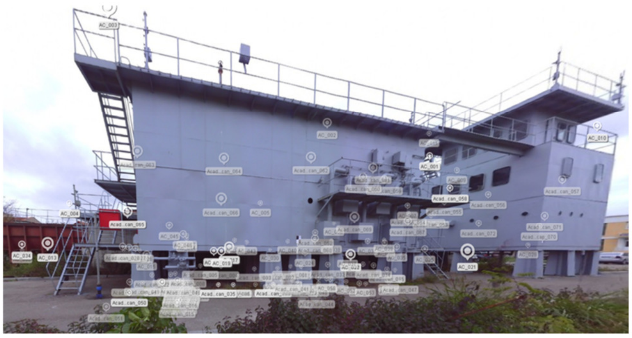

Fig. 4. Example of laser scanning positions.

Figure 5 shows the "points cloud", unprocessed, outside and inside the complex, the remarkable accuracy of measurement and subsequent modeling possibilities being suggested.

C. 3D Modeling of the New Vitality Polygon and Structural Analysis

After completing the 3D scanning process of the vitality polygon and the processing of points cloud, with the help of the SolidWorks Professional/Routing software, the three buildings of the vitality polygon were 3D modeled, its new structure being proposed. The proposed models must be evaluated in terms of the stresses (deformations, tensions) to which the building walls and the interior arrangements may be exposed during the various training exercises in the fight against water and fire. The following activities were conducted: the analysis of the total deformations and stress resistance of the building A structure when operating under maximum water load conditions and the analysis of thermal stresses at the walls of building B in temperature and humidity conditions established by the complex standard training exercises.

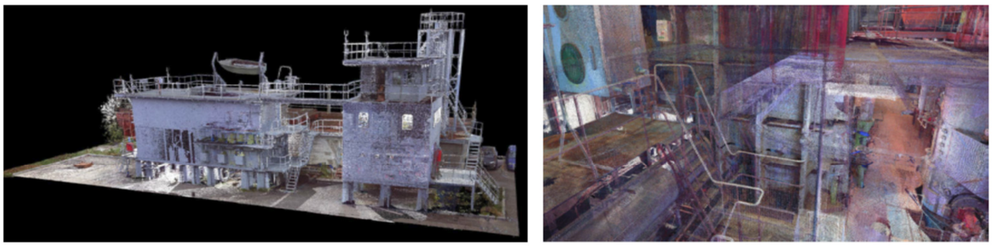

Fig. 5. Unprocessed points cloud, outdoor (left), indoor (right).

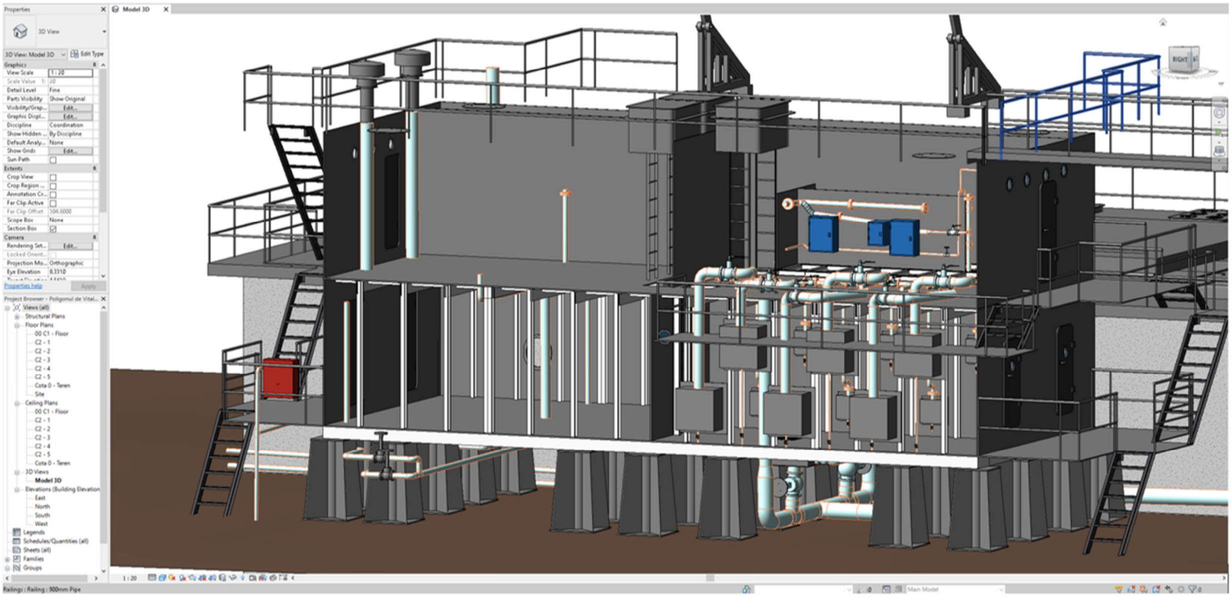

Fig. 6. 3D view of building A of the new vitality polygon.

For the above mentioned analyses, the Finite Element Method (FEM) was used and involved the following: geometrical modeling, domain discretization (which includes: construction of the network of finite elements, numbering of nodes and elements, and generating geometric properties), derivation of finite element equations, assembly of finite element equations, introduction of boundary conditions and reduction of the system of equations, solving the system of equations that describes the behavior of the studied structure, and post-processing. Obviously, 3D modeling and structural analysis steps are interconnected. The structural analysis of the proposed model assumes its remodeling until the final shape is established. In this paper, only the final models will be presented in the following sections.

1) Modeling and Structural Analysis of Building A

Building A, in its new configuration, will be dedicated to the fight against water (Figure 6). The interior partitioning and mesh of Building A resulted from the structural analyses seen in Figure 7. At the same time, the route of the flooding installation and the position of the leakage that generate the water fighting scenarios were established. Essentially, the equipment is represented by piping, manual and remotely operated valves, pumps, automation installation, signaling, etc.

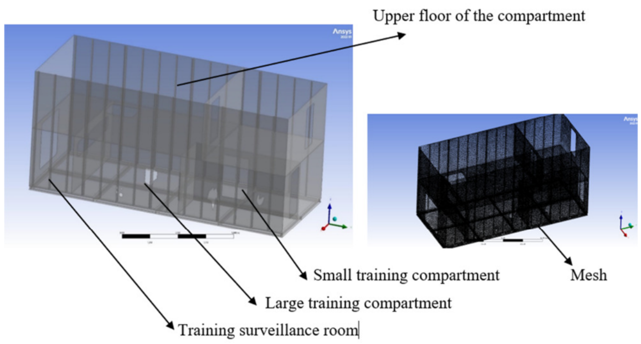

Fig. 7. Interior partitioning and mesh of the new building A.

The mesh is specific to structural mechanical analysis, with a high level of accuracy (the maximum size of an element is 10 cm, having 689,899 nodes and 344,464 elements). The considered boundary conditions and loads are: maximum admissible tension for naval steel of 235 N/mm^2 with a safety coefficient of 10%, a force of 49 KN representing the ceiling of the structure, 2 forces of 3 KN each representing the action of water on the upper floor of the structure, the use of High-Energy Beams (HEB) at the bottom of the construction, a maximum level of 1.5 m for water height in the small training compartment. Figure 8 represents the distribution of the hydrostatic pressure force into the large training compartment.

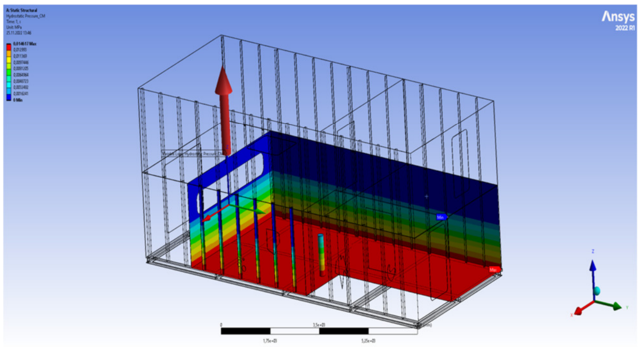

Fig. 8. Hydrostatic pressure forces into the large compartment.

The study illustrates the variations of the total deformations and stresses on the structure under analysis. Three case studies were carried out.

- Case 1. The exercise is developed only in the small exercise compartment. Figure 9 emphasizes that the required standard limits are not exceeded (the maximum stress is 116.11 MPa).

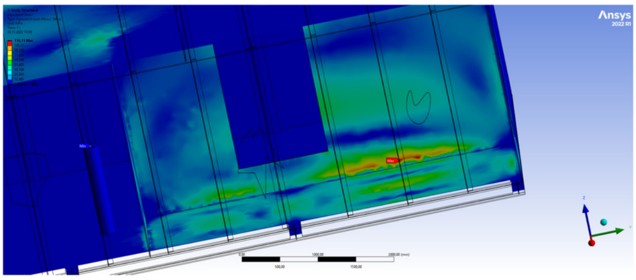

Fig. 9. Distribution of the stresses for the small compartment.

- Case 2. The exercise is carried out in both compartments at the first level. The required standard limits are not exceeded, the maximum stresses being 184.81 MPa (Figure 10).

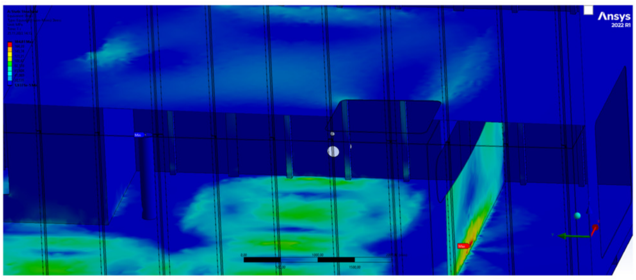

Fig. 10. Distribution of stresses for the compartments at the first level.

- Case 3. The exercise is developed in both compartments on the first level and with water in the compartments on the second level. As can be seen in Figure 11, the required standard limits are not exceeded in this situation either, the maximum stresses being 184.78 MPa.

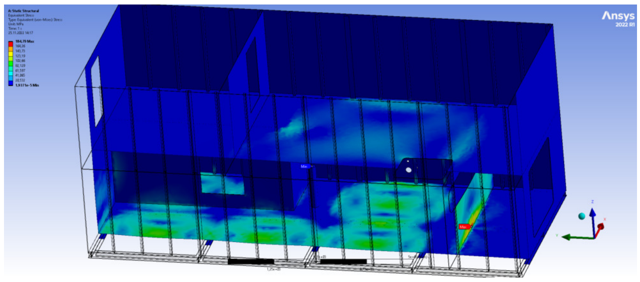

Fig. 11. Distribution of stresses in the case of existence of water in the compartments on the second level.

In the project, several possible cases were simulated, depending on the type of exercise. This paper presents the three most unfavorable cases. The bottom line is that in the version with the highest load, the structure of building A of the vitality complex does not undergo structural changes.

2) Modeling and Structural Analysis of Building B

Building B, in its new configuration (Figure 12) will be dedicated to fighting fire. As in the case of building A, the inner partitioning of building B was determined through structural analysis and, furthermore, thermal analysis was conducted.

The routes of the water and foam fire extinguishing installation, the controlled fire production installation, the ventilation installation, and the support equipment have been established, to create the most realistic scenarios for combating fires. The firefighting training platform is represented by compartments with the greatest risk of onboard fire occurrences. The following section will present the results of the thermal analysis conducted for Building B, in the framework within which the action of heat emanating from the combustion of fuel (diesel) in a burner was studied.

Following the proposal for the modernization of building B, the metallic structure was obtained. Figure 13 is presented as an example.

For the thermal analysis of the walls of the compartment in which the burner is mounted, the construction was simplified, and the following hypotheses were taken into account: the cube inside the room represents the burner, on two sides it exhibits radiation resulting from the combustion of fuel while on the other two sides of the cube it exhibits radiation to the body of the burner and then heat transfers to the walls, smoke discharges are closed, and the ambient temperature is 20°C. Figure 14 illustrates the 3D model and the mesh of building B of the vitality polygon.

The mesh is one specific to fluid flows, with a high level of accuracy (the maximum size of an element is 25 cm, having 8317 nodes and 4631 elements). The results obtained, illustrate the temperature variations on the structure under analysis. Again, three case studies were carried out.

- Case 1. Analysis of the temperature distribution on the outer walls of Building B. As it can be seen in Figure 15, the temperature in the opposite corner of the burner is lower than the temperature behind the burner.

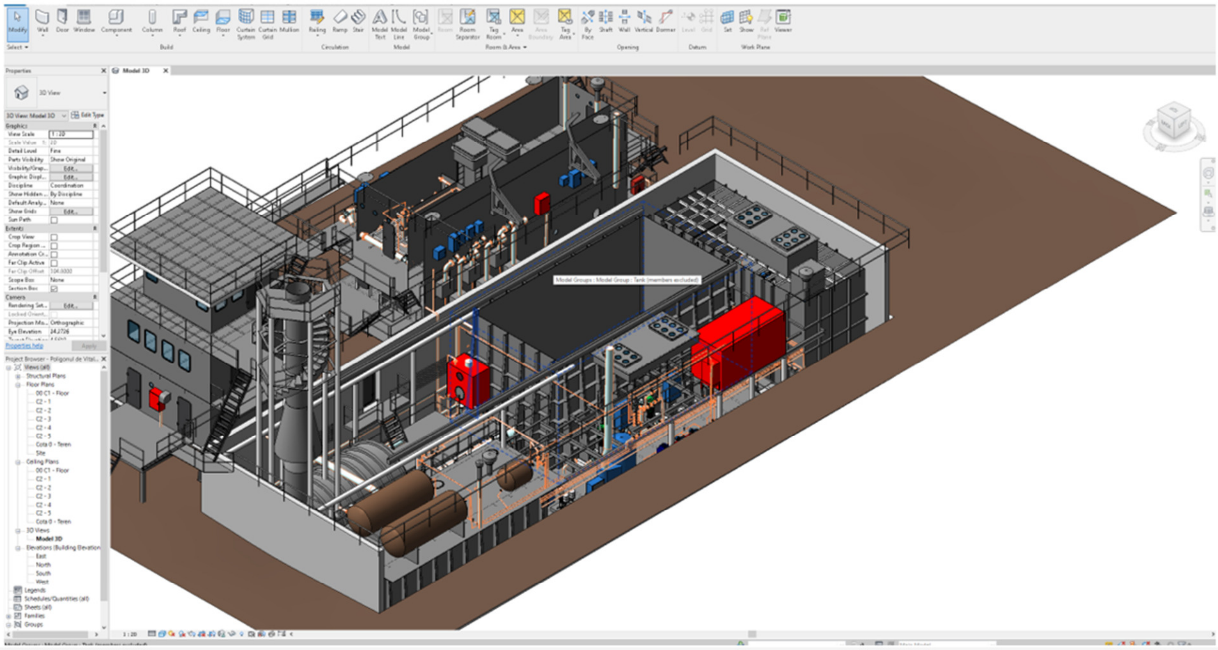

Fig. 12. 3D view of the building B of the new vitality polygon.

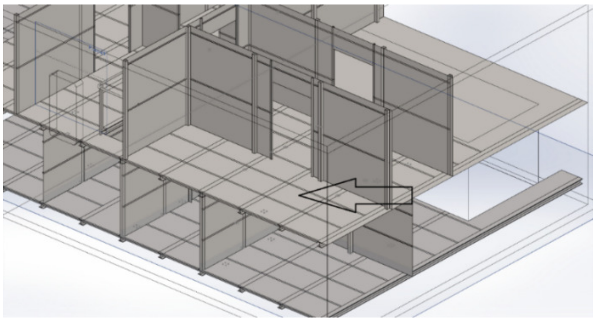

Fig. 13. Compartments used in firefighting training.

(a)

(b)

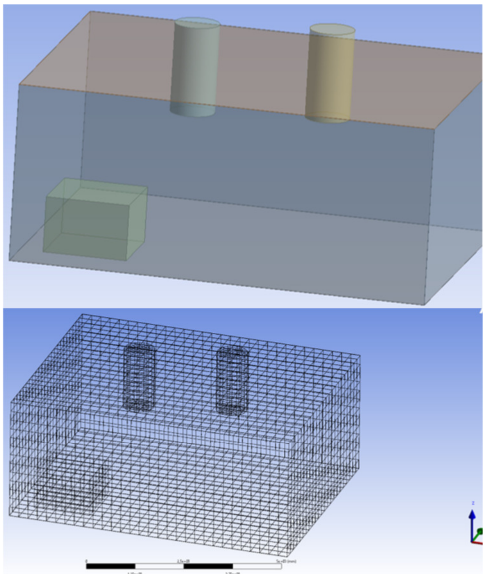

Fig. 14. (a) 3D view and (b) mesh of the new building B.

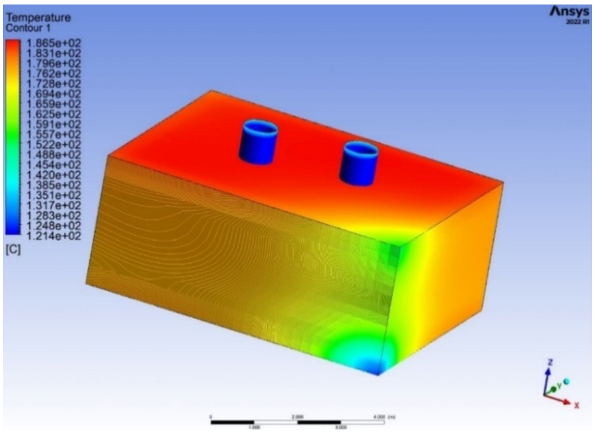

Fig. 15. Fig. 15. Temperature distribution on external walls

- Case 2. Analysis of the temperature distribution on the burner and on the back of the burner. It is noticeable, naturally, that the temperature behind the burner is lower because the box of mechanisms for the burner, which is protected against high temperatures, is located here, as can be seen in Figure 16.
- Case 3. Analysis of the temperature distribution for the air inside Building B of the vitality polygon (Figure 17).

Within the project, 3 cases were simulated (burning of methane gas, burning of marine heavy fuel, burning of diesel fuel). Since the combustion temperature of diesel fuel is the highest, it was appropriate to focus only on the case of diesel burning. The conclusion is that, under these conditions of analysis, the outer walls of this structure, thermally stressed by this heat source, are not in danger of plastic deformation.

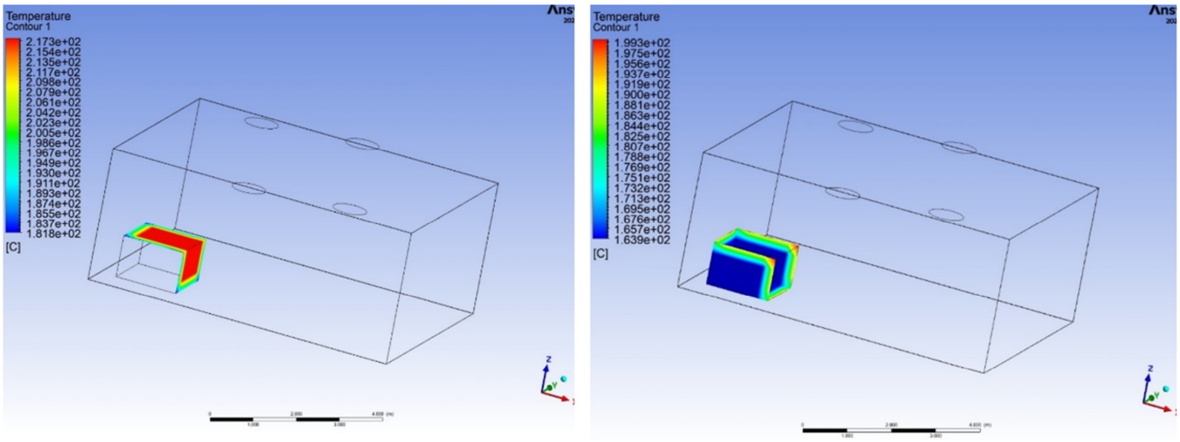

Fig. 16. Temperature distribution. Left: on the burner, right: behind the burner.

3) Modeling of Building C

Building C, in its new configuration will be dedicated to the arrangement of the command, control, and briefing station (Figure 18). The interior partitioning resulted from the structural analysis. Essentially, the equipment is represented by devices for monitoring, controlling, and supervising the training sessions. The space needed for the briefing sessions has been configured and properly equipped (blackboard, magnetic board, video projector, computer, internet access, etc.).

4) Elements of the "as built" Project

In the last stage of the project, using the Solidworks Professional software and after completing the 3D modeling stage of the new vitality polygon, the "as-built" execution drawings were extracted as preparatory elements for the running of the future stages of the project: refurbishment and modernization of buildings, and reconfiguring (partitioning) of spaces and mounting of necessary installations, systems, and equipment for the proper training for the fight against fire and water, according to the requirements and standards.

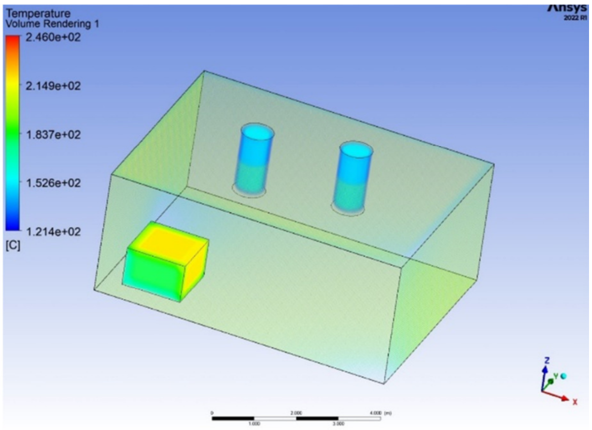

Fig. 17. Temperature distribution within the structure of building B (in air).

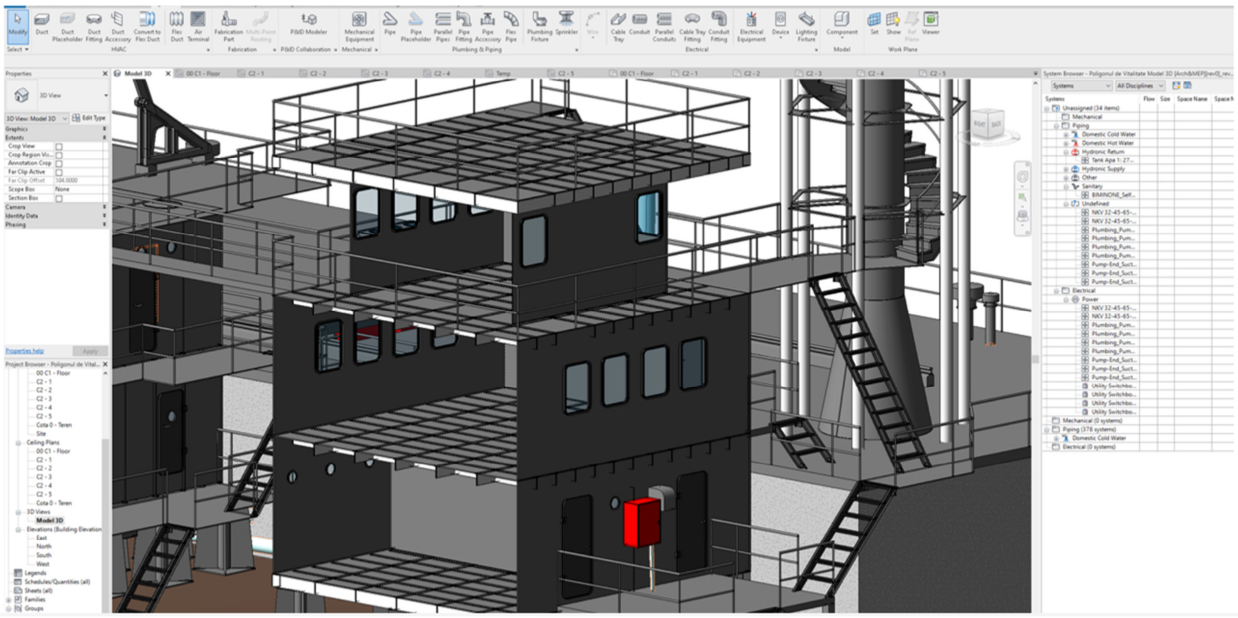

Fig. 18. 3D view of the Building C of the new vitality polygon.

IV. CONCLUSIONS AND FUTURE RECOMMENDATIONS

The content of the project "Modernization of the vitality polygon" answers the need for training (at the high-performance level imposed by NATO standards and STCW code requirements) in ensuring the vitality of the ship for the crews of military vessels and commercial fleets and, finally, for military and civilian students. In the period 2021-2022 of the project, the phases and stages related to the elaboration of the execution project were carried out, thus opening the premises to allow the development of the next phases (execution and reception of the modernization works and drawing up battle scenarios for vitality and training of the personnel who will serve the newly installed equipment and installations). In addition to presenting the results obtained in the first two years of the project, the paper aims to highlight the advantages of using the 3D laser scanning technology of buildings in the case of modernization works of an already built construction (with the exemplification of a vitality polygon). Thus, the following conclusions can be mentioned:

- Generally recognized advantages: precision and accuracy of measurements, acquisition of an impressive amount of digital information, time and staff work saving, safety and security of the method.
- Considered innovative, the terrestrial 3D laser scanning was effectively applied to the vitality polygon, which allowed its "digitization", by generating a volume of technical information (plane and spatial drawings from which execution plans can be derived, views, sections etc.) of great utility for the next phases of the project.
- Using the digital library created by laser scanning, the 3D modeling of the three buildings of the polygon was carried out, and several constructive variants were proposed and analyzed.
- Structural analysis (mechanical and thermal) of the 3D models proposed for the future vitality polygon was performed, allowing the qualitative analysis of the decisions regarding the compartmentalization and endowment with equipment, installations, and systems.

The perspectives opened by 3D laser scanning and 3D modeling can be oriented on the following axes:

- Direction of drawing and design: the digital library (which creates the opportunity to use modern, computer-assisted work techniques by drawing up "as-built" drawings) allows the realization of multiple variants and versions of the technical documentation for the modernization of the vitality polygon, much more precise and much more elaborate than in the case of using classical working techniques.
- Direction of the theoretical training of the personnel: the existence of CAD drawings will give students the opportunity to consult and analyze the training routes and to more easily anticipate future scenarios of water and fire fighting in which they are to participate.
- Direction of theoretical training: the created digital library can be used in technical drawing, infographic and computer-assisted graphics classes, the applications being thus specific, it should also be noted that the knowledge, skills and competences thus acquired by students will facilitate the correct and in-depth understanding of the strictly specialized disciplines that require CAD competences.
- Research direction for the academic staff: the digital library is to be used for the development of complex analyses on the states of stress (loads, deformations), interpretation of simple and complex stresses (bending, torsions, shearing), analyses and studies on deformations (possibly cracks) of various panels (walls, floors, ceilings) and/or piping installations.

Perhaps the most generous perspective opened by the existence of a digital library obtained through 3D laser scanning is that of the development of a virtual center for training personnel in the fight against water and fire. Virtual Reality (which we have become accustomed to, especially due to PC games) is gaining more and more ground and is imposing itself as a training tool that can give students the chance to "see" three-dimensionally, to "feel" and to "understand" in a form very close to reality, the scenarios of fighting against water and fire, not only as a static 3D image, but as a dynamic one which they can observe in different positions and under various angles of observation. For obvious reasons of time and space, the personnel to be trained does not have the opportunity to spend enough time in a physical training simulator and when faced with concrete situations, they have difficulty in understanding and reacting. The existence of a training simulator elaborated on the principles of virtual reality could compensate for this shortcoming, offering the possibility to increase the number of training hours. The recommendation could be that the first stages of training should take place in the virtual environment and only after familiarity with the training processes is ensured the training in a physical vitality complex should start.

Conclusively, the authors wish to ensure that they will revisit this topic in a future paper that will present the results obtained within the project of modernization of the vitality polygon.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of the Ministry of National Defense of Romania, which approved the proposal to develop the project with the title "Modernization of the vitality polygon" during the 2021-2024 period.

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