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Original Research

The Influence of the Variability of the Support of the Mortar Base Plate on the Quality of the Results Obtained in the Process of Its Numerical Design

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Abstract

Due to the high costs associated with the purchase of ammunition and firing in certified training ground centers, tests of retaining plate deformations are increasingly replaced by computer simulations using numerical models. Computer programs usually use a single-parameter subsoil model (Winkler-Zimmermann) for calculations, which requires providing the subgrade susceptibility coefficient. The subgrade compliance coefficient is intended to determine the mutual reaction of the subgrade and the structure due to the pressure exerted on the soil by the retaining slab, which settles. When designing slabs in computer programs, it is assumed that the substrate compliance coefficient is constant. Determining the impact of the soil on the retaining slab is important when analyzing its deformations. The subject of the work was the analysis of the influence of ground support on the results obtained during modeling of the retaining slab. In order to obtain data for FEM analysis and validation, the actual strains occurring on the thrust plate were measured using strain gauge rosettes. The plate deformations were measured during field shooting tests. In order to vary the influence of supporting the slab on the ground and obtain reliable stress values on the slab surface, a method of successive iterations was proposed. Calculations are performed using this method until the error is smaller than the assumed one.

Keywords: mortar base plate, strain measurement, finite element method

1. Introduction

When measuring the value of strains (stresses) during field shooting tests, the high costs associated with purchasing ammunition and carrying out such tests in a certified research center should be taken into account. The data obtained from real measurements are the most reliable, but the development of technology and economic considerations are increasingly reduced to performing computer simulations on computational models.

The issues of interaction between the mortar base plate and the ground are not widely described in world literature. The first and at the same time the most frequently used measurement method is the measurement of deformation using strain gauges (Szwajka et al., 2022). The main emphasis in research is on the analysis of the stress and strength of the mortar itself (Bartnik et al., 2021, Zhang et al., 2016). The quality requirements for mortars stipulate the possibility of firing from them after placing on grounds with a wide range of properties. Any proper interaction of the mortar and the terrain is largely dependent on the latter's deformation modulus (Gomez & Spencer, 2019; Lee & Park, 2015).

The main assumption of Finite Element Method (FEM) is the discretization of a continuous geometric model by dividing it into a finite number of elements connecting at nodes. The effect of this

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division is also the transformation of a system with an infinite number of degrees of freedom into a form with a specific number of degrees of freedom (Kleiber, 1989). In the case of calculations using FEM, all other physical quantities operating in the system in the form of continuous functions, such as loads, restraints, displacements and stresses, are also discretized. The result of discretization of a specific physical quantity is the pursuit of a maximum approximation of its discrete and continuous form through the use of approximation methods (Dacko et al., 1994). The complexity of the finite element method and its approximate nature place significant demands on the software user. A necessary condition for obtaining correct results is to define the appropriate computational model based on the specificity and fundamentals of finite elements (Kacprzyk et al., 2011). The basic advantages of using FEM software include undertaking increasingly complex designs and analyzes of structures for which analytical solutions are not available, and easy consideration of many variants of loads, boundary conditions, types of materials, and shapes of individual parts. Moreover, FEM programs enable automatic data conversion, preventing possible errors or time-consuming calculations, and creating reports on the analyzes performed (Anitescu et al., 2019; Bielski, 2010). The thematic reference to the characterized finite element method are publications by Wang (2019) and Wang et al. (2020), in which the computational models are mortar retaining slabs. The final effect of design optimization is the ability to make boards from light composite layers.

Another example of the use of FEM on a computational model in the form of a mortar thrust plate is the work (Ristić et al., 2009), in which the Pro/Engineer Wildfire software was used. Based on the simulations performed, the stresses occurring on the retaining plate of a 120 mm mortar were analyzed for soft, medium and hard ground. In this work, an attempt was made to compare the simulation with real measurements, however, the insufficiently well-prepared strain gauge installation and its location provided rudimentary results from shooting tests.

The work (Wang & Yang, 2021) presents a topographic design of the retaining plate of a 120 mm mortar based on the finite element method. The model of a trapezoidal-pyramidal plate was subjected to optimization of the dynamic topology of its continuous structure based on the results obtained from laboratory tests. For this purpose, a station was created enabling the impact load on the thrust plate to be applied and this force to be measured. The results obtained from the analyzes provided the basis for optimizing the original model.

The issue of the interaction of the mortar retaining plate with the ground is not widely described in world literature. The main emphasis in the research is placed on the analysis of stresses and strength of the mortar itself. Therefore, the study presents a comparison of the stresses on the mortar retaining plate obtained during the tests carried out using strain gauge measurements with the stress results obtained using FEM. A function was assumed that determines the influence of the elastic substrate on the deformations of the retaining plate. The research is complemented by the results of calculations of the plate model using the finite element method in the MIDAS program. Problems related to the cooperation of the ground and the structures resting on it are an important aspect of strength analysis. There is no detailed research in the literature regarding, among others, deformations of retaining plates on an elastic base. As previously mentioned, a very important issue in the FEM analysis of plates is their interaction with the substrate on which they rest, which are loaded not only with static, but above all dynamic forces.

Due to the specific nature of military products with closely guarded design solutions, the literature review in the area of stress measurement methods and computer simulations in relation to testing mortar thrust plates is significantly limited. Based on the literature, the concept of the work undertaken was to find effective methods to replace the firing of a retaining plate in laboratory conditions and to reduce the costs associated with shooting tests. Due to the lack of correlation between the actual deformations occurring on the retaining plate during the shot and numerical simulations on the computational model of the plate, this work was undertaken to analyze the state of stress and compare the values obtained from strain measurements and as a result of strength analyzes carried out using the finite elements.

2. Material and methods

2.1. Mortar base plate

The subject of the research was the retaining plate of a 98 mm mortar used to support the mortar barrel and to slow down the recoil during firing by transferring energy to the ground. It was made of heat-treated 30HGSA steel. 30HGSA steel is characterized by high hardenability, strength and wear resistance. Due to the decrease in strength properties after exceeding a certain thickness, it is used to produce elements up to 60 mm. It is steel intended for heat treatment consisting of hardening and tempering. After thermal improvement, it obtains excellent strength parameters, while maintaining optimal other properties. Steel is used primarily for highly loaded machine parts and heavy structures subject to heavy loads. Table 1 lists its mechanical properties. The resistance plate used in the research is part of the equipment of soldiers. We had no influence on its shape.

Table 1. Basic mechanical properties of 30HGSA steel.

Ultimate Tensile Stress R_m, MPa	Yield Stress R_e, MPa	Young's Modulus E, GPa	Elongation A_{50}, %
1070	820	210	10

The technology for making the retaining plate was cold-formed sheet metal, 5 mm thick, in the shape of a circle with stiffening embossments. The sheet is then connected to the ball socket, reinforcing ribs and plates as well as stiffening and transport elements by welding with 3.5 mm thick fillet welds. After welding, the plate was heat treated. Figure 1 shows the retaining plate of a 98 mm mortar from both sides.

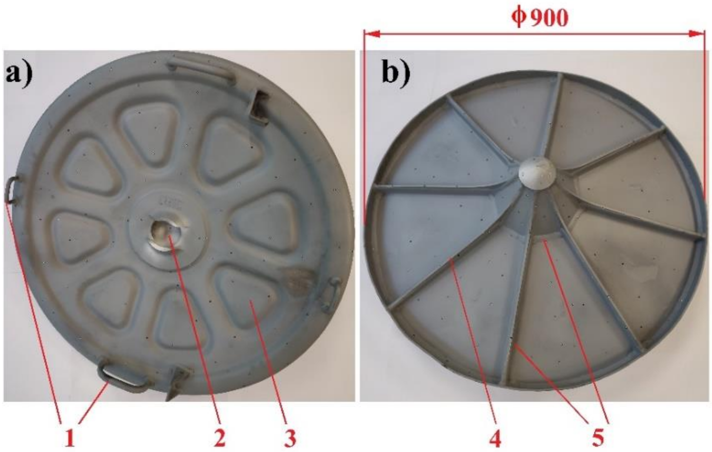

Fig. 1. Mortar base plate: a) – view from above, b) – view from below, consisting of: 1 – transport handles, 2 – ball socket, 3 – stiffening embossments, 4 – strengthening ribs, 5 – welded joints.

2.2. Experiment procedure

During the firing range tests, the deformations occurring on the thrust plate and the pressure of the gunpowder gases in the mortar barrel were measured. The firing was conducted from the ground at a barrel elevation angle of 45^{o} with smoke projectiles on reinforced propellant charges (Fig. 2).

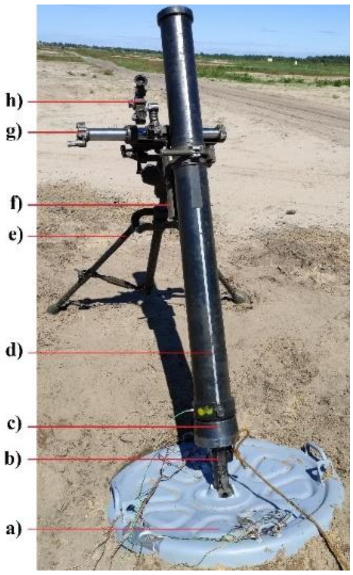

Fig. 2. 98 mm caliber mortar consisting of: a) base plate, b) ball shaft, c) lock, d) barrel, e) bipod, f) recoil dampeners, g) lifting and directional mechanism, h) sight.

Ten strain gauge rosettes were used to measure deformations on the thrust plate during firing from a 98 mm mortar, allowing measurement in three directions: 0°, 45° and 90°. Strain gauge rosettes were placed on the supporting plate in such a way as to enable obtaining as much data as possible regarding the loads acting on various areas of the supporting plate during the shot. Preliminary shooting tests (in the form of pilot tests) showed that the greatest loads on the plate occur in its lower area, and the smallest in the upper area. A symmetrical stress distribution in the vertical system was also observed, on the basis of which the arrangement of strain gauge rosettes on the retaining plate was determined, graphically shown in Fig. 3.

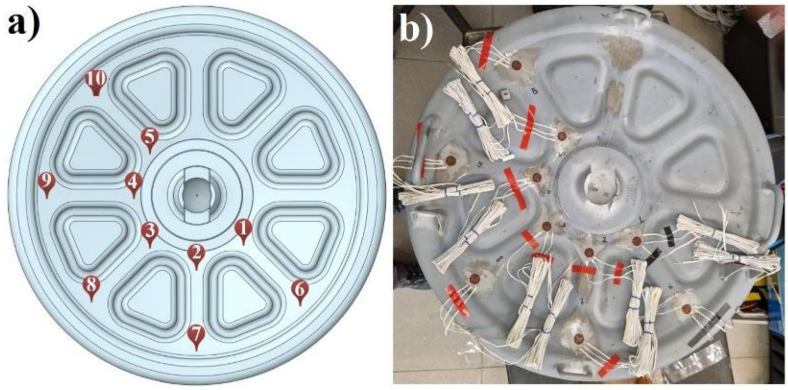

Fig. 3. Location of strain gauge rosettes on: a) 3D model of the plate, b) mortar base plate intended for field tests.

The strain gauge installation was made on the outside of the thrust plate, due to the direction of the shot force, but also due to the impossibility of securing the strain gauges if they were mounted on the side in contact with the ground. The installation consisted of 10 KYOWA rosettes, type KFGS-10-120-D17-11 L3M3S, glued using CC-33A glue from KYOWA. The frequency response of the strain gauge rosettes was 1200 Hz. The signals were recorded at a frequency of 19,200 Hz using an HBM amplifier – QuantumX MX1615B model and dedicated HBM computer software. Then, the signals were filtered to remove interference. The strain gauge rosettes used for the measurement worked in a Wheatstone quarter-bridge. Along with recording the deformations, a measurement of the pressure of the gunpowder gases was carried out in parallel, synchronized in an identical time interval using the Piezotronics 482C PCB signal conditioner. Figure 4 shows a diagram of the measurement track used during the firing range tests.

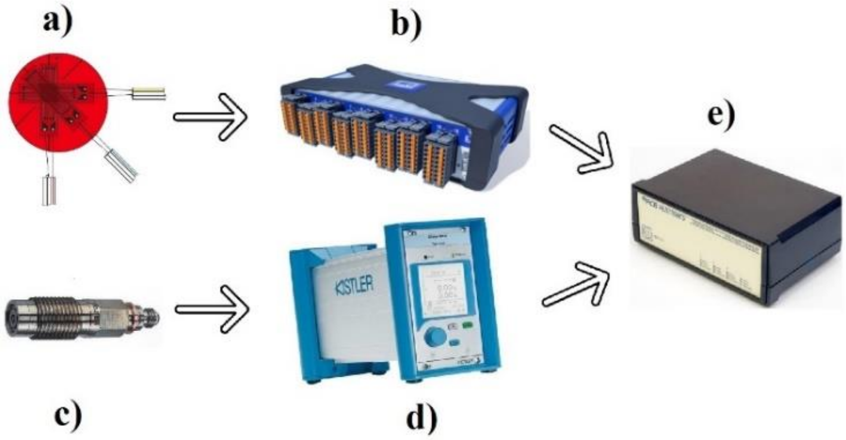

Fig. 4. Diagram of the measurement path consisting of: a) KYOWA strain gauge rosettes, b) HBM MX1615B measurement amplifier, c) Kistler 6215 piezoelectric sensor, d) Kistler 5015A charge amplifier, e) Piezotronics 482C PCB signal conditioner.

3. Results and discussion

During firing, the maximum deformation values were measured on the retaining plate of the 98 mm mortar using ten strain gauge rosettes, and the pressure of the powder gases in the mortar barrel was measured using a piezoelectric sensor. Examples of the recorded maximum signals for the R1 rosette are shown in Fig. 5a, while the pressure course over time is shown in Fig. 5b.

a)

b)

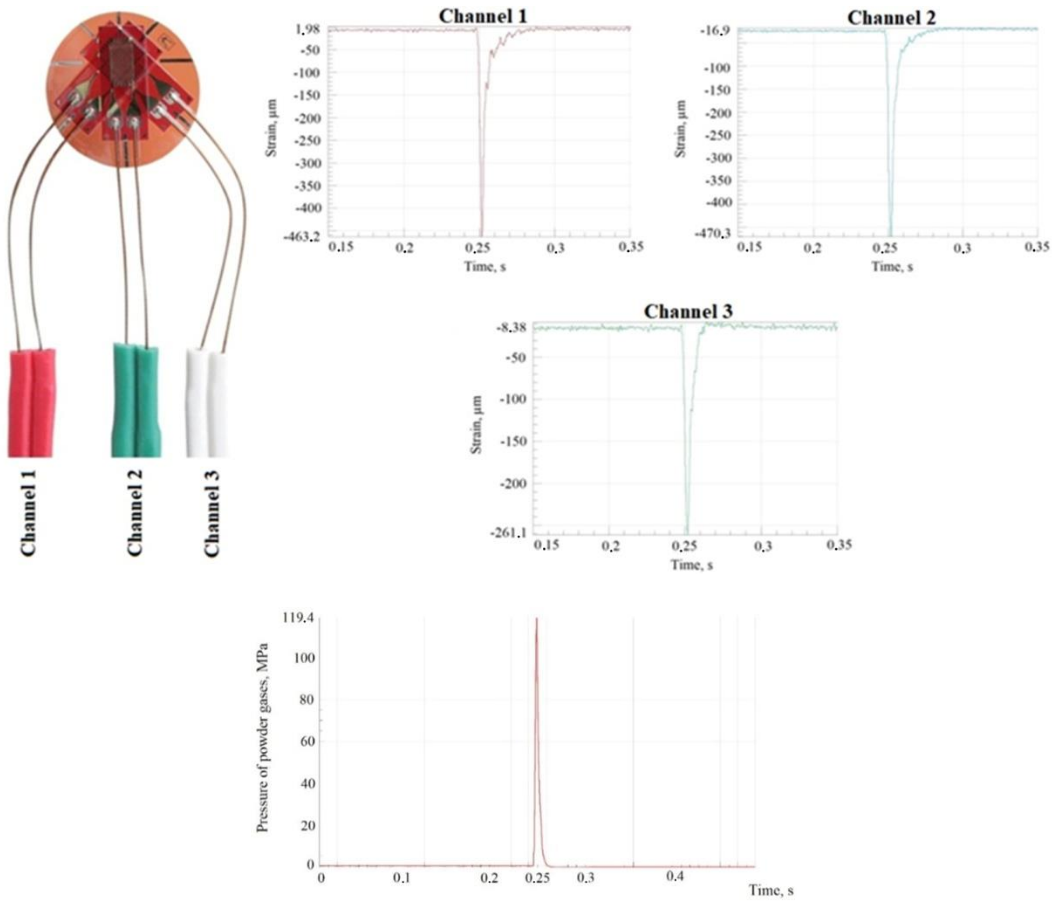

Fig. 5. a) maximum strain curves for rosette R1 and b) the course of the pressure of gunpowder gases over time.

When conducting strength analyses, the measurement results were reduced to reduced stresses in accordance with the Huber-Mises-Hencky (H-M-H) hypothesis. In the calculation program, the stresses for individual directions were converted into reduced stresses using the Von Mises module. Below is an iterative summary of the results obtained in three subsequent analyses, which allowed to obtain the correct final result of the analyses. The elements used to represent the stiffness of the soil were Bush elements. These are elements that are characterized by elasticity and damping. In the calculations, they were used as elements whose dominant component is stiffness. There is a node at each end of the bush element (this is a 1D element). One of the nodes is adjacent to the surface of the elements from which the numerical model of the plate is built. The second node is automatically supported.

The next stage was to determine the estimated values of soil stiffness, which will be expressed in N/mm. Converting the stiffness into these units is necessary because it is in them that the stiffness is defined in the Midas NFX calculation program. An axisymmetric model was prepared for this task. By assigning material parameters (Young's modulus, Poisson's ratio) determined from standard PN-81 B-03020 that describe various types of soil, a model was created into which a triangular indenter was pressed, which was supposed to approximately reproduce the shape of the plate (test this, to a large extent, looked like a microhardness test). Then, after applying the assumed force to the indenter, the indentation value was read. In this way, the stiffness parameter (N/mm) was obtained from the material parameters. This allowed us to determine the approximate order of magnitude of the individual stiffnesses that the Bush-type elements that support the model should have.

The initial assumption for modeling the structure of the mortar support plate in the numerical model in iteration 1 included the full support of the plate on the ground, both surface and edge parts, with constant soil stiffness conditions. Below is a summary of the stiffness of spring elements representing elastic support conditions:

• stiffness on surfaces 200 N/mm,
• stiffness at the edges 1400 N/mm.

The envelopes of stress values in individual views for 2D shell elements for top and bottom surfaces are shown in Figure 6.

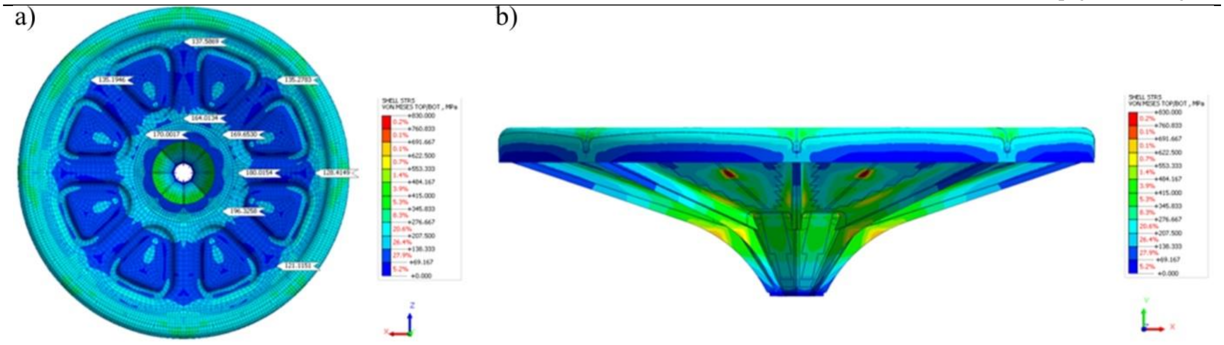

Fig. 6. Stress values in the envelope from strain gauge measurement points (first iteration): a) upper view, b) side view.

A comparison of the results of numerical analyzes and the results obtained during measurements at reference measurement points is shown in Fig. 7.

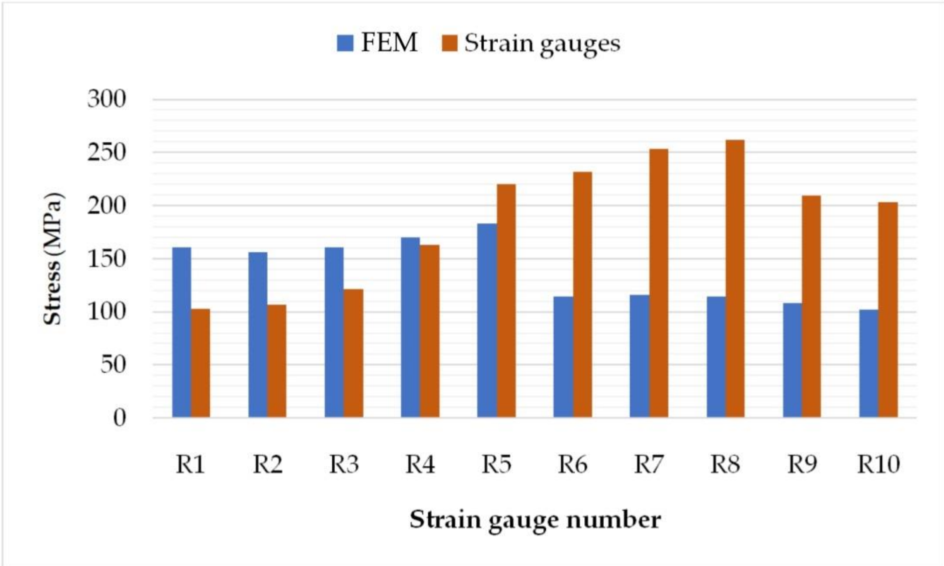

Fig. 7. Graphical summary of results obtained from numerical analyzes and measurements (first iteration).

The initial assumption for modeling the structure of the mortar support plate in the numerical model in iteration 2 included half of the support of the surface parts of the plate on the ground and full support of the edge parts of the plate on the ground, with constant soil stiffness conditions. Figure 8 presents a summary of the stiffness of spring elements representing elastic support conditions:

- stiffness on surfaces 200 N/mm,
- stiffness at the edges 1400 N/mm.

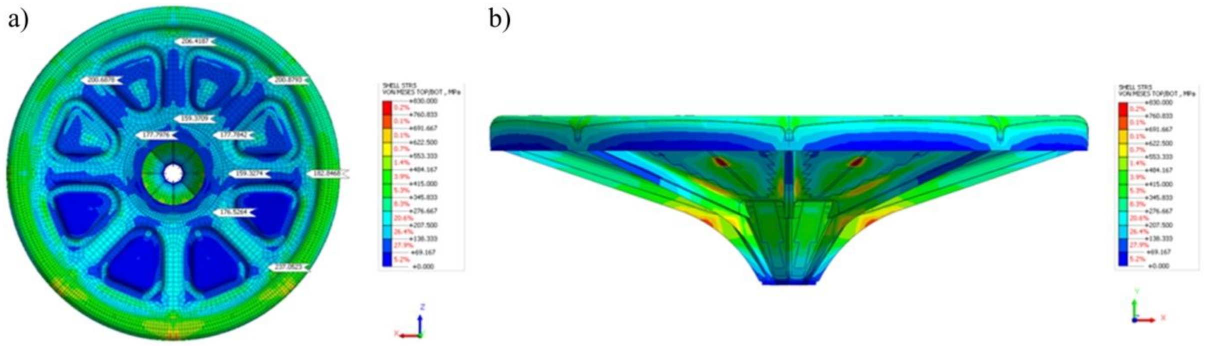

Fig. 8. Stress values in the envelope from strain gauge measurement points (second iteration): a) upper view, b) side view.

A comparison of the results of numerical analyzes and the results obtained during measurements at reference measurement points is shown in Fig. 9.

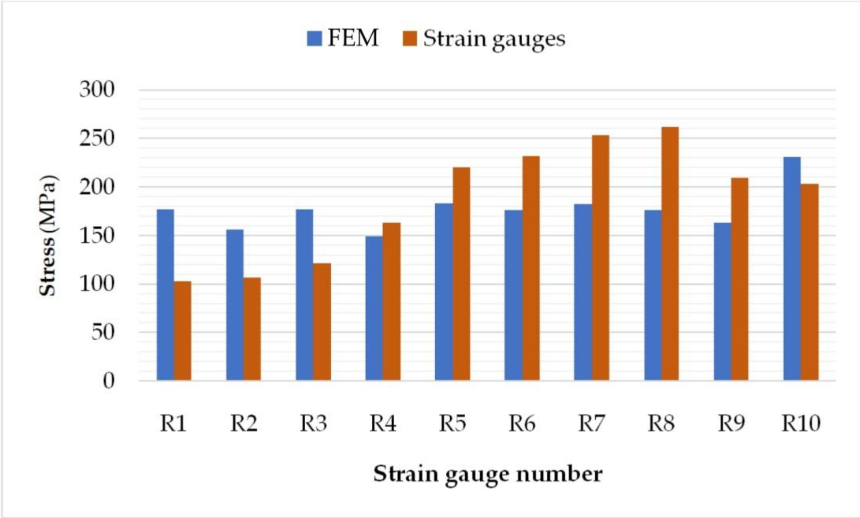

Fig. 9. Graphical summary of results obtained from numerical analyzes and measurements (second iteration).

The initial assumption for modeling the structure of the mortar support plate in the numerical model in iteration 3 took into account only the medial area of the support of the surface parts of the plate on the ground and the full support of the edge parts of the plate on the ground, with constant soil stiffness conditions. Figure 10 presents a summary of the stiffness of spring elements representing elastic support conditions:

• stiffness on surfaces 200 N/mm,

• stiffness at the edges 1400 N/mm.

A comparison of the results of numerical analyzes and the results obtained during measurements at reference measurement points is shown in Fig. 11.

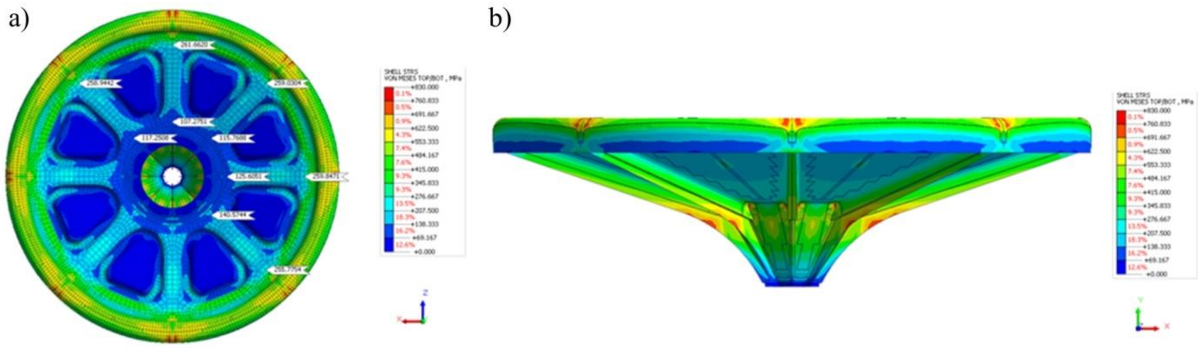

Fig. 10. Stress values in the envelope from strain gauge measurement points (third iteration): a) upper view, b) side view.

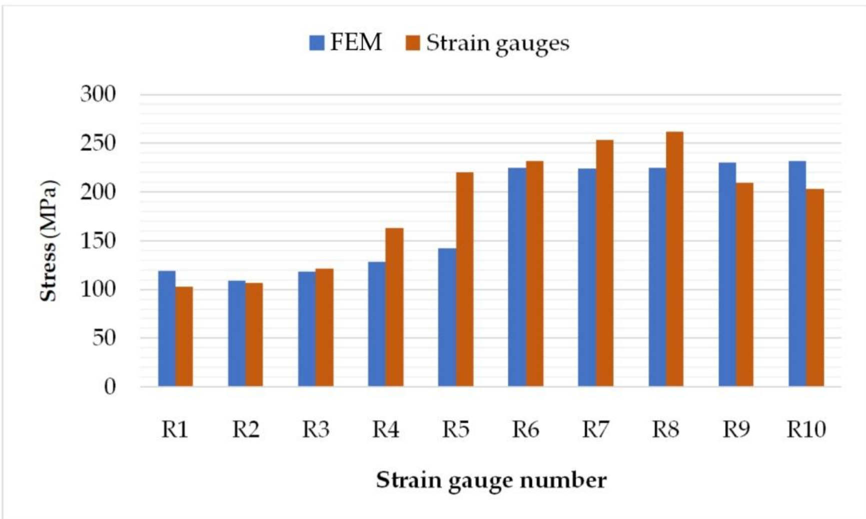

Fig. 11. Graphical summary of results obtained from numerical analyzes and measurements (third iteration).

4. Conclusions

This study proposes a continuum base plate topology optimization problem under quality and engineering constraints. The modeling method used for the mortar base plate was proven to be accurate and feasible through test verifications. In this case, topology optimization was performed on the mortar base plate structure using a force transmission path based on base plate stress analysis. The base plate optimization model could meet the requirements of structural stiffness and strength, shooting stability and lightweight structure. Thus, this study provides a benchmark for performance improvement and structural optimization design of the base plate.

The highest stress values were observed on the outer circumference of the mortar plate. This is due to the shape of the outer ring of the plate. It sinks into the ground and acts as a block to the movement of the mortar plate.

The case of obtaining the results of individual analyzes was limited to the ground, which was fill sand and shot at an angle of 45°. The iterative comparison of the results obtained in three subsequent analyzes allowed to obtain the final effect of the analyses, allowing obtaining satisfactory results, consistent with the results obtained from strain gauge measurements. The process of obtaining the final results was an iterative process, which included many computational approaches with each change of the calculation assumptions, in particular the slab support conditions.

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Wpływ Zmienności Podparcia Płyty Oporowej Moździerza na Jakość Uzyskanych Wyników w Procesie Jej Projektowania Numerycznego

Streszczenie

Ze względu na wysokie koszty związane z zakupem amunicji oraz realizacją ostrzału w certyfikowanych ośrodkach poligonowych badania odkształceń płyty oporowej są coraz częściej zastępowane symulacjami komputerowymi za pomocą modeli numerycznych. Programy komputerowe wykorzystują przeważnie do obliczeń jednoparametrowy model podłoża (Winklera-Zimmermanna), w którym wymaga się podania współczynnika podatności podłoża. Współczynnik podatności podłoża gruntowego ma na celu określenie wzajemnej reakcji podłoża i konstrukcji, przez nacisk wywierany na grunt przez osiadającą płytę oporową. Przy projektowaniu płyt w programach komputerowych zakłada się, że współczynnik podatności podłoża jest stały. Określenie oddziaływania gruntu na płytę oporową jest istotne przy analizie jej odkształceń. Przedmiotem pracy była analiza wpływu sposobu podparcia płyty oporowej o podłoże gruntu na uzyskane wyniki w trakcie jej modelowania. W celu uzyskania danych do analizy i walidacji MES, przeprowadzono pomiar rzeczywistych odkształceń występujących na płycie oporowej za pomocą rozet tensometrycznych. Pomiaru odkształceń płyty dokonano podczas poligonowych badań strzelaniem. W celu uzmiennienia wpływu podparcia płyty o podłoże oraz uzyskania miarodajnych wartości naprężeń na powierzchni płyty, zaproponowano metodę kolejnych iteracji. Metodą tą są wykonywane obliczenia do chwili uzyskania błędu mniejszego od założonego.

Słowa kluczowe: płyta oporowa moździerza, pomiar odkształceń, metoda elementów skończonych