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Building and Testing a Rosette for Spatial State of Stress

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Abstract. The article presents the results of the construction and testing of a rosette for measurements in the spatial state of stresses. using a strain gauge and a three-grid rosette. A rosette with three grids was glued onto one facet of an aluminium alloy cube, so that the convergence point of the grid axes coincided with the centre of the square facet. Using a coordinate drilling machine, a 3mm diameter hole was made, centered at this point. The depth of the hole was 15 mm. A strain gauge was glued inside the hole, so that all 4 grids were at the same distance from the centre of the facet. A finite element analysis was performed for the cube subjected to compression between prisms (plane stress state), followed by laboratory tests. The good functioning of the 3D rosette was demonstrated.

Keywords: spatial stress state, spatial strain gauge, FEA, compression, measurement.

1. Introduction

Resistive electrical strain gage is one of the most widely used methods of Experimental Stress Analysis, due to the fact that it is accurate, relatively inexpensive, and versatile [1]. Strain gauges are frequently used to determine physical characteristics of materials (such as Young's modulus, Poisson's ratio), for static or dynamic measurements performed in the laboratory or in the field, for the construction of sensors (force sensors, pressure sensors, etc.) or for the monitoring of structures, in order to prevent failures, etc. Three-grid resistive strain gauges rosettes are commonly used to determine the biaxial (2D) state of stresses, when the main directions are not known. In the case of rectangular rosettes, which have the grids positioned at an angle of 45° between them, the principal stresses and principal directions are determined with the equations [2]:

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$$\sigma_{P,Q} = \frac{E}{2} \left[\frac{\varepsilon_1 + \varepsilon_3}{1-\nu} \pm \frac{\sqrt{2}}{1+\nu} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2} \right] \quad (1)$$

$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \right) \quad (2)$$

where

- σ_P and σ_Q are the maximum and minimum stresses, respectively;
- θ is acute angle from the principal axis to the reference grid axis (grid no. 1);
- ε_1 , ε_2 and ε_3 are the measured strains with rosette's grids 1, 2 and 3 (see fig. 1).

Currently, there are no rosettes for the spatial (3D) state of stresses on the market. The paper presents the creation and testing of such a rosette, starting from the solution presented in OSIM patent 129673/2017 [3], which has been simplified. The paper describes how a 3D strain gage was made and tested.

2. Building the 3D rosette

2.1. Operating principle

To determine the spatial state of stress, we start from the idea presented in [3], which was adapted to the laboratory equipment. In short, the method provides for gluing a rectangular rosette to the component or structure being measured, making a hole perpendicular to the plane of the rosette, equidistant from the three grids and mounting a uniaxial strain gauge (SG) in this hole. With the help of the rectangular rosette, the principal stresses and principal directions in its plane (2D) can be determined. With the SG mounted in the hole, the principal stress is determined in the direction perpendicular to the plane of the rosette, thus obtaining a rosette capable of determining the spatial state of stresses (3D). From the Theory of Elasticity it is known that the three principal stresses are mutually perpendicular [4].

2.2. Rosette selection

The patent [3] provides the use of a rosette for determining residual stresses by the hole drilling method [5], [6]. A flattened pin is fixed in the hole, with a strain gauge glued on its flat surface. These rosettes allow a hole with a maximum diameter of 2mm and thus a very small strain gauge is required. In the absence of such a strain gauge, a rosette was sought that would allow a larger diameter hole to be made and A standard rectangular rosette, type MM-Vishay CEA-06-120CZA-120, was chosen (fig. 1). On this rosette, the grid axes and their intersection point are marked.

The distance from this point to the edge of the grids is then measured. For this purpose, a Leica metallographic microscope was used. In figure 2 it is observed that the distance from the center of the hole (the tip of the triangle in fig. 2) and the nearest grid is slightly more than 2 mm (2023 μ m). Consequently, a hole with a radius

of 1.5mm can be made through this rosette, without damaging the grids. Since a hole with a diameter of 3mm can be made through the rosette in fig. 1, compared to only 2mm through the rosette for residual stresses, the rosette in fig. 1 was selected.

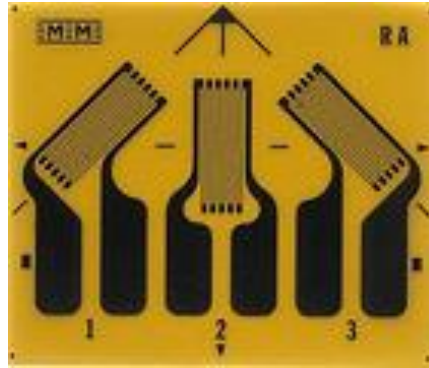


Fig. 1. Strain rectangular rosette MM-Vishay CEA-06-120CZA-120.

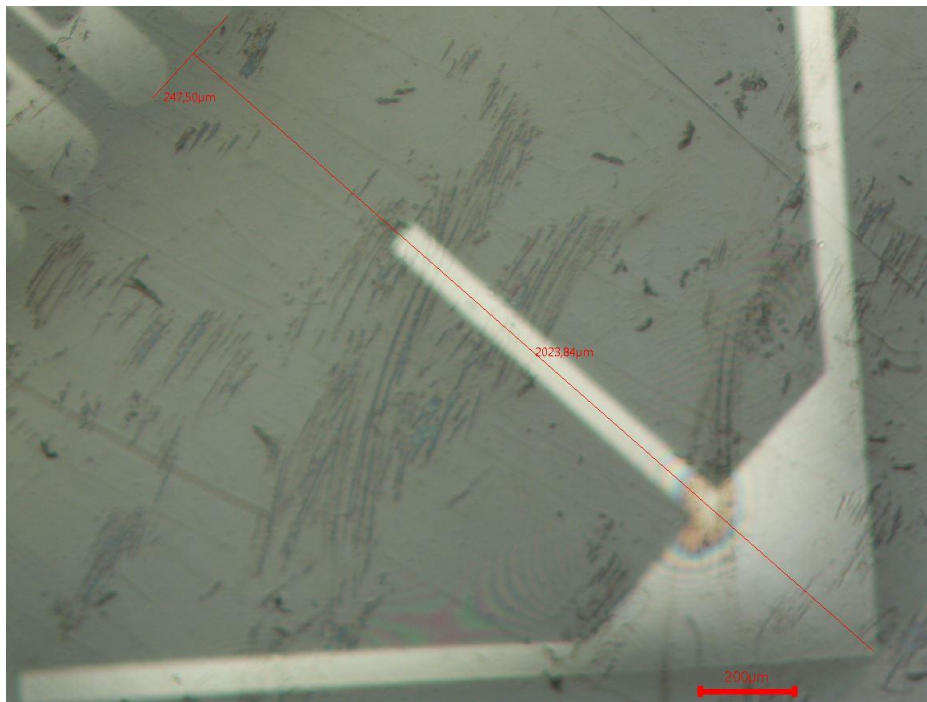


Fig. 2. Measuring the distance from the convergence point of the grid axes to the grids, for the rosette in figure 1.

The rectangular rosette was glued to one face of an aluminum alloy (7000 series) cube [7], with a side of 30mm, so that the tip of the triangle marking the convergence point of the grid axes, which will be the center of the future hole, is at the intersection of the diagonals of the square. The bonding was done with Z70 adhesive from HBK, following the manufacturer's recommendations.

2.3. Hole drilling

On the face where the rosette was glued, a blind hole is to be made, in which an SG will be mounted in a direction perpendicular to the rosette plane, to form the 3D rosette. Since the hole must be at equal distances from the three grids, since possible eccentricities can cause measurement errors, and the edge of the hole is only 0.5mm from the grids, this operation was performed on a coordinate drilling machine, with a positioning accuracy of $\pm 1\mu\text{m}$ (fig. 3).



Fig. 3. Coordinate drilling machine (a) and position display with accuracy of $\pm 1\mu\text{m}$ (b).

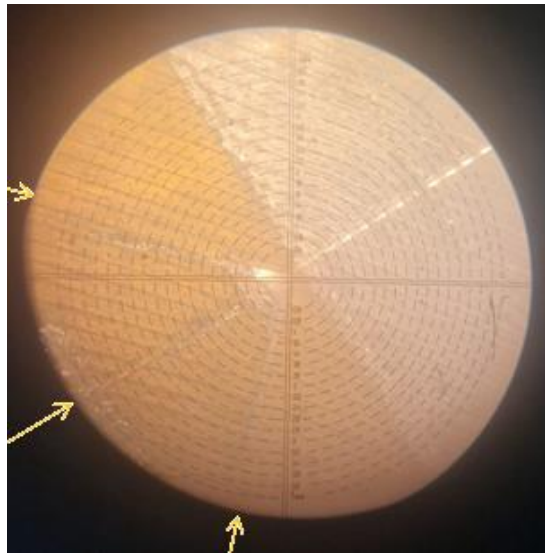
The convergence point of the grid axes was targeted using a centering microscope with a cross-shaped reticle (fig. 4). This will be the center of the hole. The microscope was removed after fixing the center of the hole and a mandrel with a $\varnothing 3$ mm drill was inserted in its place (fig. 5). A 15 mm deep hole was drilled through the rectangular rosette support, positioned as above. After removing the metallic chips by blowing with compressed air, the electrical resistance of the grids was measured to verify if their integrity was not affected by drilling. Since the grids were intact, we moved on to the next stage, mounting the SG in the hole and soldering the wires to the rosette.

The drilling must be done with great precision. The accuracy of the spatial rosette depends on the success of this technological operation. If a rosette for determining

residual stresses is chosen, drilling can be done with a special a special hole-drilling apparatus, equipped with an optical device for centering the tool holder [6].



a)



b)

Fig. 4. Targeting the mark on the rosette using a centering microscope (a) and microscope image (the arrows indicate the axes of the three grids).



Fig. 5. Drilling the hole: general view (a); approaching the drill to the cube (b)

2.4. Gluing strain gauge into the hole

In the hole made with the technology presented above, a SG with pre-attached wires, type MM-Vishay C2A-06-125LW-120 (fig. 6) was mounted, taking care that its support was permanently in contact with the walls of the hole, over its entire surface, until the adhesive hardened. The dimensions of the strain gauge polymer support are 3.2mm and 7.4mm. The strain gauge was inserted to such a depth (verified by marked marks) that the edges of the grid were 2mm from the plane of the surface on which the rosette was glued. The same distance was maintained as between the center of the hole and the edge of the rosette grid (fig. 2).



Fig. 6. Strain gauge type MM-Vishay C2A-06-125LW-120, with pre-attached wires.

3. Finite elements analysis (FEA)

3.1. Geometry and discretization

A finite element analysis (FEA) of the cube loaded in compression on two opposite sides, by means of prisms (one fixed and the other mobile), was performed. This experiment will be performed on a compression testing machine. The geometry of the cube-prism assembly was realized in the CATIA V5R19 software (fig. 7).

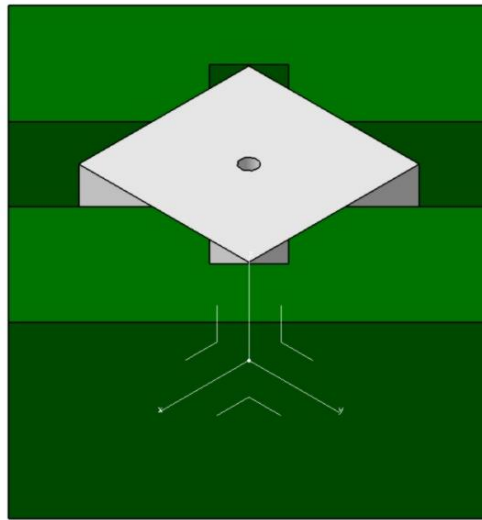


Fig. 7. Geometry of the loading cube-prisms assembly.

The geometry was imported into the numerical simulation program ANSYS Structural. The three bodies can be seen in figure 8. For the cube, the material was assigned as Aluminum Alloy. For the two prisms, a structural steel was chosen.

A mesh was created consisting of tetrahedral cells on the cube and prismatic cells on the two prisms. From a quantitative point of view, the discretization network has a total number of 725645 nodes and 424765 elements and from a qualitative point of view the discretization network is a good network with the following values of the quality parameters: Skewness: 0.81; Orthogonal Quality: 0.30 (table 1). The final discretization network is shown in figure 8.

Table 1. Characteristics of the discretization network

Statistics	
Nodes	725645
Elements	424765
Mesh Metric	Orthogonal Quality
Min	0.30031
Max	1.

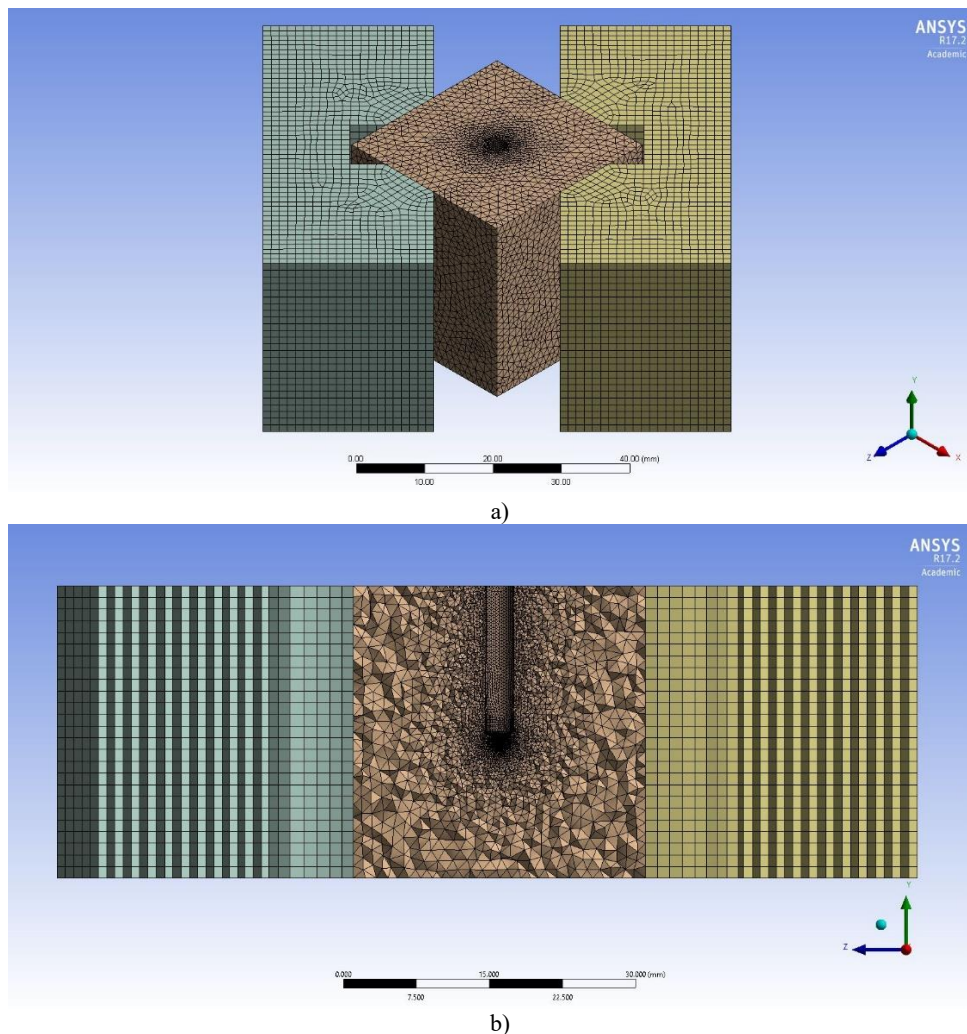


Fig. 8. The discretization network: isometric view (a) and section through the cube (b).

3.2. Loading and state of stress

The loading condition consists of applying a force of 10000 N on the diagonal of the cube. This force is the resultant of the components on the X and Z axes according to the coordinate system with the magnitude of 7071.1 N (on the X axis) and -7071.1 N (on the Z axis), respectively, figure 9. The modulus of elasticity for the Al alloy was considered 70000 MPa. The maximum tangential stress is calculated in the plane of the rectangular rosette.

The simulation results contain the distributions of the equivalent von-Mises stress and directional displacement. The distributions of the von-Mises stresses are shown in figures 9-12.

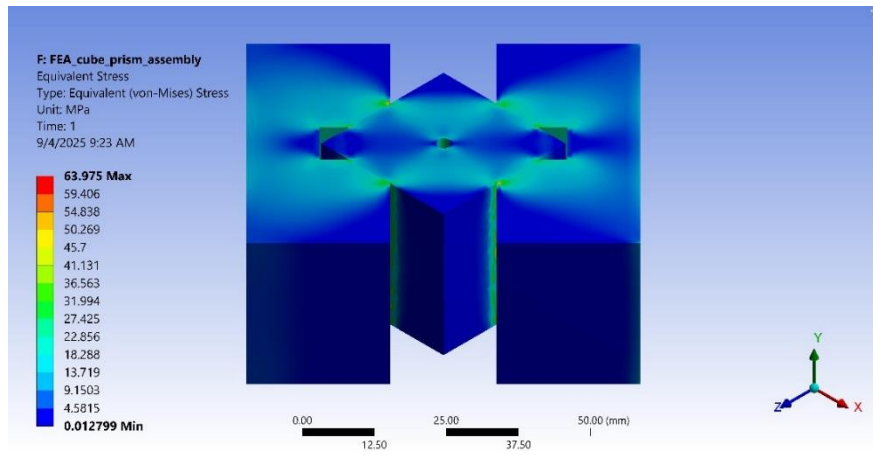


Fig. 9. Distribution of von Mises stress on the cube-prism assembly.

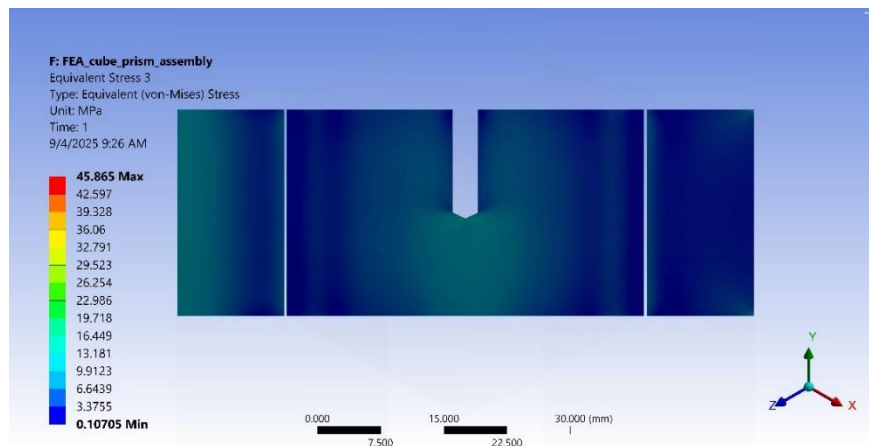


Fig. 10. Distribution of von Mises stress in the plane containing the diagonal with the loading prisms.

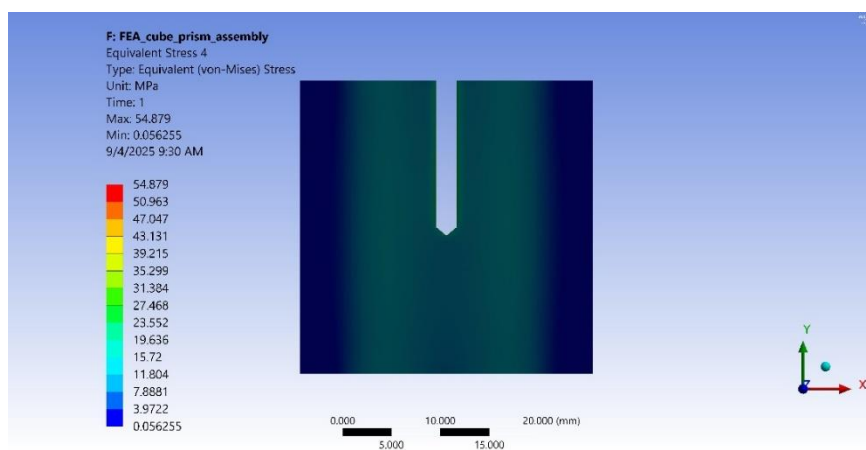


Fig. 11. Distribution of von Mises stress in the plane containing the diagonal without prisms.

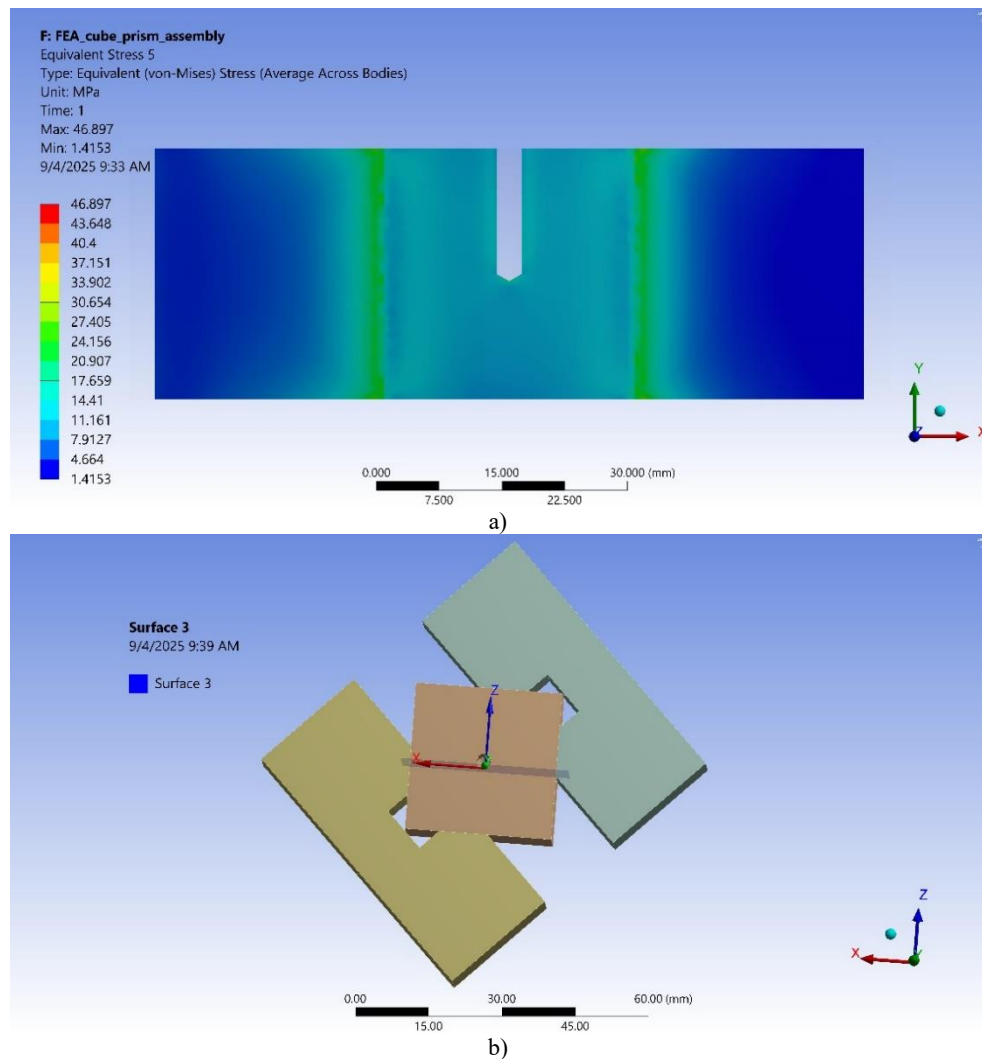
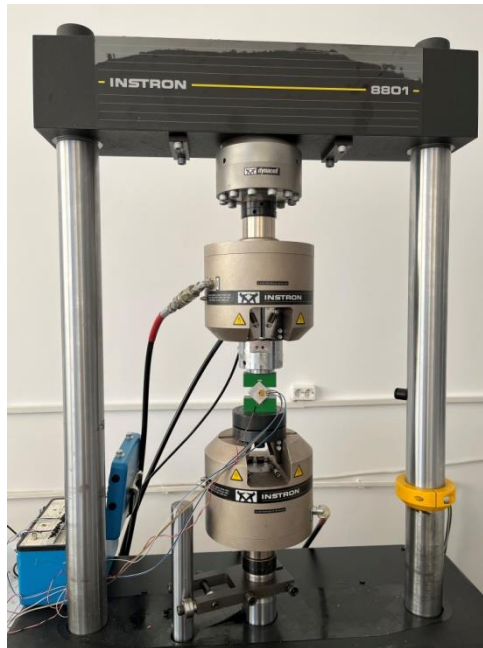


Fig. 12. Distribution of von Mises stress (a) in the XY symmetry plane (b).

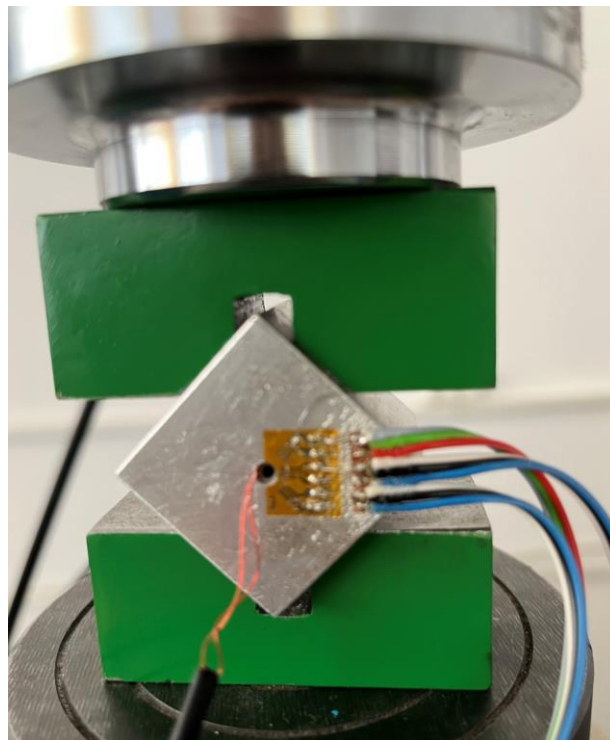
4. Experiments

The cube sandwiched between the two prisms placed on opposite sides was tested in compression on an Instron 8801 testing machine (fig. 13). The test was performed up to a maximum force of 10kN.

In Table 2 the data read from the Vishay P3 strain gauge bridge are presented. Channels 1, 2 and 3 correspond to the grids of the rectangular rosette marked with the same numbers (fig. 1). Channel 4 corresponds to the strain gauge (SG) mounted in the hole, perpendicular to the plane of the rosette. Using equations (1) and (2) the principal stresses and their directions in the plane of the rosette were calculated.



a)



b)

Fig. 13. Compression test of cube: general view (a); detail with cube placement (b).

Table 2. Experimental data processing.

Force [N]	ε measured with the channel no. [$\mu\varepsilon$]				Principal stresses [MPa]			$\tau_{\max}$ [MPa]	Principal direction [°]
	1	2	3	4	σ_P	σ_Q	σ_{SG}		
9991.2	-39	82	-63	95	2.1	-12.3	0	7.2	42.4

5. Conclusions

A 3D strain gauge rosette was constructed by gluing a 3-grid rosette onto the face of a 7000 series aluminum alloy cube, such that the convergence point of the grid axes was the center of the facet. A 3mm diameter hole was drilled at this point. Strain gauges were glued into the hole so that all grids were equally spaced from the center of the facet.

The maximum stresses did not exceed the elastic range. This is proven by FEA as well as by experiment, because after unloading no zero drift occurred.

The normal stresses σ_P and σ_Q are calculated with the experimental data for the rectangular rosette, and σ_{SG} in the direction of the strain gauge mounted in the hole (perpendicular to the plane of the rectangular rosette) is zero, because the experimental setup created only a biaxial state of stress in the cube. For a triaxial state of stress σ_{SG} can be calculated with Hooke's law.

From Table 1 it is observed that the calculated main directions resulted at 42.4°, instead of 45°, as expected. This is an acceptable measurement error with electrical strain gauges.

The proper functioning of the spatial rosette was thus demonstrated.

To reduce the influence of the stress concentrator, the hole can be filled with bulk adhesive doped with filings from the same aluminum alloy.

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