ISSN: 3066-8131
Research Article
Science Set Journal of Physics

Design and Strength Analysis of the Main Frame of an Innovative Grain Dryer with Deformation Gauge Measurement of the Mass of the Dried Material

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Submitted: 16 December 2024 **Accepted:** 23 December 2024 **Published:** 30 December 2024

https://doi.org/10.63620/MKSSJP.2024.1047

Citation: *Łykowski, W., Gierz, Ł., Modrzejewska-Sikorska, A., Javorova, J. (2024). Design and Strength Analysis of the Main Frame of an Innovative Grain Dryer with Deformation Gaug Measurement of the Mass of the Dried Material. Sci Set J of Physics, 3(6), 01-06.*

Abstract

Seeds of crops such as rapeseed, corn, and sunflowers require postharvest drying for proper storage. Inadequate seed moisture leads to the development of bacteria and fungi. Inadequate humidity increases the content of harmful fusarium micro toxins. The average moisture content of corn during harvest is up to 35%, in the case of rapeseed, 12%, and in the case of wheat - 18%, while the recommended moisture content for grain storage is 14% for corn, 6% for rapeseed, and 14% for wheat. There are mobile and stationary dryers available on the market that can be used as flow or batch dryers.

The aim of the work is to develop an innovative concept of a dryer with strain gauge measurement of the mass of dried material and to analyse the strength of its main frame. The dryers available on the market do not have scales that could control weight loss. The project included the analysis of commercialized and available solutions on the market, the development of a 3D CAD model of the entire dryer with a hopper of 8 m3, and an analysis of the strength of the dryer's main frame using the finite element method. The 3D model and FEM strength analysis were made in SolidWorks. The developed dryer has a good chance of commercialization.

Introduction

The drying process has been widely used for centuries in many industries, including the chemical, textile, food, construction, automotive, and ceramic industries, but also in mining and agriculture. Due to the growing area of corn cultivation in Poland, it was decided to develop a new mobile dryer for small and medium-sized farms with an area of up to 50 ha [1, 2]. During harvest, which occurs in October or even November, corn grains often have a moisture content greater than 30%, which is why they require additional drying [3]. To properly store corn grains, moisture content of 14-15% should be achieved. According to the guidelines of the Rural Development Program 2014-2020 (RDP 2014-2020), provided by the Agency for Restructuring and Modernization of Agriculture, a rational choice for small and medium-sized farms (area up to 50 ha) is a dryer with a capacity of 8 m3 [2]. Unfortunately, the Polish agricultural machinery market is poor in dryers of the indicated capacity, which is why it was decided to carry out such a dryer project as part of this work. The aim of the work is to perform a conceptual design of a mobile batch dryer and a strength analysis of the supporting frame of this structure using the finite element method (FEM).

The mobile batch dryer can have practical application in farms focused on plant production, especially the cultivation of cereals, including corn, but also oil plants, such as rapeseed. Additionally, it should be noted that during wheat harvest, the humidity reaches 18-20%, while during rapeseed harvest it 12%. To properly store cereal grains, it is recommended to reduce humidity to 14-15% (similarly for wheat and corn), and in the case of rapeseed to 6% [4].

The conceptual design of a mobile dryer developed will allow for obtaining the desired parameters of stored agricultural products, in particular cereals and rapeseed. It should be emphasized that the appropriate humidity has a significant impact on the favorable price of cereals and rapeseed at the collection points, because humidity is the basic determinant of quality [5]. Of course, on the agricultural machinery market in Poland, you can find other dryer designs, including those of companies such as: Agrimec, Dozamech, Drzewicz, Mecmar, Pedrotii, Riela, but they do not meet the mobility and capacity requirement of 8 m3. In the developed project, electric motors would be used to drive the basic components of the dryer, which would reduce operating costs.

Electricity drawn from the network is a cheaper solution, especially in the era of developing photovoltaic installations, than the fuel used by the agricultural tractor, which drives the dryer through the Power Take-Off Shaft (PTO) [6]. It was also decided that the heat source would be gas (gas burner), which is definitely cheaper than heating oil (heating oil burner). During the analysis of heat sources, the use of boilers that burn coal, wood, straw, or pellets was also considered [7]. However, the low calorific value of these raw materials would require their constant replenishment and thus would increase the intensity of labor during the drying process using the new mobile dryer. Analysis of the Polish agricultural machinery market shows that there is a demand for the developed mobile dryer.

Material and Research Methods

The supporting frame (7) of the new grave dryer was made of steel profiles. These profiles are a 200x75 [mm] C-profile marked in the DIN 1026-1:2000 standard as UPN 200 [8]. The overall dimensions of the frame are the result of the developed concept and are 2100x4841 [mm]. This frame was designed to support the elements of the hopper (2) and the drying system, such as the gas burner (9), the radial fan (10) and the control cabinet (5). The hopper (2) together with the dried material determines the highest loads. During normal operation (drying process), the supporting frame is supported below by 6 feet (6), while during transport it is supported on the hook (8) and transport wheels (4). It was assumed that in transport mode the dryer tank should always be empty, it can be filled using the hopper (3) only in normal operation mode (drying process) and emptied using the island system (1), when the supporting frame is supported at six feet. In Figure 1, a 3D model of a mobile batch dryer, developed in the SolidWorks 2024 program by Dassault System, is presented.

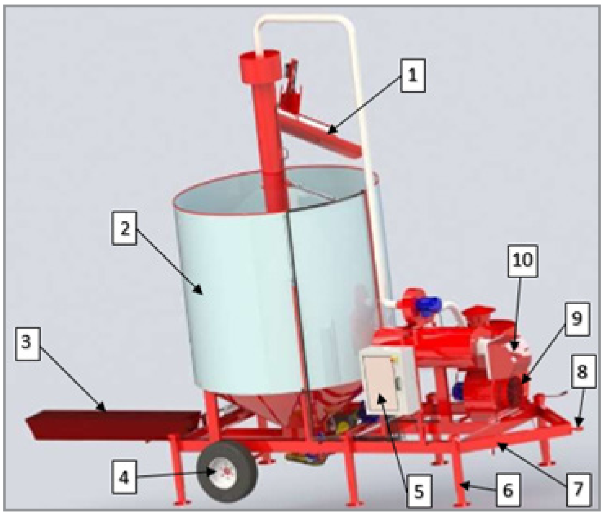

Figure 1: 3D CAD model of an innovative construction of a drye: 1-discharge system, 2-hopper for dried material, 3-hopper, 4-wheels, 5-control cabinet, 6-support feet, 7-support frame, 8-transport hook, 9-radial fan, 10-gas burner.

Then, finite element calculations (FEM) were also performed in the SolidWorks 2024 program from Dassault System. The frame structure was designed in the program as a welded structure. The analysis of stresses and deformations of the supporting frame was based on standard strength rules. These rules are based on the hypothesis of the greatest strain energy, commonly known as the Huber-Misses_Hencky Hypothesis) and allowed the following assumptions to be made (1) [12].

$$k_{dop} \leq \frac{R_e}{x}$$

where: Re – the yield point of the material (355 MPa), x – the arbitrary factor of safety.

For the purposes of stress analysis, a safety factor of 1.2 was assumed. This factor was selected based on the analysis of the scientific literature and the experience of the research team. The use of a safety factor is necessary due to inaccuracies in the manufacturing technology, the inhomogeneity of the materials used, and the error-prone calculation methods.

It was assumed that the supporting frame would be made of S355 steel characterized by the following properties:

- Tensile strength 470-630 MPa, for thickness >3-100mm;
- Yield strength (Re) ≥ 355 MPa, for thickness ≤16mm;
- Elongation, for thickness 3-40mm, ≥22% for longitudinal sample, ≥20% for transverse sample.

When starting a strength analysis, the first step is to establish boundary conditions. For the indicated supporting frame of the dryer, the boundary conditions were determined and are presented in Fig. 2:

- The supporting frame was fixed in place at 6 support feet (the fixing points are indicated by green arrows (see Fig. 2);
- The supporting frame was loaded in 4 places, reflecting the load from the hopper, as indicated by purple arrows. It was assumed that the hopper has a capacity of 8000 [cm3], i.e., it exerts a force of 80000 N on the frame. This force is evenly distributed at four points (load indicated by purple arrows) (see Fig. 2).

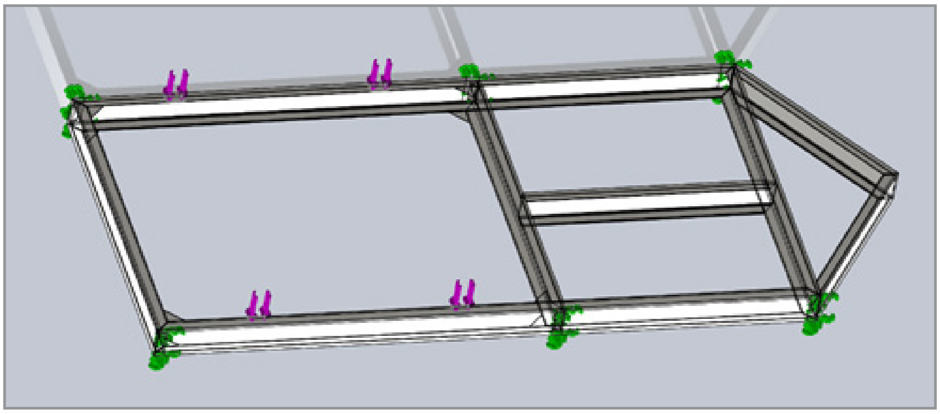

Figure 2: Designation of fixed support (green arrows) and load force (purple arrows).

The next step is to prepare the computational model, i.e. discretization of the supporting frame model. A standard mixed curvature mesh generator with high mesh quality was used to describe the mesh of the supporting frame model. The generated mesh is shown in Figure 3, which consists of 355857 nodes and 166259 elements for the first version, and 356279 nodes and 166378 elements for the second version (version with reinforcements).

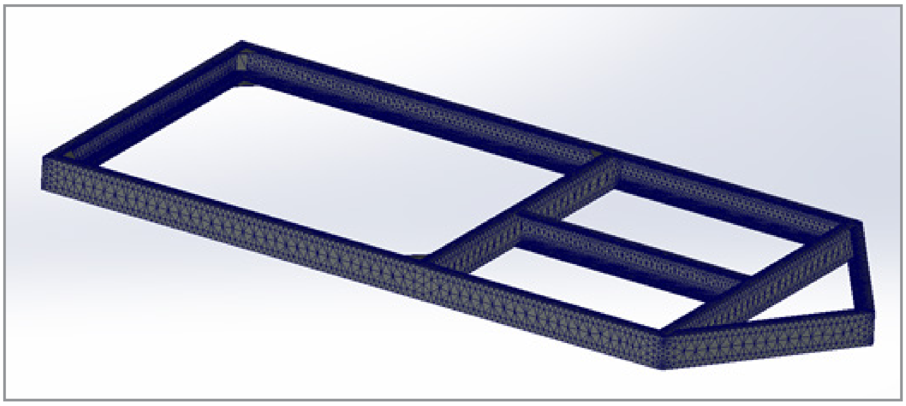

Figure 3: Generated FEM mesh for the analyzed model

Results

The stress and strain analysis were performed in Solid Works 2024. Research results found in the world literature indicate that the program is ideally suited for the development of 3D models and performing strength of machine elements, especially support frames [9-11]. The finite element method (FEM) is widely used in mechanics and, as the authors state, it can be used in many industrial fields, for example, for optimizing the support structure in mechanical engineering [13-16]. Fig. 4 presents the reduced Von Misses stresses for the first variant of the support frame, which indicates that the most stressed nodes (marked with a red circle, see Fig. 4) appear in the corners of the frame on which the hopper for the dried material (grain) is placed. On the other hand, Fig. 7 presents the reduced Von Misses stresses for the second variant of the support frame (frame with reinforcements). The applied reinforcements allowed to reduce stresses by 144.6 MPa and displacements by 0.428 [mm]. Reinforcements in the form of triangular ribs (see Fig. 6) were welded in the corners of the frame structure on which the hopper is mounted.

Based on the assumptions made in Chapter 2, it was calculated that the allowable stresses for the indicated material (slal S355) are: 295.8 MPa. The stress results for the first variant of the supporting frame indicate that the strength condition was not met (maximum stresses were 436.302 MPa), therefore it was necessary to develop a second variant of the supporting frame (the second variant reinforced by welding triangular ribs at the corners; see Fig. 6). To more accurately visualize the place where the greatest stresses occur, an enlarged area of the connection of the supporting frame profiles marked with a red arrow was added to Fig. 5.

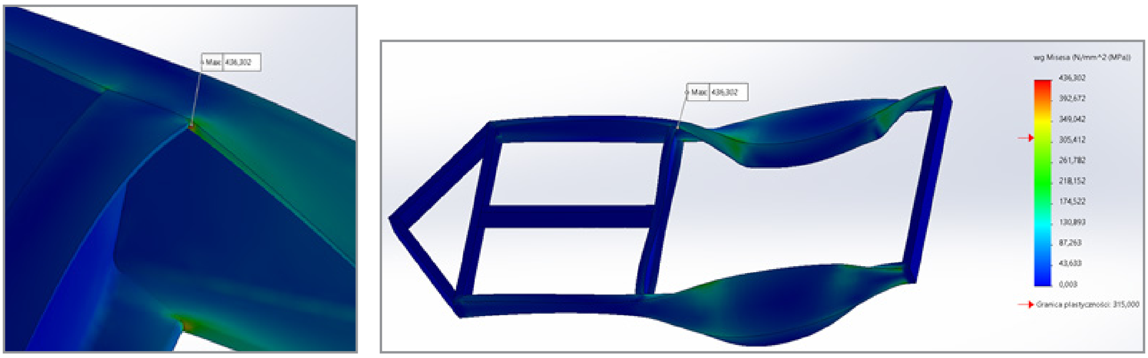

Figure 4: Maximum stresses of the unreinforced variant.

Figure 5 also shows the results of the dryer support frame displacement analysis. It can be seen that the maximum displacements occur in the middle of the rear part of the frame, where the hopper is mounted.

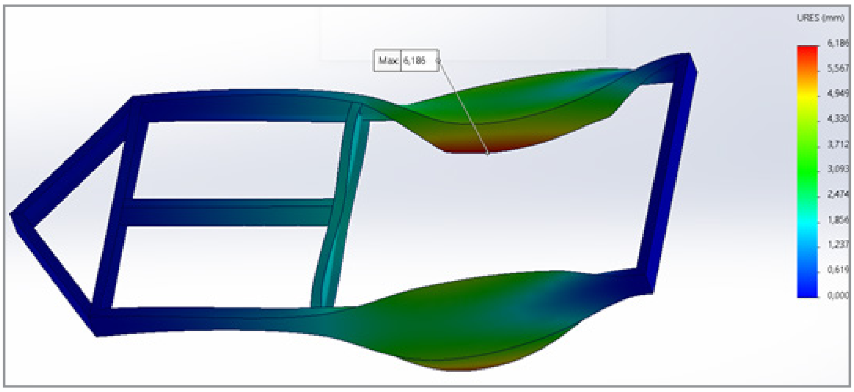

Figure 5: Maximum displacement of the unreinforced variant.

When developing the second variant of the dryer support frame, to improve stiffness and reduce deformations, it was decided to weld reinforcements in the form of triangular ribs at the places of the greatest stresses. To precisely visualize the reinforced support frame, its fragment with triangular ribs marked with a red circle is shown in Figure No. 6.

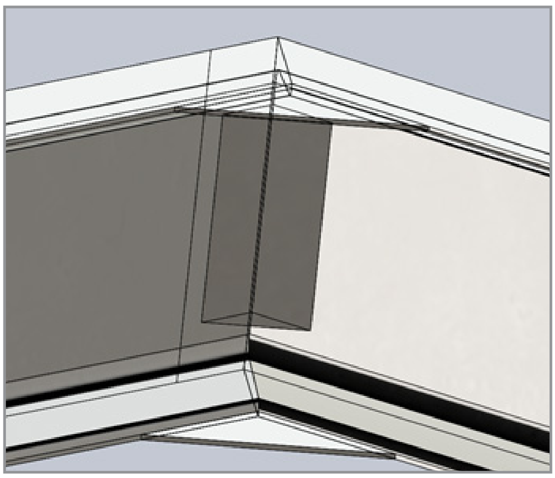

Figure 6: Reinforcements in the corners of the structure.

The frame reinforcements (see Figure 6) allowed one to reduce the maximum stresses to an acceptable level of 291.7 [MPa], which is shown in Figure 7. Maximum displacements were also reduced to 5.758 [mm], which is confirmed by the results of the displacement analysis presented in Figure 8.

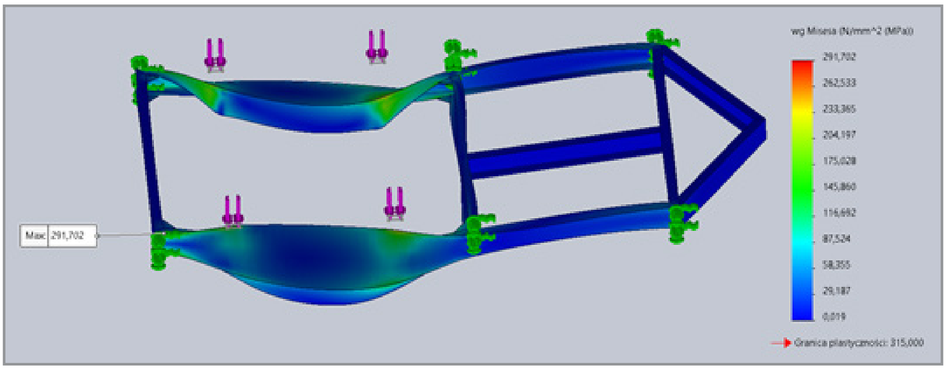

Figure 7: Maximum stresses of the reinforced variant.

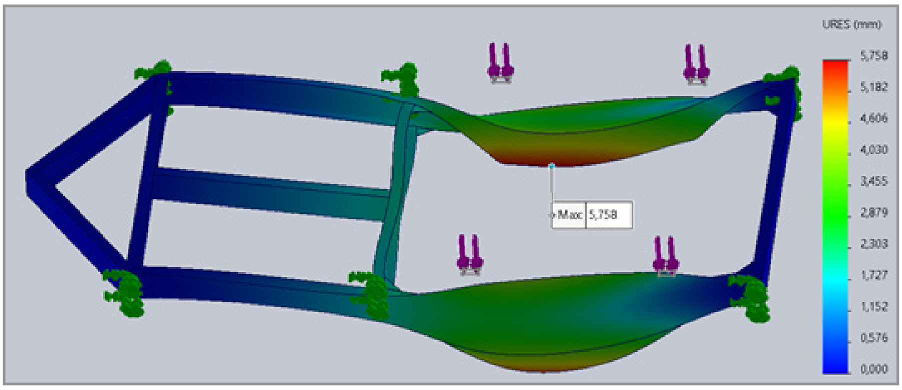

Figure 8: Maximum displacement of the reinforced variant.

Strength tests were performed in the PLM Siemens NX 8.5 program. This program has previously been used by others to develop 3D models and analyze the strength of various elements of machines and marine vessels or to examine the root of the human aorta [13]. Figure 2 shows the Von Misses reduced stress analysis, which shows that the most stressed nodes occur in the areas marked with red arrows, which amount to 48 MPa after rounding. Figure 3 shows an enlarged view of the reduced Von Misses stresses in the sweeper frame. Due to this, it can be seen that the greatest stresses occur at the point of connecting profiles or where welds are used (also marked with red arrows).

Conclusions

The results obtained from the Finite Element Method (FEM) tests for the second variant of the dryer support frame indicate that the proposed structure meets the strength conditions in accordance with the Huber-Misess-Hencki hypothesis, i.e.

$$k_{sym}=k_{dop} \quad (2)$$

$$291{,}702 \text{ MPa} \leq 295.833 \text{ MPa} \quad (3)$$

The maximum stresses in the model of the support frame of the mobile batch dryer are 291,702 MPa, which with a small margin guarantees the rigidity of the structure. The maximum displacements of 5,758 [mm] also show that the second variant of the frame is resistant to deformations. Therefore, it can be clearly stated that only the second variant of the support frame (the variant reinforced by welding triangular ribs) meets the strength conditions defined in Chapter 2. For the first variant of the support frame, the maximum stresses amounted to 436,302 MPa, which would threaten the destruction of this frame during the first use process. The developed structure of the support frame of the mobile batch dryer has a great chance of practical application both in Poland and in neighboring countries. In order to specify further directions of work, it would be necessary to validate the obtained simulation results using the finite element method (FEM) through actual measurements of stresses and deformations using the tensometric method on the built prototype of the new mobile batch dryer.

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