CAD MODELING, FEM ANALYSIS AND ADDITIVE MANUFACTURING FOR A SCREW JACK - CASE STUDY

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Abstract: *Additive manufacturing (AM), commonly known as 3D printing or rapid prototyping, is increasingly covering a wider area in the industrial sector through multiple innovative opportunities for the production process, offering rapid, economical, and increasingly complex alternative solutions to products obtained through traditional technologies. This paper presents the method of three-dimensional graphic design of a screw jack assembly using the parametric software Autodesk Inventor, a design calculation of the component elements using MathCad, and a finite element method (FEM) analysis of the screw jack assembly in two structural variants - a screw with a square thread and a screw with a trapezoidal thread, for two different materials (Steel AISI 1050 and Steel Alloy) based on the CAE capabilities provided by Autodesk Inventor. The three-dimensional model of the screw jack was created through additive manufacturing using the Creality Ender 3 Pro printer to study the functionality of a thread with small dimensions and reduced pitch. For converting 3D models into thin horizontal 2D layers and generating a set of instructions to be followed by the printer, Creality Slicer 3D software was used. The actual printing was performed using a 0.4 mm nozzle and thermoplastic polyester filament of the PLA type, in a range of four colors: red, white, black, and brown, using the FDM – Fused Deposition Modeling 3D additive manufacturing technology.*

Keywords: *Screw jack, MathCad, Autodesk Inventor, FEM analysis, 3D printing*

1. Introduction

Screw jacks are mechanisms used for lifting and lowering various loads, and they have been the subject of multiple research and development efforts concerning the improvement of screw designs specifically, and various types of screw jack thread analysis generally. A key advantage of screw jacks over other types of jacks is that they are self-locking, which means that once the rotational force on the screw is removed, it will remain stationary where it was left and will not rotate back, regardless of the applied load. Mechanical jacks are typically tested for maximum lifting capacity. To provide more lift over greater distances, jacks operate on mechanical [Kumar, 2015], hydraulic [Aniekan, 2019], or electro-hydraulic principles [Dhumal, 2022].

The materials used to create a screw jack should have the capacity and qualities to lift enormous loads, while also preventing buckling, wear, and other issues that might arise in unexpected accidents [Ezurike, 2017]. At the same time, the use of robust software packages for mathematical calculation is useful in the design phase. MathCad is a much better calculation solution than many other programs and offers an efficient way to perform and manage engineering calculations, which are easy to create, verify, communicate, and logically track [Brent, 2023]. The design of such screw jacks is important in the work economy of designers, and the various proposed CAD models of the components can be relatively easily subjected to strength analysis using the finite element method [Dixit, 2021]. Autodesk Inventor Professional is one such CAD product that includes an integrated suite of three-dimensional modeling commands and the creation of execution and assembly drawings. It is also used in the design of injection molds, the creation of pipe routes, the simulation of mechanisms, and the validation of electronic data to reduce the number of physical prototypes [Mereuță, 2015].

In a screw jack, rotational motion is converted into translational motion. Stresses such as shear and tensile stresses induced during loading are responsible for the yielding of the screw. After analyzing the screw jack, an adequate safety factor must be obtained; the jack must meet certain mechanical characteristics so that it can withstand random sudden stresses [Kumar, 2021]. Borse and Patel [Borse, 2019] analyzed and compared ACME and SQUARE threads from the perspective of studying the state of stresses and deformations, using FEM to improve performance in terms of safety and durability of a screw jack. They analyzed square-profile screws, which are the most efficient power screws but also the hardest to machine, therefore the most expensive. ACME threads are machined with a multi-point cutting tool on a thread milling machine, which is an economically costly operation

Lokhande [Lokhande, 2012] studied optimizing the efficiency of the mechanical screw jack with a square thread by modifying the helix angle.

Thrugnanam, Kumar, and Rakesh [Thirugnanam, 2014] studied the design and analysis of the screw jack using Pro-E and ANSYS under torque and compression forces as loads and determined the induced shear stress in the square thread.

Egwero et al. [Egwero, 2014] designed a system that could be used to lift various vehicles, using a microcontroller to operate the screw jack and at the same time to improve performance and minimize the cost of developing the screw jack system that controls the receiver circuit.

Udgirkar [Udgirkar, 2014] et al. studied the possibility of using an electrically operated Toggle plug using the power of the car's battery so that the lifting power increases according to the transmission ratio. This modification aims to make jack operation easier, safer, and more reliable, to save the operator's energy and minimize health risks and problems associated with working in uncomfortable positions. The analysis of the results was performed using CATIA software for modeling and FEM analysis.

Yadav [Yadav, 2014] studied the creation of a solar-powered screw jack. Conclusions were determined through appropriate calculations and practical demonstrations; a mathematical model was developed to estimate the power needed under different loading conditions. The model operated efficiently over a wide range of loading conditions, but the creation and operating costs were high.

2. Designing component elements using the MathCad program

MathCad was created in 1986 by MathSoft, and in 2006 it was acquired by PTC, the developer of the Pro/Engineer software solution, now integrated into CREO. The program offers a unique, intuitive "whiteboard"-style design environment that allows engineers to solve, document, and share engineering calculations quickly, including product requirements, critical data, methods, equations, and assumptions. The design of the screw jack is staged and starts from certain initial input data. Since the torque moments are unknown, it is pre-sized for compression stress with a maximum force.

- The diameter d_1 of the screw:

$$d_1=\sqrt{\frac{4\cdot k\cdot G}{\pi\cdot\sigma_{ac}}};\quad d_1=16\ mm \tag{1}$$

G - the axial force in the screw;
k - coefficient that accounts for the influence of torsion;
σ_{ac} - the allowable yield limit for the screw.

- The allowable yield strength for the screw:

$$\sigma_{ac} = 80\ N/mm^2 \qquad (2)$$

The material from which the screw is made will be selected in the Autodesk Inventor program. The screw will be checked using FEM analysis.

The calculation of the nut will be performed in stages, and the chosen material will be an anti-friction cast iron with:

$$P_a = 13\ N/mm^2 \qquad (3)$$

$$\sigma_a = 60\ N/mm^2 \qquad (4)$$

- The number of threads within the limits of the equivalent stress:

$$z = \frac{G}{\tau \cdot D \cdot b \cdot \sigma_a} \cdot \sqrt{3 + 36 \cdot \frac{(0.5 \cdot H_1 + a)^2}{b^2}} \qquad (5)$$

$$z = 8 \text{ number of threads} \qquad (6)$$

G - axial load;
D, b, H_1, a - the thread elements;
σ_a - the allowable contact pressure.

- The height of the threaded bushing

$$m = z \cdot p; \quad m = 24\,mm \qquad (7)$$

- The diameter of the nut is calculated based on limiting the contact pressure and the body of the jack.

$$D_g = \sqrt{D_e^2 \cdot \frac{4 \cdot G}{\pi \cdot \sigma_{as}}}; \quad D_g = 65\,mm \qquad (8)$$

D_e - the outer diameter of the nut;
σ_{as} - the allowable contact pressure for stationary surfaces.

Similar to the above calculations, the other elements of the jack such as the cup, operating lever, washer, bolt, and body are also calculated and checked.

3. Modeling of the screw jack assembly

The modeling of the screw jack was carried out in stages, starting from sketches, which were transformed into solid three-dimensional models using commands such as: *Extrude*, *Revolve*, *Coil* etc. The actual modeling of the screw was done using a sketch presented in Figure 1. This was transformed into a solid model using the *Revolve* command, which is part of the program, Figure 1.

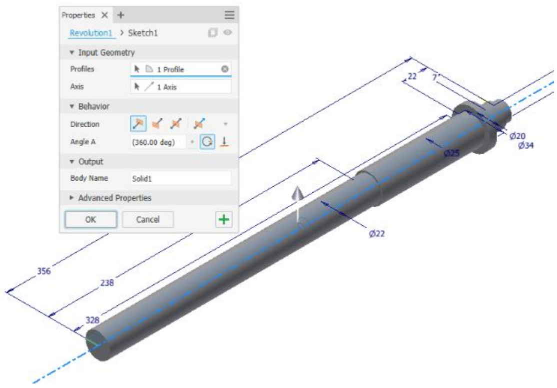
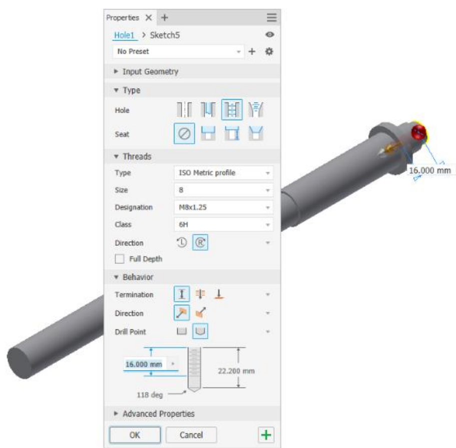
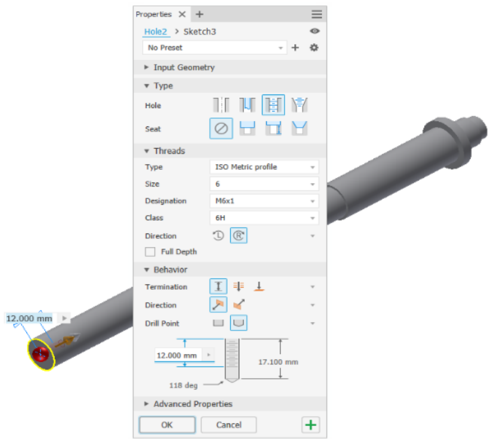


Figure 1: *Transforming the sketch into a solid model*

Modeling of the threaded hole for the washer and the cup was done using the Hole command, Figure 2a and 2b.



a)



b)

Figure 2: *Hole command to create threaded holes.*

From the design stage, two types of threads were chosen for analysis and comparison: one square and one trapezoidal. Their modeling into solids was achieved using different sketches and the *Coil* command from the Autodesk Inventor program, Figure 3.

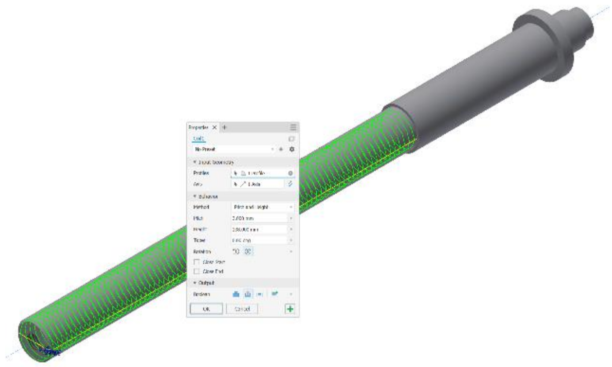


Figure 3: *Modeling of the trapezoidal thread.*

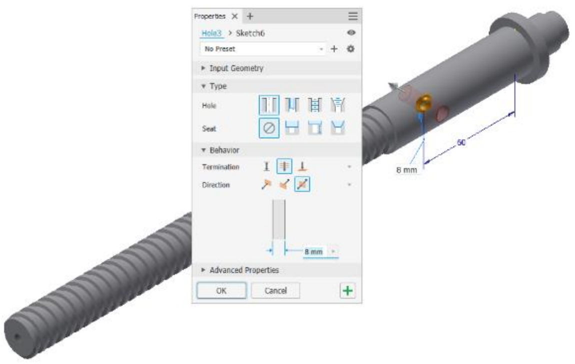


Figure 4: *Modeling of the hole for the crank.*

Figure 5: *The final model of the trapezoidal screw, analogous to the square one.*

Similarly, the other component parts such as the washer, body, nut, and cup were also created, Figures 6 and 7.

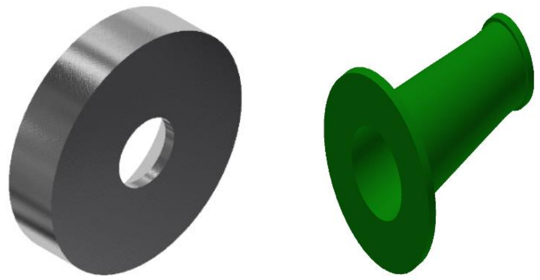


Figure 6: *The washer and the body of the jack.*

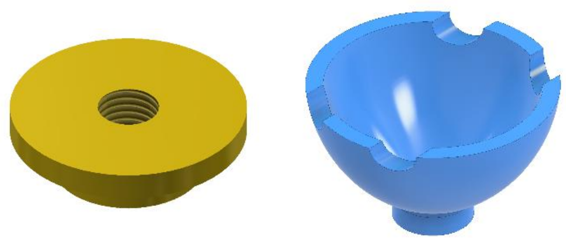


Figure 7: *The nut and the cup of the jack.*

The assembly was accomplished using constraints such as axis-to-axis, surface-to-surface at a given distance, center-to-center, etc., Figures 8 to 12.

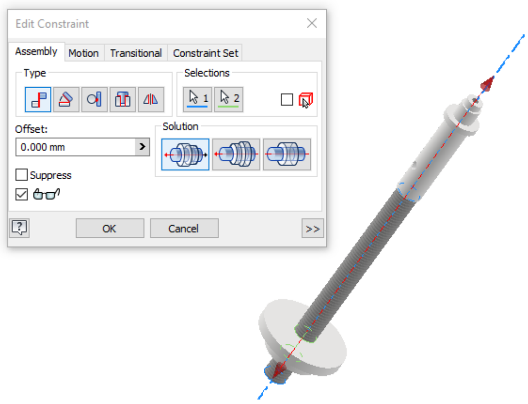


Figure 8: *Axis-to-axis constraint.*

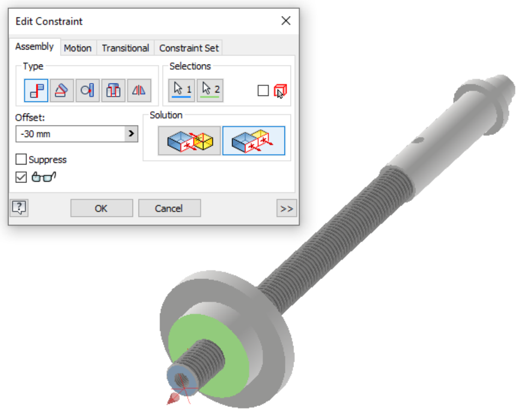


Figure 9: *Surface-to-surface constraint at a distance (offset) of 30mm.*

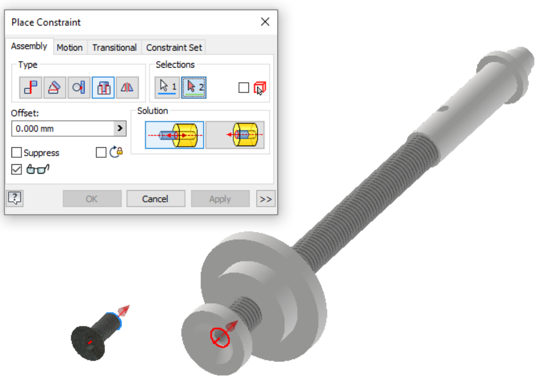


Figure 10: *Screw-end constraint of the jack screw with the Insert option.*

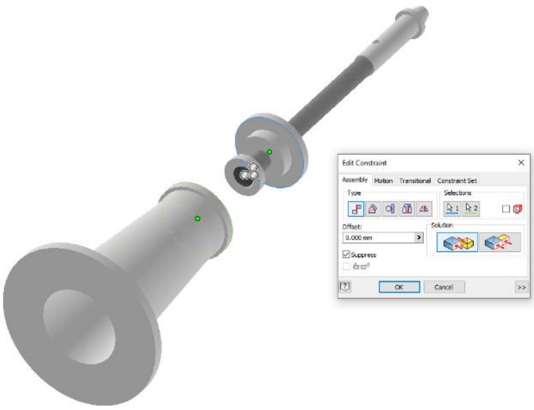


Figure 11: *Center-to-center constraint between the body and the shoulder washer.*

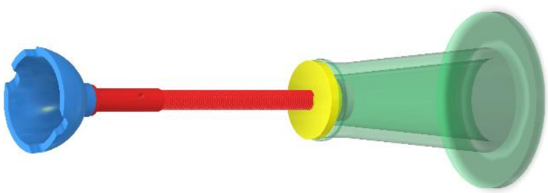


Figure 12: *The final assembly of the screw jack.*

4. The finite element analysis of the screw jack assembly

4.1 The material selection

For the FEM analysis of the assembly, the following materials are chosen: Cast Iron, Carbon Steel, Steel, Gray Cast Iron ASTM A48 Grade 40.

For the jack screw, the materials analyzed in the paper are those commonly used in screw construction: Steel AISI 1050 and Steel Alloy, with properties presented in Figure 13.

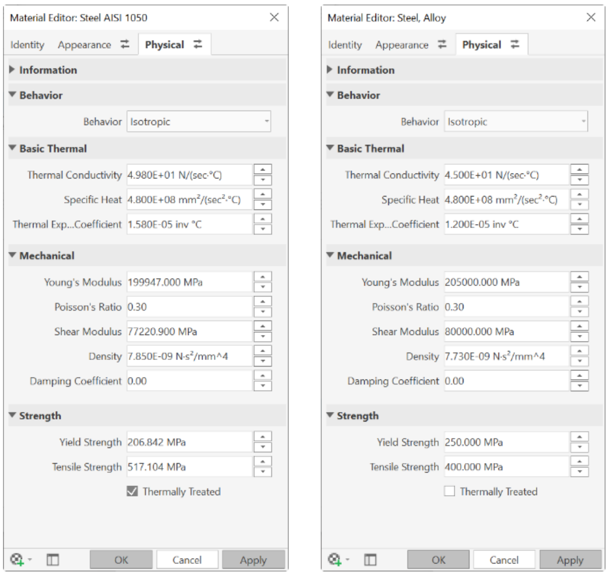


Figure 13: *Material properties.*

4.2 Boundary Conditions. Discretization of the assembly

The boundary conditions were applied in accordance with the literature [Kumar, 2021], [Borse, 2019].

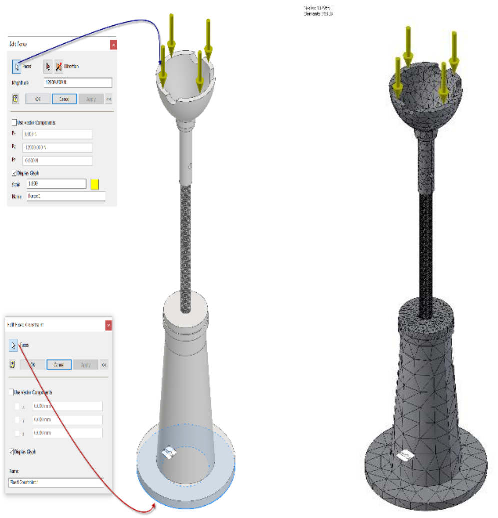
Applied constraints:

- On the base of the jack body, Figure 14a.

Applied loads:

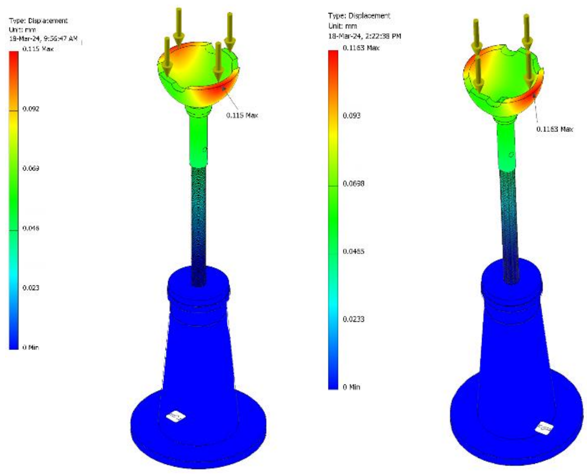
- On the cup of the jack, based on obtained data, Figure 14a.

The finite element analysis was performed using implicit discretization, with tetrahedral elements. The assembly was discretized into 78918 elements and 132965 nodes, Figure 14b.



a) *b)*

Figure 14: *Boundary conditions and discretization.*



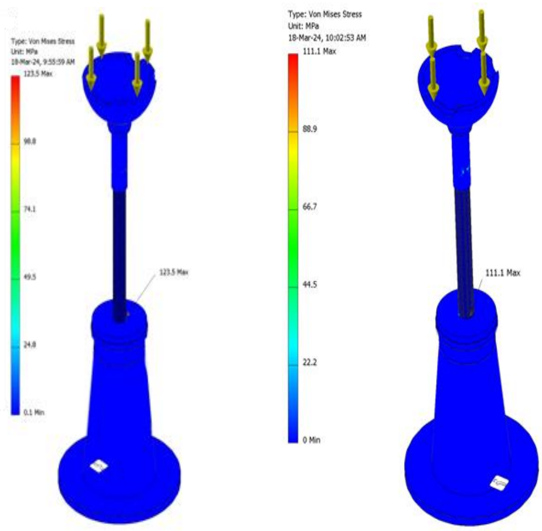
a) *b)*

Figure 16: *Maximum deformations:*
a) square thread; b) trapezoidal thread.

4.3 The results of the FEM analysis

The results of the analysis for the Steel AISI 1050 screw.

The following figures present the obtained results.

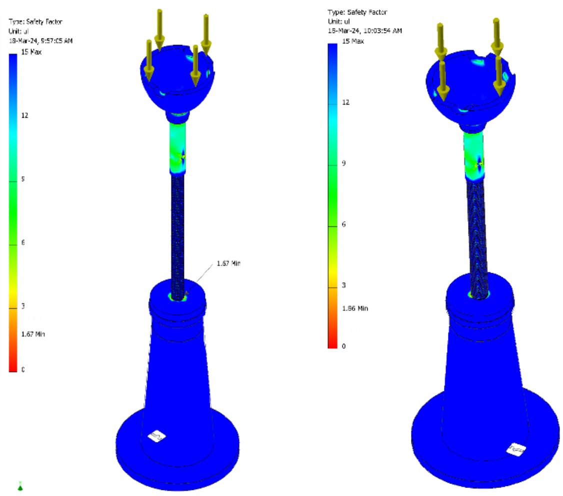


a) *b)*

Figure 15*: Von Mises stresses:*
a) square thread; b) trapezoidal thread.

It can be observed that the maximum value of the Von Mises stresses was recorded in the contact area between the screw threads and the nut threads, with a maximum value of 123.5 MPa for the square thread and 111.1 MPa for the trapezoidal thread, Figure 15. The maximum deformation was recorded at the jack cup, 0.115 mm for the square screw jack and 0.117 mm for the trapezoidal thread, Figure 16.

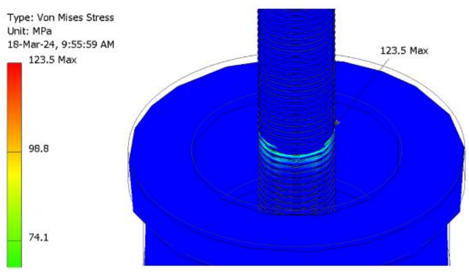
The minimum safety factor value was 1.67 for the square thread and 1.86 for the trapezoidal thread.



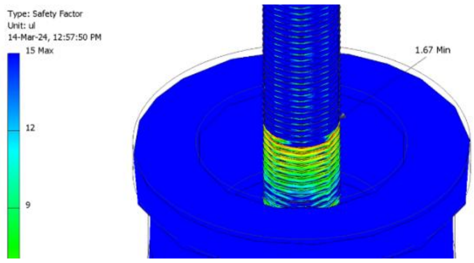
a) *b)*

Figure 17: *Thread safety factor:*
a) square thread; b) trapezoidal thread.

It can be observed that both the maximum stresses and the minimum safety factor are located in the same area, at the contact between the screw and the jack nut, Figure 18.



a)

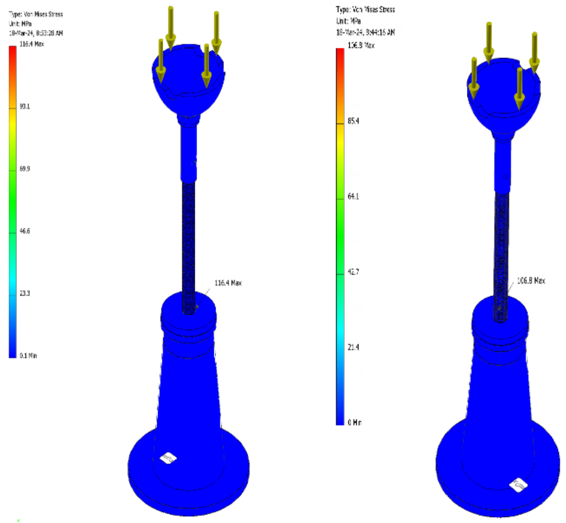


b)

Figure 18: *Von Mises Stresses Detail Minimum Safety Factor (b).*

The results of the analysis for the Steel Alloy screw

For the Steel Alloy screws, a maximum Von Mises stress value of 116.4 MPa was recorded for the square thread and 106.8 MPa for the trapezoidal thread, in the same area as in the previous analysis, Figure 19.



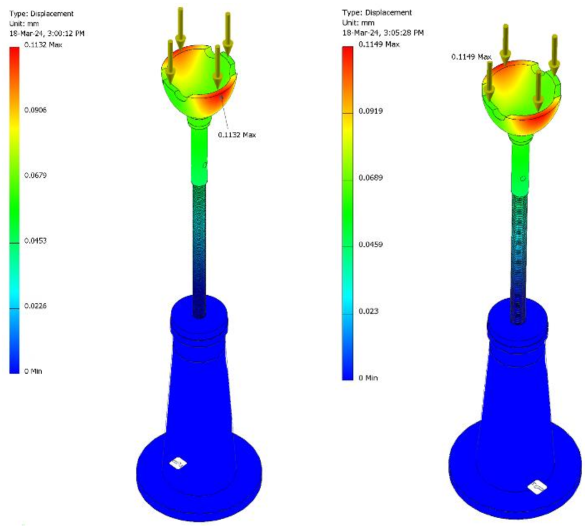
a) ***b)***

Figure 19: *Von Mises stresses: a) filet pătrat; b) trapezoidal thread.*

The maximum deformation was still recorded at the jack cup, 0.113 mm for the square thread and 0.115 mm for the trapezoidal thread, Figure 20.

The finite element analysis of the assembly aimed to study the behavior under the action of the maximum load of the screw. For this purpose, a comparative analysis was conducted between the square thread screw and the trapezoidal thread ASME screw. Within this analysis, the results obtained for two materials used in the construction of the jack screws were compared.

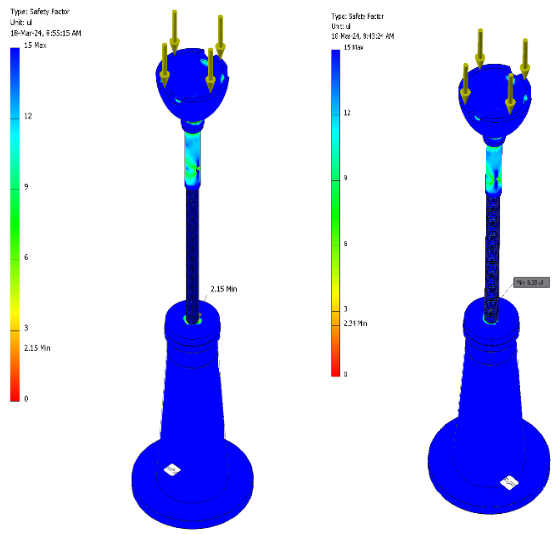
The FEM analysis was conducted under the most unfavorable condition of jack usage, when it is used at its maximum lifting height.



a) ***b)***

Figure 20: *Maximum deformations: a) square thread; b) trapezoidal thread.*

The minimum safety factor value was 2.015 for the square thread and 2.34 for the trapezoidal thread, Figure 21.



a) ***b)***

Figure 21: *Safety Factor: a) square thread; b) trapezoidal thread.*

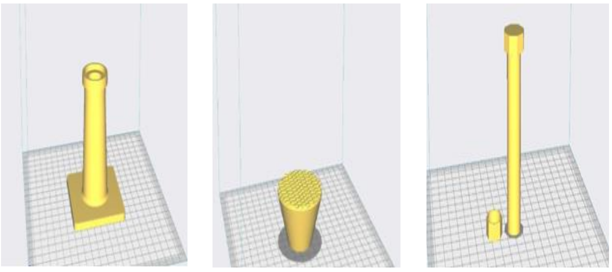
5. Printing the model using a 3D printer

The screw jack was created as a 3D model using the Creality Ender 3 Pro printer [Creality, 2024], which can achieve a resolution of 400 µm, Figure 22.

PLA (polylactic acid) material was used for printing, and the model was slightly modified for easier printing.

Figure 22: *Creality Ender 3 Pro printer.*

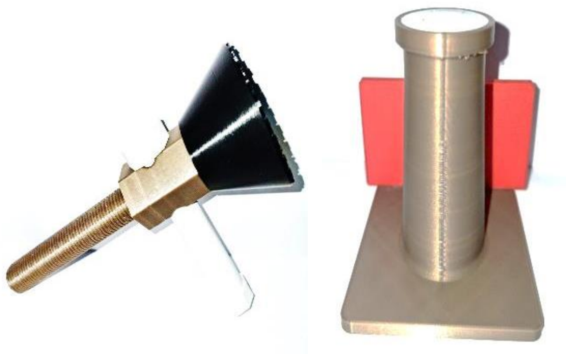
For visualizing the parts, the Slicer program was used, where all files were converted into .gcode files to be recognized and executed by the 3D printer software, Figure 23.



a) ***b)*** ***c)***

Figure 23: *Components of the jack in the Creality program: a) body; b) cup; c) nut and handle.*

The screw jack was assembled into subassemblies, which were then joined together into a final assembly, Figure 24.



a) ***b)***

Figure 24: 3D printed subassemblies: a) cup-screw-handle; b) body-nut

The screw jack was printed using FDM - Fused Deposition Modeling technology [Sandu, 2023], both to demonstrate the advantages of 3D printing - often much faster than traditional manufacturing methods for prototypes and small-scale production, as well as to study the functionality of a small-sized and fine-pitched thread.

6. Conclusions

In order to improve the performance of the actuating screw, it is necessary to modify the design of the screw jack components and reduce the effort required to operate it. The objective of designing power screws is to reduce the effort required by the user to operate the lifting and lowering mechanism.

From the study, the following conclusions can be drawn:

- Maximum Von Mises stress values were recorded within the allowable limits of the analyzed materials.
- Maximum deformation values were approximately equal regardless of the thread profile and material.
- The maximum value of the minimum safety factor was recorded for the alloy steel screw with a trapezoidal profile.
- From the analysis conducted, it can be concluded that ACME trapezoidal threads, having a larger mean diameter compared to square threads, provide greater resistance in use compared to an equivalent square-threaded screw.

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