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FINITE ELEMENT ANALYSIS AND TOPOLOGY OPTIMIZATION OF FABA BEAN METERING PLATES

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Abstract

The main objective of this research study is the use of 3D printing to manufacture of a metering plates with different materials and slots shapes for the planting of faba beans. Also, testing the manufactured metering plates by the finite element, fatigue, and topology optimization. Metering plates were designed and tested at department of agriculture engineering, faculty of agriculture, Tanta university, Egypt. through 2022.the maximum values of finite element indices such as von mesies, yield strength, INT (stress intensity), TRI (triaxle stress), ERR (energy norm error), static displacements, RFRES (resultant reaction force), ESTRN (equivalent strain), SEDENS (strain energy density), and ENERGY (total strain energy) were (9.72e+05, 4.04e+06, 8.53e+05, 3.87e+06, 1.00e-16, 1.58e-02, 3.40e-02, 1.52e-4, 8.27e+01, and 4.72e-07) respectively. Also, the minimum values for same indices were (2.54e+04, 7.89e+05, 1.33e+04, 4.71e+03, 1.00e-16, 2.84e-5, 9.19e-03, 1.04e07, 5.06e-07, and 7.88e-08) respectively, with different shapes index of first, second, third, and fourth metering plates were (1.76, 1.78, 3.01, and 1.65) respectively. And for fatigue analysis results, damage, load factor, total cycles, and stress amplitude were (3.36e+05, 5.32e+06, 1.39e+06, and 1.60e+00) respectively. Also, the minimum values for same indices were (2.92e+00, 2.26e-07, 2,21e+04, and 8.26e+00) respectively. And for topology optimization analysis results, the maximum values of topology optimization indices such as best stiffness, and displacement were (4.82e-02, and 3.90e-10) respectively. Also, the minimum values for same indices were (7.97e-2, and 2.61e-06) respectively, and the maximum efficiency of the metering plate was 98% for the first metering plate with TPU material.

Key words: *Faba Bean, 3D printing, Finite Element Analysis, Fatigue Analysis, Topology Optimization*

INTRODUCTION

The faba bean (*Vicia faba* L.) is an important legume crop in North and East Africa, particularly in Arabia. The faba bean plays an important role in Egypt as a low-cost food with great nutritional value, notably in terms of protein content, which ranges from % to 38% [1].

The world population is growing over time, and by 2050 it is expected to reach 13 billion people therefore the request for faba bean as a replacement for animal proteins as well as food and nutritional security has increased over the next 10 years [12].

Machine design is the production of new and improved machinery as well as the improvement of existing ones. A new or improved machine is one that is more cost effective in terms of output and operation. The design process is lengthy and time-consuming. Many topics are required to design a machine component, including mathematics, mechanical engineering, material strength, workshop procedures, and engineering drawing [4].

Alexander Paul Hrennikoff developed the field structural framework method for stress analysis and its application to two fields of elasticity in the 1940s. The method is essentially an arithmetic procedure that can be applied to a problem involving a rectangular plate by the two-dimensional stress and strain situation in a bent plate. The framework method's most essential feature is that it may be utilised to solve a wide range of unsolvable elastic problems. The finite element approach is credited with establishing the framework for this technology [3].

Finite element method (FEM) is a numerical technique used for solving complex engineering and mathematical problems by dividing them into smaller, more manageable subdomains or elements. These elements are interconnected at specific points called nodes, and by applying mathematical equations to each element and their interactions, FEM approximates and solves the behavior of the entire system [2].

the finite element approach is the most stable numerical scheme; it is the most commonly employed method. The computational domain is initially divided into tiny parts for this procedure. For each element, a so-called localized support function is built, which is a function that is specified just within that element [14].

Three-dimensional finite element analysis represents the geometry more realistically. [6].

The advantages of FEM include the broad availability of research codes, as well as the method's ability to provide a physically correct representation of most problem geometries [10].

Topology optimization is a powerful technique used in engineering and design to optimize the shape and distribution of material within a given design space, with the objective of achieving desired performance criteria while minimizing mass and maximizing structural efficiency. By exploring and analyzing various design alternatives, topology optimization allows engineers to push the boundaries of conventional design practices, resulting in lighter and more efficient structures that meet safety requirements. The goal here is to design a lighter and more efficient hanging apparatus [8].

Additive manufacturing techniques create parts by the deposition of successive layers which helps engineers overcome the limits of traditional manufacturing techniques and gives them the freedom to design complex parts. The association of additive manufacturing and topology optimization allows us to take full advantage of these manufacturing techniques. It became the most widely used structural design technique in agriculture to optimize weight and improve the mechanical properties of planting machines. The structures obtained by topology optimization are characterized by complex geometry, which makes their manufacture difficult by conventional manufacturing techniques [5].

If fatigue resistance is chosen as the performance criterion for determining network efficacy, the following criteria The technique and set criteria used to analyze test findings can have a considerable impact on the stiffness reduction criterion [9].

topology optimization is advantageous for manufacturers, as it determines the optimal material distribution in a design space based on required loads. Nowadays, topology optimization extends its applications to simulations in other technical fields [11]

The fundamental purpose of fatigue analysis is to determine how materials and structures decay, crack, or fail when subjected to recurrent loading from variables such as vibration, heat cycling, or fluctuating mechanical forces. Stress Analysis, S-N Curve, Load History, and Fatigue Life Prediction are all important components of fatigue analysis [16].

Digital manufacturing technology, often known as 3D printing or additive manufacturing, uses a continual addition of materials to build actual items from geometric representations. 3D printing is a relatively new technology. 3D printing is now widely utilized all around the world. Also,3D printing technology has transformed the way to think about production and design, allowing to creation of complicated geometries and fine features that would be hard to produce using traditional manufacturing processes. 3D printing is a more environmentally friendly and sustainable method of generating models and prototypes [15].

3D printing has the potential to revolutionize manufacturing and product development by opening up new design, customization, and efficiency opportunities. Its uses are expanding as the technology advances and becomes more widely available [7].

Several sets of metering plates are used in precision planters, each having orifices tailored to the size of the seed to be planted. Several variables contribute to keeping the space between seeds planted in a row constant. The spacing between the seeds is supposed to be consistent during the design phase, although this may vary based on the degree of tillage, sowing characteristics, and, most importantly, the physical features of the seeds [13].

In this context, the purpose of the research is to use 3D printing to manufacture metering plates with different materials and slots shapes for the planting of faba beans. Also, to test the manufactured metering plates by the finite element, fatigue, and topology optimization.

MATERIALS AND METHODS

The metering plates were designed and simulated by Solidworks software at the Agricultural Engineering Department, Faculty of Agriculture, Tanta University. The metering plates were manufactured by using 3D printing technology with different materials in Tanta Motors AbouFreikha factory, Tanta, Egypt

Faba bean metering plates

The faba bean metering plates were designed by using Solidworks software with four different shapes and printed with five different materials (ABS+, TPU, NYLON, PTFE, and Ertalon) as shown in Figures 1 and 2.

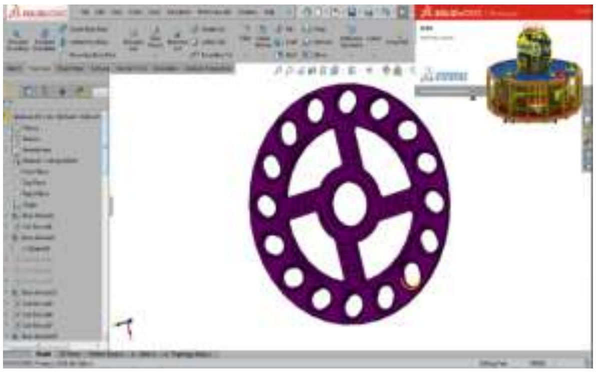

Fig. 1. The Interface of Solidworks Software
Source: Authors' determination.

3D Printer machine

A 3D printer or fused filament fabrication, is an additive manufacturing (AM) technology that involves pushing thermoplastic material through a heated nozzle to build objects layer by layer. The machine was of the type (Creality-CR 10) was used to print metering plates as shown in Figure 3. 3D printer mostly consists of the following components, Printing Bed, Extruder, Moving Parts, Touch Screen, Hot Ends, and Filament.

Fig. 2. Faba Bean Metering Plates
Source: Authors' determination.

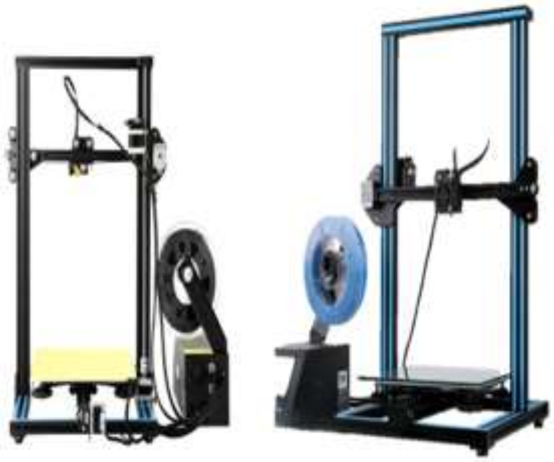

Fig. 3. 3D printer (Creality-CR 10)
Source: Authors' determination.

Finite Element Analysis

Using Solidworks simulation to measure the finite element indicators such as von mises stress, yield strength, INT (stress intensity), TRI (triaxle stress), ERR (energy norm error), static displacements, RFRES (resultant reaction force), ESTRN (equivalent strain), SEDENS (strain energy density), and ENERGY (total strain energy) of faba bean metering plates as shown in Figure 4.

- Von Mises, MPa

$$\text{V.Mises}=\left\{\frac{[(\sigma1-\sigma2)^2+(\sigma2-\sigma3)^2+(\sigma1-\sigma3)^2]}{2}\right\}^{\frac{1}{2}}$$

-Yield Strength, MPa

$$\textbf{Yield Strength}=\frac{\text{Stress at Yield}}{\text{Original Cross}-\text{Sectional Area}}$$

-INT (stress intensity), N/m^2

INT=σ∗sqrt(pi∗a)

- ERR (energy norm error)

$$ERR=\sqrt{\frac{\Sigma e\Sigma\Omega e(\nabla uh-\nabla u)^2}{\Sigma e\Sigma\Omega e(\nabla u)^2}}$$

-RFRES (resultant reaction force), N

$$RFRES=\sum_{i=1}^{n} Ri$$

-Equivalent strain

$$ESTRN=2[\frac{(\varepsilon1+\varepsilon2)}{3}]^{\frac{1}{2}}$$

$$\varepsilon1 =0.5[\quad (EPSX-\varepsilon^*)2+(EPSY-\varepsilon^*)2+(EPSZ-\varepsilon^*)2$$

$$\varepsilon2 =\frac{[(GMXY)2 + (GMXZ)2 + (GMYZ)2]}{4}$$

$$\varepsilon^* =\frac{(EPSX + EPSY + EPSZ)}{3}$$

-URES

$$URES=\sqrt{X^2+Y^2}$$

-SEDENS (strain energy density), Nm/m^3

SEDENS =0.5$\sigma * \epsilon$

-ENERGY (total strain energy), N.m

ENERGY=$\int V * 0.5\sigma ij * \epsilon ij\ dV$

where:

- ε 1, ε 2, and ε 3 =Normal strain in the first, second, and third principal direction.

-EPSX, EPSY, and EPSZ= Normal strain in the X.Y.Z -direction of the selected reference geometry.

-GMXY, GMXZ, and GMYZ= Shear strain in the Y, Z direction in the YZ- XZ plane of the selected reference geometry.

- $\sigma1\backslash\sigma2\backslash\sigma3$=principal stresses. X=is the first direction that the object is traveling. Y=the second direction that the object is traveling.

-σ = the applied stress

- a = the length of the crack or the distance from the center of the crack to the point of interest.

- $e =$ represents each element in the computational domain.

-Ωe= is the domain of each element.

- ∇uh = represents the numerical solution (approximation) obtained by the finite element method.

-u= represents the exact or reference solution.

- Ri = represents the reaction forces at each support point or node in the direction of interest.

-n= is the total number of support points or nodes that provide reactions in that direction.

- σ =is the applied stress.

-ϵ =is the corresponding strain (deformation) that results from the applied stress.

-σij =represents the components of the stress tensor.

- ϵij= represents the components of the strain tensor.

-V = is the volume of the deformable body.

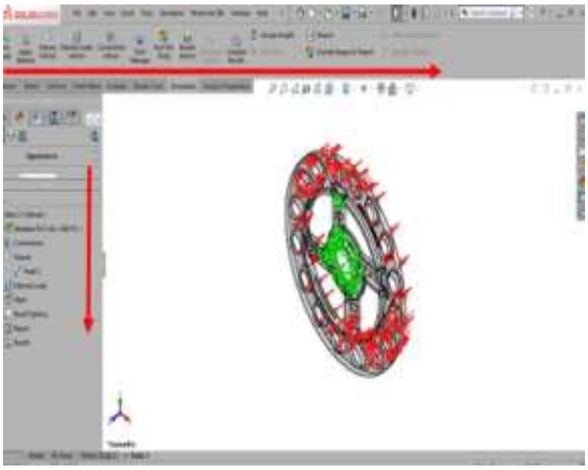

Fig. 4. Finite Element Analysis of Faba Bean Metering Plate
Source: Authors' determination.

Fatigue Analysis

Using Solidworks simulation to measure the fatigue indicators such as damage, total life cycles, loaf factor, and stress amplitude. as shown in Figure 5.

-Damage

$$Damage=\frac{n1}{N1}+\frac{n1}{N1}+\frac{n1}{N1}+\frac{n1}{N1}\dots\dots\frac{ni}{Ni}$$

-Total life cycles

$$\text{Total life cycles} =(\frac{Se}{\sigma a})^b$$

-Load factor

$$\text{Load factor}=\frac{\text{Load Design Value}}{\text{Load Calculation Value}}$$

-Stress amplitude, Mpa

$$\text{Stress amplitude}=\sigma a=\frac{\sigma\ max-\sigma\ min}{2}$$

where:

-n1,n2,n3,…,ni = the number of cycles experienced at various stress levels or load amplitudes during the life of the component.

-N1,N2,N3,…,Ni = the fatigue life or endurance limits corresponding to those stress levels or load amplitudes.

-Se = the endurance limit (also known as the fatigue strength or fatigue limit) of the material, representing the stress level below which the material can endure an infinite number of cycles without failure.

-σa = the stress amplitude, which is the difference between the maximum and minimum stress levels in a loading cycle.

-b=the fatigue exponent, which is a material property determined from experimental data.

- σmax = the maximum stress experienced during a loading cycle.

- σmin = the minimum stress experienced during the same loading cycle.

Fig. 5. Fatigue Analysis of Faba Bean Metering Plate
Source: Authors' determination.

Topology Optimization Analysis

Using Solidworks simulation to measure the best stiffness, and displacement as shown in Figure 6.

-Best stiffness

-Best stiffness = E·ϵ

where:

E=Young's Modulus or Elastic Modulus, and

ϵ =represents the strain experienced by the material

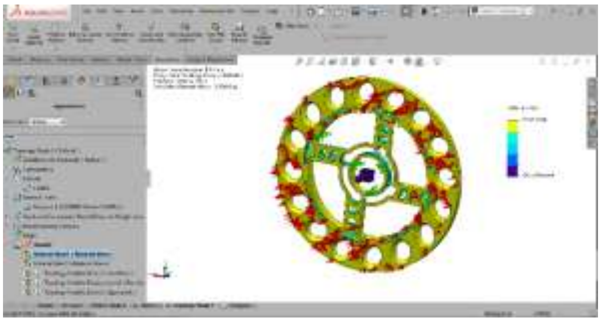

Fig. 6. Topology Optimization Analysis of Faba Bean Metering Plate
Source: Authors' determination.

Metering plates efficiency

$$\text{Metering plate efficiency, \%} = \frac{Number\ of\ output\ seeds}{Number\ of\ total\ seeds} x100$$

$$\text{Seed damage , \%} = \frac{Number\ of\ \ damaged\ seeds}{Number\ of\ total\ seeds} x100$$

RESULTS AND DISCUSSIONS

Finite Element Analysis

Figure 7 to Figure 11 showed the maximum values of finite element indices such as von mesies, yield strength, INT (stress intensity), TRI (triaxle stress), ERR (energy norm error), static displacements, RFRES (resultant reaction force), ESTRN (equivalent strain), SEDENS (strain energy density), and ENERGY (total strain energy) were (9.72e^{+05}, 4.04e^{+06}, 8.53e^{+05}, 3.87e^{+06}, 1.00e^{-16}, 1.58e^{-02}, 3.40e^{-02}, 1.52e^{-4}, 8.27e^{+01}, and 4.72e^{-07}) respectively. Also, the minimum values for same indices were (2.54e^{+04}, 7.89e^{+05}, 1.33e^{+04}, 4.71e^{+03}, 1.00e^{-16}, 2.84e^{-5}, 9.19e^{-03}, 1.04e^{-07}, 5.06e^{-07}, and 7.88e^{-08}) respectively, with different shapes index of first, second, third, and fourth metering plates were (1.76, 1.78, 3.01, and 1.65) respectively.

Fatigue Analysis

indices such as damage, load factor, total cycles, and stress amplitude were (3.36e^{+05}, 5.32e^{+06}, 1.39e^{+06}, and 1.60e^{+00}) respectively. Also, the minimum values for same indices were (2.92e^{+00}, 2.26e^{-07}, 2,21e^{+04}, and 8.26e^{+00}) respectively, with different shapes index of first, second, third, and fourth metering plates were (1.76, 1.78, 3.01, and 1.65) respectively as shown in Figure (12) and Figure (13).

Fatigue Analysis

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Topology Optimization Analysis

Figure 14 showed the maximum values of topology optimization indices such as best stiffness, and displacement were (4.82e^{-02}, and 3.90e^{-10}) respectively. Also, the minimum values for same indices were (7.97e^{-2}, and 2.61e^{-06}) respectively, with different shapes index of first, second, third, and fourth metering plates were (1.76, 1.78, 3.01, and 1.65) respectively.

Metering plates efficiency

Figure 15 showed the maximum value of the metering plate efficiency was 98% for the first metering plate with TPU material and a shape index of 1.76 while the minimum value of seed damage was 1% for the same metering plate and shape index with Nylon material.

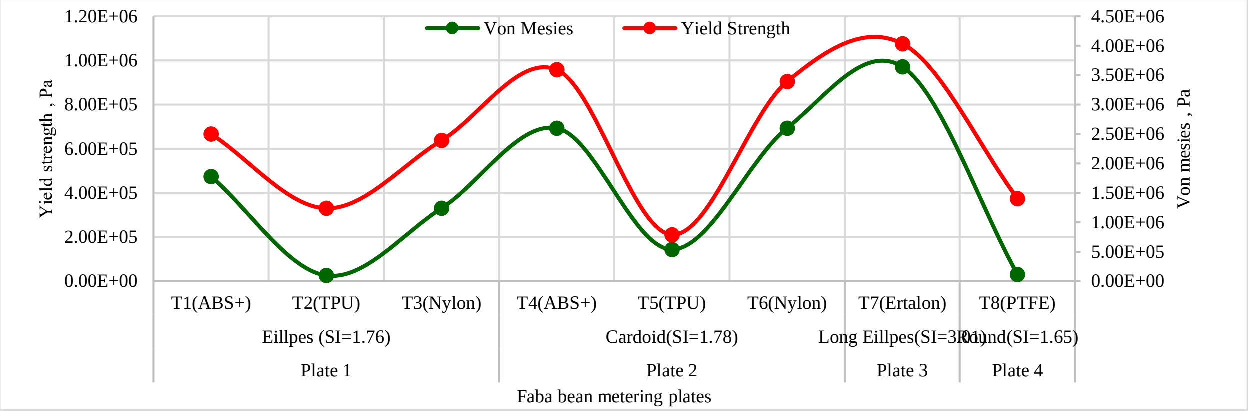

Fig. 7. Von Mesies and Yield Strength at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

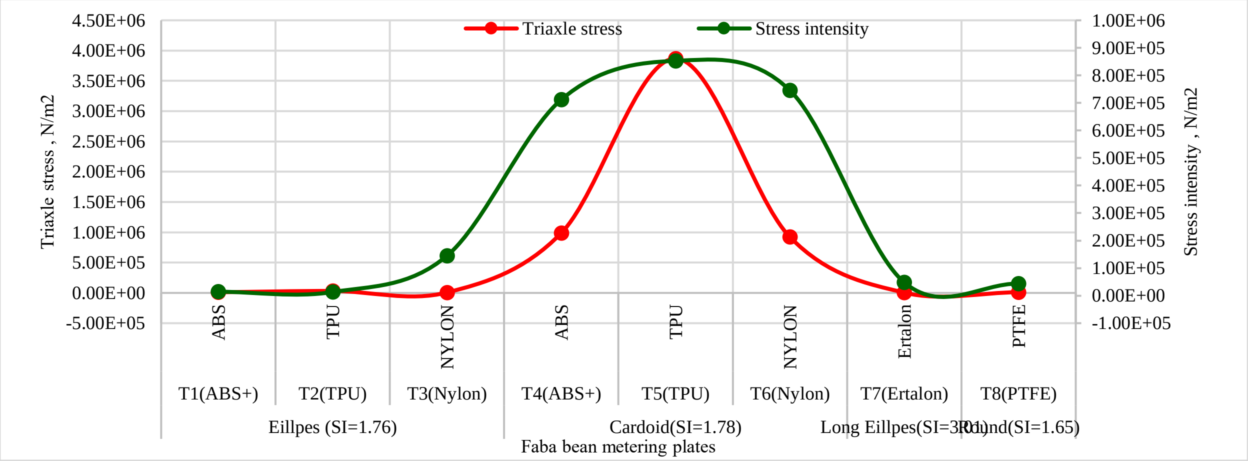

Fig. 8. Triaxle Stress and Stress Intensity at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

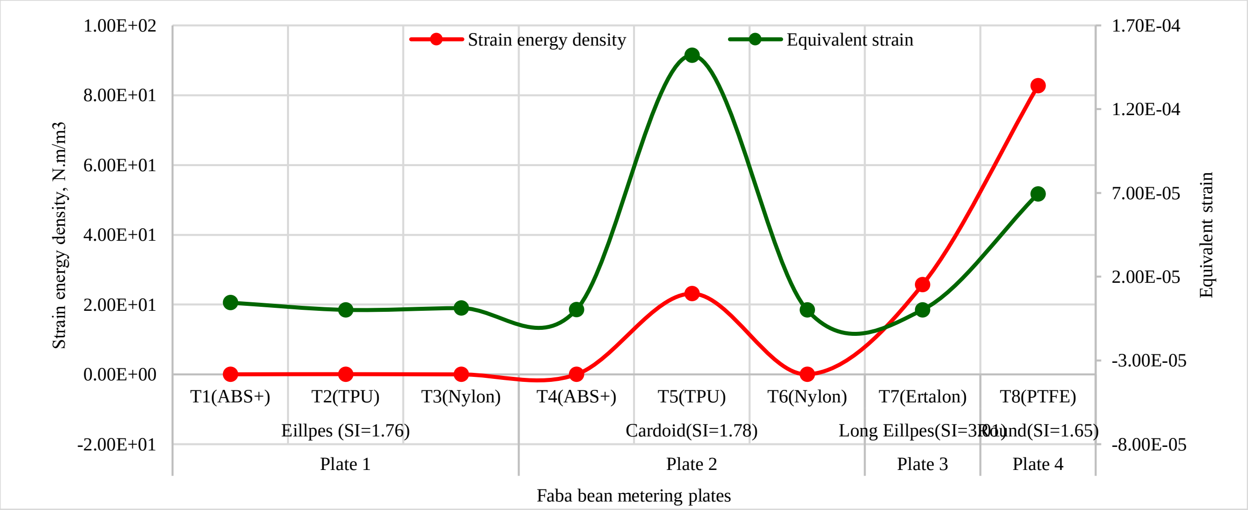

Fig. 9. Strain Energy Density and Equivalent Strain at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

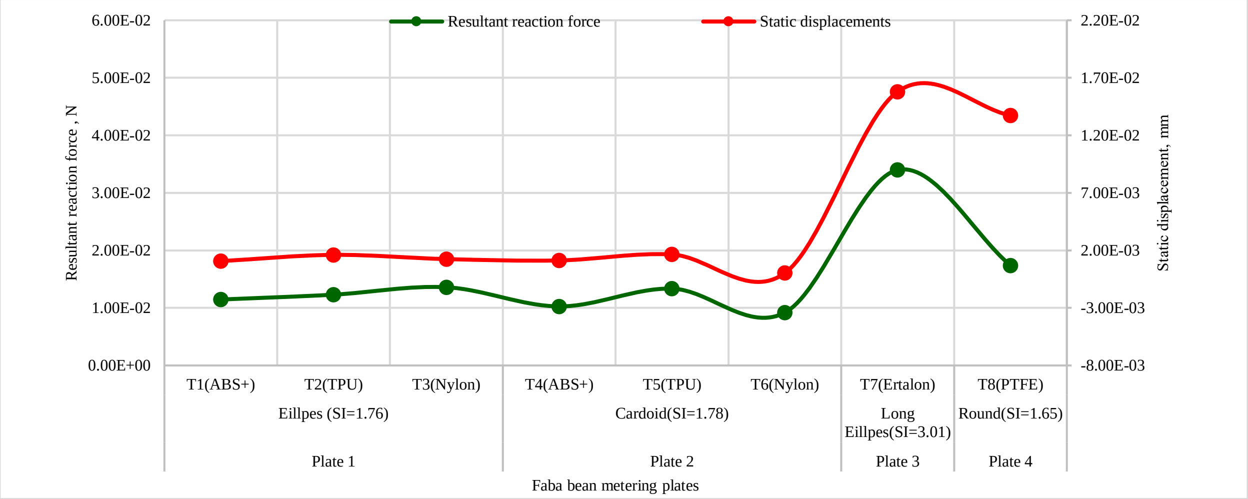

Fig. 10. Resultant Reaction Force and Static Displacement at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

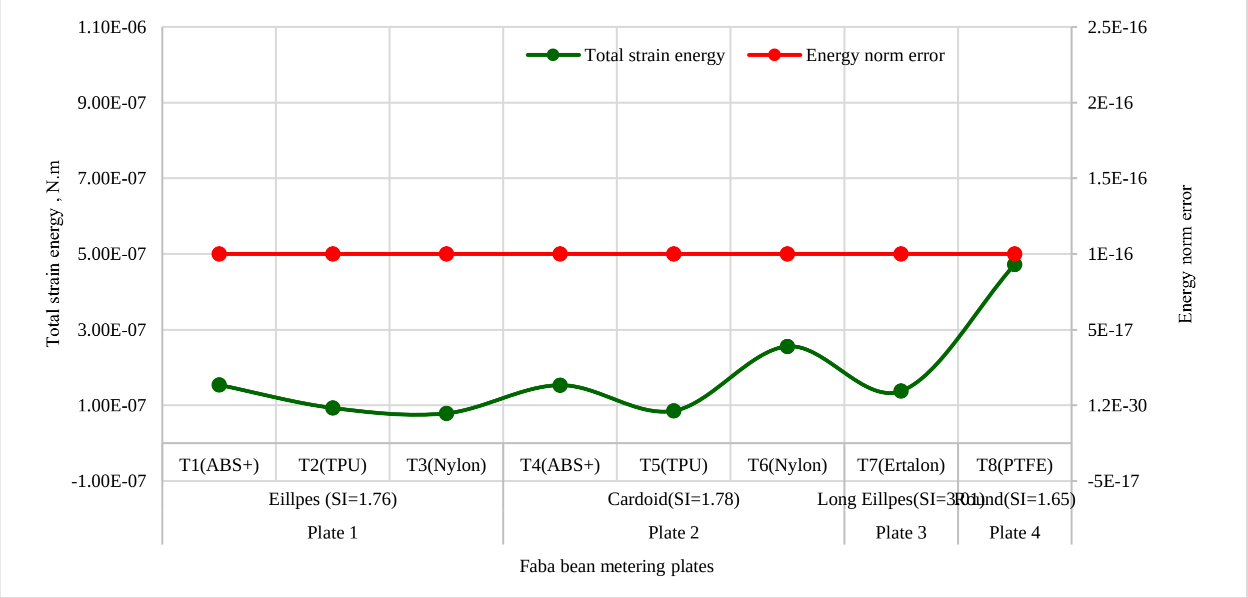

Fig. 11. Total Strain Energy and Energy Norm Error at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

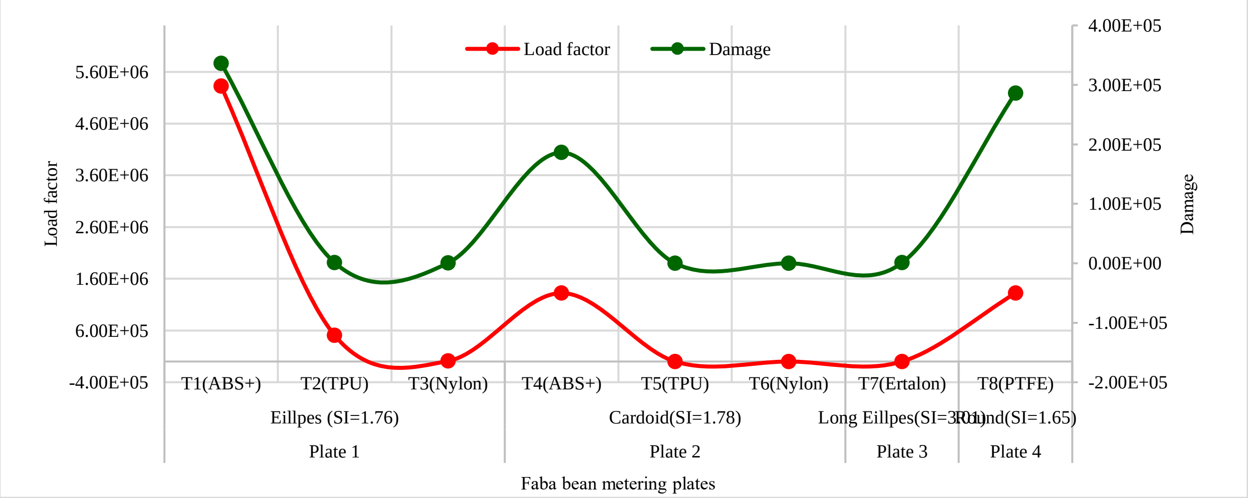

Fig. 12. Load Factor and Damage at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

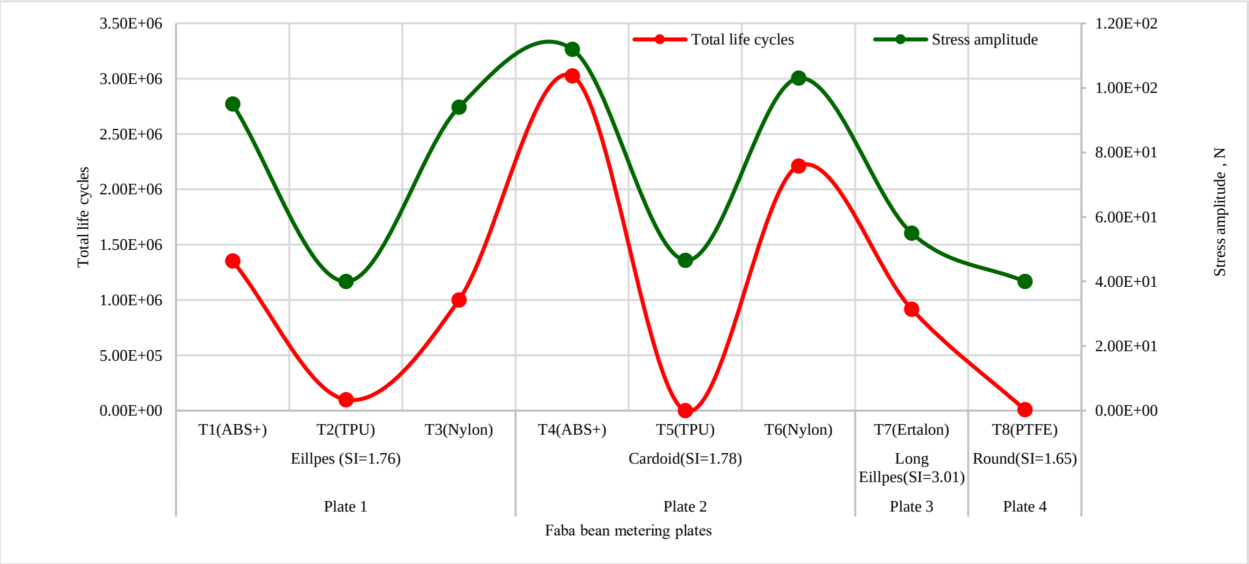

Fig. 13. Total Life Cycles and Stress Amplitude at Different Parameters of Faba Bean Metering Plates
Source: Authors' determination.

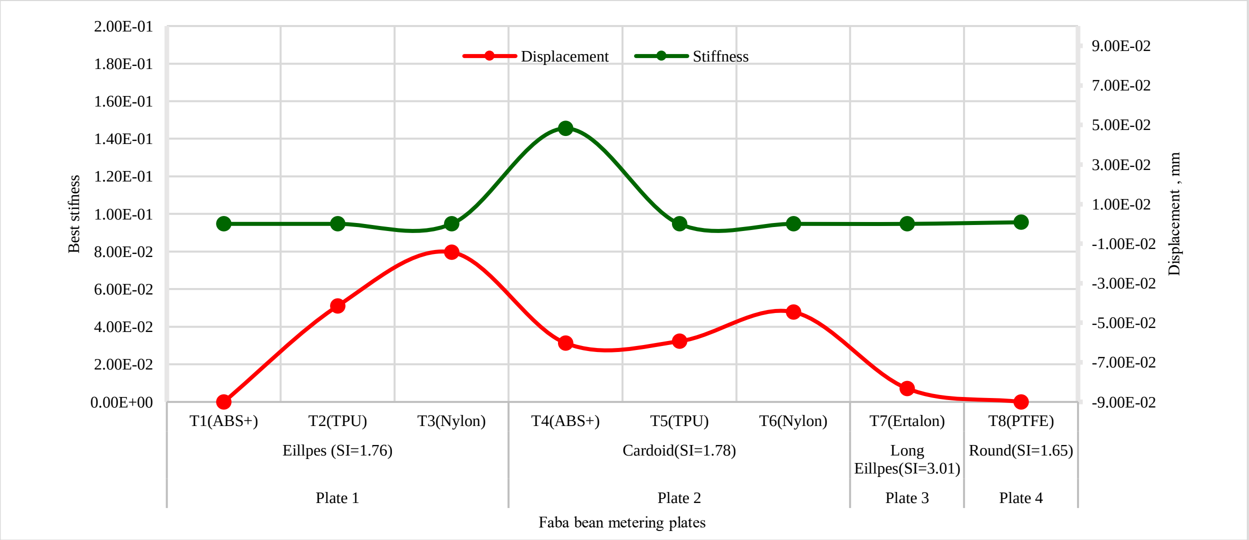

Fig. 14. Best Stiffness and Displacement at Different parameters of Faba Bean Metering Plates
Source: Authors' determination.

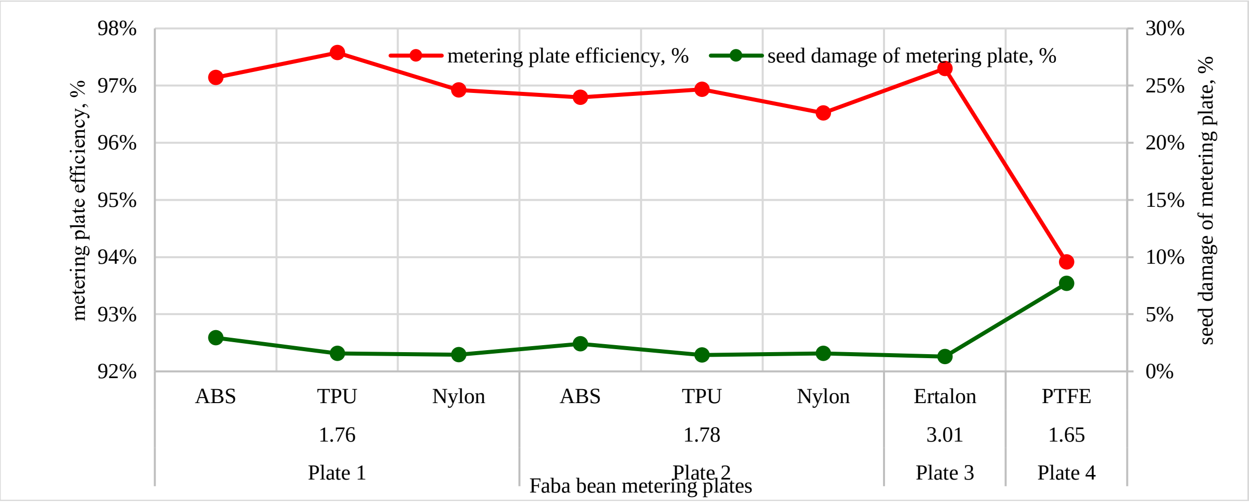

Fig. 15. Metering plate efficiency and seed damage of metering plate at different metering plates
Source: Authors' determination.

CONCLUSIONS

The study showed the plate with "TPU" material will not fail under the given stresses as the maximum stresses are much lower than the yield strength of the plate material will not carry out any significant deformations according to the loading conditions applied. Also give the maximum value of the metering plate efficiency for the same plate.

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