STRUCTURAL ANALYSIS OF A COMBINED CULTIVATOR WORKING TOOL / СТРУКТУРЕН АНАЛИЗ НА КОМБИНИРАН КУЛТИВАТОРЕН РАБОТЕН ОРГАН

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ABSTRACT

This paper presents a structural analysis of a combined cultivator working tool designed to integrate primary soil cutting and loosening with secondary soil fragmentation within a single pass. A three-dimensional model of the working tool was developed using specialized engineering software, and a numerical analysis based on the finite element method was performed. The structural assessment was carried out by applying a uniformly distributed surface load of up to 0.2 MPa, corresponding to typical contact pressures encountered in moderately compacted soils. The analyses were conducted for different working depths and for three tine geometric profiles - circular, square, and rhomboidal.

Structural integrity was evaluated using the von Mises yield criterion, while the factor of safety (FOS) was adopted as the primary indicator of strength reserve. The results show that, for all analysed configurations, the equivalent von Mises stresses remain below the yield strength of normalized AISI 4340 steel, with FOS values ranging from 1.2 to 5.3. Tine geometry was found to have a significant influence on stress distribution and structural response. The rhomboidal profile exhibits the most favourable performance, characterized by lower and more uniformly distributed stresses and reduced draft resistance. The results confirm that the proposed combined cultivator working tool represents a promising solution for modern tillage machinery aimed at reducing field passes and improving soil cultivation quality.

РЕЗЮМЕ

В статията е представен структурен анализ на комбиниран култиваторен работен орган, предназначен за съчетаване на първично рязане и разрохкване на почвата с вторично раздробяване в рамките на едно преминаване. С помощта на специализиран софтуер е разработен триизмерен модел на работния орган и е проведен математичен анализ чрез метода на крайните елементи. Структурната оценка е извършена чрез прилагане на равномерно разпределено повърхностно натоварване до 0.2 MPa, съответстващо на характерните контактни налягания при работа в средно уплътнени почви. Анализите са проведени за различни работни дълбочини и за три геометрични профила на зъбите – кръгъл, квадратен и ромбоиден.

Структурната устойчивост е оценена чрез критерия за провлачване по von Mises, като коефициентът на безопасност (FOS) е използван като основен показател за запаса на здравина. Резултатите показват, че при всички анализирани конфигурации еквивалентните напрежения по von Mises остават под границата на провлачване на нормализирана стомана AISI 4340, като стойностите на FOS са в диапазона 1.2 до 5.3. Установено е, че геометрията на зъбите оказва съществено влияние върху разпределението на напреженията и структурната реакция. Ромбоидният профил показва най-благоприятно поведение, характеризиращо се с по-ниски и по-равномерно разпределени напрежения и понижено теглително съпротивление. Получените резултати потвърждават, че предложеният комбиниран култиваторен работен орган представлява перспективно решение за съвременните почвообработващи машини, насочени към намаляване на броя на технологичните преминавания и подобряване качеството на почвената обработка.

INTRODUCTION

Soil tillage is a key technological process in agriculture that has a significant impact on soil physical properties, water regime, and crop productivity.

Recent studies indicate that intensive tillage technologies, accompanied by multiple passes of agricultural machinery, often lead to soil compaction, formation of ruts, and deterioration of soil structure. Experimental results show that vertical load, number of passes, and machine operating speed have a substantial influence on rut depth and the degree of soil compaction (*Demirev and Bratoev, 2012; Pulido-Moncada et al., 2019; Farhadi et al., 2025*).

Soil compaction results in deterioration of the water, air, and thermal regimes and restricts root system development. Field and laboratory studies demonstrate that different tillage methods directly affect soil hardness, moisture retention, and crop yields, and that optimization of tillage operations can lead to improved soil moisture conservation and higher productivity (*Delchev et al., 2017*; *Dobrinov, 2021*; *Modiba et al., 2024*). Long-term experiments further confirm that conventional tillage technologies often result in more unfavourable structural changes compared to reduced and conservation tillage systems (*Oliveira et al., 2024*).

One of the effective approaches to limiting the negative impact on soil is reducing the number of technological passes through the use of combined tillage machines. Analyses of selected modern designs indicate that combined working tools integrating passive and active elements can provide high-quality soil cultivation while reducing the overall mechanical load on the soil mass (Manushkov et al., 2013; Prem et al., 2016; Behera et al., 2021; Dimitrov et al., 2025). Such solutions are increasingly being adopted in contemporary agricultural practice (Kadiev, 2024).

The performance of tillage machines is largely determined by the interaction between the working tool and the soil, as well as by the geometry and arrangement of the functional elements. Mathematical models indicate that the shape and orientation of cultivator sweeps and tines have a significant influence on soil response, soil particle movement, and stress distribution (*Tekeste et al., 2019*). Modern numerical modelling approaches, including the finite element method and smoothed particle methods, enable an in-depth analysis of both soil–tool interaction and the structural condition of the working tools themselves (*Hu et al., 2023; Ibrahimi and Bentaher, 2025*).

A number of recent studies have applied the finite element method (FEM) for the structural analysis and optimization of agricultural machinery components, including cultivator frames, soil loosening mechanisms, and working tools. These investigations demonstrate the applicability of FEM for evaluating stress–strain states, identifying critical zones, and improving structural reliability under real operating conditions (*Biris et al., 2016; Croitoru et al., 2017; Ungureanu et al., 2018; Vlădut et al., 2018*). The results of these studies confirm that numerical modelling represents an effective approach for the design and assessment of soil tillage equipment.

In addition to scientific studies, a number of patented engineering solutions for combined tillage working tools have been reported, aiming to improve soil deformation and operational efficiency (*Akhalaya, 2022; Lobachevsky et al., 2021*). However, despite these developments, many existing designs do not ensure sufficient soil loosening beneath the working depth, which may lead to additional soil compaction in deeper layers (*Kadiev, 2023; Trendafilov et al., 2024*).

Despite the existing research, further investigation is required to evaluate the structural behaviour of combined working tools under representative loading conditions using advanced numerical modelling approaches.

The objective of the present study is to provide a theoretical justification of the parameters of a combined cultivator working tool through the development of a three-dimensional model and the performance of a structural analysis using specialized engineering software.

MATERIALS AND METHODS

The three-dimensional (3D) model of the combined cultivator working tool was developed using the SolidWorks software package Figure 1 (*Solidworks Design Help, 2022*). The virtual model comprises a cultivator sweep with harrow tines mounted on it. The design was developed to simulate two successive operations within a single pass - primary soil cutting and loosening performed by the sweep, followed by secondary soil fragmentation and surface levelling achieved by the tines.

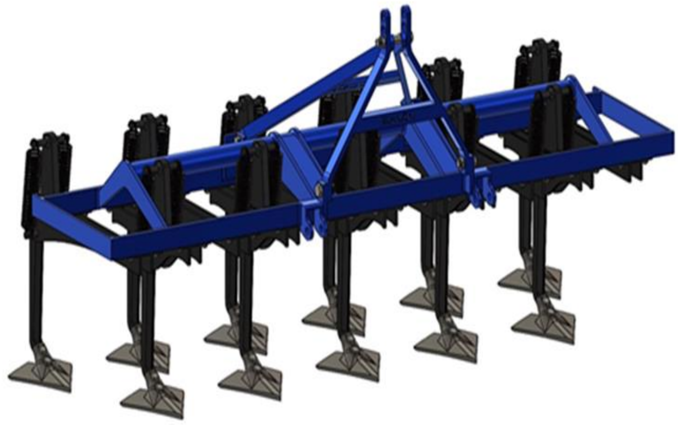
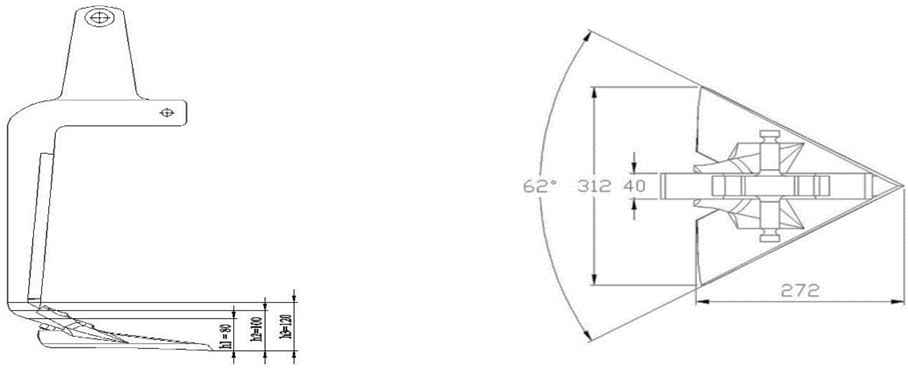


Fig. 1 - Three-dimensional model of the cultivator developed using SolidWorks software

The structural assessment of the working tool was performed using the SolidWorks Simulation module based on the finite element method. The analyses were conducted as linear static simulations, assuming a linear-elastic material behaviour, and were focused on determining the distribution of equivalent von Mises stresses and evaluating the strength reserve under representative operating loads.

The finite element mesh was generated using tetrahedral elements, with local mesh refinement applied in regions where high stress gradients were expected - primarily in the transition zone between the cultivator sweep and the harrow tines. The final finite element model consisted of approximately 199613 elements and 317167 nodes. A mesh sensitivity analysis was performed by refining the mesh in critical regions, and the variation in maximum equivalent von Mises stress was found to be within an acceptable range, confirming the numerical stability and convergence of the solution.

The following main geometric and operating parameters were used for model development and structural analysis: working depths of 80, 100, and 120 mm (Figure 2 a); cultivator working width of 2760 mm (Figure 2 b); and installation of harrow tines beneath each cultivator sweep, which increases the effective tillage depth directly beneath the sweep to 80 mm.



a) b)

Fig. 2 - Technical parameters of the cultivator

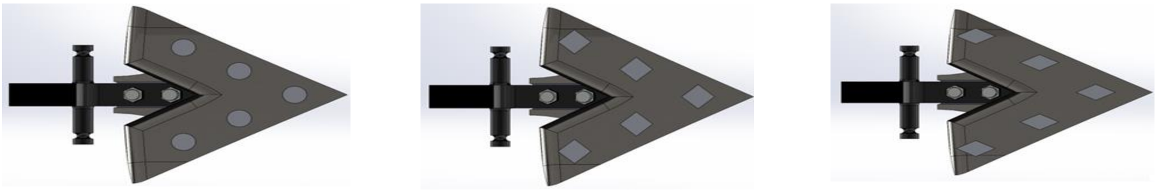
a) working depths; b) dimensions of the cultivator sweep

The working tool was constrained by fixing the mounting region to the cultivator frame, with all degrees of freedom restricted. This boundary condition reflects the actual mounting configuration and ensures proper load transfer within the structure.

A uniformly distributed surface load of up to 0.2 MPa was applied to all analysed models. This value was selected as a representative contact pressure corresponding to moderately compacted soils, based on literature data and typical operating conditions of cultivator tools. The adopted loading level ensures a realistic yet conservative estimation of the structural response under field conditions. The soil medium was represented by an equivalent pressure, which constitutes a simplified but widely accepted approach for preliminary structural assessments of tillage working tools. This approach represents a commonly used simplification in preliminary structural analyses of soil-engaging tools, where the primary objective is to evaluate the structural response of the tool rather than to model the complex nonlinear behaviour of the soil medium.

Although real soil–tool interaction involves highly nonlinear and heterogeneous conditions, the use of an equivalent distributed load allows for a consistent comparative assessment of different geometric configurations under representative loading conditions. For an indicative characterization of the soil environment, a bulk density of up to 2000 kg/m³ was assumed. The selected parameters correspond to typical values reported for clay and loamy soils under moderate compaction conditions. Although the soil behaviour is not explicitly modelled, these parameters provide a reasonable physical basis for the definition of the applied loading conditions.

The harrow tines were arranged at an angle of attack of up to 80° relative to the vertical plane, allowing the decomposition of soil forces into vertical and horizontal components. Each supporting shank was equipped with five replaceable tines featuring three different geometric profiles: a circular profile with a diameter of 30 mm, a square profile with dimensions of 30 × 30 mm, and a rhomboidal profile with a side length of 30 mm and an angle of attack of 60° (Figure 3).



a) b) c)

Fig. 3 - Tine profiles

a) circular; b) square; c) rhomboidal

The combined cultivator working tool was designed to ensure effective soil–tool interaction by integrating primary soil cutting and loosening with additional fragmentation and levelling of the surface layer, thereby reducing the need for extra technological passes.

The working tool material was selected as low-alloy AISI 4340 steel in a normalized condition, characterized by high strength, good ductility, and impact toughness. The main mechanical properties of the material are as follows: yield strength of 470-560 MPa; tensile strength of 740-850 MPa; elongation at break of 20 - 25% and an elastic modulus of approximately 210 GPa.

The selected material is particularly suitable for working tools subjected to dynamic loads, vibrations, and localized impacts from the soil environment, providing a sufficient strength reserve and stable structural behaviour under real operating conditions.

The structural evaluation was carried out based on the von Mises yield criterion, which is the primary failure criterion for ductile materials. Yielding is considered to occur when the equivalent stress reaches or exceeds the material's yield strength. The factor of safety (FOS) was defined as the ratio between the yield strength and the maximum equivalent stress obtained from the structural analysis.

The equivalent von Mises stress is a scalar quantity that combines the effects of normal and shear stresses within the material and enables the assessment of its response under complex stress states. The von Mises criterion is based on the distortion energy theory and is widely used in the analysis of ductile metallic materials, such as the AISI 4340 steel employed in the present study.

In Equation (1), the equivalent von Mises stress is expressed as a function of the three principal normal stresses and the shear stresses acting within the element, which are automatically calculated by the SolidWorks Simulation software based on the specified boundary conditions and applied loads. The resulting value does not represent direct tensile or compressive stress, but rather a measure of the energy accumulated in the material as a result of deformation.

$$\sigma_{VM} = \sqrt{\frac{1}{2}\left[\left(\sigma_x-\sigma_y\right)^2 + \left(\sigma_y-\sigma_z\right)^2 + (\sigma_z-\sigma_x)^2 + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\right]} \quad (1)$$

where σ_{VM} is the equivalent von Mises;

σ_y is the yield strength of the material;

$\sigma_x, \sigma_y, \sigma_z$ are the normal stresses acting along the three orthogonal axes of the coordinate system for the corresponding structural element. These stresses may be tensile (positive) or compressive (negative) and are generated by forces acting perpendicular to the surface:

$\tau_{xy}, \tau_{yz}, \tau_{zx}$ are the shear stresses acting in the planes formed by the pairs of axes XY, YZ and ZX. They arise when forces act parallel to the plane rather than perpendicular to it.

According to the von Mises yield criterion, plastic deformation of the material is considered to occur when the equivalent stress reaches or exceeds the material's yield strength, which is expressed by Inequality (2). For values of the equivalent stress lower than the yield strength, the material remains in the elastic regime and recovers its original shape after unloading.

$$\sigma_{VM} \geq \sigma_y \tag{2}$$

The factor of safety (FOS), defined by Equation (3), represents the ratio between the material yield strength and the maximum equivalent stress obtained from the structural analysis. This parameter provides a quantitative measure of the structural strength reserve and allows comparison between different design configurations and geometric parameters of the working tool. For FOS values greater than unity, the structure is considered structurally stable under the specified operating conditions.

$$FOS = \frac{\sigma_y}{\sigma_{VM}} \tag{3}$$

The adopted modelling approach enables a reliable comparative evaluation of different design configurations under controlled and repeatable loading conditions.

RESULTS

Structural response of the combined cultivator working tool

The structural analyses demonstrate that the combined cultivator working tool maintains a stable structural response under a uniformly distributed load of up to 0.2 MPa. For all analysed configurations, the maximum equivalent von Mises stresses remain below the yield strength of AISI 4340 steel.

The calculated factor of safety (FOS) ranges from 1.2 to 5.3, indicating a sufficient strength reserve under the considered operating conditions.

The highest stress levels occur in the transition zone between the harrow tines and the cultivator sweep, which is expected due to the abrupt change in geometry and the concentration of bending and shear stresses in this region. With increasing distance from the mounting zone, the stresses gradually decrease along the length of the tines, indicating a favourable load distribution and the absence of critically high stresses at the free ends.

Influence of tine profile geometry

Figures 4 to 6 present the structural response of the working tool equipped with circular, square, and rhomboidal tine profiles. The results indicate that tine geometry has a significant influence on both the magnitude and distribution of equivalent stresses.

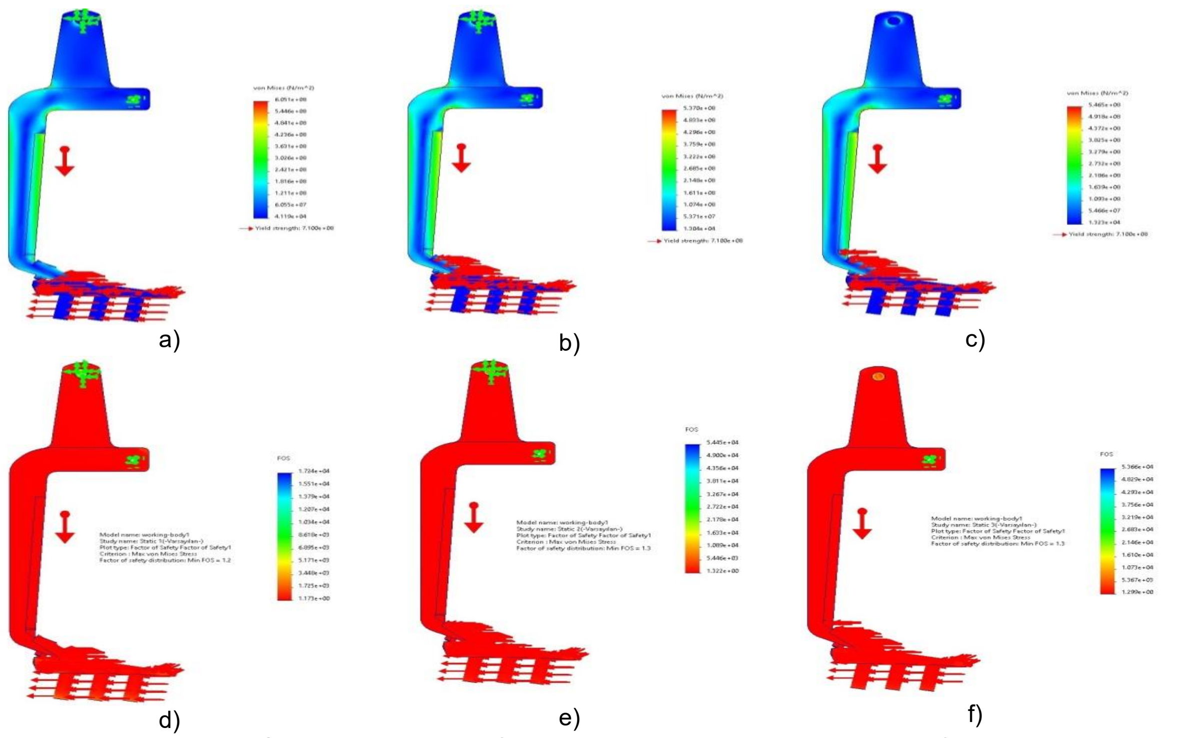


Fig. 4 - Structural analysis of the working tool with circular tine profile

a) working depth of 8 cm; b) working depth of 10 cm; c) working depth of 12 cm; d) factor of safety, FOS ≥ 1, at a working depth of 8 cm; e) factor of safety, FOS ≥ 1, at a working depth of 10 cm; f) factor of safety, FOS ≥ 1, at a working depth of 12 cm

The circular profile exhibits the highest stress levels, primarily concentrated at the mounting zone. The square profile demonstrates a moderate structural response, with localized stress concentrations along the edges. The rhomboidal profile provides the most favourable performance, characterized by lower and more uniformly distributed stresses along the tine length.

These results confirm that geometric optimization of the tine profile plays a key role in improving structural efficiency and reducing stress concentration.

The circular profile is characterized by higher stress concentration in the mounting zone, particularly at increased working depths, which confirms its less favourable structural behaviour.

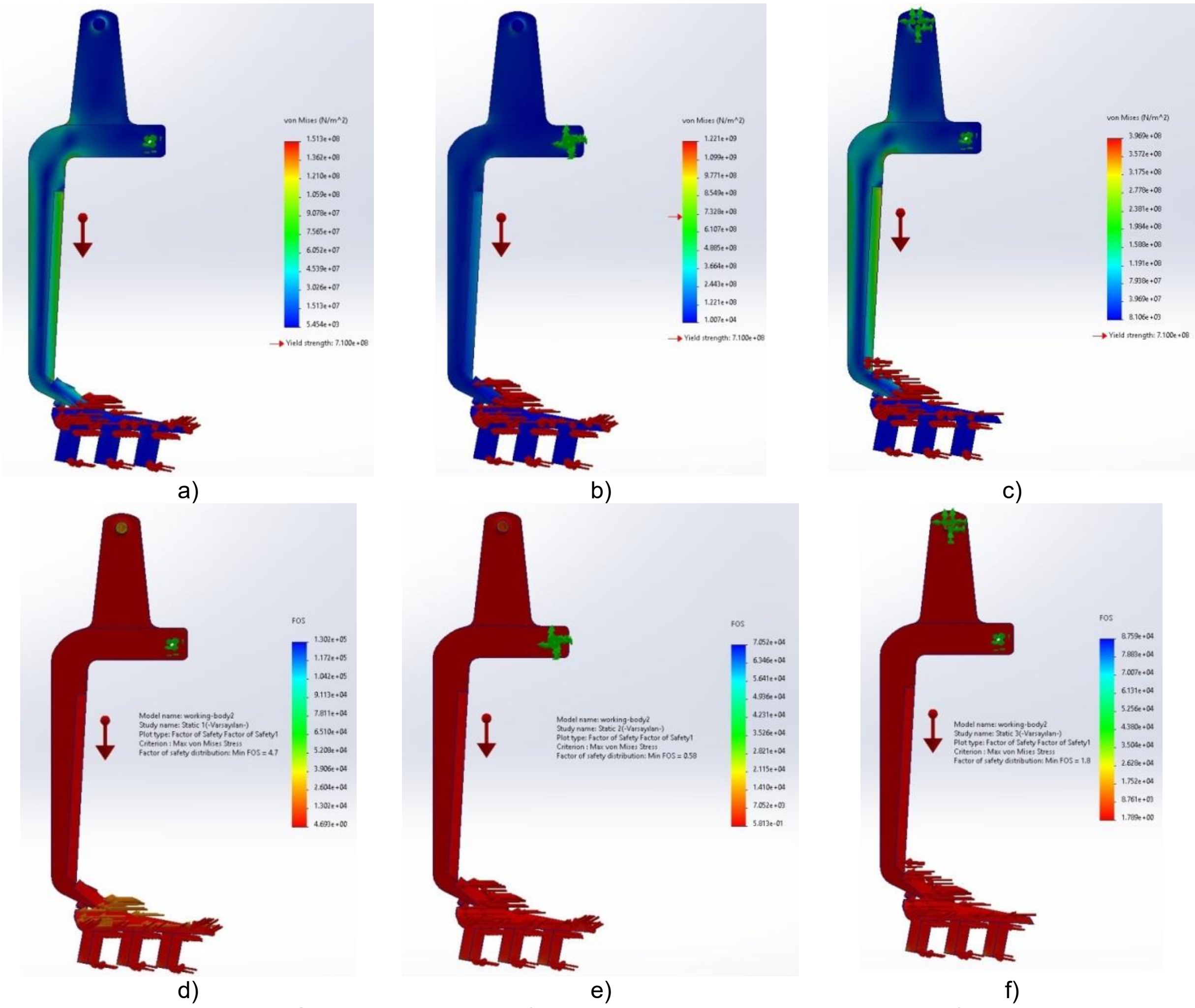


Fig. 5 - Structural analysis of the working tool with square tine profile

a) working depth of 8 cm; b) working depth of 10 cm; c) working depth of 12 cm; d) factor of safety, FOS ≥ 1, at a working depth of 8 cm; e) factor of safety, FOS ≥ 1, at a working depth of 10 cm; f) factor of safety, FOS ≥ 1, at a working depth of 12 cm

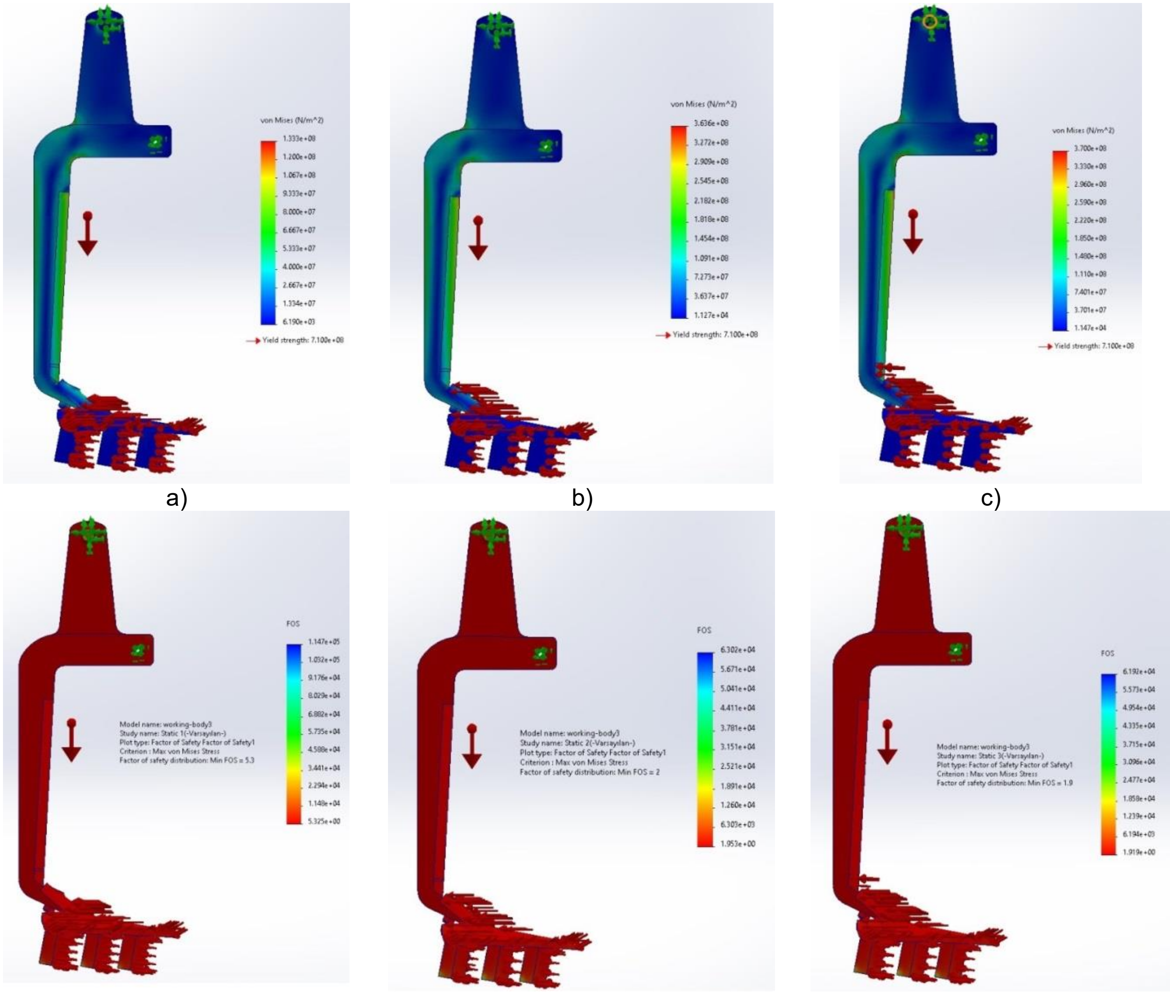
The square profile demonstrates a more uniform stress distribution compared to the circular profile, although localized stress concentrations are still observed along the profile edges.

The rhomboidal profile exhibits the most favourable stress distribution, with lower stress levels and a more uniform distribution along the tine length, indicating improved structural performance.

Influence of the angle of attack

The results indicate that the angle of attack significantly affects the stress distribution within the structure. Increasing the angle of attack leads to higher bending moments at the base of the tines and consequently higher equivalent stresses. Conversely, reducing the angle promotes a more favourable distribution of forces and results in lower stress levels.

This demonstrates that optimization of the angle of attack represents an effective approach for improving the structural performance of the working tool.



a) b) c)

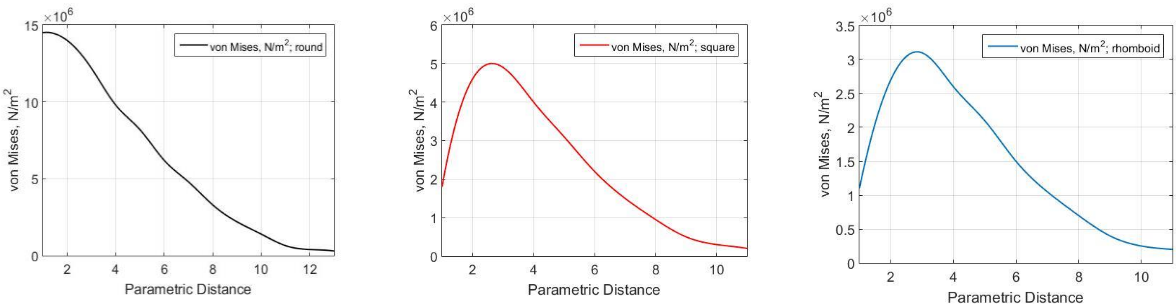
d) e) f)

Fig. 6 - Structural analysis of the working tool with rhomboidal tine profile

a) working depth of 8 cm; b) working depth of 10 cm; c) working depth of 12 cm; d) factor of safety, FOS ≥ 1, at a working depth of 8 cm; e) factor of safety, FOS ≥ 1, at a working depth of 10 cm; f) factor of safety, FOS ≥ 1, at a working depth of 12 cm

Stress distribution during soil interaction

The stress distribution resulting from the interaction between the cultivator sweep, the tines, and the soil is presented in Fig. 7. The maximum stress values occur in the mounting region between the tines and the sweep, where the majority of the mechanical load generated by soil penetration and shearing is concentrated.



a) b) c)

Fig. 7 - Structural analysis of tine profiles in the horizontal plane (angle of attack)

a) circular; b) square; c) rhomboidal

The stress distribution in the horizontal plane, presented in Fig. 7, confirms the influence of both the geometric profile and the angle of attack, with the lowest stress levels observed for the rhomboidal profile.

With increasing distance from this region, the stresses gradually decrease toward the free end of the tines, reflecting the natural attenuation of the applied forces along the profile length.

The analysis confirms that both the geometric profile and the angle of attack have a significant effect on the structural response of the working tool.

Table 1 presents a comparative evaluation of the three tine profiles. The results clearly demonstrate the advantage of the rhomboidal profile, which provides the most uniform stress distribution, the highest structural efficiency, and the lowest expected draft resistance. This confirms that geometric optimization of the tines is a key factor in improving the performance and reliability of the combined cultivator working tool.

Table 1

Comparative evaluation of tine profiles

Tine profile	Stress characteristics	Location of maximum stresses	Structural efficiency	Expected draft resistance
Circular	High, concentrated	At the tine base	Low	High
Square	Moderate, with local peaks	Along the edges	Medium	Medium
Rhomboidal	Low, uniformly distributed	Distributed along the length	High	Low

Overall, the results demonstrate that both tine geometry and angle of attack have a significant influence on the structural behaviour of the working tool, with the rhomboidal profile providing the most favourable stress distribution and structural performance.

CONCLUSIONS

The conducted structural analyses demonstrate that, under a uniformly distributed load of up to 0.2 MPa, the maximum equivalent von Mises stresses remain below the yield strength of AISI 4340 steel. As a result, the proposed combined cultivator working tool maintains a sufficient strength reserve and structural integrity across all analysed configurations and working depths.

The obtained factor of safety (FOS) values range from 1.2 to 5.3, indicating an adequate strength reserve for the considered depths and configurations.

Tine geometry has a significant influence on stress distribution: the rhomboidal profile exhibits the lowest and most uniformly distributed stresses and is therefore evaluated as the most efficient configuration.

The integration of harrow tines with the cultivator sweep does not lead to an unfavourable increase in stresses but contributes to more uniform loading and enables combined soil processing within a single pass.

Optimization of the angle of attack is an effective approach for limiting bending stresses at the base of the tines and improving the overall structural performance of the working tool.

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