Black Sea Journal of Agriculture
doi: 10.47115/bsagriculture.1833758

Open Access Journal
e-ISSN: 2618 – 6578

Research Article
Volume 9 - Issue 2 : 212-221 / March 2026

IMPROVEMENT OF THE RIGID NARROW-POINT HEAVY CULTIVATOR SHANK DESIGN AND ANALYSIS OF STRESS DISTRIBUTION USING THE FINITE ELEMENT METHOD

Mustafa ÇOMAKLI[1]*, Bahadır SAYINCI[2]

[1]Ataturk University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, 25240, Erzurum, Türkiye
[2]Bilecik Şeyh Edebali University, Faculty of Agriculture and Natural Sciences, Department of Biosystems Engineering, 11200, Bilecik, Türkiye

Abstract: Heavy cultivators, which are widely used under dry farming conditions, are among the secondary tillage implements preferred for their ability to preserve soil moisture. Cultivator shanks that function by means of profound soil ripping generate considerable draft forces depending on the tractor's forward speed, and substantial deformations occur in the main frame connections due to the normal and shear stresses induced by these loads. It has been observed that the fastening components of fixed-shank heavy cultivators, which are widely used in the Eastern Anatolia Region, often fail to develop sufficient resistance against shear forces. This results in frequent damage and increased repair costs associated with the connection elements. In this study, a finite element analysis was conducted on a cultivator shank whose design had been improved and material selection re-evaluated, taking into account the operational field conditions under which the implement is used. Consequently, displacement and equivalent stress analyses were conducted under static loading conditions for the shank point and its fastening components. Thereafter, the safety factor of the parts against the applied loads was determined. The attachment of the shank point to the main frame is achieved by means of detachable fastening elements, namely bolts. The operating speed of the tillage implement and the soil structure were considered in the theoretical calculation of the force acting on a single shank, and an optimum mesh structure was generated accordingly. The rigid shank point and fixed shank were defined as normalized carbon steel (C30E); the support components as structural steel (S235JR); and the bolts as tempered steel of grade 8.8 (C45E). As demonstrated by the design improvements and analysis results, the total displacement was found to be 0.31 mm, while the equivalent stress on the connection bolts was determined as 71.81 MPa, and the safety factor was calculated as 8.91. It was concluded that, given the applied boundary conditions, the implemented design improvements and material selection, the calculated maximum equivalent stresses for the fasteners are significantly lower than the yield strength of the materials. This indicates that the cultivator leg components can operate safely.

Keywords: Cultivator tip/point, Computer-aided design, Finite element method

***Corresponding author:** Ataturk University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, 25240, Erzurum, Türkiye
E mail: mustafa.comakli@atauni.edu.tr (M. ÇOMAKLI)
Mustafa ÇOMAKLI https://orcid.org/0000-0002-3974-1354
Bahadır SAYINCI https://orcid.org/0000-0001-7148-0855

Received: December 01, 2025
Accepted: February 10, 2026
Published: March 15, 2026

Cite as: Çomaklı, M., & Sayıncı, B. (2026). Improvement of the rigid narrow-point heavy cultivator shank design and analysis of stress distribution using the finite element method. *Black Sea Journal of Agriculture*, 9(2): 212-221.

1. Introduction

The primary objective of conservation tillage practices is to minimise the mechanical stresses that compromise soil integrity by permitting the presence of crop residues on the field surface or in the near-surface layers. This methodology confers numerous advantages, including the prevention of erosion, the reduction of surface runoff, the promotion of organic matter accumulation, and the conservation of soil moisture (Önal, 1995; Lal, 2015). The extensive adoption of conservation tillage systems is imperative for the execution of sustainable production practices.

Despite the technological advancements that have facilitated the development of more sophisticated machinery in the contemporary agricultural sector, seedbed preparation, shallow loosening and secondary tillage operations continue to be predominantly executed through the utilization of mechanical tools and equipment (Nazemosadat et al., 2022). Narrow-tipped implements, including chisels and heavy cultivators, which are frequently employed as secondary tillage tools, play a crucial role in these processes by ensuring uniform loosening at a specific depth, facilitating subsoil aeration, breaking hardpan, and providing support for plant root development (Raza et al., 2005; Marakoğlu et al., 2013). Nevertheless, the structural integrity of such implements is susceptible to degradation over time, owing to the impact of variable dynamic forces experienced under field conditions.

During operation, tillage implements are subjected to complex loading due to factors such as high draft resistance, variable clod formation, stones, roots, and hard soil obstacles. It has been demonstrated that these forces have the capacity to induce deformations, cracks and fractures in the shank, tip, body and connection areas. This, in turn, has been shown to result in a significant reduction in the functional performance and service life of the implements (Çelik et al., 2020; Kesner et al., 2021). Indeed, empirical evidence from field observations has demonstrated that failures such as fractures at the shank connection points, tip deformations, and bolt breakages are prevalent, even during the initial season, particularly in domestically produced heavy cultivators (Yang, 2024). In cultivators used for tillage operations to prepare the seedbed in agriculture, friction-induced wear occurs at various connection points during operation, and it has been emphasised that the most common damage takes place in the connection regions where the shank is attached to the chassis (Elavarasan and Manimaran, 2024).

Technological advancements have led to an increased importance of computer-based analysis methods, which facilitate the verification of engineering designs in a digital environment. In contemporary agricultural machinery manufacturing, there is an observable trend towards the utilization of methodologies such as solid modelling, finite element analysis (FEA), rapid prototyping and simulation-supported design applications. This development is consistent with the broader adoption of such practices in numerous other industries (Saygılı and Çakmak, 2025).

Altuntaş et al. (2018) investigated the stress and deformation behaviours of narrow cultivator tips using the finite element method under six different loading conditions. Pirogov et al. (2019) developed a flexible cultivator shank design with variable stiffness to prevent buckling caused by soil resistance, and demonstrated through the finite element method that this structure is structurally safe even under heavy soil conditions. Boyar et al. (2020) investigated the deformation behaviour and equivalent stress distributions of a specially designed manure scraper used in livestock farms through Finite Element Analysis (FEA) software. Terzi et al. (2021) performed stress and deformation analyses of rectangular and circular cross-section axles used in agricultural trailers using the ANSYS finite element software. Sayıncı et al. (2021) determined the critical stress and displacement values of an agricultural trailer platform designed using two materials with different strength classes under static conditions by means of the finite element method.

These methods enable the prediction of structural weaknesses in implements, the correction of design errors, and the reduction of costs prior to prototype production. Nevertheless, in Türkiye, particularly amongst small-scale manufacturers in the Eastern Anatolia Region, the restricted utilization of technology engenders considerable challenges in the implementation of design-based enhancements to address the prevalent structural issues encountered in the field (Şahin et al., 2018).

In this context, the integration of computer-aided engineering (CAE) techniques into local manufacturing processes will enhance the durability of implements, providing significant benefits to both manufacturers and users. Despite the existence of numerous studies addressing the structural analysis of tillage implements in the international literature (Erdem Korkmaz and Dilay, 2025), research specifically examining the stresses and deformations experienced by cultivator shanks produced by regional manufacturers under actual working conditions remains limited.

The present study was conducted with a view to resolving the frequent pin shear problems encountered at the shank connections of heavy cultivators commonly used in the Eastern Anatolia Region. In extant Three distinct loading scenarios, representing field conditions, were defined for the potential load alternatives that the cultivator shank may encounter. The equivalent stress and displacement values in the shank, tip, and connection elements were determined using the finite element method. The obtained results are significant in terms of revealing the structural characteristics of heavy cultivators with respect to their mechanical strength. The present study is of significance in terms of the systematic evaluation of the structural performance of cultivator shanks manufactured on a local level. It provides an explanation for the frequent breakage and deformation problems that occur in the field from an engineering perspective, and it provides concrete improvement recommendations for the design process. Furthermore, the present study offers insights that can contribute to the technological adoption levels of regional manufacturers and the improvement of the field performance of heavy cultivators.

2. Materials and Methods

2. 1. Rigid-Narrow Tip Heavy Cultivator

This study focuses on a heavy duty 17 shaft cultivator with dimensions (2400×130×100 mm) produced by small-scale agricultural machinery manufacturers in the Eastern Anatolia Region. The dimensions of the cultivator were measured on-site in order to create a detailed solid model in SolidWorks, which served as the reference for the study (Figure 1). Each shank is rigidly attached to the cultivator frame and is equipped with a narrow tip that is responsible for the cutting and breaking of soil during tillage operations.

2.1. Properties of the Tip

In order to reveal the structural behaviour of the cultivator under different draft force conditions, the narrow-tip shank body, along with all components connecting this body to the chassis, were used. The technical dimensions and assembly view of the rigid narrow-tip cultivator shank are demonstrated in Figure 2a, while Figure 2b presents a comprehensive representation of all components of the cultivator shank. The tip, with dimensions of 259×71×12 mm, is securely mounted to the shank body through a weld seam measuring 142 mm in length. The tip body is connected to the cultivator frame at two points using two connection plates (150×50×10 mm), each featuring three concentric holes spaced 60 mm apart. M8-sized fasteners (bolts and nuts) were used for the three-point connection.

The tip, forged from carbon steel C30E, is subjected to a process of normalizing heat treatment, a method employed to enhance its impact resistance. The tip undergoes a heat treatment process to achieve its curved shape, and is subsequently formed through forging and bending procedures. The tip body, which is mounted to the main cultivator frame using fasteners, is composed of C30E medium-carbon steel. The connection plates are fabricated from S235JR structural steel, while the fasteners are defined as tempered C45E carbon steel with a grade of 8.8. For the analyses conducted using the Finite Element Method (FEM), the mechanical properties (such as elastic modulus, Poisson's ratio, yield strength, etc.) of all selected materials were defined based on the literature (MatWeb, 2025). The physical and mechanical properties of all components comprising the rigid narrow-tip cultivator shank are presented in Table 1.

2.3. Mesh Structure of the Solid Model

The implementation of a multizone mesh method on the tip model was undertaken with the objective of enhancing the representation of complex surfaces with greater accuracy and uniformity. This method facilitates the integration of both hexahedral and tetrahedral elements within a unified model, thereby ensuring high solution accuracy and stability for machine components that encompass both flat and curved surfaces. Given the nature of the support elements, which possess a rectangular cross-section, it was determined that a patch-independent mesh method should be employed for these components. This method facilitates the generation of automatic tetrahedral elements, irrespective of surface divisions, thereby ensuring the establishment of a more stable, uniform, and low-error mesh structure in complex assemblies. Furthermore, contact-specific mesh refinement (contact sizing) was applied between the detachable fasteners and the central support element, which is expected to come into contact under load. This will allow for precise analysis of localized stress concentrations and potential failure regions in the bolts. The skewness metric was utilized to assess the quality of the finite element mesh. This metric constitutes a primary quality criterion, denoting the extent of deviation of a mesh element from its ideal geometry. The proximity of a value to 0 is indicative of an ideal (i.e. equilateral and uniform) element, whilst the proximity of a value to 1 is indicative of a distorted element that has the capacity to reduce solution accuracy (ANSYS Documentation, 2019; Çelik et al., 2020). In this study, the average skewness metric of the generated finite element mesh was calculated to be 0.19, indicating that the mesh is of high quality and the solution stability is excellent. As illustrated in Figure 3, the mesh structure of the cultivator shank is demonstrated, while the mesh evaluation criteria are outlined in Table 2.

Table 1. Selected physical and mechanical properties of the rigid narrow-tip cultivator shank*

Components	Material	m (g)	R_e (MPa)	R_m (MPa)	E (GPa)	ρ (kg m^{-3})	υ
Narrow tip	C30E	2179	350	519	210	7850	0.3
Narrow tip body	C30E	2346	350	519	210	7850	0.3
Side support parts	S235JR	1152	235	400	210	7850	0.3
Connecting elements	C45E	81	640	800	210	7850	0.3

* m= mass, Re= yield strength, Rm= tensile strength, E= elastic modulus, ρ= density, υ= Poisson's ratio.

Figure 1. Rigid narrow-tip heavy cultivator model.

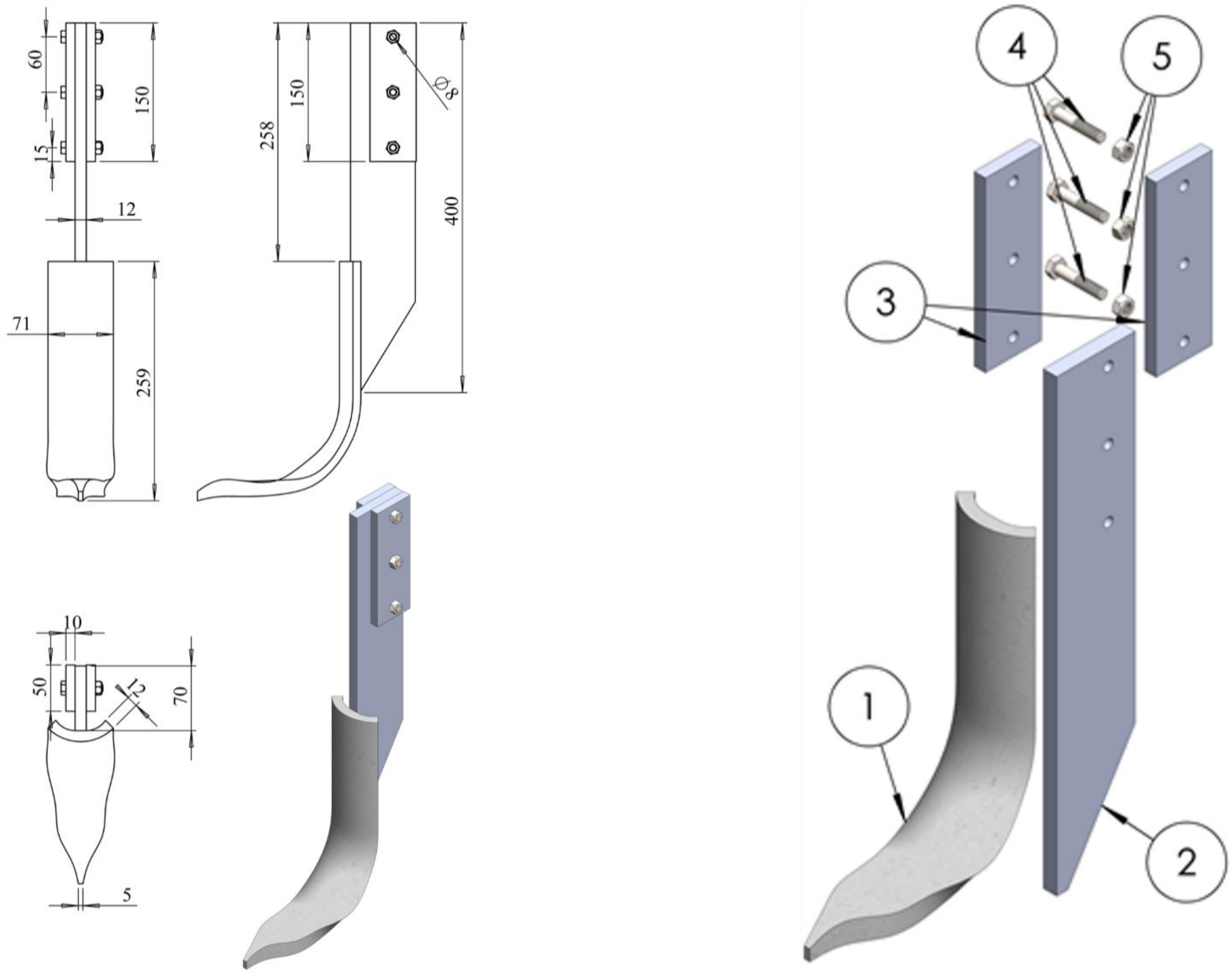

Figure 2. Rigid narrow-tip cultivator shank (a) Technical dimensions and assembly view, (b) Components of the cultivator shank (1: narrow tip; 2: tip body; 3: connection plates; 4: bolt; 5: nut).

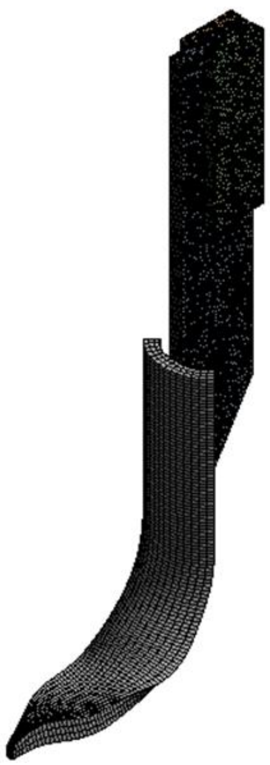

Figure 3. Mesh structure of the cultivator shank.

Table 2. Mesh evaluation criteria for the cultivator shank

Element size (mm)	3.1
Elements Number	223306
Nodes	352550
Element quality (average)	0.84
Aspect Ratio (average)	1.94
Skewness (average)	0.19
Orthogonal quality (average)	0.80

2.4. Contact Interactions

In the finite element analysis of the cultivator shank, the contact interactions between assembled components were defined with appropriate contact types in accordance with boundary conditions representing field working conditions. In the assembly of the detachable fasteners, the connection plates were affixed to the cultivator body, and these plates were subsequently mounted to the tip support using bolts. Due to the limited horizontal movement permitted between the support plates, their contact interaction was defined as frictionless. In the case of the bolted connections, the no-separation contact model was implemented, thereby enabling sliding in the tangential direction whilst preventing separation in the normal direction. This was done in order to realistically represent potential shear, slip, and fracture under loading. For all other component interactions, a bonded contact definition was applied with a view to preventing relative movement and separation.

2.5. Definition of Forces Acting on the Cultivator Shank and Constraints

The analysis was subject to certain boundary conditions, which were established on the basis of loading scenarios representing field conditions and relevant literature data. The most important dynamic parameter to be known in the design and optimization of tillage tools and machinery is the draft force (Boydaş., 2023). Sucuoğlu et al. (2025) defined the load values to be applied in the topology optimization analyses conducted for the mounting bracket of Lister/cultivator shanks in accordance with the ASAE 497.5 Standard. Askari and Khalifahamzehghasem (2013) determined the power requirements of moldboard plow, chisel plow, disk harrow, and field cultivator through field trials using a dynamometer. They compared the experimental results with the predictions of ASABE Standard D497.5 and confirmed that ASABE standards are a reliable estimation tool for such equipment. The draft force of the cultivator was calculated using Equation (1), with reference to the standards specified by the American Society of Agricultural and Biological Engineers (ASABE, 2006).

$$D = F_i \cdot [A + B \cdot S + C \cdot S^2] \cdot W \cdot T \quad (1)$$

where:

D: Total draft force (N), *Fi*: Soil texture correction factor (sandy-loam: 0.66; loam: 0.85; clay: 1.0), *A, B, C*: Machine-specific table values (for cultivator A = 32, B = 1.9, C = 0), *S*: Forward speed of the tractor (km h^{-1}), *W*: Working width of the implement (m) or number of shanks/teeth, *T*: Tillage depth (cm).

For a tillage depth of 15 cm, considering a single cultivator shank and a forward speed of 6 km h^{-1} (Üçgül., 2019), the forces acting on each shank were determined to be 430 N, 550 N, and 650 N for sandy loam, loam, and clay soils, respectively. These values constitute the input draft forces experienced by the cultivator shank for different soil types and were applied as a resultant force to the cultivator shank surface. The model constraints were established by keeping the contact surfaces of the connection plates welded to the cultivator body fixed. The draft force, self-weight, and fixed surface constraints acting on the cultivator shank are illustrated schematically in Figure 4.

2.6. Verification of the Model's Mesh Structure, Loading, and Contact Definitions

The quality of the mesh employed in the analysis, as well as the accuracy of the contact definitions and loading conditions, was verified. The force convergence curve gradually decreased over the iterations, falling below the convergence criterion (Force Criterion) around the 8th iteration, at which point the solution became stable. This behaviour indicates that the finite element solution was performed numerically in a stable, reliable, and highly accurate manner.

2.7. Structural Analysis Using FEM

The Finite Element Method (FEM) was utilized to analyse all components constituting the cultivator shank. The structural analysis module of ANSYS Workbench software was employed for this purpose. In this study, loading scenarios representing different soil types (sandy-loam, loam, and clay) with forces of 430 N, 550 N, and 650 N were applied to the cultivator shank. Under constant tillage depth (15 cm) and forward speed (6 km h^{-1}), the stress distributions and displacement behaviour of the tip and connection elements were examined in detail.

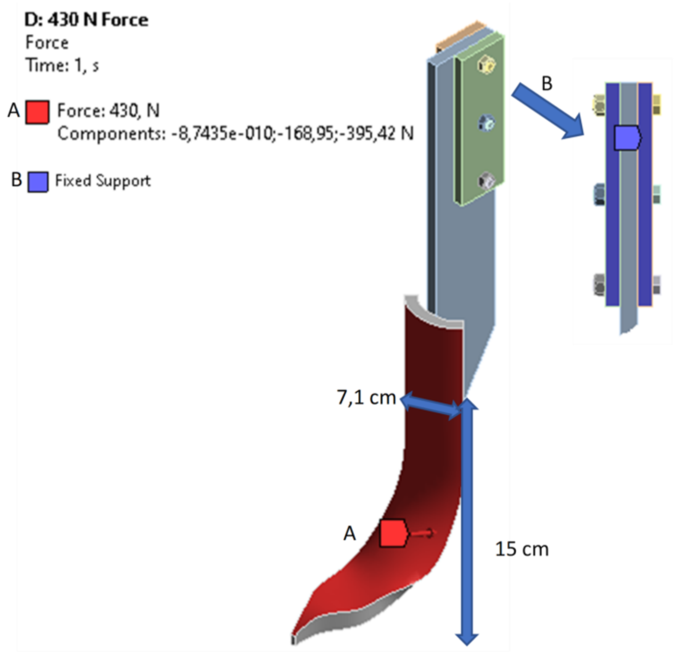

Figure 4. Definition of forces acting on the cultivator shank and the fixed surface.

3. Results and Discussion

3.1. Structural Analysis of the Cultivator Shank Under 430 N Loading

The structural analysis results of the cultivator shank under 430 N loading are presented in Figure 5. In the analysis of the cultivator shank under sandy soil conditions with a 430 N load, the total displacement at the lower region of the tip was determined to be 0.21 mm. The maximum equivalent stress in the tip was 12.35 MPa, concentrated at the area near the ground on the connection plate and at the welded joint region. In the evaluation of the assembly, the maximum equivalent stress on the bolts was determined to be 47.98 MPa, and the safety factor was found to be 13.34. Given that the bolts are composed of tempered steel with a grade of 8.8, the calculated values remain well below the material strength limits, thereby indicating that the fasteners operate safely. In a study conducted by Çelik et al. (2007), it was determined that the maximum stresses in a chisel occurred in the bolts used in the front-middle shank connection clamps. In this study, an analysis of the equivalent stress distributions reveals the occurrence of local plastic deformation tendencies in the regions where the spring steel connection plate comes into contact, particularly on the thread surfaces of the upper bolts. The design of the cultivator shank has been modified to ensure a more balanced distribution of equivalent stresses among the three bolts. In the previous design, the rigid narrow-tip cultivator shank was connected to the main chassis by a single bolt and pin; as a result of strength analyses performed under a 430 N load, the maximum equivalent stress in the fasteners was determined to be 108.7 MPa, and the safety factor was found to be 2.2 (Çomaklı and Sayıncı, 2022). After the implemented design improvement, it was determined that under the same 430 N loading condition, the maximum equivalent stress occurring in the fasteners decreased to 47.98 MPa, while the safety factor increased to 13.34.

This is in comparison to the previous design, which utilised a cultivator shank. It can thus be posited that the force transmission is shared among the three bolts, which in turn allows the fastening elements to operate both more safely and stably over a longer period.

3.2. Structural Analysis of the Cultivator Shank Under 550 N Loading

The structural analysis results of the cultivator shank under 550 N loading are presented in Figure 6. The total displacement in the cultivator shank was determined to be 0.26 mm at the lowermost region of the tip. The maximum equivalent stress in the tip was 15.68 MPa, occurring at the region of the welded joint. In the overall assessment of the assembled structure, the equivalent stress occurring in the bolts was found to be 60.99 MPa. The safety factor of the bolted connection was determined to be 10.49. The equivalent stress distributions obtained on the bolts produce visual patterns that are analogous to those from the 430 N load analysis; however, it was observed that the numerical stress values increased in comparison to the 430 N load case.

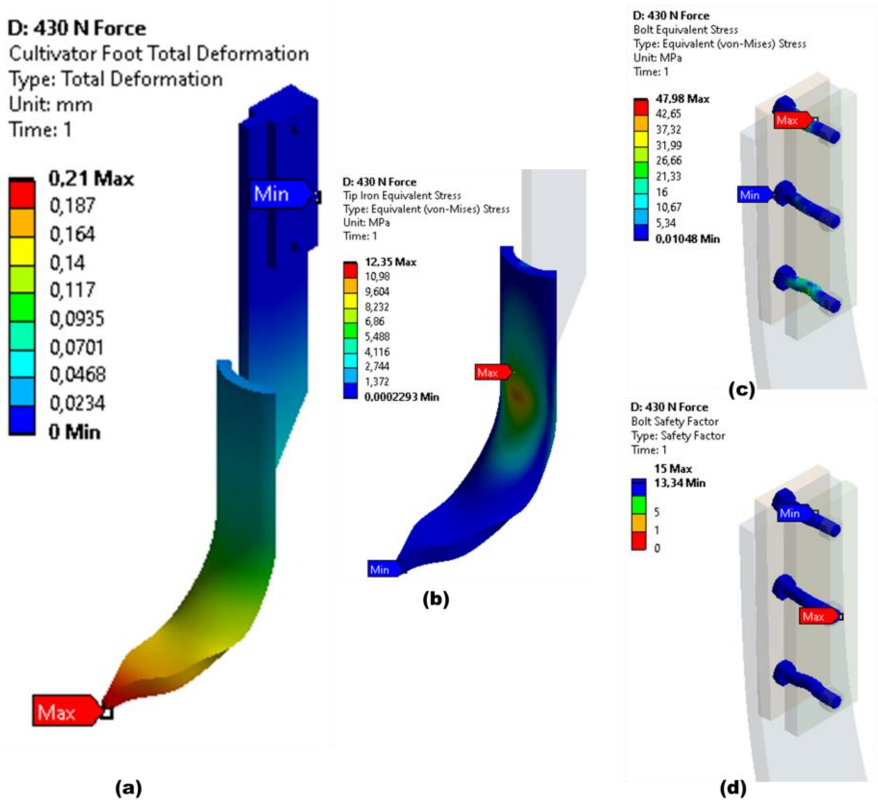

Figure 5. The application of load 430 N. (a) Total displacement, (b) Equivalent stress in the narrow-tip shank, (c) Equivalent stress in the bolt, (d) Safety factor of the bolt.

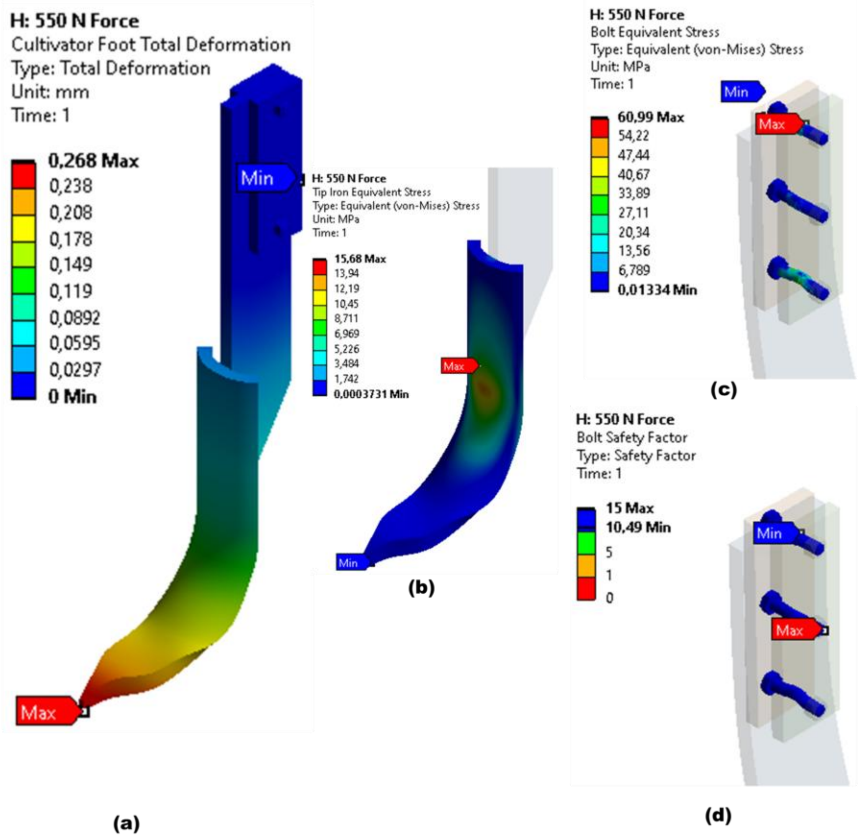

Figure 6. The application of load 550 N. (a) Total displacement, (b) Equivalent stress in the narrow-tip shank, (c) Equivalent stress in the bolt, (d) Safety factor of the bolt.

3.3. Structural Analysis of the Cultivator Shank Under 650 N Loading

The structural analysis results of the cultivator shank under 650 N loading are presented in Figure 7. The displacement in the cultivator shank was calculated as 0.31 mm in the same region, which is similar to the other applied loads. The maximum equivalent stress occurring in the narrow tip was 18.45 MPa and was concentrated at the welded joint. In the comprehensive evaluation of the assembled structure, the maximum equivalent stress experienced by the bolts was ascertained to be 71.81 MPa, and the safety factor of the joint was determined to be 8.91. Given that the bolts are composed of tempered steel, the calculated stress values remain below the material's strength limits, thereby indicating that the cultivator shank fasteners function with an approximate safety factor of 9. It was determined that the design enhancements implemented on the cultivator shank ensure adequate strength, even in conditions characterized by substantial clay soil compaction. Based on the equivalent (von-Mises) stress distributions observed on the bolts, it was noted that there was a notable increase in the propensity for local plastic deformation on the thread surfaces of the bolts that were in contact with the connection plate. In conditions of clay soil, the cultivator shank approaches its yield limit in comparison to other soil types. Cracking or failure of the fasteners may occur even during shorter operating periods. Similar studies have emphasized that as the magnitude of the force applied to the surface of cultivator shanks increases, both total displacement and equivalent stresses also increase (Çelik et al., 2007; Şahin et al., 2018). The mechanical properties of the soil exert a decisive influence on the stress and displacement behaviour of the cultivator shank. The analysis results indicate that, in sandy soil conditions characterized by low cohesion, the stress and deformation values remained at limited levels. Conversely, in loam and clay soils, the increased soil compaction and cohesion led to a gradual rise in these values. In a similar vein, Dipankar Mandal (2017) highlighted in his study that an increase in soil compaction and cohesion led to a gradual rise in both displacement and equivalent stresses. This, in turn, resulted in elevated structural loads on the cultivator foot. The analysis results, obtained under a range of loading conditions and taking into account design improvements and material selection, indicate that the equivalent stress values remain below the bolt strength limits. Consequently, the risk of shear failure in the fasteners under the operating loads of the cultivator foot is deemed to be negligible.

As demonstrated in Figure 8, the displacement values resulting from the application of different loads on various soil types are presented. In accordance with this data, it can be concluded that the displacement of the cultivator shank tip increases in proportion to the magnitude of the applied forces.

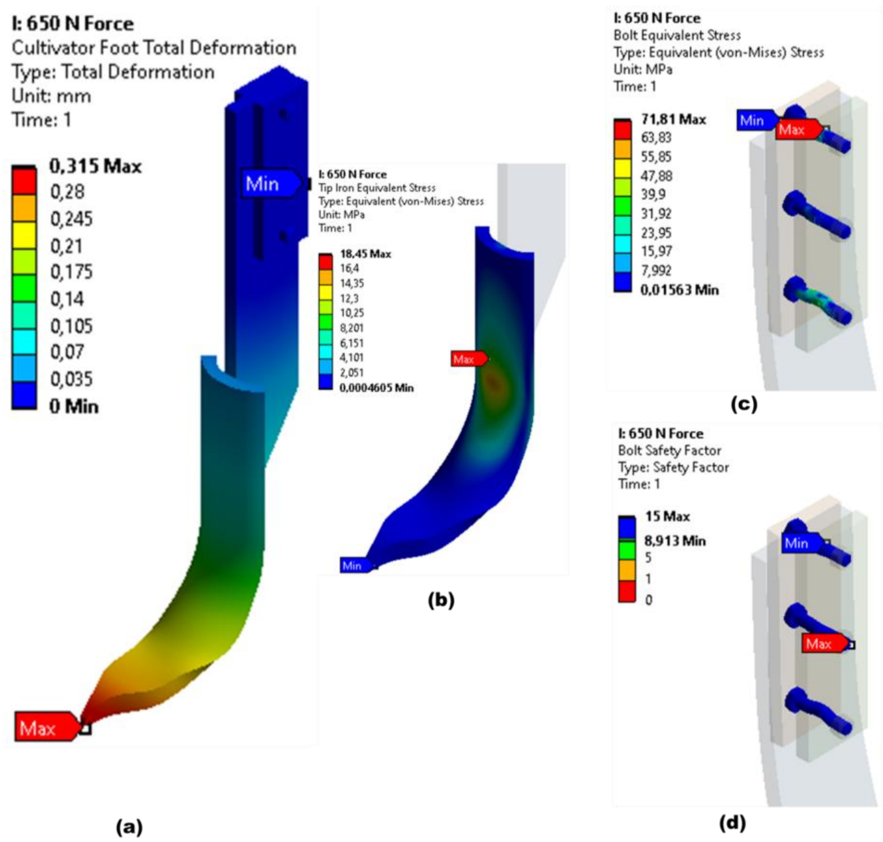

Figure 7. The application of load 650 N. (a) Total displacement, (b) Equivalent stress in the narrow-tip shank, (c) Equivalent stress in the bolt, (d) Safety factor of the bolt.

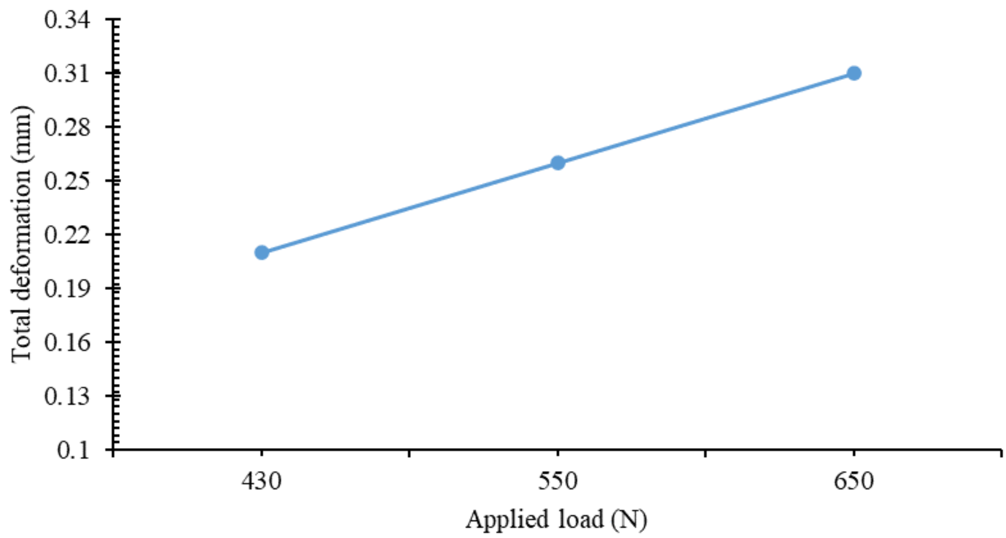

Figure 8. Displacement in the tip of the cultivator shank (mm) according to the magnitude of the applied force (N).

The linear relationship between force and displacement is expressed by Equation (2), with the regression coefficient between the two variables determined as R^2 = 99.95. As stated by Şahin et al. (2018), the total displacement and equivalent stress strength characteristics of cultivator tips produced by four different manufacturers under six different loads were determined. The coefficient of determination between the applied force and deformation was reported to range from R^2 = 99.97 to 99.99. Following the implementation of design improvements and material selection optimization on the cultivator shank, it was determined that the total displacement of the shank exhibits a linear relationship with the applied load.

$$D_f = 0.0005F + 0.0139 \quad (2)$$

where; Df = displacement (mm) and F= applied load (N).

4. Conclusion

In this study, the rigid narrow-tip cultivator shank used in conservation and secondary tillage applications was structurally redesigned; the material selection of the fasteners was optimized, and the strength behavior of the design was examined in detail using the finite element method. As a result of the different loads of 430 N, 550 N, and 650 N applied to the cultivator shank, the maximum equivalent stresses were determined as 12.35, 15.68, and 18.45 MPa for the tip, and 47.98, 60.99, and 71.81 MPa for the fasteners, respectively. Considering the material properties of the cultivator tip, it was determined that the stresses generated under the applied loads remained well below the yield limit, and the component exhibited sufficient strength within safe operating conditions. Thanks to the implemented design improvements and the use of high-strength class fasteners, the safety factor of the structure increased by six times under the same loading conditions compared to the previous design, and it was determined that the fasteners operate well above the reliable safety limits. According to the analysis results, the total displacement of the cultivator shank was determined as 0.21, 0.26, and 0.31 mm for the three scenarios, respectively, with the maximum displacement occurring in the lower regions of the tip. For field operating conditions of the cultivator, it is recommended to perform fatigue analyses against the repetitive loads occurring during operation. Considering the adaptable structure of the cultivator to different operating conditions, it is recommended that manufacturers take farmers needs into account during the design process and utilize the strength analysis results obtained through the finite element method (FEM) in design and production optimization. This approach is expected to provide positive contributions both to manufacturers in terms of product durability and material efficiency, and to agricultural producers in terms of improved operational reliability and performance.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	M.Ç.	B.S.
C	50	50
D	70	30
S	30	70
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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