Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Structural analysis of cotton stalk Puller and Shredder Machine

Alamgir Akhtar Khan a, Umair Sultan a,* , Ramesh P. Rudra b, Farrukh Ehsan a, Muhammad Kashif a, Muhammad Mohsin Khan a, Sarfraz Hashim a, Muhammad Zohaib a, Syed Imran Ahmad b,c

a Department of Agricultural Engineering, MNS University of Agriculture Multan, Pakistan
b School of Engineering, University of Guelph, Canada
c NED University of Engineering and Technology, Karachi, Pakistan

Received 2 January 2022; revised 4 June 2022; accepted 2 September 2022
Available online 13 September 2022

KEYWORDS
Energy conservation; Food security; Agricultural Mechanization; Finite Element Analysis; Structural analysis

Abstract World scenario after pandemic COVID-19 has been drastically changing and researchers more focusing on, to minimize the post-pandemic effects on economy, energy sustainability and food security. Agriculture sector is playing pivotal role in world food security and energy sustainability. There is high need to optimize the mechanization technologies to increase the yield in limited energy inputs and operation time to fulfill the world growing food demand. This research is mainly focused on the design development and structural analysis aiding with Finite Element Analysis (FEA) approach for Cotton Stalk Puller and Shredder machine (CSPS) to cut the crop leftovers, soil conditioning (shredding the plant waste into soil) and sowing of next crop in single run by conserving input resources. The experimental trials revealed that there is high pressure on cutting blades, chocking of shredder section and excessive pulling load on tractor hitches, which affected the machine’s performance. To mitigate deficiencies and design optimization to improve the machine safety/reliability, the structure analysis carried out. Six core components of machine including baseplate, blade, gear system, root digger, pulley and shaft has investigated as per field conditions. The results revealed that the material of blade, root digger and teeth of gear system receiving the high stress under the operational conditions which results the edge wear and damage. The carbonization up to one-millimeter thickness can provide the extra strength to bear the excessive load on edge layers.

© 2022 THE AUTHORS. Published by Elsevier BV on behalf of Faculty of Engineering, Alexandria University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Agriculture is the backbone of any country and food availability relies on the quality and consistent advancements in this sector. Researchers are working on modernization in Agricul-
ture to increase the yield in limited resources. As population, increasing the cultivable land is being reduced. To mitigate this concern, crop cultivation and harvesting operations need to be optimized with minimum available resources. In conventional approach, the farmer harvests the cotton sticks for domestic fuel or tries to shred into the soil with the help of rotavator. These processes are time-consuming and there is very little time available to meet the best sowing time of wheat crop in the area. A series of work on energy efficiency and role of mechanization in crop production has been reported [1,2]. Moreover, the leftover crop shredding size is not enough to decompose in soil for next crop use. Keeping in view the all-conventional practices, a next version mechanized solution was necessary.

Current study is based on the unique mechanized solution to conserve time, organic matter, and seed (high germination due to timely sowing of wheat). This machine is Cotton Stalk Puller and Shredder (CSPS) that is specially designed for cotton and wheat crop (Fig. 1). After completing the cotton picking, the leftover cotton plants need to be cleaned to cultivate the next crop (wheat) as earliest. This machine designed with integrated and need-based technology to cut, shred, and mix the leftover plants into the soil and the seeding section drill the next crop seed. All processes complete in one pass of the machine. The leftover plant mixing in soil increased the organic matter of the soil, aeration, and soil structure.

The CSPS needed to be investigated to increase its reliability, safety, and scope in advanced farming. A number of scientists have reported the fatigue, stress, and strain studies to investigate the morphology of the failure by using advanced computational tools [2,3]. The shear stress response of soil to the machine blades, the load application, and power requirements are directly interrelated [4].

The experimental trials revealed some key issues, which are need to be optimized before commercializing phase of CSPS. This study is mainly focused on design structure analysis to find breakage of primary cutting blades and allied core components as it directly affect the tillage operation [4], choking of shredder section and excessive pulling load on tractor hitches.

2. Research methodology

Pilot design of the machine was completed at MNS University of Agriculture Multan as shown in Fig. 1. The experimental trials of the machine were carried out at research farm of MNS University of Agriculture, Multan, Pakistan (30°07′31.1″ N, 71°26′16.2″ E). The machine analysis was com-

| Assembly Unit     | Parameters               | Value  |
|-------------------|--------------------------|--------|
| Cutting Assembly  | No. of Blades            | 2      |
|                   | Length of each blade (mm)| 914    |
|                   | Blade width (mm)         | 102    |
|                   | Distance between blades (mm) | 1245 |
|                   | Angle                    | 30°    |
| Pulling Assembly  | Number of Chains         | 8      |
|                   | Number of Sprockets      | 16     |
|                   | Diameter of Sprocket (mm)| 127   |
|                   | Clearance b/w chains (mm)| 2.54  |
| Shredding Assembly| No. of Cylinders         | 3      |
|                   | Length of Cylinder (mm)  | 1524   |
|                   | Dia. of Cylinder (mm)    | 76–114 |
|                   | Clearance between Cylinders (mm) | 76 |
|                   | No. of knives on each cylinder | 40–90 |
|                   | Distance b/w knives (mm) | 76–104 |
pleted in two phases. In first phase the lab and field testing of the machine was completed and needful modifications were carried out. In 2nd phase the structural analysis (FEA) was carried out to study, the possible design failure and optimization need in the machine.

3. Machine specifications

A tractor operated cotton stalk puller shredder for removing cotton stalk from field and timely sowing of wheat in the cotton field was designed and developed by MNSUAM, Multan. The machine consists of three sub-assemblies i.e., cutting assembly, pulling assembly and shredding assembly. The overall dimensions of the machine were 2133.6 x 3048 mm. The height of the frame is 686 mm from ground. The specifications of each assembly are described in Table 1.

In 1st phase, CSPS machine was tested in AMRI on lab scale to measure the difference parameters. These parameters were tested by using different equipment i.e. torque meter (used to measure torque, rpm and power) and tachometer.

| Machine components | Description/problem | Solutions/improvement of design |
|--------------------|---------------------|---------------------------------|
| 1. Number of shredding drums | Two shredding drums were initially designed and fabricated to shred the cotton stalk pulled by the machine. Following observations were recorded: i. Incomplete shredding of stalk of cotton plant ii. Clogging of shredding unit iii. Overloading of machine operational system | Third shredding drum was added and special care was considered upon arrangement of shredding blades. Result: i. Blades arrangement worked safely without hitting blades of the previous two drums ii. Shredding of pulled stalk of cotton improved |
| 2. Flywheel | During operation in field, it was observed that machine need supplement of power to run smoothly. | Flywheel was attached with rotary component of the machine and inertia stored in flywheel helped operate the CSPS smoothly. |
| 3. Drive belts | Initially power transmission in the machine components were made by belts. Two major problems were faced with belts. 1. Belts slippage 2. Belts breakage | Belts power transmission mechanism was replaced by driving chains and sprockets |
| 4. Chain size | Belts were replaced by chains with size of 60 No. But when field tests were made with this chain, it breaks several times due to low bearing capacity. | 60 No. chains were replaced by 80 No. chains. This arrangement overcome the problem linked with power transmission. |
| 5. Grid size of concave in the outer cage of shredding system | Initial design of concave was having large openings. Large opening allowed un-shredded cotton bolls to escape. In addition to it, large sized opening allowed long un-shredded cotton sticks to come out from the machine. | Grid size was reduced to almost half of previous design. Improvement in design overcome the reported issue. |
| 6. Location of tires behind the CSPS | Two tires were installed in rear side of the machine. These two tires were initially installed to operate on the beds. This arrangement created difficulty during the phase of machine turning | Tires were moved on rear ends of the machine. Later it was decided to move tires under the main frame so that wheel drill could be attached successfully |
| 7. Installation of wheat drill | Initially runner type furrow opening option was adapted for wheat drill attached with the CSPS. Runner type collected shredded material during operation in the field | Runner type wheat drill was replaced with Coulter drill. Coulter drill successfully operated in the field. Coulter either cut the shredded material and sow see or it rolled over the stick if any and it did not cause any difficulty during the phase of operation in the field. |
| 8. Drive wheel of seed drill | Firstly, drive wheel for seed drill was installed at one side of drill. This cause the problem of not rotating all seed devices equally. During uplifting and lowering the machine, universal joint (PTO operated) got intersect with machine hitch point. This may cause breakage of whole Power take off shaft mechanism. | Drive wheel installed at center of the seed drill to equally rotate all seed devices. Moreover it operated without difficulty on the beds. |
| 9. Hitch Point of machine | Upper part of hitch point was cut off with help of Arc welding. It created gape between universal cross shaft and the hitch. | |

Table 3  Detail of instruments.

| Device | Specification | Picture |
|--------|---------------|---------|
| Digital Torque Meter (100 HP) | Serial#151668 Peak Measuring Range: 100000 N Accuracy: within ± 0.1% F.S. | Digital Torque Meter (100 HP) Picture |
| Draft Dynamometer | Dillon E DXtreme Load Range: 25,000 lbf /10000 kgf Accuracy: within ± 0.1% F.S. | Draft Dynamometer Picture |

Structural analysis of cotton stalk Puller and Shredder Machine 337
(used to count RPM) purchased under the project TDF-053. Performance evaluation of the cotton stalk puller shredder includes different parameters are listed below.

i. Engine RPM
ii. Power takeoff (PTO) RPM
iii. RPM of CSPS flywheel
iv. Torque (N-m)
v. Power (W) or Horse Power (HP).
vi. Hardness of critical components.

Some challenges were faced in the mechanical transmission system of the machine. Initial power transmission system comprised belts and pulleys and this system did not support to transfer of power from PTO to rotary parts. Belt and pulleys system was shifted to chains and sprockets. This system performed better than belt and pulleys while slippage of sprocket teeth and breakage of chain during operation was also noticed. Machine was tested (Table 3) in the field and multiple modifications were made to improve the design of MIM. Table 2 describes summary of the challenges and improvements made in the design of the machine.

The following devices were used to collect the experimental data for structural analysis (Table 2):

Fig. 3 provides pictorial presentation of the modifications made to improve design of the CSPS. First row of photographs displays comparison of belts (initial version) with chain sprockets and flywheel (improved version). Second row displays reduction in grid bars spacing to control infested small sized cotton bolls in shredding area. Third, fourth and fifth rows display continuity in improvement of machine by moving tyres from center to sides and attaching runner type furrow opener and coulter type furrow opener with wheat drilling systems.

In 2nd phase for further optimization in design of the machine FEA Structural was carried out by commercially available tool (ANSYS). The selection of boundary conditions and results comparison were performed based on already reported data [5] by the authors with application on cotton leftovers by the CSPS. Structure reliability is always a major concern for any machinery, and it can be identified with FEA approach [6]. As the whole model is very intensive for FEA therefore the core parts (based on field experiments) were selected in 3D structure analysis under field load/conditions (Fig. 2). The parts including baseplate, blade, gear system, root digger, pulley and shaft were taken under investigation for initial design optimization. Grid analysis was carried out of all these parts to achieve the significant results in context of machine reliability.

4. Results and discussion

4.1. Field analysis

Tractor MF 385 was used in the Field test. Torque meter was attached with tractor system through PTO shaft. Torque was recorded in N-m at corresponding engine rpm and tractor PTO rpm. Table 4 shows summary of field test obtained.

A normal trend of speed and torque was observed without any load on tractor. Consequently, horsepower needed to operate the system displayed increasing trend against increasing speed of engine to a certain level of speed test. Power is a function of both speed and torque. According to Engine Standard Performance Curve, when rpm of PTO increases, torque also increases up to a certain level but continuous increase in rpm decreases torque [7,8]. Perhaps in our case, rotary speed remained in first phase of the curve as reported the certain level. However, investigation team gives due regard to the comment, a detailed study can be conducted during the next phase of machine testing in the field. The detail of first design and the field performance analysis were already reported by the authors in first phase of research [9].

Table 5 displays circular speed of flywheel corresponding to engine rpm. Circular speed of flywheel was 585 rpm at engine speed of 1200 rpm and it rose to 950 rpm at engine speed of 2000 rpm. Means arrangement of sprocket size and chain made to determine this speed.

![Fig. 2 3D model of the CSPS machine with all core parts.](image-url)
Belts and pulleys for the transmission of power

Chain, Gears and Fly Wheel for the transmission of Power

Wide spacing in grid bar allowing cotton bolls to pass.

Narrowed spacing in grid bars helped retain small sized cotton bolls in the shredding area

1st version of CSPS with inner side location of Tyres

Latest version of CSPS with outer side location of Tyres

Runner type furrow opening system in wheat sowing Seed Drill. Seed drill drive wheals on the two end to operate in the furrows

Coulter type seed drill with central location of drive wheat to run over beds

Universal joint shaft hitting the upper edge of hitch of CSPS

Upper edge was cropped and hitting action was fixed

Fig. 3 Pictorial presentation of modifications made to improve design of the MIM.
Table 4  Summary of torque corresponding to engine and PTO RPM and estimated HP.

| Working Condition | Gear Level | Engine RPM | PTO RPM | Avg. value of Torque (N-m) | Horse Power* |
|-------------------|------------|------------|---------|---------------------------|-------------|
| Without Load      | Neutral    | 1200       | 360     | 50.6                      | 11.56       |
|                   |            | 1400       | 405     | 48.8                      | 13.00       |
|                   |            | 1600       | 475     | 55.6                      | 16.93       |
|                   |            | 1800       | 525     | 53.4                      | 18.30       |
|                   |            | 2000       | 582     | 58.6                      | 22.31       |

Table 5  Speed of flywheel corresponding to engine RPM.

| Serial No. | Working Condition | Gear Level | Engine RPM | RPM of CSPS Fly Wheel |
|------------|-------------------|------------|------------|------------------------|
| 1          | Without Load      | Neutral    | 1200       | 585                    |
|            |                   |            | 1400       | 670                    |
|            |                   |            | 1600       | 780                    |
|            |                   |            | 1800       | 865                    |
|            |                   |            | 2000       | 950                    |

Fig. 4  Glimpses of machine testing.
Fig. 4 shows glimpses of laboratory test of the machine. Photographs include testing of system for torque, speed of flywheel, coupling of torque meter with tractor PTO shaft and it included display screen of torque meter.

4.2. Structural analysis (FEA)

4.2.1. Base Plate:
Stress Analysis of Baseplate was performed (Fig. 5) with the load magnitude of 10,116 N in the direction as shown. Force is applied in term of Pressure. Deformation results reveals the deformation of 0.005 mm at the center of baseplate as shown. Stress coming onto the Baseplate is shown as Von Mises Stress having the Magnitude of 1.09 MPa in the form of Stress Concentration. Elastic Strain value for Baseplate is 5.456e-6 mm/mm. All these values are well within Elastic limits. As the Stress Values are within Elastic limits therefore no yield point occurred in the material. Yield point would have occurred if and only if there have any Plastic deformation in materials. Failure would have occurred if material would have gone into the Plastic Region. As Stress Values are within Safety limits, therefore Baseplate component is completely safe under the given load conditions.

4.2.2. Blade:
Stress Analysis of Blade was performed (Fig. 6) with the load magnitude of 10,116 N in the direction as shown. Deformation results reveals the deformation of 0.0087 mm at the edge of
blade. Stress coming onto the Blade is shown as Von Mises Stress having the Magnitude of 7.158 MPa in the form of Stress Concentration. Elastic Strain value for Blade is 3.57 e-5 mm/mm. All these values are well within Elastic limits. As the stress Values are within Elastic limits therefore no yield point occurred in the material. Yield point would have occurred if and only if there have any Plastic deformation in materials. Failure would have occurred if material would have gone into the Plastic Region. As Stress Values are within Safety limits, therefore Blade component is completely safe under the given load conditions. Blade Edges are the Critical Components therefore recommendation is to carburize the blade edges with maximum thickness of 1 mm.

4.2.3. Gear System:
Stress Analysis of Gear was performed (Fig. 7) with the load magnitude of 38,500 N-mm in the form of torque in the direction as shown. Deformation results reveals the deformation of 2.6 e-6 mm at the end of Gear Teeth. Elastic Strain value for Gear is 5.49 e-9 mm/mm. Stress coming onto the Gear is shown as Von Mises Stress having the Magnitude of 0.00100995 MPa in the form of Stress Concentration. All these values are well within Elastic limits. As the stress Values are within Elastic limits therefore no yield point occurred in the material. Yield point would have occurred if and only if there have any Plastic deformation in the material. Failure would have occurred if the material would have gone into the Plastic...
Region. As Stress Values are within Safety limits, therefore Gear component is completely safe under the given load conditions. Critical Component of Gear is its Teeth Edges, therefore it is recommended to carburize the Edges of the teeth with 1 mm Thickness. Critical component of Gear is its Teeth Edges, therefore it is recommended to carburize the Edges of the teeth with 1 mm Thickness.

4.2.4. Root Digger:
Stress Analysis of Root Digger was performed (Fig. 8) with the load magnitude of 10,116 N in the direction as shown. Deformation results reveals the deformation of 0.034 mm at the end of Root Digger. Stress coming onto the Gear is shown as Von Mises Stress having the Magnitude of 1.46 MPa in the form of Stress Concentration. Elastic Strain value for Root Digger is 3.57 e-5 mm/mm. All these values are well within Elastic limits. As the Stress Values are within Elastic limits therefore no yield point occurred in the material. Yield point would have occurred if and only if there have any Plastic deformation in materials. Failure would have occurred if material would have gone into the Plastic Region. As Stress Values are within Safety limits, therefore Root Digger component is completely safe under the given load Conditions. Edges of Root Digger are the critical component. Recommendation is to carburize the edges of root digger with maximum thickness of 1 mm.
4.2.5. Pulley:
Stress Analysis of Pulley was performed (Fig. 9) with the load magnitude of 38,500 N-mm in the form of torque in the direction as shown. Deformation results reveals the deformation value of 1.75e-6 mm at the Pulley Edge. Stress coming onto the Pulley is shown as Von Mises Stress having the Magnitude of 0.00013372 MPa in the form of Stress Concentration. Elastic Strain value for pulley is 1.215 e-6 mm/mm. All these values are well within Elastic limits. As the stress Values are within Elastic limits therefore no yield point occurred in the material. Yield Point would have occurred if and only if there have any Plastic Deformation in materials. Failure would have occurred if material would have gone into the Plastic Region. As Stress Values are within Safety Limits, therefore Pulley is completely safe under the given load conditions.

4.2.6. Shaft Drum:
Stress Analysis of Shaft Drum was performed (Fig. 10) with the load magnitude of 38,500 N-mm in the form of torque in the direction as shown. Deformation results reveals the deformation value of 7.24e6 mm at Drum outer Circumference. Stress coming onto the Shaft Drum is shown as Von Mises Stress having the Magnitude of 0.00033759 MPa in the form of Stress Concentration. Elastic Strain Value for Shaft Drum is 2.56e-9 mm/mm. All these values are well within Elastic limits. As the Stress Values are within Elastic Limits therefore no yield point occurred in the material. Yield point would have occurred if and only if there have any Plastic deformation in materials. Failure would have occurred if material would have gone into the Plastic Region. As Stress Values are within Safety limits, therefore Shaft Drum is completely safe under the given load conditions.

Fig. 8  Root Digger structural analysis.
Fig. 9  Pulley structural analysis.
5. Conclusion

The CSPS is the need based indigenized technology development for better crop production in limited resources. This study was taken to strengthen the model design and analyze the scope of further development. Due to integrated units/functions the machine over all weight was higher. It needs more HP and high pulling force at core parts of the machine. This study specially focused to study the pulling force/load analysis for field operations. The FEA revealed the structural reliability of core component and fatigue analysis as following:

- The machine’s blade, root digger and gear teethe are under intensive edge load conditions so it is recommended that the edge of these parts should be carbonize upto 1 mm to increase the effectiveness and reliability under the exerted load.
- The machine’s base plate, pulley and shaft drum is completely safe under applied load conditions.

In further study, the 3D dynamic analysis of the operation of the machine will be studied for possible minimization the overall dead weight of the machine.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge the support for project funding by Higher Education Commission (HEC-TDF 053) and technical support by TUSDEC-NIDA, AMRI Multan and Agri. Tech.

References

[1] A. Abbas, M. Waseem, M. Yang, An ensemble approach for assessment of energy efficiency of agriculture system in Pakistan, Energy Efficiency 13 (4) (2020) 683–696.
[2] B.o. Ning, H. Liu, J. Cui, Y. Xia, L. Lin, S. Zhao, J. Fu, Failure analysis of center cutter mount in shield machine under tuff layer, Engineering Failure Analysis 117 (2020) 104940, https://doi.org/10.1016/j.engfailanal.2020.104940.
[3] W.-H. Feng, J. Fang, Failure analysis of extractor slipping in the cartridge case extraction process under different working
conditions, Eng. Fail. Anal. 130 (2021) 105749, https://doi.org/10.1016/j.engfailanal.2021.105749.

[4] L. Zhu, J.-R. Ge, X.i. Cheng, S.-S. Peng, Y.-Y. Qi, S.-W. Zhang, D.-Q. Zhu, Modeling of share/soil interaction of a horizontally reversible plow using computational fluid dynamics, J. Terramechanics 72 (2017) 1–8, https://doi.org/10.1016/j.terra.2017.02.004.

[5] L. Zhu, X.i. Cheng, S.-S. Peng, Y.-Y. Qi, W.-F. Zhang, R. Jiang, C.-L. Yin, Three dimensional computational fluid dynamic interaction between soil and plowbreast of horizontally reversal plow, Comput. Electron. Agric. 123 (2016) 1–9, https://doi.org/10.1016/j.compag.2016.01.034.

[6] F. Luo, L. Zhu, M. Wei, J.-W. Zhang, D.-Q. Zhu, T.-C. Jen, Tillage Condition Effects on Soil/Plow-breast Flow Interaction of a Horizontally Reversible Plow, Procedia Manuf. 35 (2019) 980–985, https://doi.org/10.1016/j.promfg.2019.06.045.

[7] Z. Wu, D. Lei, G. Yuan, J. Shao, Y. Zhang, Z. Wang, Structural reliability analysis of parabolic trough receivers, Appl. Energy 123 (2014) 232–241, https://doi.org/10.1016/j.apenergy.2014.02.068.

[8] Y. Wang, L. Wang, J. Zong, D. Lv, and S. Wang, “Research on Loading Method of Tractor PTO Based on Dynamic Load Spectrum,” Agriculture, vol. 11, no. 10, 2021, doi: 10.3390/agriculture11100982.

[9] F. Ahmad, M.T. Jamil, A. Akhtar Khan, Z. Mehmood-Khan, B. Qiu, J. Ma, F.A. Chandio, Field performance evaluation and finite element simulation of cotton stalk puller-shredder: A sustainable mechanical solution to control pink bollworm (pectinophora gossypiella), Sustainability (Switzerland) 12 (8) (2020) 3407, https://doi.org/10.3390/su12083407.