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Original Article

Analysis of Variant Stresses Acting on Modified Animal Drawn Mouldboard Plough Share using Finite Element Method

Isaac Azegura Nyaaba[1], Alex Kojo Okyere[2], Sherry Kwabla Amedorme[3]

[1,3]*Department of Mechanical and Automotive Engineering Technology, AAMUSTED, Kumasi, Ghana.*
[2]*Department of Vocational and Technical Education, Ada College of Education, Ada-foah. Greater-Accra, Ghana.*

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Abstract *- Agriculture nowadays is a man with modern, sophisticated equipment. However, due to the high cost of maintenance coupled with past failures of tractor mechanization schemes, farmers need reliable and low-cost agricultural tools that may be hand or bullock driven for small-scale farming. This paper seeks to re-design an improved animal-drawn plough to complement tractor services. Autodesk Inventor is used for the design and structural finite element analysis (FEA) performed on the models using ANSYS Mechanical. Low alloy steel, American Iron Steel Institute (AISI 4140), is used for the new model and compared with the existing cast iron designs. The analytical comparison of the two models shows that the low alloy steel (AISI 4140) made share exhibits favorable results. The percentage difference of total deformations is 40.8% and 40.64%, and the equivalent elastic strain of 41.24% and 41.46%, respectively, in favour of the low alloy steel (AISI 4140) made share. The implication is that the cast iron models will deform and reach the yield point faster than the low alloy steel models. The results of this study predict that the low alloy steel (AISI 4140) can be a suitable material for making farm implements such as mouldboard ploughs because the factor of safety of the low alloy steel (AISI 4140) made share is 1.4. The results of the developed model can be useful for the design and subsequent fabrication of new tillage tools adaptable to different soil types in terms of application.*

Keywords *- Light Mouldboard Plough, Design, Finite Element Analysis, Von Mises, Stress and Strain, Deformation*.

1. Introduction

The animal mouldboard plough plays a very important role in land preparation which should be light in weight for easy to be drawn by the animals. However, complaints by smallholder farmers in Zimbabwe revealed that ploughs are heavy and difficult to use [1]. Meanwhile, of the 570 million farms worldwide, most are small-scale (less than 2 ha), with family farms accounting for approximately 75% of global agricultural land management [2]. Modern machine design employs very sophisticated design and simulation software capable of aiding engineers to optimise any design structure for weight reduction before fabrication. Adequate knowledge of the mechanism and working principle of machines and forces are paramount to the engineer. Engineering design is the technique of inventing a system or component to meet desired needs. It is a decision-making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to optimally convert resources to meet a stated objective [3]. Professional designers use intellectual instincts and well-established and proven scientific knowledge in designing to ensure the product satisfies an agreed market need and product design specification whilst permitting manufacture by the optimum method. Over the years, the technologies employed in farming have shifted instantaneously from monochromatic traditional farming practices to modern mechanized farming practices [4].

The history of animal traction in eastern and southern Africa, except for Ethiopia, began with the use of ox-plough by the missionaries. In Ethiopia, animal power has been used for thousands of years [5,6]. Using a mouldboard plough as a farm tool is labour intensive, time taking, making the shallow depth and narrow cutting width [7]. However, most farmers own more than one field, and the distance between plots is often several hundred meters or even several kilometers, which makes machine operators travel a long distance but work only a few acres, which increases the operating cost of machinery and results in low economic efficiency [8]. The cost of maintenance, design, construction, and operation of the mouldboard plough is less expensive than that of the tractor since the land size keeps reducing due to its high demand for infrastructural and industrial purposes [9]. It is also less difficult to operate. However, operators often face problems with the frequent breakdown of their ploughs. It is usually due to rocky grounds, stumps, roots, and embedded stones. Therefore, frantic efforts are being sought to ensure that plough breakdown is minimized drastically [10]. In order to do this, the design principles of machines must be considered. These include but are not limited to mechanical behaviour such as statics, dynamics, vibration, reliability and fatigue, as well as the type and strength of the material used to manufacture the equipment.

Currently, manufacturing is moving towards more advanced, flexible, and environmentally friendly, demanding intelligent computer-aided production and planning (CAPP) systems [11]. Hamou et al. [27] developed a computer-aided production and planning simulation module to optimise manufacturing tolerances, overcome stochastic aspects and complexity and compute manufacturing dimensions. The availability of software such as this and many others can be effectively and efficiently used to design and simulate a well-modified mouldboard plough capable of meeting modern standards and application conditions.

Though the tractor provides an efficient, convenient, and faster means of tilling the land, it is very expensive for the average farmer. Owing to escalating global fuel costs and the past failures of tractor mechanization schemes in many developing countries, there are converted interest in research and extension activities on the well-organized use of animal traction, especially for ploughing and carting [13].

Bullocks still gain popularity in agricultural operations in some countries around the world. The considerable demand for animal ploughing services in Eastern and Southern Africa and the Northern part of Ghana is enormous. However, the frequent breakdown of the plough during farming is a blow to the owners. This phenomenon results from embedded stones, rocks, roots, and stumps which need to be tackled with the requisite engineering finesse. The agricultural tools production industry emerged in Britain and the United States in the 19th Century. Until then, the common tools for farming were the plough and the sickle. However, draught animals remain a major power source utilised by many small farm-holding farmers. The frequent breakdown of the plough during ploughing, with particular mention of the mouldboard and share, is a worrying phenomenon [14].

This research seeks to determine; the best way to overcome the extent to which the reaction forces that tend to damage the plough can be reduced using modern design mechanisms and materials with high-quality and durable properties. The plough's weight will be reduced to leverage the bearing on the animals and the operators. The study will provide expert knowledge to manufacturers to guide them in selecting the best material for plough fabrication. In the basic mouldboard plough, the penetration of the soil profile is determined by lifting the wheel against the runner in the furrow, limiting the weight of the plough to what the ploughman could easily lift. These ploughs were often frail and unsuitable for Northern Europe's hardened farmlands.

The addition of wheels to replace the runner allowed the weight of the plough to increase, which in turn necessitated the use of a larger mouldboard made of metal. These heavy ploughs led to increased food production and eventually a pronounced population increase, beginning around Anno Domini (AD) 1000 [15]. By the period the Chinese were distinguished from the non-Chinese, the entire plough share was made of cast iron.

These are the earliest known heavy mouldboard iron ploughs. A major advance for this type of farming was the turn plough, also known as the mouldboard plough United Kingdom (UK), moldboard plough United States (US), or frame plough. The mouldboard plough introduced in the 18th Century was a major technological advance [16].

Fig. 1 Scots wooden plough

Fig. 2 James' small plough

In 1791, James Small advanced the design using mathematical methods and eventually came out with a shape cast from a single piece of iron (Figure 2). It improved the Scot's plough (Figure 1) of James Anderson of Hermiston [17]. A single-piece cast-iron plough was also designed and patented by Charles Newbold in the United States in 1797. The development was further improved by Jethro Wood, a blacksmith of Scipio, who made a three-part Scots plough such that a broken piece could be replaced.

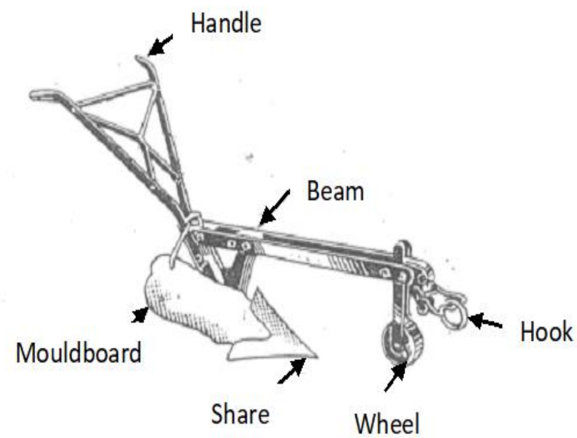


Fig. 3 Traditional mouldboard plough

The plough in Fig. 3 is wholly made of cast iron and is considered very heavy and has a narrow mouldboard and V-shape share, which is not capable of turning furrow at 180º and completely covers weeds. It has metal handles which are not friendly to use when the sun is scorching hence the focus of this research.

Nowadays, in any agricultural crop production system, humans, draught animals, and engines or motors provide the motive power in various proportions for crop production, harvesting, transport and processing [18, 19]. Although it will continue to be contributions from tractor power to land preparation, much of the region will continue to be cultivated using hand and animal power [18]. Animal-drawn mouldboard plough is widely applied for farming in developing countries in Africa. In Ghana, notably, the Northern regions greatly rely on this means for tilling the farms. Even those who do not own that source of animal power still prefer the service because of its low cost, among other factors. It is largely due to the availability of oxen, cattle, donkeys and horses.

Moreover, the mouldboard plough works well as a less-speed soil inverting tool and significant improvement in its design could be obtained efficiently by reducing draught and wear. In developing countries, there are approximately 100 million smallholdings of less than five hectares [17], and Ghana is no exception. Therefore, tractors would be uneconomical for most of these small and marginal farmers, except on a hire service basis. For paddy cultivation and in waterlogged areas, the uses of tractors are not practicable. Such conditions exist in parts of Bangladesh and Thailand, some rice-growing areas in India and the People's Republic of China.

The contributions of smallholding farmers (peasant farmers) cannot be understated. The Committee for World Food Security of the Food and Agriculture Organization (FAO) stresses the importance of peasant agriculture and the need to invest in it [21]. Peasant agriculture is a land-labour institution that has existed for thousands of years. It ties land and labour together in a distinctive way. It sustains a mode of farming that not only has been able to face changing times but also successfully adapt itself to a bewildering range of contrasting ecological and socioeconomic conditions [22]. It has been represented in many different ways, and many different narratives have been employed to announce its impending disappearance.

Nonetheless, there are now more peasant farmers than ever before, and the world's future critically depends on them. One reason is that peasant agriculture provides the world with at least 70 % of its food [28]. Peasant agriculture is farming gently yet highly productive [24].

2. Materials and Methods

The implement could be pulled by either one or a combined pair of bullocks or other animals for similar purposes. One or two ploughmen are required to control the animals and the plough. A chain or very strong robe hooks it between a wooden bar holding the draught animals’ necks.

The materials selected for the construction work were based on the following factors, availability of the material in the market, cost and affordability, durability, malleability, rigidity and resistance to wear and corrosion. The materials used were cast iron and low alloy steel (AISI 4140).

The study aims to re-design a mouldboard plough focusing on improving strength and reducing weight. The plough is designed using similar data from an existing model but with significant modification. Parameters such as weight and dimensions were taken into consideration. Analysis was done to check whether or not maximal stresses at the highest workloads exceed the materials' yield or ultimate strength limits with the imposed force of 1,900N on the share. Two software solutions were used to evaluate and check design solutions, selection of materials, stiffness and stresses in the share. Designing the structural parts and assembly was done using Autodesk Inventor 2020, while all the numerical calculations were performed with ANSYS Workbench.

Meshing is an integral part of the engineering simulation process. Complex geometries are divided into simple elements that can be used as discrete local approximations of the larger domain in the static structural and modal analysis process. The mesh influences the accuracy, convergence and speed of the simulation. If meshing is accurate, then the results are also anticipated to be feasible. The meshing details of the model of the plough share are the number of nodes 13,451 and elements 6355. The meshed plough share is shown in Figure 4.

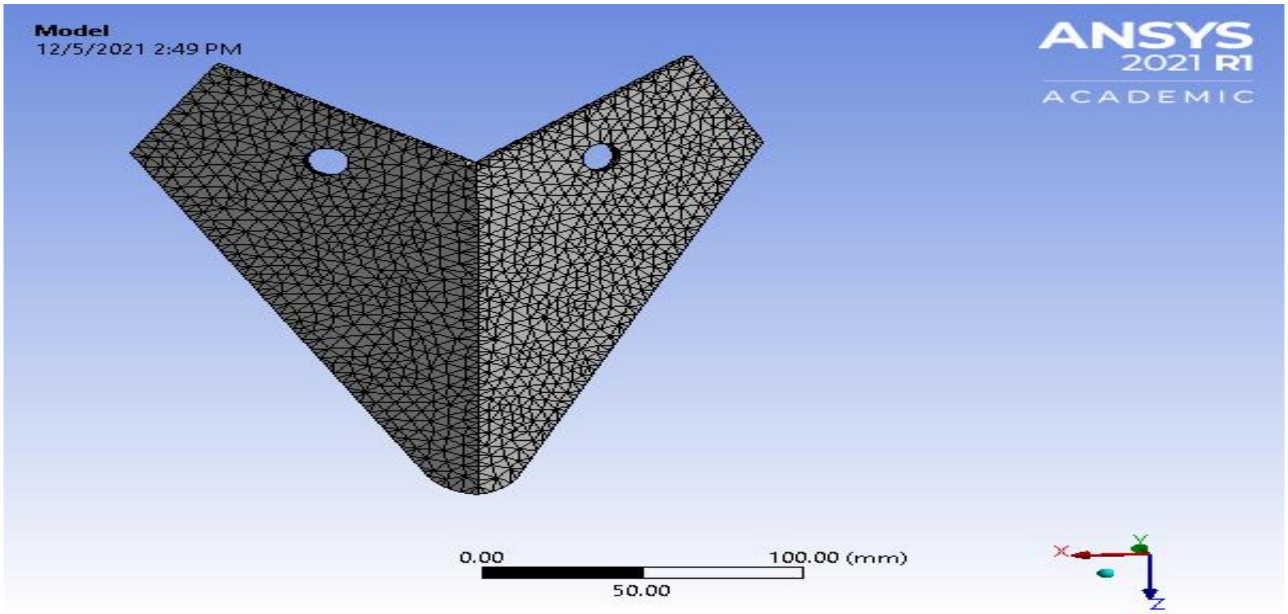


Fig. 4 Mesh of plough share

2.1. Design Calculation of Area of Share

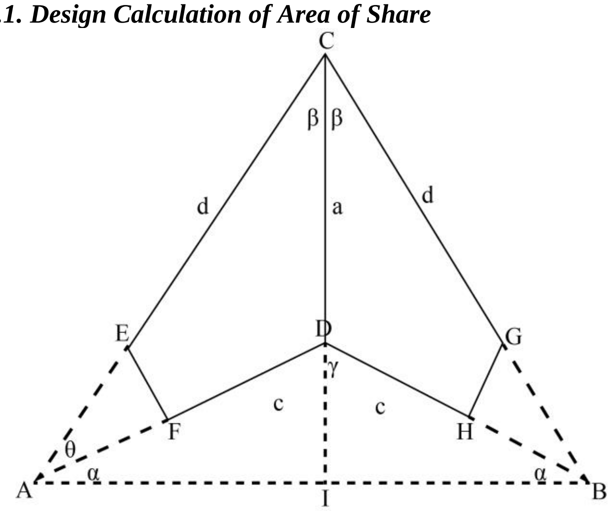


Fig. 5 Schematic Diagram for calculation of area of share

Table 1 shows the dimensions of the plough share in Figure 5

Table 1. Dimensions of the plough share

AB = 355mm	**FD** = 98.26mm
AC = 328.52mm	**GH** = 57.50mm
CD = 179.99mm	**AE** = 115mm
CE = 213.60mm **AD** = 199.19mm	**AF** = 100.93mm

From Figure 4, triangles (Δ) ACD and BCD are similar triangles. Hence, angle (∢ CAD = <CBD and <ACD = <BCD)

Using cosine rule, $a^2 = b^2 + c^2 - 2bc\cos\theta$

$179.99^2 = 328.52^2 + 199.19^2 - 2(328.52 \times 199.19\cos\theta)$

$32396.40 = 107925.40 + 39676.66 - 130875.8\cos\theta$

$32396.4 = 147602.06 - 130875.8\cos\theta$

$-115205.66 = -130875.8\cos\theta$

$$\frac{-115205.66}{-130875.8} = \frac{-130875.8\cos\theta}{-130875.8\cos\theta}$$

$\cos\theta = 0.88$

$\theta = \cos^{-1}$

$\theta = 28^o$

From Δ ACD, $\frac{\sin A}{a} = \frac{\sin C}{c}$ (1)

$$\frac{\sin 28}{179.99} = \frac{\sin C}{199.19}$$

$179.99\sin C = 199.19\sin 28$

$\sin C = \frac{93.514}{179.99}$

$\sin C = 0.52$

$C = \sin^{-1}(0.52)$

$C = 31^o$

But $C = \beta$

Therefore, $\beta = 31^o$

Again, ΔABD is an isosceles triangle, so base angles are equal.

$\alpha + \alpha + \gamma = 180$ (2)

$2\alpha + 120 = 180$

$\alpha = 30^o$

The various forces can be determined as follows: Since pull (P) of the plough, θ and α are now known, the Draft, D is given by Equation 3

Draft (D) = $P \times \cos\theta \times \cos\alpha$ (3)

Where, P = pull of plough, kg or N

θ = Angle of pull with the horizontal plane,

α = Angle of pull with the vertical plane, degrees.
D = 2000 x cos28 x cos30
D = 1,529.31N

Side draft (S) = P × cosθ × sinα (4)

S = 2000 x cos28 x sin30
S = 882.95N

Vertical component (V) =P × sinθ × cosα (5)

V = 2000 x sin28 x cos30
V = 813.15N
Total sum of draft = 1,529.31N + 882.95N + 813.15N = 3,225.41N.

The derived force obtained from the calculation is within the range of draft forces in the literature, which has the least value of 308.17 N [22].

The share may be assumed to be like a rectangular plate of area (ΔACD + ΔBCD) subjected to bending, as shown in Figure 4.

Area of share = area of ΔACD + area of ΔBCD. Since there is no height, Heron's triangular formula is applied. Let a, b and c represent the sides, and S represent one-half of the perimeter.

From Fig. 4, Perimeter, S of ΔACD = 1/2(AC+ CD+ DA) (6)

a = c = 328.52mm, d = e = 199.19mm, b = 179.99mm
AE = 115mm, AF = 100.93mm, EF = 57.50mm
S = 1/2(328.52 + 179.99 + 199.19) = 353.85mm
Therefore, the perimeter of ΔACD (S_1) = 353.85mm

Therefore, area (A) of
ΔACD = √S (S – AC) (S – CD) (S – DA) (7)

A=√353.85(52.85-328.2) (353.85S-179.99) (353.85S-199.19
A=√353.85(52.33) (173.86) (154.66)
A=√497,906,294.58
A= 22,313.814mm^2

Area of Share = Area of ΔACD + area of ΔBCD and ΔACD = ΔBCD
Area of share = 22313.814 + 22313.814
Total Area of Share = 44,627.628mm^2

Again, Perimeter, S of ΔAEF = 1/2 (AE+ EF+ FA) (8)

S = 1/2(115 + 100.93 + 57.50)
S = 1/2(273.43)
S = 136.715mm
Therefore, the perimeter of ΔAEF
S_2=136.715mm

Therefore, area (A) of ΔAEF =
A=√S (S – AE) (S – EF) (S – FA) (9)

A=√136.715(136.715-115(136.715-100.93) (136.715-57.50)
A=√136.715(21.715) (35.785) (78.215)
A=√841557.669
A = 917.365mm^2
Area of ΔAEF = Area of ΔBGH and ΔAEF = ΔBGH
Area = 917.365 + 917.365
Area = 1,834.73mm^2
Area of the required shape of Share = (Area of ΔACD + Area of ΔBCD) – (Area of ΔAEF + Area of ΔBGH)
44,627.628mm^2 - 1,834.73mm^2
Therefore, the area of required share = 42,792.90mm^2 or 0.0427929m^2

Unit draft of share = unit draft of soil × factor of safety (10)

Unit draft of share = 3,225.41N x 1.85 = 5,967 N.

Total design draft of mouldboard plough share = width × depth × unit draft (11)

The depth of cut and Width of the mouldboard plough is estimated to be 177.8mm or 0.1778m and 224mm or 0.224m, respectively.

Total design draft of mouldboard plough share = 0.224 × 0.178 × 5,967 = 237.92 N/m^2

The total draft force will act on an entire area of share. It is assumed that the soil pressure is uniformly distributed on the share.

Therefore, soil pressure on share = Total design draft of plough share
Total area of share (12)

237.92N/m^2
0.0427929m^2 = 5,559.8 N = 0.00556 MPa = 5.56 x 10^{-3}MPa

This pressure acts on the share at an angle Ψ = 20°.
Therefore, uniformly distributed load = Soil pressure on share × sinΨ (13)

Uniformly distributed load (Pressure) = 0.0556 x sin20 = 0.0019 MPa = 1,900 N

Length breadth ratio of share = L/b = 0.23/0.224 = 1.0
Share thickness (t) = 0.003m

Table 2. Parts List of the modified mouldboard plough

Item	Description	No Off	Material
1	Mouldboard	2	Low alloy steel (AISI 4140)
2	Share	1	Low alloy steel (AISI 4140)
3	Frog	1	Low alloy steel (AISI 4140)
4	Beam	1	Medium carbon steel
5	Wheel	1	Medium carbon steel
6	Wheel holder	1	Medium carbon steel
7	Handle frame	2	Medium carbon steel
8	Hitch	1	Medium carbon steel
9	Chain hook	1	Medium carbon steel
10	Beam-Handle brace	2	Medium carbon steel
11	Beam-Frog brace	1	Medium carbon steel
12	Handle	2	Bakelite
13	Handle Holder	1	Medium carbon steel
14	Bolt	15	High-Speed Steel
15	Nut	15	High-Speed Steel
16	Washer	15	High-Speed Steel

For uniformly distributed loads on a rectangular plate:

$$Smax = B \times F \times b^2/t^2 \quad (14)$$

Where, Smax= Maximum stress developed load, MPa/m^2
F = uniformly distributed load, MPa/m^2
b = Width of share, m
t = Thickness of share, m
B = A constant which depends on the length and breadth ratio of share.
$Smax = B \times F \times b^2/t^2$
$Smax = 1.0 \times 0.0019 \times 0.224^2 / 0.003^3 = 10.59 MPa/m^2$

Table 2 shows the parts list of the modified mouldboard plough in detail, as shown in Figure 6.

3. Results and Discussion

The plough in Figure 6 has a wide mouldboard and U-shape share made of low alloy steel (AISI 4140), which can turn furrow at 180º and completely cover weeds. It has handles made of Bakelite which is friendly to use when the sun is scorching.

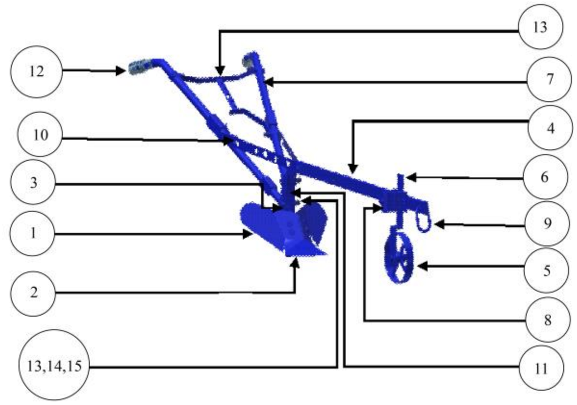
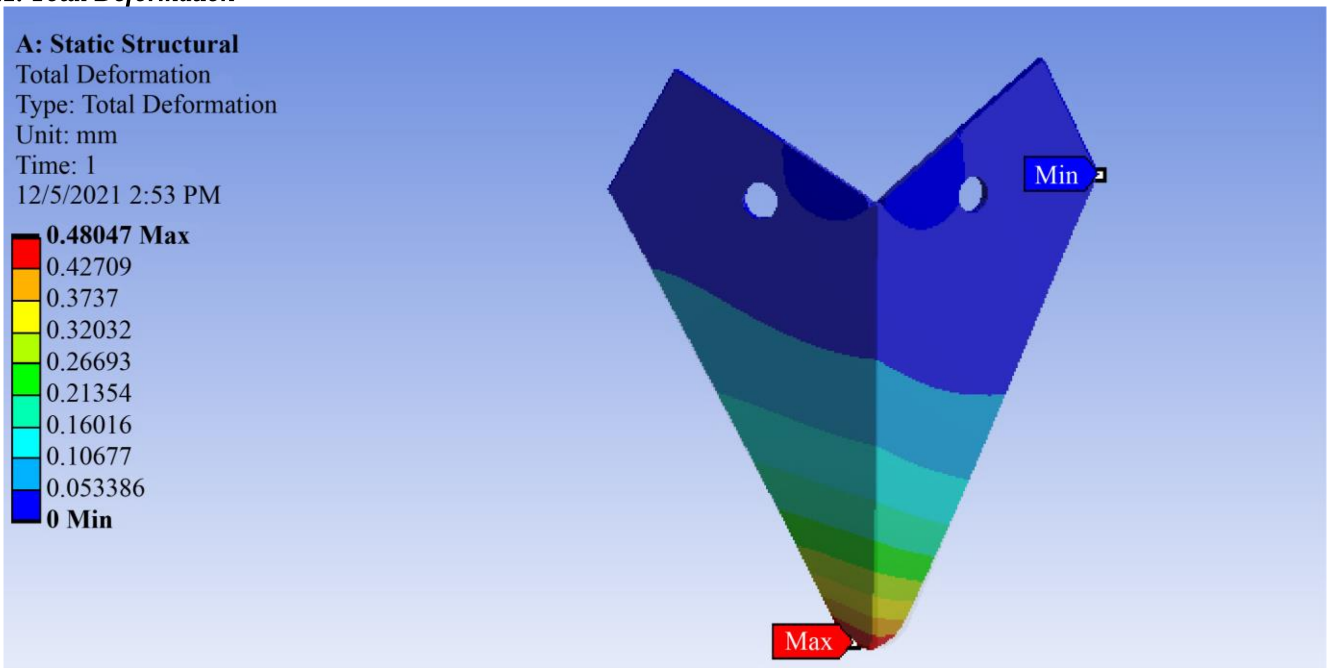
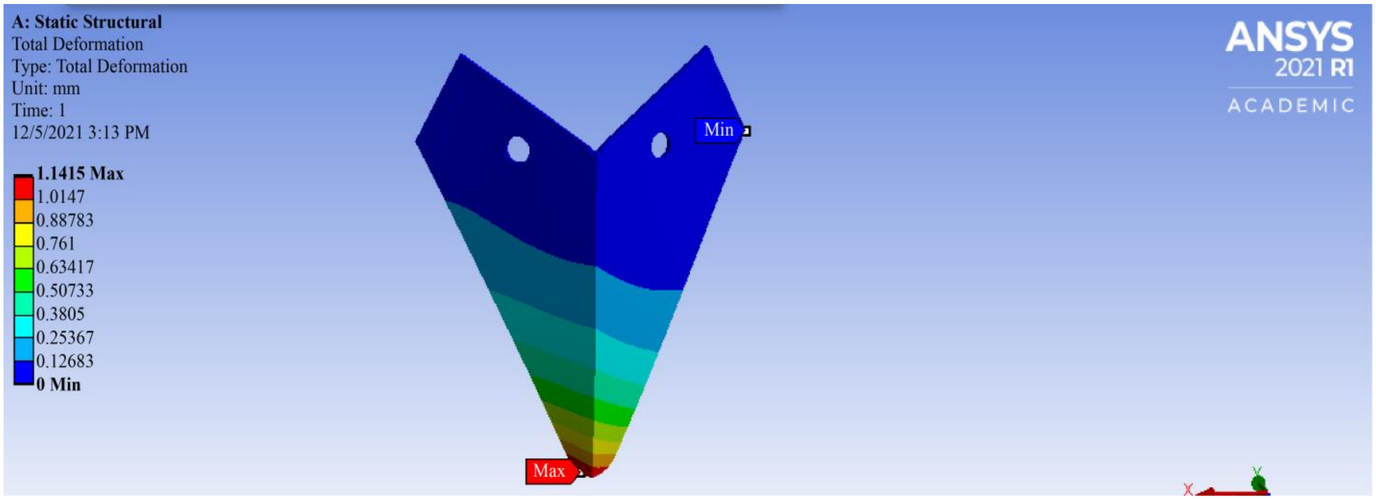


Fig. 6 Modified mouldboard plough

3.1. Total Deformation



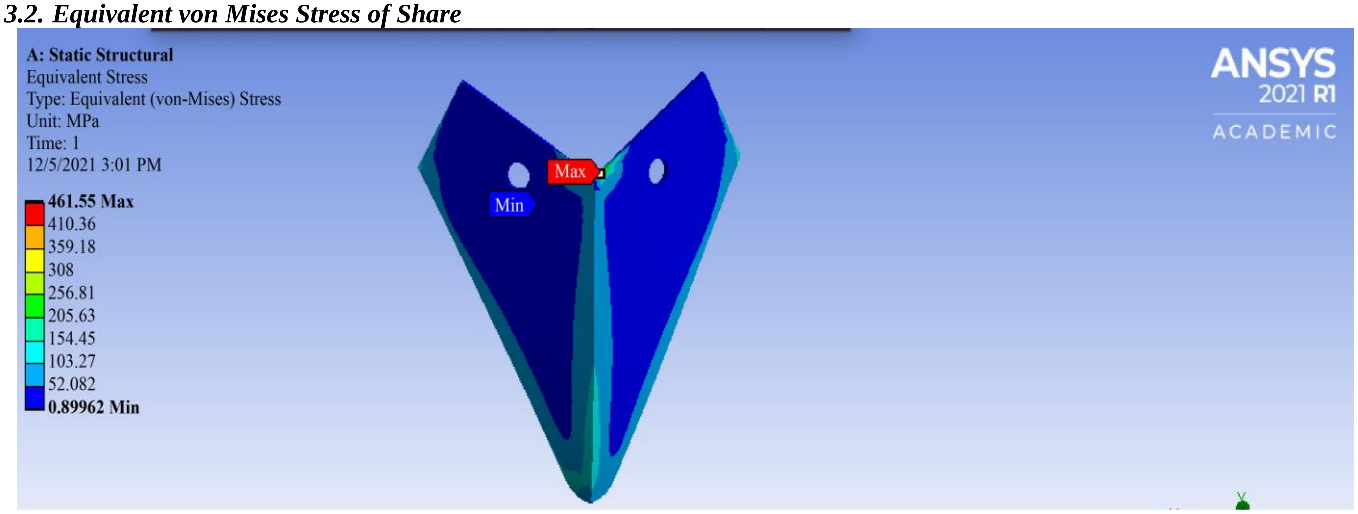
(a)



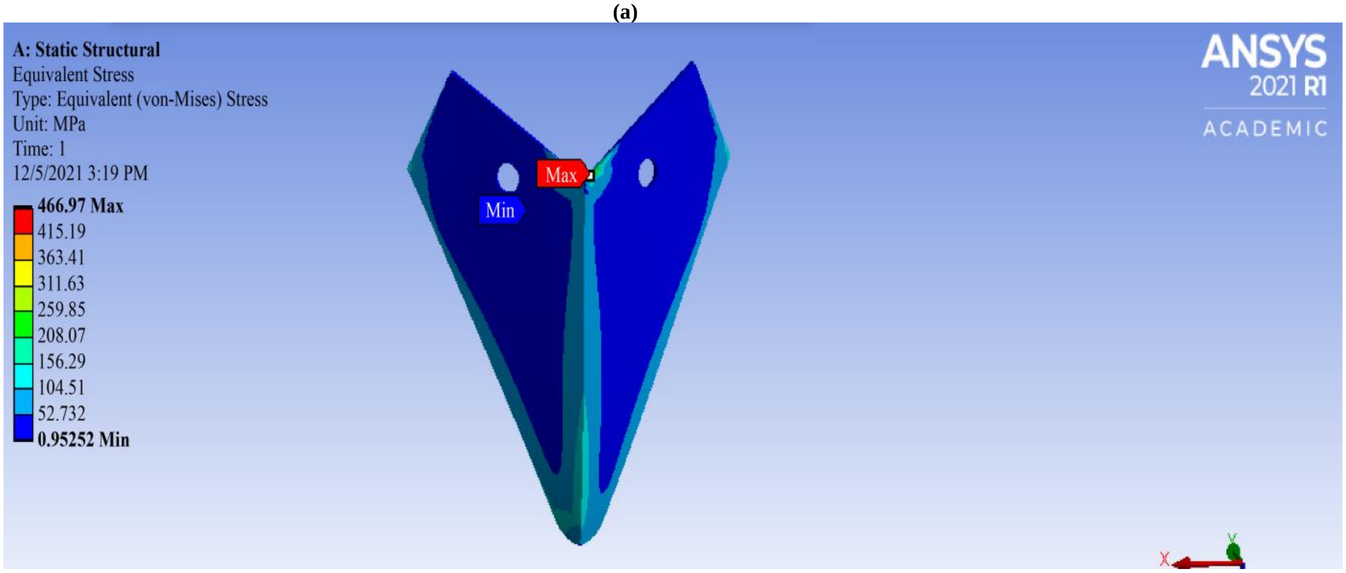
(b)

Fig. 7 (a) Low alloy steel share (b) Cast iron share

3.2. Equivalent von Mises Stress of Share



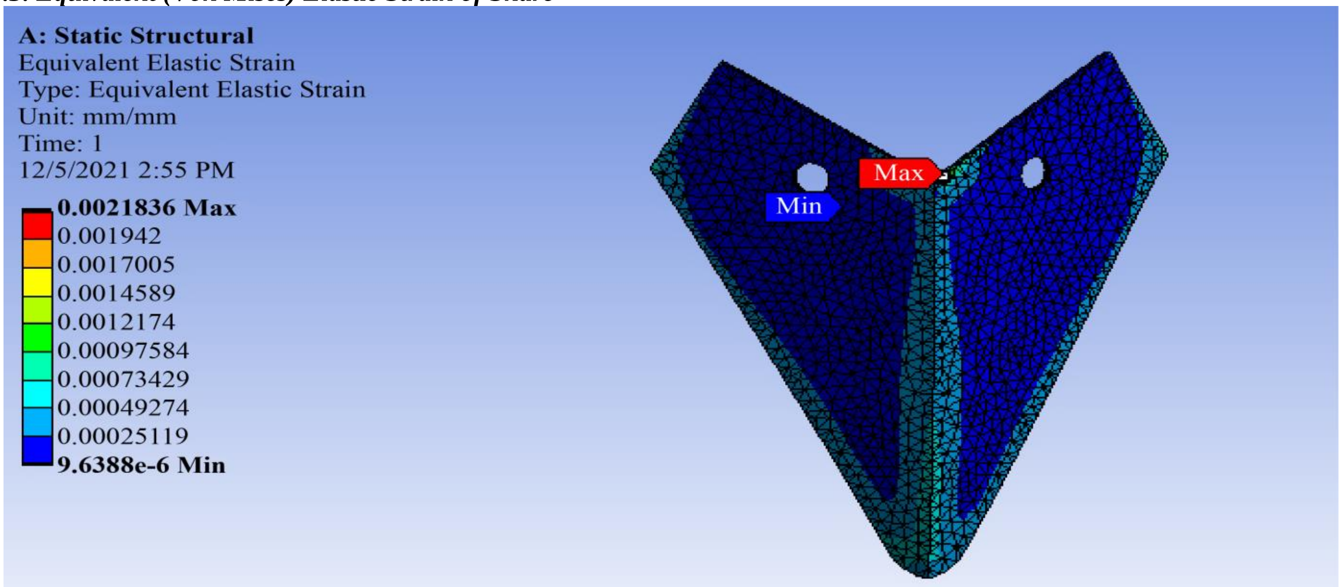
(a)



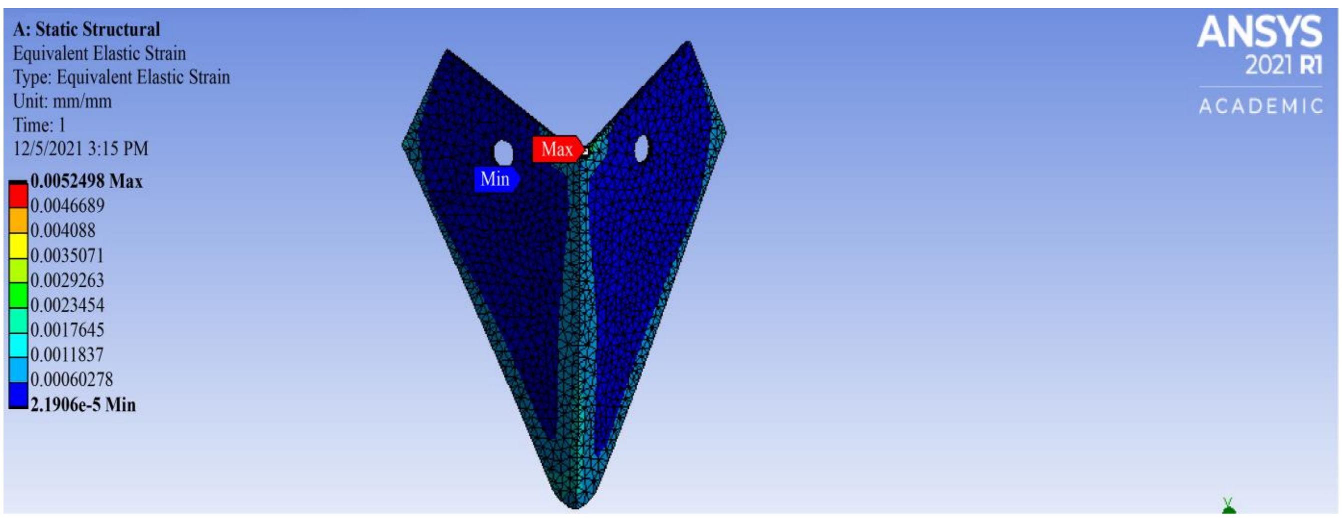
(b)

Fig. 8 (a) Low alloy steel share (b) Cast iron share

3.3. Equivalent (Von Mises) Elastic Strain of Share



(a)



(b)

Fig. 9 (a) Low alloy steel share (b) Cast iron share

The maximum total deformation indicated in Figure 7a is 0.480 mm, and the minimum total deformation is 0.0503 mm with the imposed force of 1900N relative to its area. It can be observed that a maximal deformation has occurred at the tip, which penetrates the soil directly during ploughing, while the minimal deformation is located at the top edge. In Figure 7b, the maximal total deformation occurred at the same point but with a value of 1.1415 mm and a minimum value of 0.127. Compared to the yield and ultimate tensile strengths of low alloy steel (AISI 4140) and Cast iron. It is very clear to suggest that the selected materials are durable and can adequately serve the intended purpose; however, the former has better resilience.

Using the Von Mises yield criterion, which depends solely on the value of the scalar Von Mises stress as the basis for comparison, the maximal equivalent von Mises stress (Figure 8a) occurred at the middle vertex corner, and the minimal is at the top surface of the share which is 461.55MPa and 0.8996MPa respectively. However, the yield stress developed on the Low alloy AISI 4042 steel share is far lesser than its yield strength of 652.2 MPa. It can therefore be deduced that the materials selected for use have very good properties capable of withstanding the force with a safety factor of 1.4, that is, the yield strength ratio and the developed stress since it is ductile material and the margin of safety is 0.4. Furthermore, in Figure 8b, the same can be said of the stress locations. However, the maximal stress is

466.97MPa and the minimal of 0.9525MPa. When juxtaposed to the yield strength of the material (79.81MPa) and ultimate strength of 141.4MPa, it is noticed that the developed stress is higher than its yield strength but has a safety factor of 0.3; that is, the ratio of the ultimate yield strength and the yield stress developed since it is a brittle material. According to the von Mises yield criterion, which depends solely on the scalar von Mises stress value, a larger von Mises value implies that the material is closer to the yield point. Based on this, the implication is that the share will fail at a point undesirably due to permanent deformation. The equivalent elastic strain which occurred at the middle vertex corner in both Figures 9a and b has a maximum value of 2.184×10^{-3} mm/mm and 5.250×10^{-3}mm/mm and a minimum value of 9.640×10^{-6}mm/mm and 2.191×10^{-5}mm/mm. Both values are way below Young's modulus of elasticity, which implies that the material can stretch, but with former has better elasticity.

4. Conclusion

The findings have established that the low alloy AISI4140 steel-made model is a suitable engineering material for animal-drawn mouldboard plough based on its safety factor. The study has again shown that the cast iron components are less likely to withstand stress from increasing pressure with time compared to the low alloy AISI4140 steel for share and mouldboard, respectively, of the low safety factor.

It has also been revealed that the cast iron components' total deformation and equivalent elastic strain are extremely higher than that of the low alloy AISI4140 steel components. These implications are that the cast iron components will deform permanently (deteriorate) faster, reaching the yield point than the low alloy AISI4140 steel components. It is worth noting that, apart from the likelihood of suitability, the proposed model is also aesthetically attractive. Finally, based on the characteristics of the material, the low alloy steel (AISI 4140) model is expected to be harder and tougher than the cast-iron plough in practice. Other potential features of the new model are the plough's high fatigue strength and wear resistance. It will also be highly resistant to abrasion, shock and impact and can last longer than the cast-iron ploughs, which concretise findings [25].

Although animals' draught forces and soil requirements from previous literature have been used to determine the force exerted on the model, it is necessary to indicate that the designed model has not physically experimented with various soil types to draw conclusions.

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