Design of high-strength threshing rack for variable-diameter cylinders

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Abstract. In order to solve the problems of deformation caused by traditional threshing rack applied to the variable-diameter cylinder, two high-strength threshing racks (truss-type threshing rack, reinforced plate-type threshing rack) were designed. Through statics quantitative analysis on the basis of theoretical analysis and finite element analysis and calculation conducted on the rigidity and strength characteristics of traditional threshing racks, truss threshing racks and reinforced plate threshing racks, it shows that the reinforced plate threshing rack with higher strength, simpler structure and lighter weight is more suitable for the operation requirements of variable diameter cylinders.

1. Introduction

As an important component in the threshing device, the threshing rack is equipped with various types of threshing elements, such as spike tooth, plate tooth, short rasp bar, etc. In the threshing process, the threshing rack and its elements directly contacts with the crop in the threshing device, and the material will produce a large reaction force on the device[1-3]. Taibai Xu and his peers[4] made a spike-tooth pressure sensor and installed it on the threshing rack. They measured the material reaction force on each spike teeth of the threshing rack on the horizontal axial flow cylinder at 80 to 120N. While the vertical axial flow cylinders was affected by the threshing rack due to its large feed volume and long cylinder, the force on it will be greater, and therefore, threshing device has higher requirements for the strength of the threshing rack on the vertical axial flow cylinders.

In order to improve the strength of threshing rack and prevent it from deforming during the working process, the traditional threshing cylinder is provided with front and back support plates, which are installed in the middle section of the threshing part to fix and protect the threshing rack[5-6]. In recent years, the variable-diameter threshing cylinders developed by some scholars needs to have their diameters changed in real time during the working process[7-8], so it is impossible to install a support plate in the middle section of the threshing part. However, since the traditional threshing rack does not have a fixed central plate for support, during high-speed rotation of the cylinder, the threshing rack will be deformed by a greater centrifugal force and the reaction force of the material, causing threshing failure.

Therefore, in order to meet the operation requirements of the variable diameter cylinder, this paper designed two kinds of high-strength threshing racks with light weight and anti-deformation features, namely the truss type and the reinforced plate type threshing rack. Through statics quantitative analysis on the basis of theoretical analysis and finite element analysis and calculation conducted on the rigidity and strength characteristics of traditional threshing racks, truss threshing
racks and reinforced plate threshing racks, the high-strength threshing rack is shown to be most suitable for the variable-diameter cylinder.

2. Design of high-strength threshing rack

2.1. Truss-type threshing rack

This paper intended to design two types of high-strength threshing racks, to be compared with traditional threshing racks. The first one adopted the principle of plane truss[9], as shown in Figure 1(a), which was mainly composed of threshing racks and claw connecting rods, reinforced rods located below the threshing rack, and a reinforced grid connecting the threshing rack and the reinforced rod. Both ends of the reinforced rod were welded to the claw connecting rod, and the reinforced grid was welded to the threshing rack and the reinforced rod. The threshing rack is denoted as the upper chord in Figure 1(b), the reinforced rod as the lower chord, the reinforced grid in the middle as the vertical rod and inclined rod, and the panel length as the tooth spacing, which is 65mm. The truss height is the distance between the reinforced rod and threshing rack. Let it be 30mm.

![Three-dimensional drawing of truss threshing rack](image)

(a)Three-dimensional drawing of truss threshing rack

![Simplified diagram of threshing rack](image)

(b)Simplified diagram of threshing rack

**Figure 1.** Truss type threshing rack

The force analysis of the reinforced grid inside the threshing rack was carried out and simplified into an equivalent beam, as shown in Figure 2.

![Truss-type threshing gear bar and simplified equivalent beam](image)

**Figure 2.** Truss-type threshing gear bar and simplified equivalent beam

The section method was adopted to cut the middle part of the threshing rack from section I-I, the left side of which is used as the isolator and the center point 7 as the research object. The torque is calculated at point 7:

\[
P_{N68} = -\frac{(p_x d - \frac{a}{2}) \times 3d - p \times 2d - p \times d}{h}
\]  

(1)
The numerator of $P_{N68}$ is equivalent to the bending moment of the cross-section on the threshing rack corresponding to node 7, denoted as $M^0_u$, and the denominator $h$ is the arm of force to the centroid of $P_{N68}$, then the formula (1) can be simplified as:

$$P_{N68} = -\frac{M^0_u}{h}$$

(2)

In the same way, the force of other chords can be expressed by a similar formula:

$$P_{NU} = \pm \frac{M^0_u}{h}$$

(3)

$M^0_u$ is the bending moment of the corresponding section on the equivalent beam (threshing rack). The lower chord (reinforced rod) is under pulling force and receives a positive sign; the upper chord (threshing rack) is under pressure and receives a negative sign.

In a parallel truss structure, $h$ is a constant, and the internal force of the chord changes proportionally with $M^0_u$. The internal force of the chord is distributed as follows: the internal force of the middle chord is larger, while the internal force of the chords on both sides is smaller.

The internal force of the vertical rod 6-5 or 6-7 can be obtained by the balance condition of the left part of the section I-I:

$$\Sigma Y = 0$$

(4)

The vertical components of the internal force on the vertical rod and the internal force on the oblique rod are both equal to the shear force at the corresponding joints of the equivalent beam $P^0_s$, namely:

$$P_{NY} = \pm P^0_s$$

(5)

The internal force of the vertical rod and the oblique rod in the threshing rack can be positive or negative, and its value is related to the shear force of the equivalent beam. The internal force near the two ends of the threshing gear is relatively larger, while the internal force of the vertical and inclined rods in the middle of the threshing rack is relatively higher. This kind of threshing rack and reinforced rod mainly bear the bending moment, while the reinforced grid mainly bear the shearing force.

2.2. Reinforced plate-type threshing rack

It is known that in the geometry, the triangle has the strongest stability[10]. Therefore, the reinforced plate of the second high-strength threshing rack adopted a triangular structure. As shown in Figure 3(a), an inverted triangular reinforced plate with 5mm thickness was installed under the threshing rack. The two ends of the plate were welded to the claw connecting rod, and the top was welded to the threshing rack.

![Figure 3. Reinforced plate threshing rack](image-url)

(a) Three-dimensional diagram of reinforced plate threshing rack  
(b) Strength analysis of reinforced plate threshing rack
The force analysis of the inverted triangle reinforced plate under the threshing rack is shown in Figure 3(b). Since the threshing rack is welded to the reinforced plate, the centrifugal force $F$ received by the threshing rack is regarded as the pressure received by lower vertex $O$ of the reinforced plate and both sides are also under pressure. The left and right end points of the triangle are respectively subjected to horizontal pulling force $F_x$ and vertical counter-supporting force $F_y$.

$$F_y = \cos \beta = \cos \frac{\theta}{2}$$  \hspace{1cm} (4.6)

It can be seen that the larger the angle $\theta$, the smaller the pulling force on the claw connecting rod. Therefore, let the angle of the inverted triangle reinforced plate be $160^\circ$. Compared with the first truss threshing rack, the reinforced plate threshing rack has a simpler structure and more convenient processing. In order to thoroughly compare and analyze the strength and practicability of traditional threshing racks, truss threshing racks and reinforced plate threshing racks, ANSYS software was used to analyze the force of these three threshing racks.

### 3. Simulation analysis of threshing rack statics

In order to compare and analyze the strength of the two new types of threshing racks and the traditional threshing racks, three threshing rack models established by SolidWorks software were first converted and saved as X-T format. Then the models were imported into Ansys workbench to establish static structural for force analysis[11-12]. The structural material of the threshing rack is Q235A, and its specific parameters are shown in Table 1.

**Table 1.** Material characteristics of threshing rack.

| Attribute name       | Value      | Unit     |
|----------------------|------------|----------|
| Density              | 7654       | Kg/m3    |
| Elastic Modulus      | 203*109    | Pa       |
| Poisson's ratio      | 0.3        | ———      |
| Yield Strength       | 235*106    | Pa       |
| Strength limit       | 125*106    | Pa       |

Various parts in the threshing rack were welded, so Bonded contact was used for simulation in the contact setting. The threshing spikes, racks, claw connecting rods, reinforced grids and reinforced plates were tightly fixed with bonded contact and no relative displacement occurred.

After being imported, the model of threshing rack needed to be meshed, and the local mesh size was set to 5mm as shown in Figure 4. The grid after the division of the truss threshing rack had 101,753 nodes and 68,982 unit bodies.

![Grid size](image1.png) ![Threshing rack after meshing](image2.png)

**Figure 4.** Truss type threshing rack model
In the finite element analysis, setting correct load and constraint adjustment on the threshing rack model can effectively improve the accuracy of the simulation calculation results and reflect real load situation. First, the force of the threshing rack during the rotation of the threshing cylinder was analyzed. When the threshing cylinder was idling, the threshing rack was mainly affected by its own centrifugal force and the pulling force generated by the claws connected to the two ends of the threshing rack. When the threshing cylinder was harvesting crops, the threshing spikes on it were also subjected to the lateral reaction force generated by the crops.

Restraints and loads were applied to the above two situations, as shown in Figure 5. The force and deformation of three kinds of threshing racks were analyzed when they were subjected to the centrifugal force and the cross-acting reaction force of the crop when hitting the material.

![Centrifugal force load diagram](image1.png)

![Lateral force load diagram](image2.png)

**Figure 5.** Load distribution diagram of threshing rack.

Figure 5(a) showed the restraint and load when the threshing rack was subjected to centrifugal force. The restraints were applied on both sides of the claw connecting rod. The radius of the threshing cylinder was set to 300mm with rotation axis 300mm below the center of the threshing rack, and speed of 600r/min for rotation analysis. Figure 5(b) showed the restraint and load when the side reaction force experienced by the threshing gear bar hits the material. Similarly, restraints were applied on both sides of the claw connecting rod, and the load force applied on each threshing gear bar was 120N.

### 4. Analysis of simulation results

#### 4.1. Force and deformation of threshing rack under centrifugal force

Because the three kinds of threshing racks have different structures and qualities, there are differences in their displacement and deformation distribution clouds as well as their equivalent stress distribution clouds under the centrifugal force. The material of the threshing rack was selected as Q235A, and its minimum yield strength was 235Mpa. The maximum stress of the threshing rack during the working process should be lower than its yield strength to ensure that the parts on it will not fail.

Figure 6 demonstrates the traditional threshing rack with a mass of 6.5kg. The maximum stress of this rack is 369.9 MPa, located at the connection part of the threshing rack and the claw connecting rod, where is also the welding point and whose maximum stress is much greater than the yield strength of the material for the threshing rack. Therefore, the strength of the traditional threshing rack cannot meet the requirements of use. The maximum deformation of the traditional threshing rack is 8.59 mm, which is located in the center of the threshing rack. That is, during the rotation of the threshing cylinder, the center of the traditional threshing gear bar will deform by about 8 mm along the radial direction of the cylinder. The threshing device’s threshing gap is generally 10-40mm, so the 8 mm radial displacement and deformation of the threshing rack will seriously affect the quality of threshing. Even when the threshing gap is small, the spikes on the threshing rack will hit the concave screen, causing serious damage to the threshing device.
(a) Equivalent stress cloud diagram of traditional threshing rack  
(b) Displacement and deformation cloud map of traditional threshing rack

Figure 6. Force and deformation of traditional threshing rack under centrifugal force.

Figure 7 shows the truss threshing rack with a mass of 9.6kg and a maximum stress of 185.63 MPa, which is located at the welding point of the two ends of the threshing rack and the connecting rod of the claw as well as the welding point of the reinforced rod and the connecting rod of the claw. The maximum stress value is less than the yield strength of the threshing rack material, and the strength of the truss threshing rack can meet the requirements of use. The maximum deformation of the truss-type threshing rack along the threshing cylinder radial direction is 1.25mm, which is also located at the center of the threshing rack and much smaller than the deformation requirement (3mm) of general threshing racks in practical application. Due to the use of principle of truss, the force and deformation on other parts of this device are smaller. Therefore, no major deformation occurs during the working process of the threshing cylinder, which affects the quality of threshing. However, the disadvantages of the truss-type threshing rack are its complicated structure and heavier weight.

(a) Equivalent stress cloud diagram of truss threshing rack  
(b) Displacement cloud diagram of truss threshing rack

Figure 8. The force and deformation of the truss threshing rack under the action of centrifugal force.

Figure 8 shows the reinforced plate-type threshing rack with a mass of 8.1kg and a maximum stress of 198.32 MPa, located at the welding point of the two ends of threshing rack and the claw connecting rod. The maximum stress value is less than the yield strength of the threshing rack material, so the strength of the reinforced plate threshing rack can meet the requirements of use. The maximum deformation of the reinforced plate-type threshing rack along the threshing cylinder radial direction is 2.579mm, which is also located at the center of the threshing rack and smaller than the deformation requirement (3mm) of general threshing racks in practical application by small difference and small allowance. But it can also ensure that there would be no major deformation during the working process of the threshing cylinder, which will affect the threshing quality.
Folks have used a double disc cutter as the separating cutter of the rape header. The results of the operation have proved that this type of cutter has high cutting efficiency and low vibration, but it is easy to be entangled and blocked, and there is a risk of failure. Based on similar cases and referring to the research status of the main cutter, various types of crop cutters, such as multi-disc cutters and circular chain cutters, which can be developed in the future. This type of separating cutter does not need to be driven by a crank slider mechanism, and can be powered directly by the working parts of the header, thereby reducing vibration and loss. At the same time, there is no need to install a motor or hydraulic motor on the header, which can reduce the cost and weight of the header, and improve the working reliability of the whole machine.

4.2. Force and deformation of threshing rack under lateral force
At present, there have been certain research results on the follow-up control of each working part of the header, but its realized function is relatively single, and there are other aspects worthy of in-depth study.

Due to different structures of the three kinds of threshing racks, there are differences in their displacement and deformation distribution clouds as well as their equivalent stress distribution clouds under the centrifugal force the action of the lateral force generated by the material on the threshing spikes.

Figure 9 shows the traditional threshing rack with a maximum stress of 204.9MPa, which occurs at the welding point of the threshing rack and the claw connecting rod. The maximum stress is less than the yield strength value of the threshing rack material. Therefore, the strength of the threshing rack when subjected to lateral force can meet the requirements of use. The maximum deformation of the traditional threshing gear is 2.71mm, which is located in the center of the threshing rack and also less than the deformation requirement (3mm) of the general threshing racks in practical applications, and meet the requirements for use.
Figure 9. Force and deformation of traditional threshing rack under lateral force.

Figure 10 is a cloud diagram of displacement and deformation distribution and an equivalent stress distribution cloud diagram of the truss-type threshing rack under the action of the lateral force generated by the material on the threshing spikes. The maximum stress is 224.83 MPa, located at the connection point of threshing rack and claw connecting rod, less than the yield strength value of the threshing rack. The maximum deformation of the truss-type threshing rack is 3.83mm, located in the center of the threshing gear bar and slightly larger than the deformation requirement (3mm) of general threshing racks in practical application.

Figure 11 shows the displacement and deformation distribution cloud diagram and equivalent stress distribution cloud diagram of the reinforced plate-type threshing rack under the action of the lateral force generated by the material on the threshing nails. The maximum stress value was 214.31 MPa, located at the connection point of the threshing rack and the claw connecting rod, less than the yield strength value of the threshing rack. The maximum deformation of the reinforced plate threshing rack was 2.56mm, located at the center of the threshing rack and smaller than the deformation requirement (3mm) of general threshing racks in actual use and meet the requirements of use.
Figure 1. Force and deformation of the reinforced plate threshing rack under the action of lateral force.

The simulation analysis results of the above three kinds of threshing racks showed that when subjected to centrifugal force, the maximum stress, displacement and deformation of the traditional threshing racks were the largest and exceeded the yield strength of the material, which could not be applied to variable diameter cylinders. The maximum stress, displacement and deformation of truss threshing racks were the smallest, while the maximum stress, displacement and deformation of the reinforced plate threshing racks were in the middle level, and both met the requirements of use. When subjected to lateral force, the maximum stress of the truss-type threshing rack was close to the yield strength of the threshing rack material, and its displacement and deformation was slightly larger than those in actual use. In this condition, reinforced plate threshing rack also met the requirements of use. Considering that the need of six threshing racks in variable-diameter cylinder, and complicated structure, difficult operation process, heavy weight and possible risks of hanging grass of the truss-type threshing racks during operation, reinforced plate-type threshing rack with relatively convenient processing, lighter weight and higher structural reliability was selected as the optimal threshing rack for the variable-diameter cylinder. The actual processing picture is shown in Figure 12.

Figure 12. Physical image of reinforced plate threshing rack.

5. Conclusion
In this paper, two high-strength threshing racks (truss-type threshing racks, reinforced plate threshing racks) were designed. Through statics quantitative analysis on the basis of theoretical analysis and finite element analysis and calculation conducted on the rigidity and strength characteristics of
traditional threshing racks, truss threshing racks and reinforced plate threshing racks, the research results show that: when subjected to centrifugal force, the maximum stress, displacement and deformation of the traditional threshing rack exceeded the yield strength of the material, and the truss-type threshing rack had the smallest force and deformation. The maximum stress, displacement and deformation of the reinforced plate threshing rack are in the middle level. When subjected to lateral force, both the truss type and the reinforced plate type threshing rack met the requirements, but the reinforced plate had the best effect. At the same time, the reinforced plate-type threshing rack has the characteristics of light weight, simple structure, high deformation resistance and can be applied to the variable diameter threshing cylinder.

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