Fatigue Analysis and Structural Optimization Design of the Slot of Knotted Frame of the Square Baler

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Abstract. The frame is a key part to ensure the reliability and life of the knotting device of the square bale baler, and it is also the difficulty of localizing the knotting device. The inner wall of the frame slot of the frame is at a right angle structure, and the stress concentration is obvious. Under the impact load, the stopper will cause premature shear failure, delay the timing of forage bale, increase maintenance costs, and reduce the operating efficiency of the baler. This paper analyzes the failure characteristics of the D-type knotter frame slot, uses ANSYS-nCode joint method to simulate the fatigue life of the knotter frame slot, and uses the response surface method to optimize the design of a U-shaped slot. The simulation results show that when the radius of the U-shaped slot is 2mm and the gap between the bottom of the slot and the first rope clearing piece is 1mm, the fatigue life of the U-shaped slot increases. This research is of reference value to improve the fatigue performance of the knotter frame and enhance the durability of the knotter.

1. Introduction

The performance of the knotter plays a decisive role in the bale quality and reliability of the bale baler [1-2]. The frame is a key part to ensure the reliability and life of the knotter, and it is also the difficulty of localizing the knotting device. Affected by factors such as processing quality, working environment, use and maintenance, during the actual baling operation in China, the knotter frame often fails prematurely, affecting the timely harvesting of pastures, straw and other crops, which increases the cost of operation maintenance [5-6]. Improving the structural strength of the knotter frame and improving the reliability of the knotter frame will still be one of the important directions for the research and development of the knotter.

At the beginning of the knotting of the D-type knotting device, the secondary bale rope introduced by the baling needle is pressed against the rope clearing piece, and then the worm gear drives the rope clamping disc to rotate, and the hook-shaped notch of the rope clamp dial pulls the rope to the contact opening of the rope clamp disc and the rope presser. Each knotting makes the stopper of the limit rope clearing piece on the frame subject to instantaneous impact load, and the bundling operation Not only will it cause serious wear on the rope clearing blades, but it may even cause shear failure to the stopper [7]. After the stopper on the knotter frame is damaged, the frame needs to be disassembled and replaced, which delays the timing of forage baling, increases the maintenance cost, and seriously affects the operating efficiency of the baler. The impact fatigue damage of the stopper is closely related to the structural characteristics, load course and material characteristics of the frame slot. The ANSYS-nCode module has rich fatigue analysis functions, can

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clearly identify the material fatigue properties of key areas of complex structures, and is easy to achieve two-way interaction with CAD design parameters. It has become an efficient tool for structural fatigue design and optimization \[8-9\]. In this paper, according to the failure characteristics of the D-type knotter frame stop block, the fatigue life of the knotter frame body slot is studied by the ANSYS-nCode joint analysis method, and a U Type slot can increase the rated life of the frame slot, and provide a reference for comprehensively improving the durability of the domestic knotter. In this paper, according to the failure characteristics of the D-type knotter frame stop block, the fatigue life of the knotter frame slot is studied through the ANSYS-nCode joint analysis method. And the response surface method \[10-11\] is used to design and optimize a U-shaped slot, which can increase the rated life of the rack body slot and provide a reference for the overall improvement of the durability of the domestic knotter.

2. Structural analysis of the slot of the knotter frame

2.1 Slot structure characteristics
The space configuration of the rope clearing piece and the slot is shown in Figure 1. The slot structure of the D-type knotter frame is shown in Figure 2. From the figure, it can be seen that the bottom of the slot and the inner wall are at right angles and sharp edges. The inner wall of the slot is not smooth. It is easy to cause stress concentration at the bottom of the slot, thereby reducing the fatigue life of the slot and causing damage to the frame stop dog. The shape of the slot stopper is a square cylinder of 8mm × 10.5mm × 15mm.

Fig 1. The assembly of clearing piece and slot.  
Fig 2. The structure of slot.

2.2 Slot failure analysis
Figure 3 shows that after the stop of the outer edge of the slot breaks, the user directly welds and repairs the knotter without disassembling it to reduce the downtime of the bale baler. It can be seen from the figure that the outer edge of the slot is seriously damaged. Although the welding repair method can solve the urgent problem, due to space constraints, it is not possible to form fillet welds around the broken column. After welding, the cracks still exist, and the stress concentration is not Eliminated, and the surface quality of the slot is more deteriorated, so after a limited number of knots, the outer cylinder of the slot will still break, which seriously affects the efficiency of the bale baler operation\[12\].
By collecting the D-type knotter frame that was damaged during the operation, it was found that many of the slot stoppers equipped with the rope clearing pieces were broken. But at this time, the damage area of the rope cleaning piece is not large (Figure 4), and the measurement of the damaged part shows that most of the damage depth is 1.4mm-2.6mm. And from the form of damage, it is known that the damage is mainly caused by the friction of the rope. Therefore, the main force of the rope clearing piece is the frictional force of the rope, and the direction is the axial direction of the rope clearing piece. The radial force of the rope to the rope clearing piece, that is, the force exerted by the shoulder of the rope clearing piece on the contact surface of the slot, is found in the literature to have an average value of about 200N\textsuperscript{[13-14]}. For the slot stop dog cylinder with a size of 8mm×10.5mm ×15mm, it breaks when subjected to a load of 200N within the rated life of the knotter, which is obviously inconsistent with normal damage. Considering the right-angle structure of the inner wall of the slot, the stress concentration is obvious, and the fatigue life of the structural parts will be significantly reduced under the impact load. Therefore, to improve the fatigue performance of the slot structure and its bearing capacity will become one of the important means to effectively guarantee the reliability of the knotter frame.

### 2.3 Improvement of slot structure

The knotter frame is a precision casting, and the process is complicated. In view of the above structural defects, one of the effective solutions is to replace the original right-angle structure with a circular milling cutter to mill the U-shaped groove, which can effectively eliminate the stress concentration at the bottom of the card groove, and there will not produce a tool withdrawal groove. The structural change of the scheme is small, the processing procedure is simple, the surface quality is easy to ensure, and the processing cost is low, which is beneficial to improving the fatigue life of the frame slot stop dog. The three-dimensional diagram of the improved slot structure is shown in Figure 5.
3. Finite element analysis of the slot of D-type knotter frame

3.1 Applied load
Use the finite element to analyze the simplified model of the slot, and import the obtained static solution into the nCode module, select the appropriate algorithm to calculate the fatigue life \([15-17]\) Through the establishment of the solid assembly model of the rack, in the finite element analysis, load is applied at the assembly position of the slot according to the rope clearing piece as shown in Figure 6.

![Fig 6. The assembly position diagram of the rope clearing piece.](image)

It can be seen from the figure that the distance between the two rope clearing pieces is 3.3mm, the bottom surface of the slot is 3.8mm away from the first rope clearing piece, and the thickness of the rope clearing piece is 3mm. The loading area of the slot finite element analysis is shown in Figure 7.

![Fig 7. The diagrammatic sketch of the load on the slot.](image)

After the application of the load is completed, a static solution is performed, and then the result of the solution is imported into the constant load stress life module of nCode to calculate the fatigue...
life. The knotter is knotted once in 0.67 seconds. Within these 0.67 seconds, the actual load condition starts from zero and gradually increases to the maximum load at the moment of cutting the rope. Therefore, when nCode calculates the stress fatigue life, the load is applied as the form of the time series load. That is to create a time series load spectrum as shown in Figure 8 to simulate the loading method of actual numerical.

Fig 8. The load spectrum in time series.

Since there are special requirements for the file format of the time series load spectrum in nCode \([18]\), the process of creating the load spectrum in nCode is shown in Figure 9 below. First, add the load data to the Excel Input module. Set the sampling frequency in the Multicolumn To Time Series module, and then the TS Output module outputs the load spectrum file with the suffix -out and the format as s3t.

Fig 9. The flow chart of load spectrum creation.

3.2 Simulation results
Load the above time series load spectrum into the nCode fatigue calculation engine. The calculation results are shown in Figure 10. It can be seen from Figure 10 (a) S-N curve, that static failure occurs near the No. 20006 node, that is, the right-angled edge of the slot has a crack or a direct fracture under a load of less than 15,000 cycles. Once the material cracks, the fatigue life algorithm based on the material SN curve will no longer be applicable, and the fatigue life algorithm based on the EN curve will be used to calculate the fatigue life \([19-20]\), the calculation results are shown in Figure 10 (b) E-N curve. The strain fatigue life is about 4300 times. The rated bundling life of the imported knotter is 40,000 bales, which indicates that the frame slot structure is the weak link of the knotter, which seriously affects the overall life of the knotter.
In order to prevent the static failure of the slot from generating cracks, the right-angle slot is changed to a U-shaped slot, the radius of the corner is set to 2mm, and the gap between the first rope clearing piece and the bottom of the slot is adjusted to 1.8mm. The simulation results are shown in Figure 11. From the figure, it can be seen that the minimum stress fatigue life of the U-shaped slot is 96,000 cycles, and no static failure has occurred, that is, it is not necessary to calculate its strain fatigue life. The simulation calculation results show that the U-shaped slot can effectively reduce the stress concentration and extend the fatigue life of the slot.

4. Parameter optimization of U-shaped slot
Response surface analysis (RSM) method uses a reasonable experimental design method and obtains a set of data through experiments, and uses a multiple quadratic regression equation to fit the functional relationship between the factor and the target value, thereby determining the optimal process parameters. The response surface optimization method works best when the factors have a non-linear influence on the indicator, the number of factors is small (generally less than 4) and the parameter range is close to the optimal region. According to the clearance between the first rope clearing piece and the bottom of the slot, the size of the milling cutter is selected, and the response surface optimization analysis of the fillet radius at the bottom of the slot is performed. The Workbench optimization module is shown in Figure 12. First, parameterize the radius of the fillet and the depth of material removal in the Design Modeler module, and then parameterize the maximum stress and maximum total displacement in the Model module. After the setting is completed, enter the optimization module shown in Figure 12, and set the boundaries of radius and depth, and finally calculate. According to the above calculation results, the radius of the rounded corner at the bottom of the slot is determined to be 1-3mm, and the milling depth is also 1-3mm.
Fig 12. The response surface.

The response surface optimization process module.

The Table 1 shows the calculated results of the 17 groups of programs. It can be seen from the table that the equivalent stress and strain calculated by the sixth group of schemes are the smallest. At this time, the radius of the fillet is 2mm, and the material removal depth is 1mm, that is, the clearance between the first rope clearing piece and the bottom of the slot is 2.8mm. The fatigue life of the optimal design scheme is calculated in nCode. The static solution of the sixth group of schemes shown in Table 1 are imported into nCode, and the fatigue calculation result is shown in Figure 13.

Table 1. The calculation results of the 17 sets of schemes.

| 序号 | P6-Fblend 3.FD1 /m | P2-Extrude1. FD1 /m | P3-Equivalent Stress Maximum /Pa | P4-Total Deformation Maximum /mm | P5-Equivalent Elastic Strain Maximum /mm⁻¹ |
|-----|-----------------|-----------------|---------------------------------|---------------------------------|---------------------------------|
| 1   | 0.002           | 0.002           | 2.4589 E+07                     | 2.3787 E-06                     | 0.00019626                     |
| 2   | 0.001           | 0.002           | 2.2986 E+07                     | 2.1667 E-06                     | 0.00018349                     |
| 3   | 0.0015          | 0.002           | 2.6755 E+07                     | 2.2513 E-06                     | 0.00021345                     |
| 4   | 0.003           | 0.002           | 1.6518 E+07                     | 3.0036 E-06                     | 0.00013545                     |
| 5   | 0.0025          | 0.002           | 2.4965 E+07                     | 2.4933 E-06                     | 0.00019924                     |
| 6   | 0.002           | 0.001           | 1.4788 E+07                     | 2.7134 E-06                     | 0.00011885                     |
| 7   | 0.002           | 0.0015          | 1.8936 E+07                     | 2.5182 E-06                     | 0.00015114                     |
| 8   | 0.002           | 0.003           | 1.9029 E+07                     | 2.1634 E-06                     | 0.0001519                      |
| 9   | 0.002           | 0.0025          | 2.3317 E+07                     | 2.2522 E-06                     | 0.00018612                     |
| 10  | 0.001           | 0.001           | 2.3166 E+07                     | 2.394 E-06                      | 0.0001849                      |
| 11  | 0.0015          | 0.0015          | 1.9821 E+07                     | 2.3885 E-06                     | 0.00015819                     |
| 12  | 0.003           | 0.001           | 1.6221 E+07                     | 2.8881 E-06                     | 0.00013219                     |
| 13  | 0.0025          | 0.0015          | 1.5332 E+07                     | 2.8617 E-06                     | 0.00012622                     |
| 14  | 0.001           | 0.003           | 2.2083 E+07                     | 1.9658 E-06                     | 0.00017629                     |
| 15  | 0.0015          | 0.0025          | 2.0245 E+07                     | 2.1664 E-06                     | 0.00016162                     |
| 16  | 0.003           | 0.003           | 2.0691 E+07                     | 2.3674 E-06                     | 0.00016514                     |
| 17  | 0.0025          | 0.0025          | 2.227E+07                       | 2.3754 E-06                     | 0.00017775                     |

It can be seen from Figure 13 that the stress life of the sixth group of schemes is greater than the fatigue life of right-angle slots, so it is proved that the scheme of changing the U-shaped slot is feasible, and after optimization, its stress fatigue life can be further increased to 124,900 times. It is more than three times the design service life of the knotter.
Fig 13. The stress fatigue life of sixth groups of schemes.

5. Conclusions

(1) The bottom of the slot of the knotter frame is in a right angle structure with the inner wall, and the stress concentration is obvious, which significantly reduces the fatigue life of the slot. This leads to premature damage to the frame stop block.

(2) Through the fatigue failure analysis of the slot structure, the anti-fatigue design scheme of the U-shaped slot is proposed. The joint analysis of ANSYS-nCode shows that the design can effectively improve the stress fatigue life of the slot.

(3) The response surface parameters were optimized for the fillet radius of the U-shaped slot and the gap length between the bottom of the slot and the first rope clearing piece. The optimal fillet radius is 2 mm, and the gap between the bottom surface of the slot and the first rope clearing piece is 1 mm. At this time, the fatigue life of the slot is improved.

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