Journal of Engineering Mechanics and Machinery (2021) Vol. 6: 1-10
Clausius Scientific Press, Canada
DOI: 10.23977/jemm.2021.060101
ISSN 2371-9133

# *Optimization Design of the Support Plate of Large-scale Split Jack Multifunctional Rescue Attachments*

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***Keywords:*** rescue accessories, finite element analysis, structural optimization, response surface analysis

***Abstract:*** Aiming at the problem of low strength and low rigidity of the support plate of the large-scale split jack multifunctional rescue attachment, a simulation model of the attachment is established based on the working principle of the split jack rescue attachment. The limit working condition is used as the input condition, and the finite element analysis is carried out on the support plate of the split jack rescue attachment. Based on the response surface method and multi - objective genetic algorithm, the main size parameters of the support plate are selected as the design parameters, and the maximum equivalent stress, maximum deformation and mass minimization are the optimization goals, and the optimization model of the support plate is established. Optimize its structure. The result shows that the strength and rigidity of the support plate are improved without increasing the mass.

## 1. Introduction

China is one of the countries with the most earthquake disasters in the world [1]. Therefore, life rescue after a devastating earthquake is one of the most important issues facing domestic rescue teams. The traditional equipment used in earthquake rescue mainly includes small manual rescue equipment and large rescue engineering machinery. Small manual rescue equipment is easy to transport and carry, but it has low power and poor safety. Large construction machinery has great power and safe operation, but due to the bad traffic conditions in the disaster area, transportation is restricted [2-3]. Rescue attachments have become a new research direction of rescue equipment due to their advantages of easy transportation, great power, and safe operation.

At present, research on rescue equipment at home and abroad is still in its infancy. Gentes [4] developed a rescue attachment that can automatically remove gravel and rubble. This attachment needs to be integrated on the excavator, with a single function and complicated installation and disassembly. Wang [5] proposed a rescue attachment with cutting, crushing and grasping functions. Wu [6] proposed a rescue attachment that integrates the functions of hole-opening and coring, which can realize quick docking with ordinary construction machinery and implement rescue operations. He [7] proposed a shear-type rescue attachment with a single function. The attachment needs to be replaced frequently during rescue operations, which may reduce rescue efficiency. Although the above four types of attachments do not involve supporting and splitting functions, a preliminary design process of rescue attachments in complex scenarios is given. Li et al. [8] proposed a patent on attachments with integrated supporting function. Zhao et al. [9] proposed a patent on rescue attachments with functions of clamping, cutting, grasping and splitting. These two patents preliminarily propose the structural design and working principle of a large rescue attachment with splitting and supporting functions. The rescue robots proposed by Zang [10] and Zhang [11] are equipped with a splitting expanding rescue attachment. The rescue robot proposed by Zang [12] is equipped with an attachment with grinding and supporting functions. These three kinds of attachments, which are small rescue attachments, have novel structures and are installed on small rescue robots. Sun [13] proposed a rescue attachment with splitting and supporting functions, which is complex in structure, low in strength, and low in power, making it difficult to deal with large concrete components in the ruins.

In order to solve the problem of low strength and low rigidity of the support plate of the large-scale split jack multifunctional rescue attachment, the structure of the support plate is optimized. Firstly, according to the working principle and limit conditions of the split jack rescue attachment, the finite element analysis of the brace is carried out. Secondly, the response surface function of the support plate is established. The main size parameters of the support plate are used as input parameters, and the maximum equivalent stress, maximum deformation and mass minimization of the support plate are used as output parameters. The design variables are then subjected to sensitivity analysis. Finally, the multi-objective optimization model of the support plate is established and solved by the multi-objective optimization algorithm. The optimization results show that the strength and rigidity of the support plate are effectively improved without increasing the mass.

## 2. Split Jack Multifunctional Rescue Attachment

The split jack rescue attachment is a new multifunctional rescue attachment developed for earthquake rescue scenarios, as shown in Figure 1. It has both the functions of splitting and jacking, and is mainly used to quickly open the rescue channel. The split jack rescue attachment is mainly composed of a box body, a support plate, a split device, four connecting rods, four hydraulic cylinders and four guide rails. It has two main working states, split state and jack state.

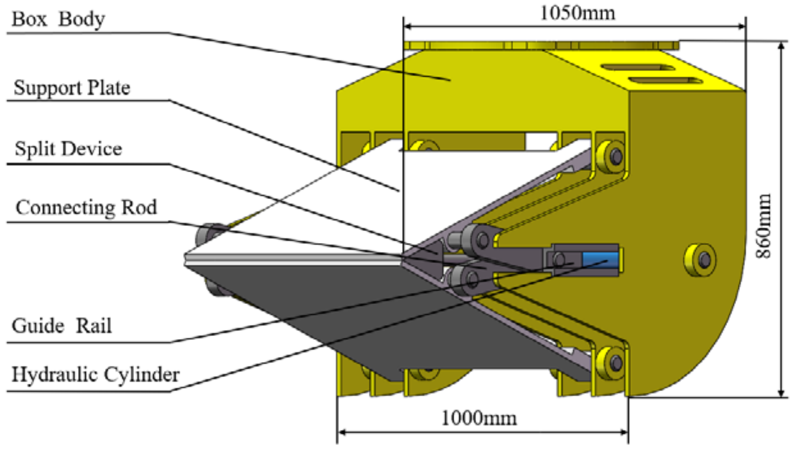
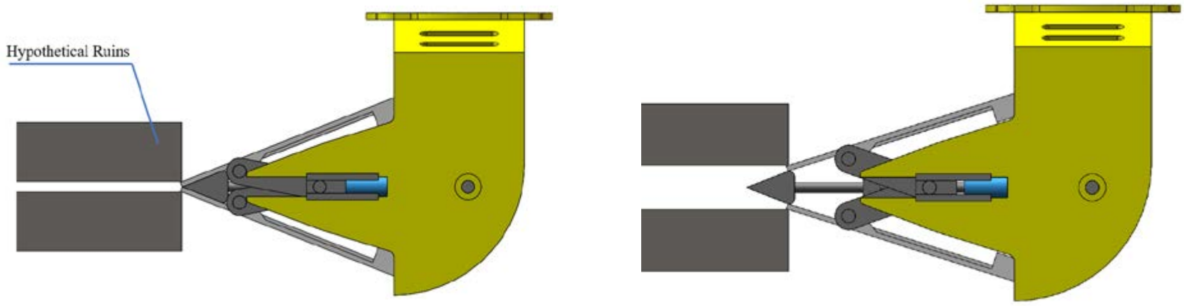



*Figure. 1 Model of split jack multifunctional rescue attachments.*

When the attachments are in the split state, align the ends of the two supporting plates and insert them into the crevices of the rubble as shown in Figure 2(a).The hydraulic cylinder pushes the split device forward, squeezing the support plates on the upper and lower sides of the device to enlarge the gap, so as to meet the needs of the rescue channel or workspace, as shown in Figure 2(b).

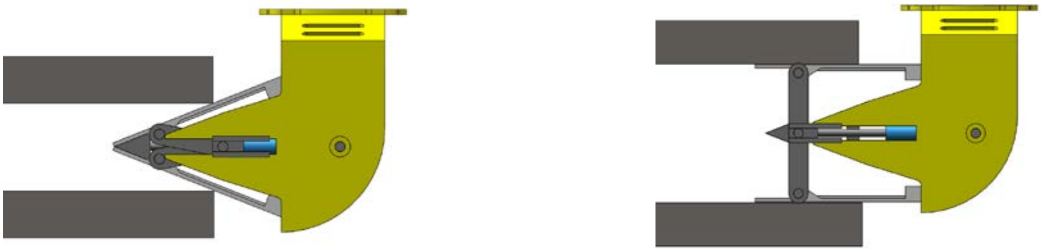



(a) Initial state of rescue attachment split process (b) Completion state of rescue attachment split process

*Figure. 2 Split process of split jack multifunctional rescue attachments.*

Insert the support plate into the rubble when the attachments are in the jack state as shown in Figure 3(a).Driven by the hydraulic lever, the connecting rod extends the support plate on both sides until both connecting rods are in the same straight line as shown in Figure 3 (b).At this time, a rescue channel with a cross-section of 51cm x 54cm is formed in the middle of the two plates, which can meet the needs of follow-up rescue work.

According to the working principle of the attachments, the top plate is the most important support member of the attachments. During the process of jacking concrete members, the pressure of concrete members directly acts on the support plate, which makes the support plate bear large bending moment and undergo deformation. Due to the special positioning of the rescue equipment, the multi-functional rescue attachments needs to be safe, reliable and easy to transport at the same time. Therefore, the support plate needs higher rigidity and strength as well as less mass, and structural optimization is required to improve its performance.



(a) Initial state of rescue attachment jacking process (b) Completion state of rescue attachment jacking process

*Figure. 3 Jacking process of split jack multifunctional rescue attachments.*

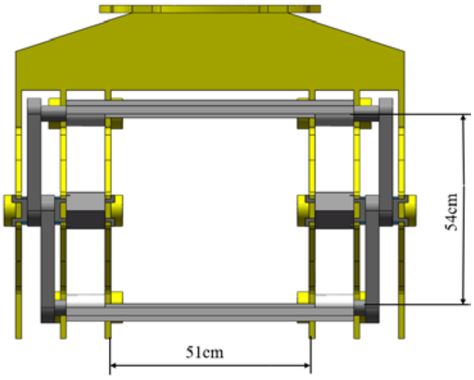



*Figure. 4 Schematic diagram of split jack multifunctional rescue attachments.*

## 3. Optimum Flow of the Support Plate Structure

Based on the working principle of split jack rescue attachments, the structure of the key component, the support plate, is optimized to improve its stiffness and strength. The specific optimization process is shown in Figure 5.

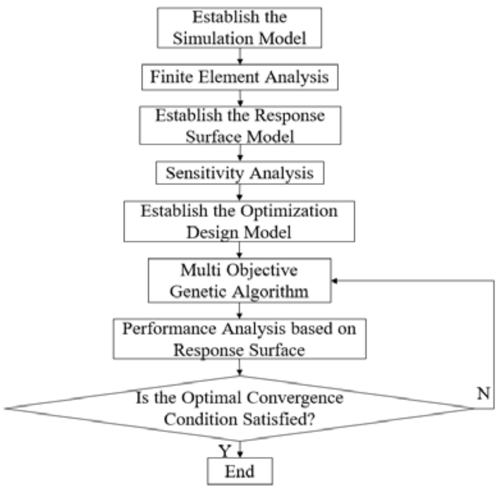



*Figure. 5 Flow chart of the support plate structure optimization.*

The specific structure optimization process is as follows:

1) Establish the parametric simulation model of the support plate, determine the force of the support plate, and carry out the finite element analysis to obtain the force and deformation of the support plate under the initial design.

2) Response surface method is adopted to construct the response surface relationship between the design parameters of the support plate and the maximum equivalent stress, maximum deformation and mass, and to carry out sensitivity analysis.

3) Maximum equivalent stress, maximum deformation and mass minimization of the support plate are selected as optimization objectives, design parameters with high sensitivity of the support plate are selected as design variables, and reasonable range of design variables is selected as constraints to establish the optimum design model of the support plate.

4) Apply multi-objective genetic algorithm to optimize the design parameters of the support plate and obtain three recommended points. Select one of the three recommended points and substitute it into the simulation model for verification.

## 4. Structural Optimization of the Support Plate

### 4.1 Finite Element Analysis of the Support Plate

Three-dimensional model and parametric simulation model of split jack rescue attachment were established. The boundary condition at the joint between the attachments and the excavator quick connector is fully constrained.

The loads acting on the support plate include its own gravity, the supporting forces acting on it by the rotating shafts and the pressure acting on it by concrete members. Due to the complex and changeable situation in the rescue site, the concrete pressure has various functions on the support plate. When the maximum load acts on the middle position between the two shafts, the bending moment of the top brace plate is the maximum, and the support plate is most likely to be damaged. For ease of solution, the load on the contact surface is simplified as a uniform load acting on a rectangular area between the two axes with the precondition of ensuring the calculation accuracy, as shown in Figure 6.

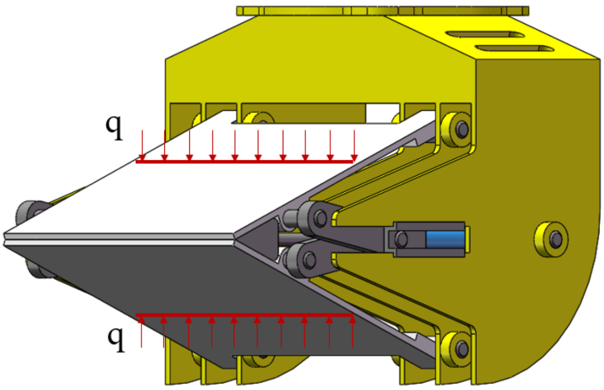
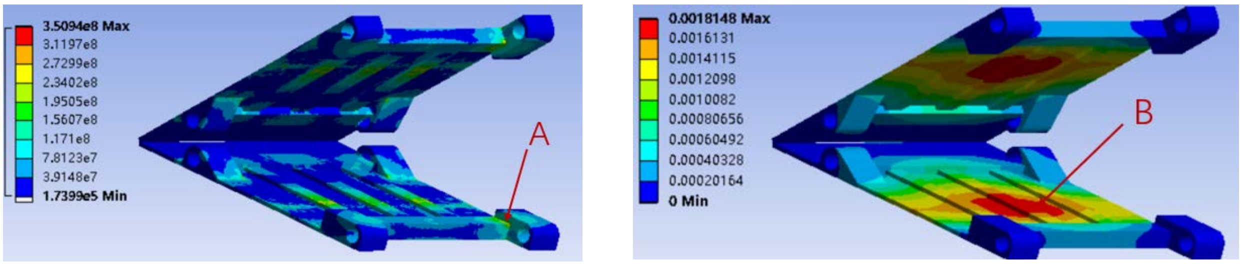



*Figure. 6 Load distribution of support plate.*

The maximum jacking force of the split jacking rescue attachments is 150 kN, and the compressive strength of common concrete is less than 30 MPa. It can be calculated that the area of the contact surface is not less than 0.005 m2. A rectangle with 740mm long and 6 mm wide contact surface can be obtained.

The results are shown in Figure 7.The results show that the stress of the support plate is mainly concentrated near the shaft and in the middle of the rib plate, the maximum equivalent stress point is point A and the maximum equivalent stress is 350.9 MPa; the deformation of the support plate is mainly concentrated in the center of the plate, the maximum deformation point is point B and the maximum deformation amount is 1.81 mm. It is necessary to optimize the structure of the support plate in order to improve the strength and stiffness of the support plate.




(a) Nephogram of equivalent stress of the support plate (b) Nephogram of deformation of the support plate

*Figure. 7 Mechanical analysis of the support plate.*

## 4.2 Response Surface Model and Sensitivity Analysis of the Support Plate

Split jack and support multi-functional rescue attachments, due to its special positioning, need to be safe, reliable and easy to transport at the same time. This requires that the support plate not only has higher strength and rigidity but also has lower mass. But mass, rigidity and strength are contrary to each other. Traditional experience-based design methods are difficult to balance these design indicators. Therefore, the optimization design based on response surface method and multi-objective genetic algorithm is selected to select the optimum design point and achieve the optimum of multiple performance characteristics.

Five structural dimensions are selected as input parameters for the response surface of the support plate structure. As shown in Table 1, the width of the beam W1. Beam thickness D1, rib width W2. Rib Thickness D2 and the thickness D3 of the support plate. The maximum equivalent stress, maximum deformation and mass of the support plate are selected as output parameters of the response surface. Within the constraints of the five input parameters, the Latin hypercube sampling design method is adopted to carry out the test design, and the response values of each point are obtained by running simulation, thus the response surface model of each input parameter and output parameter is constructed.

*Table 1 Input parameters of response surface of the support plate.*

| Order Number | Meaning of Parameter | Input Parameter | Value Range /mm |
|---|---|---|---|
| 1 | Beam Width$W_1$ | $x_1$ | [45, 75] |
| 2 | Beam Thickness $D_1$ | $x_2$ | [32, 48] |
| 3 | Rib Width $W_2$ | $x_3$ | [50, 70] |
| 4 | Rib Thickness $D_2$ | $x_4$ | [6 , 14] |
| 5 | Plate Thickness $D_3$ | $x_5$ | [6 , 14] |

Sensitivity analysis can help designers choose the design variables with high sensitivity at the stage of product design and process parameter determination [14].

According to the static equilibrium equation there are

$$\boldsymbol{KY} = \boldsymbol{F} \tag{1}$$

$\boldsymbol{K}, \boldsymbol{Y}$ and $\boldsymbol{F}$ are stiffness matrix, displacement and load vector respectively.

Where, the load vector $\boldsymbol{F}$ is a constant value, and the partial derivatives of the design variable x on both sides of the equal sign in equation (2) are calculated, that is

$$\boldsymbol{Y}_{i,j} = -\boldsymbol{K}\boldsymbol{K}_{i,j}\boldsymbol{Y} \tag{2}$$

Where $\boldsymbol{K}_{i,j}$ and $\boldsymbol{Y}_{i,j}$ are the partial derivatives of stiffness matrix $\boldsymbol{K}$ and displacement vector $\boldsymbol{Y}$ to $x_j$ respectively.

The influence of various design variables on the structural performance of the support plate can be analyzed by equation (2). Figure 8 is the sensitivity analysis diagram of the maximum equivalent stress, maximum deformation and mass of the support plate to each design variable. The results show that the design parameters are negatively correlated with the maximum deformation and the maximum equivalent stress, and positively correlated with the mass. The thickness of the support plate has the greatest influence on the maximum deformation, the maximum equivalent stress and the mass. Compared with adjusting other design parameters, increasing the thickness of the support plate can significantly reduce the maximum deformation and the maximum equivalent stress of the support plate, but also increase more mass.

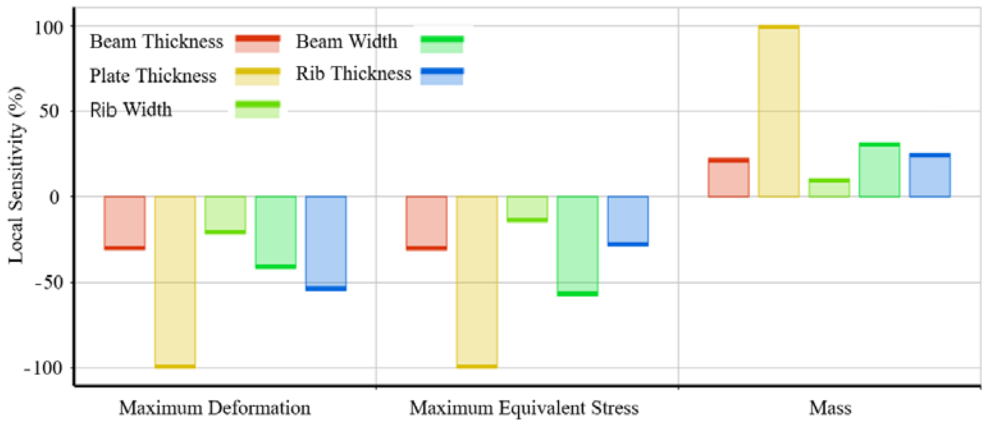



*Figure. 8 Sensitivity analysis diagram of the support plate.*

## 4.3 Multi Objective Optimization Design Model and Optimization Results of the Support Plate

The beam width W1, the beam thickness D1, the rib width W2, the rib thickness D2 and the thickness D3 of the top support plate are selected as the design variables, and the maximum equivalent stress, maximum deformation and minimum mass of the support plate are taken as the optimization objectives. The multi-objective optimization problem of the support plate is as follows

$$\begin{cases} \min(m, Y_{max}, \sigma_{max}) \\ \text{s. t. } G(x) = (g_1(x), g_2(x), \cdots, g_n(x)) \leq 0 \\ x_{i_{min}} \leq x_i \leq x_{i_{max}}, i = 1,2,\cdots 5 \end{cases} \tag{3}$$

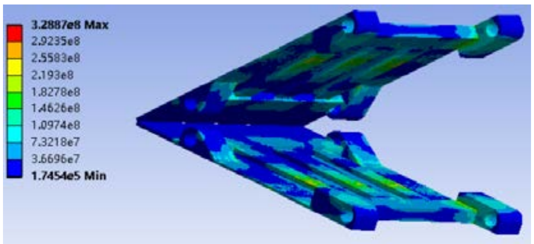
Where: $\sigma_{max}$ is the maximum equivalent stress of the support plate; $Y_{max}$ is the maximum deformation of the support plate; $m$ is the total mass of the support plate.

The multi-objective genetic algorithm is applied to solve the optimal solution of the optimization model, and three candidate points are obtained. When the strength and stiffness are satisfied, and considering the comprehensive performance of the support plate structure, candidate 1 is selected as the optimal design point from the three candidate design points.

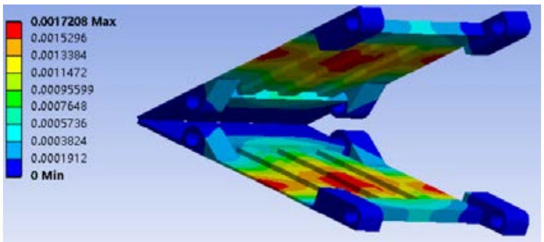
*Table 2 Parameters of the best candidate points.*

| Name | W1/mm | D1/mm | W2/mm | D2/mm | D3/mm |
|---|---|---|---|---|---|
| Candidate point1 | 73.650 | 35.912 | 68.723 | 13.934 | 7.408 |
| Candidate point2 | 69.531 | 39.192 | 69.915 | 13.797 | 7.300 |
| Candidate point3 | 64.834 | 42.508 | 68.533 | 13.261 | 7.523 |

The optimal design point is updated to the simulation model and recalculated. As shown in Figure 9 below, the deformation nephogram and equivalent stress nephogram of the optimized support plate are shown.




(a) Nephogram of equivalent stress of the optimized support plate




(b) Nephogram of deformation of the optimized support plate

*Figure. 9 Stress and deformation nephogram of the optimized support plate.*

According to the simulation results, it can be seen from Figure 7 that the maximum deformation appears in the center of the support plate, which is 1.72mm and 5.0% lower than that before optimization. The maximum equivalent stress of the support plate is 328.9 MPa, which is 6.3% lower than that before optimization. Overall, the total mass is almost unchanged, as shown in Table 3.

*Table 3 Comparison of the support plate before and after optimization.*

| properties | maximum deformation /mm | maximum equivalent stress /MPa | total mass /kg |
|---|---|---|---|
| Before optimization | 1.81 | 350.9 | 144.1 |
| After optimization | 1.72 | 328.9 | 144.0 |
| Rate of change | -5.0% | -6.3% | 0.0% |

## 5. Conclusion

Aiming at the problem that the strength and stiffness of the support plate of a new type of split support rescue attachment is small, the structure optimization design is carried out. On the basis of the working principle of the split support rescue attachment, the stress of the attachment is analyzed; the parametric model of the support plate is established; the response surface relationship between the design parameters and performance parameters of the support plate is established; the optimization model of the support plate is established; the optimal solution is obtained by using the multi-objective optimization algorithm; the optimal solution is substituted into the parametric model of the support plate, and the results show that The results show that the maximum deformation of the support plate is reduced by 0.09 mm, the maximum equivalent stress is reduced by 22.0 MPa, the total mass is almost unchanged, and the stiffness and strength of the support plate are effectively improved.


## Acknowledgements

The authors are grateful for the research grants given by the National Key Research and Development Program of China (No. 2018YFC0810203).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