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Light-weight Design Method for Force-Performance-Structure of Complex Structural Part Based Co-operative Optimization

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1. Introduction

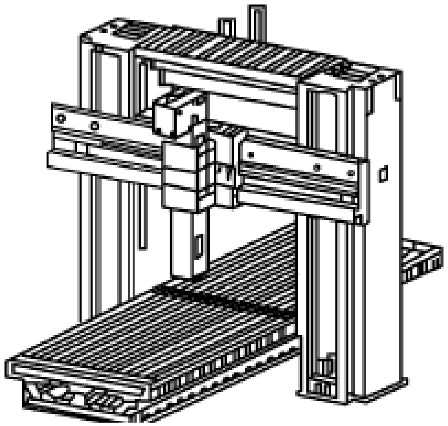
1.1 Background

Complex parts:

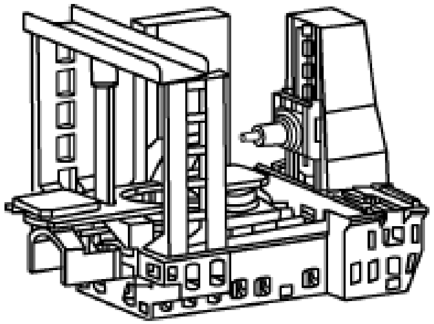
Parts have larger size and weight than others in machine.

Supporting function:

Withstanding the work loads and its own gravity, and transmitting the loads and forces to the foundation.



Gantry machining center



Horizontal machining center

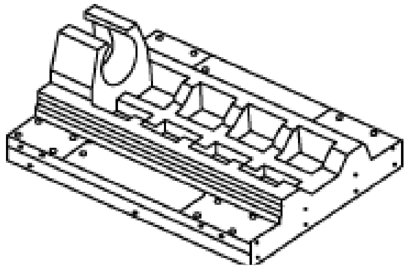
Main feature:

Heavy

Various work condition

Complex structure

Difficult to design



Sliding plate in lathe

1. Introduction

1.1 Background

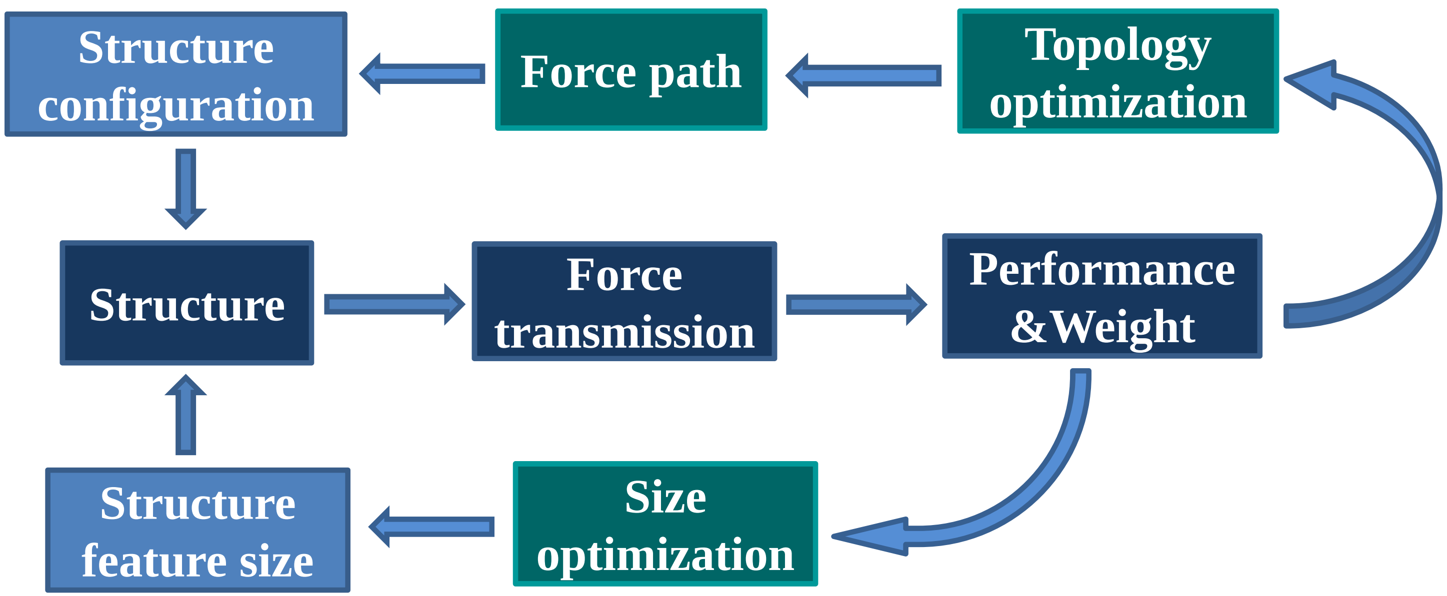
Problems of complex parts design

- The traditional structural design adopts manual calculations and design by experience and analogy. The traditional design can be bulky, heavy and costly.
- Lack of proven and reliable design methodology. Difficult to design the structures which having light weight while meeting the performance requirements.

Explore the high performance, light weight structure design method of complex parts.

1.2 Research approach

Force-Performance-Structure design Based on Co-operative Optimization



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2.1 Mathematical optimization model

Model of structural configuration

Optimization Objective:
The static and dynamic combined strain energy
Optimization Constraints:
The proportion between initial volume and optimized volume
Optimization variable:
Element density

Topology optimization

$$\begin{cases} \min \quad S(\boldsymbol{x}) = \sum w_{\mathrm{i}} \mathbf{u}_{\mathrm{i}}(\boldsymbol{x})^T \mathbf{K} \mathbf{u}_{\mathrm{i}}(\boldsymbol{x}) + NORM \dfrac{\sum w_j / \lambda_j(\boldsymbol{x})}{\sum w_j} \\ s.t. \begin{cases} V_{\mathrm{i}}(\boldsymbol{x}) / V_0 \le \Delta \\ 0 \le x_{\mathrm{k}} \le 1, \quad (k = 1, 2, \ldots, N) \end{cases} \end{cases}$$

Model of structural feature size

Optimization Objective:
Stiffness, strength and mass of parts
Optimization Constraints:
Size constraints
Optimization variable:
Structural feature size

Size optimization

$$\begin{cases} \min\limits_{\boldsymbol{X}} (D_1(\boldsymbol{X}), \ldots D_i(\boldsymbol{X}), D_p(\boldsymbol{X})) \ i = 1, 2, 3 \ldots, p \\ s.t. \quad f_1(\boldsymbol{X}) \ge f \\ \boldsymbol{X} = (\boldsymbol{X}_1, \boldsymbol{X}_2, \boldsymbol{X}_i, \ldots, \boldsymbol{X}_n) \quad i = 1, 2, 3 \ldots, n \end{cases}$$

2.Optimization Model of Part

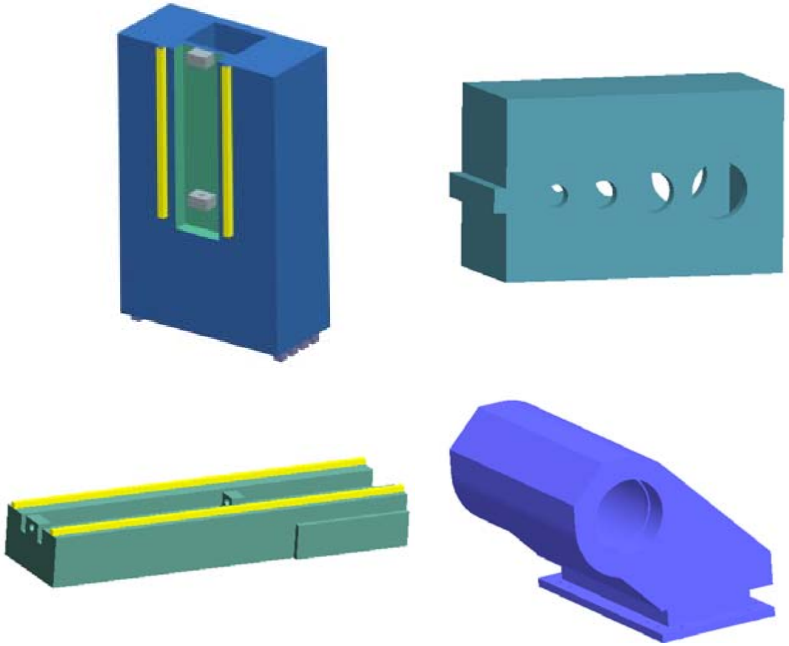
2.2 Physical optimization model

Physical model *is a finite element model containing geometric model, design domain, loads (directions and magnitudes) and constraints.*

Key point: Geometric model & Load and Constraint equivalence

(1)Geometric model *c*an be constructed following **Function rule**, **Geometry rule** and **Size rule**.

It's to describe the shape and structural characteristics and show the spatial connection between the adjacent parts.



2.Optimization Model of Part

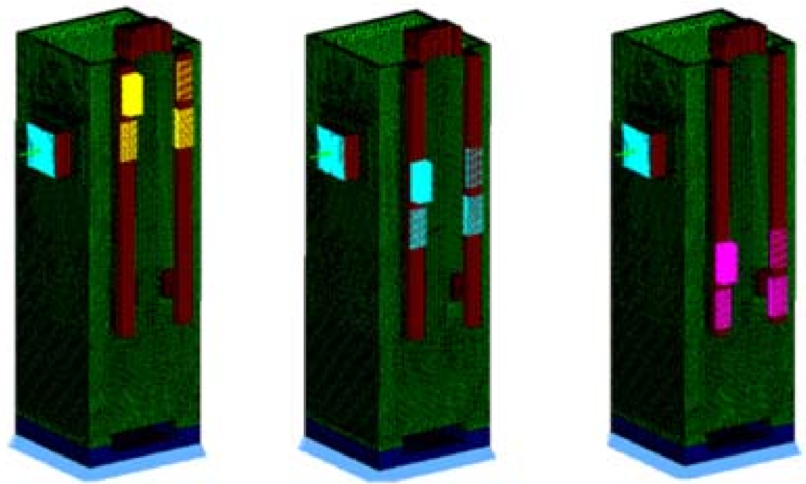
2.2 Physical optimization model

（2） Loads and Constraints equivalence

Loads equivalence

Complex part often works in multi-conditions, and the working loads change correspondingly.

The working loads of multi-conditions should be weighted equivalent performed based on dangerous conditions, typical conditions and the working frequency.



Load equivalence of a column of machining center

2.Optimization Model of Part

2.2 Physical optimization model

（2） Load and Constraint equivalence

Constraints equivalence

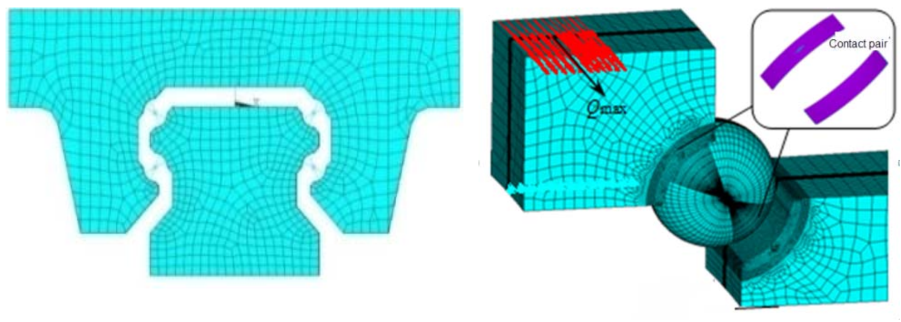
Constraints degree of freedom and the stiffness characteristics determined by the connection type, which is difficult to accurately solve.

Degree of freedom equivalent:

Determine the number and direction of the degree of freedom constraints based on the type of connection.

Stiffness equivalent:

Equal the stiffness characteristic of actual joint surface by using spring equivalent or contact equivalent method.



a) Spring equivalent **b) Contact equivalent**

Constraint equivalence

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3.Force-performance-structure design

Connection structure:

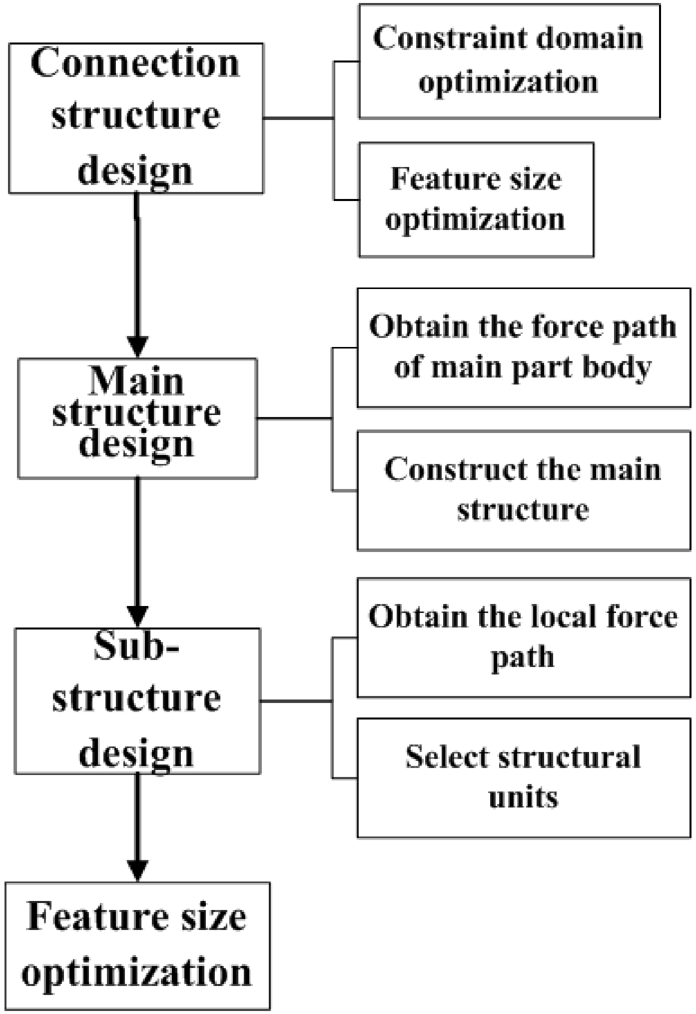
The structure connected two parts, it determines the **load and the constrain position.**

Main structure:

The structure of **main body** of part. It directly affects the parts performance.

Sub-structure:

Local structure **be attached to the main structure** to improve the **local performance of part.**



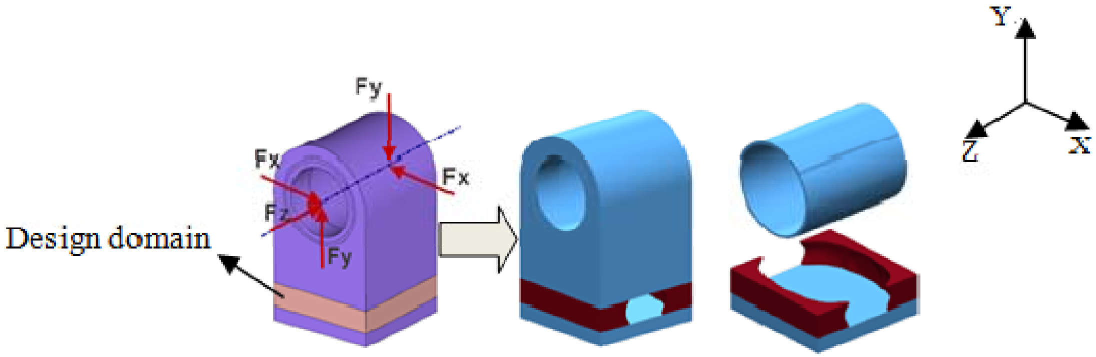
The optimization design process for structure light-weight method

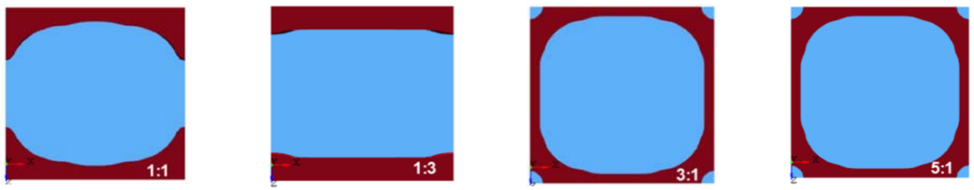
3.Force-performance-structure design

3.1 Connection constraint-performance-structure design

Connection structure and the main feature size are obtained by using structural topology optimization and size optimization method based on performance.

(1) ***Connection domain optimization design***





Fx/Fy=1:1 Fx/Fy=1:1 Fx/Fy=1:1 Fx/Fy=1:1

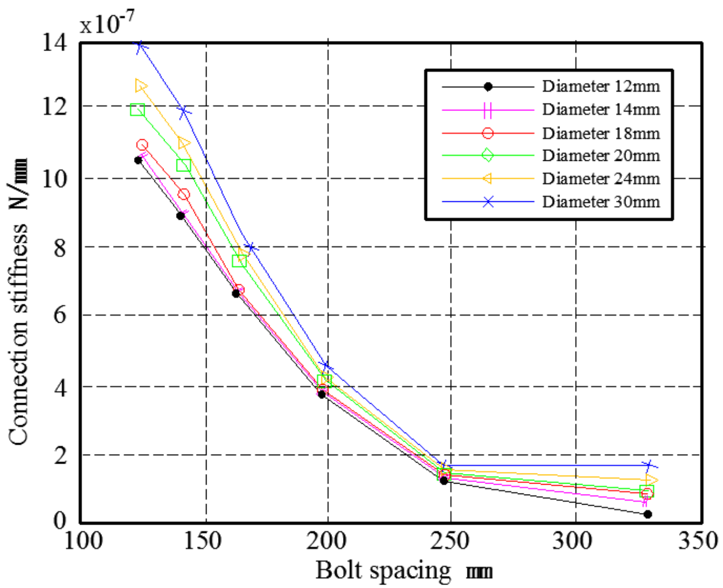
The relationship between the load value ratio and the bolt connection domain

3.Force-performance-structure design

3.1 Connection constraint-performance-structure design

(2) *Feature size optimization of connection structure*

How to select the main feature size?



Influence of bolt spacing and bolt diameter on connection stiffness

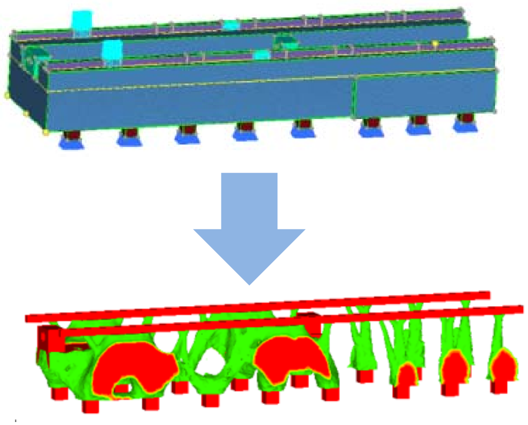
Obtain the objective function and the constraint function by response surface method

$$D_k(\boldsymbol{X}) = a_0 + \sum_{i=1}^{n} b_i \boldsymbol{X}_i + \sum_{i=1}^{n} c_{ii} \boldsymbol{X}_i^2 + \sum_{ij(i \prec j)} c_{ij} \boldsymbol{X}_i \boldsymbol{X}_j \quad (k = 1, 2, \ldots p)$$

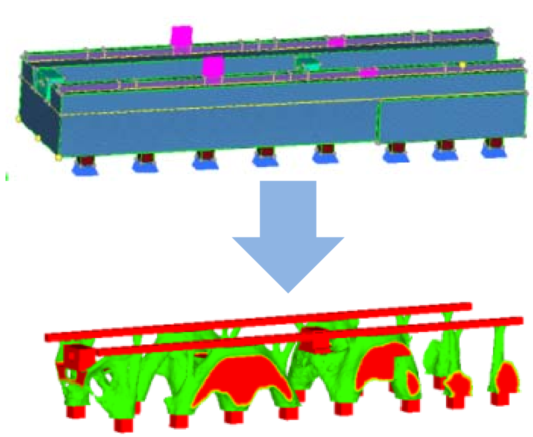
3.Force-performance-structure design

3.2 Force path-performance-main structure design of part

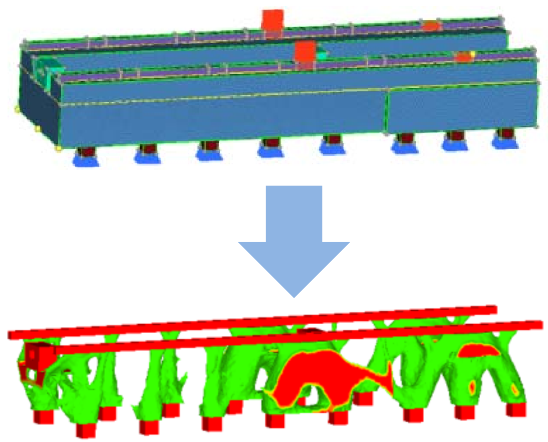
Main structure is mapped by the **main force path**. The topology optimization of **multi-conditions** and multi-objectives is carried out to obtain the main force path.



a) Left limit condition



b) Intermediate condition



c) Right limit condition

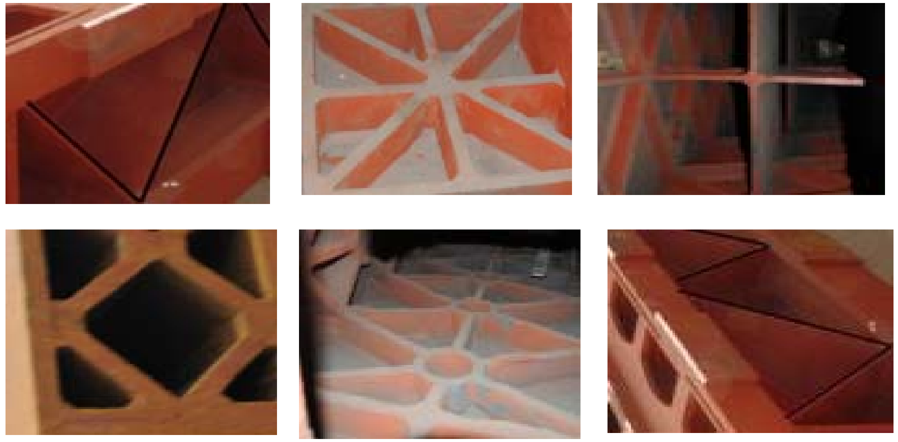
The force paths under different working conditions of gantry-type machining center bed

3.Force-performance-structure design

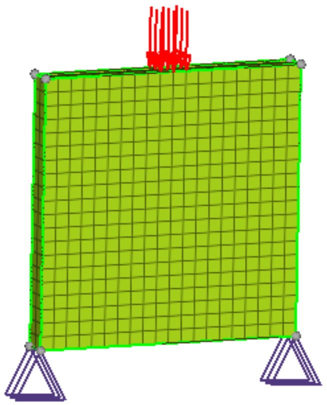
3.3 Force path-performance-sub-structure design of part

Sub-structure:

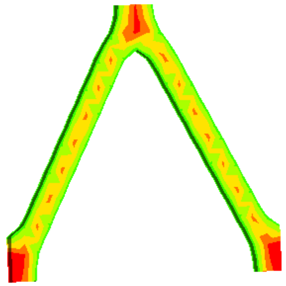
Some sub-structures will often be attached to the main structure under actual engineering situation to improve the local performance of part.



Physical model of sub-structure



Local force path

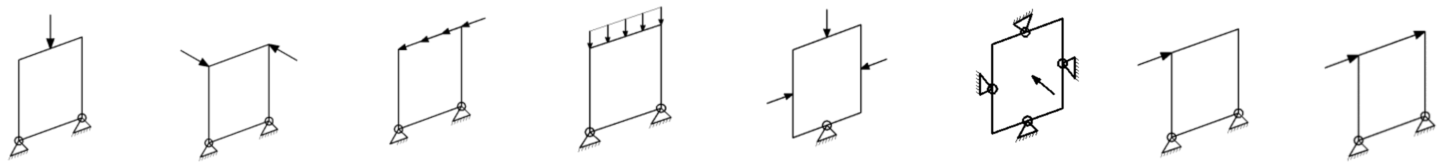


Local force path:

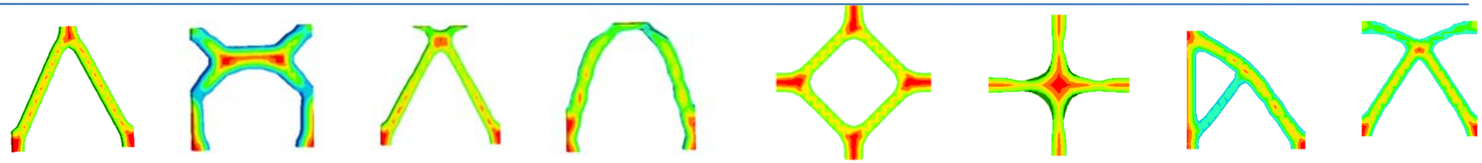
Obtained by using the structure topology optimization method and force-structure rule.

3.3 Force path-performance-sub-structure design of part

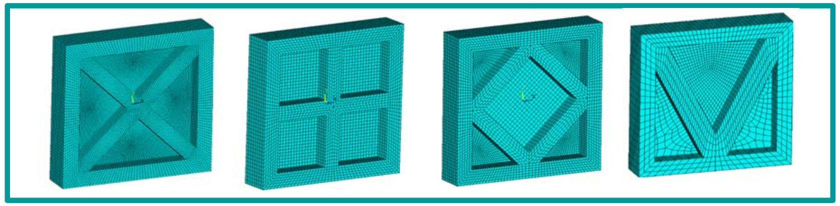
Loading way



Force path



Four kinds of structural units



Static performance of structural unit

Load type	Pull force/ Pressure	Vertical bending moment	Horizontal bending moment	Torque
Unit type	Stiffness and mass ratio （1/kg*mm）	Stiffness and mass ratio （1/kg*mm）	Stiffness and mass ratio （1/kg*mm）	Stiffness and mass ratio （1/kg*mm）
X	24.73	2.14	29.24	22.01
◇	27.15	2.15	29.18	22.43
十	37.26	2.50	21.45	16.90
V	30.84	2.45	25.41	21.38

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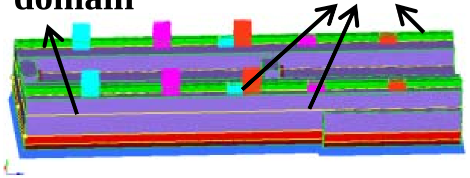
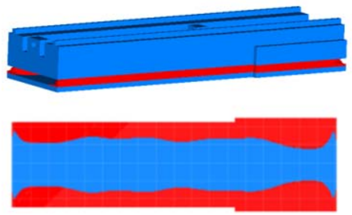
4.1 Connection structure design

The part connection constraints, the main and sub-structure configuration and the feature size optimization design are carried out with a gantry machining center bed.

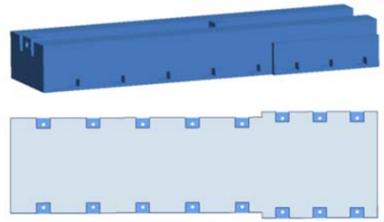
Topology optimization



Physical optimization models of bed bolt connection structure



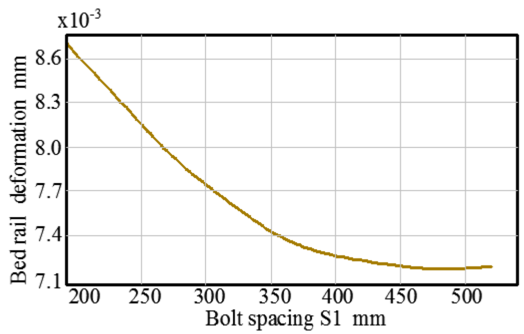
Constraint domain



Connection structure

Size optimization

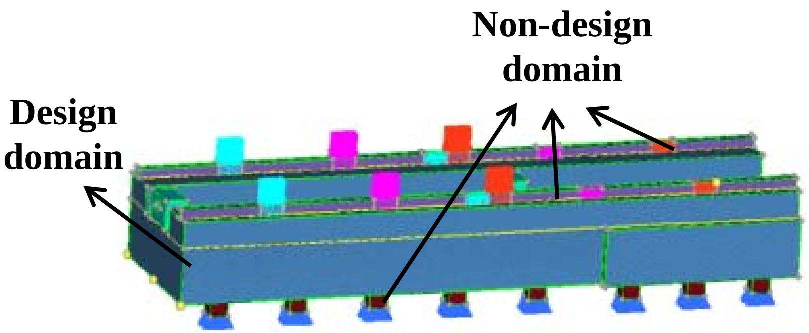
Objective:
Maximum deformation of the bed rail
Constraints:
Size constraints
Variable:
Bolt spacing



Relationship between bolt spacing and maximum deformation of bed guide

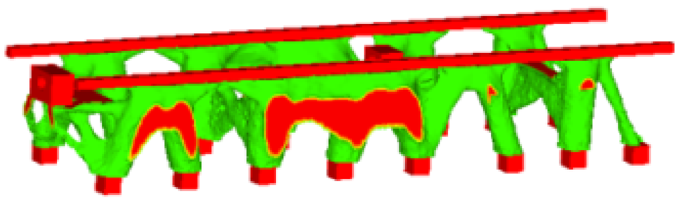
Optimized bolt spacing

4.2 Main structure design

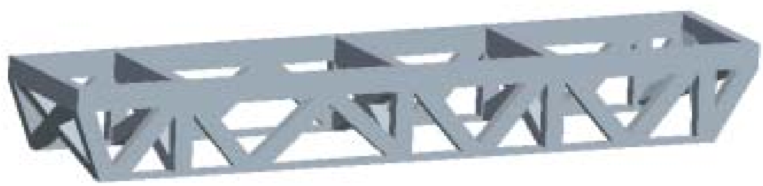


Physical optimization model of bed main structure

The main force path obtained by topology needs to further rectify following the **Configuration symmetry**, **Configuration path closure** , and **Configuration path consistent rules** to eventually realize the design from the force transmission path to the structure.



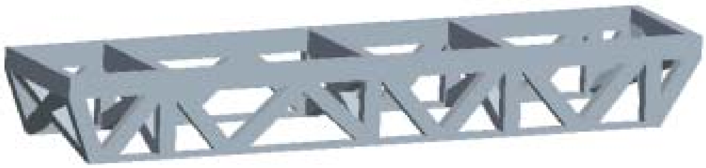
Force path of bed main structure

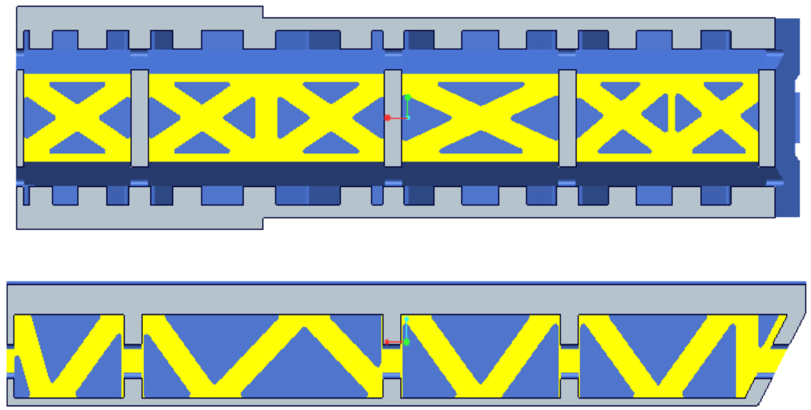


Rectified force path

4. Design example

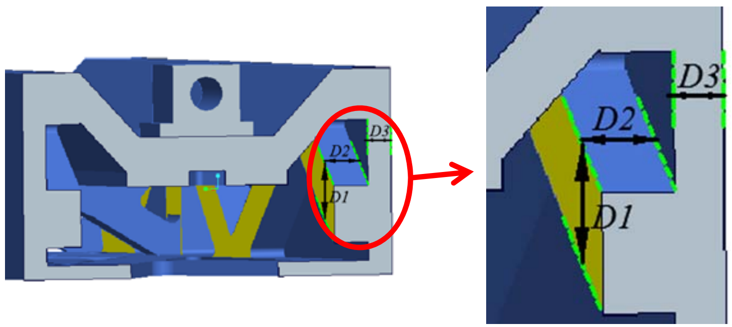
4.3 Sub-structure design





As the upper wall of the bed is mainly subjected to bending moments, the **"X" structural unit** is added to the upper wall of the bed.

Feature size optimization



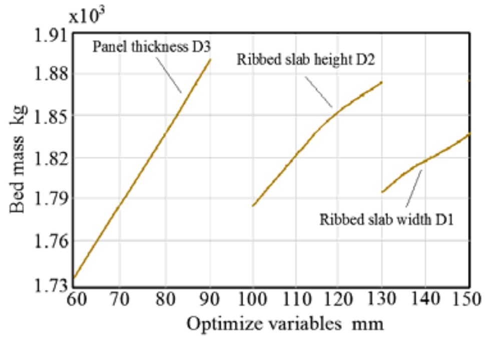
Objective:
Minimum bed mass and rail deformation

Constraints:
Size constraints

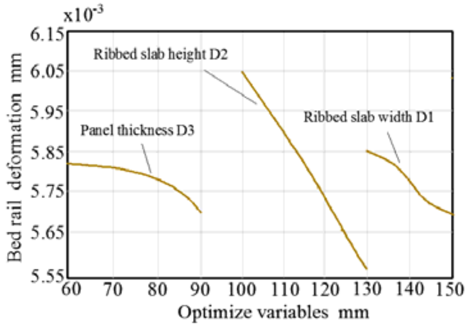
Variable:
Ribbed slab width *D1*
Ribbed slab height *D2*
Panels thickness *D3*

4. Design example

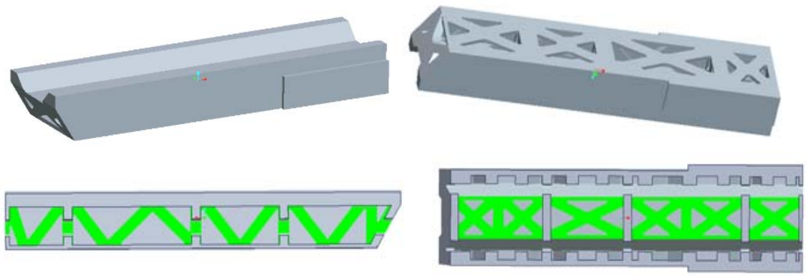
4.3 Sub-structure design



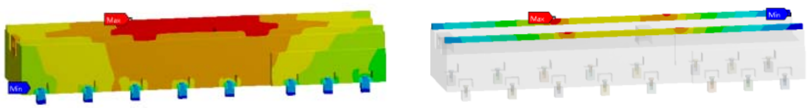
The relationship between the variable and bed mass



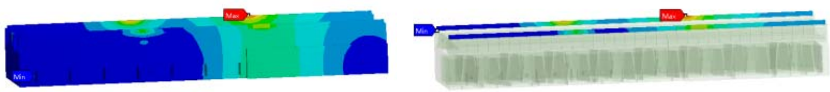
The relationship between the variable and bed rail deformation



The new bed structure



Deformation cloud of original bed



Deformation cloud of optimized bed

Comparison of Bed Performance

Mass	Original bed	Optimized bed	Optimization percentage
Mass(t)	18.5t	17.1t	8%
Total deformation (mm)	0.0081	0.0080	1%
Rail deformation (mm)	0.0062	0.0059	5%

5.Conclusions

(1) The proposed light-weight design can effectively obtain **structure configuration** and **main feature size** under multi-condition. The method can be performed through **topology and size optimization** of connection structure, main structure, and sub-structure design.

(2) The load and constraint domain of part (joint surface) directly **affect the optimization results of structure**. And the load ratio of different directions affects the optimization results of constraint domain distribution.

(3) The optimized bed **is lighter 8%** than original bed, and the rail deformation is **reduced by 5%.** The design method proposed is effective and reasonable.

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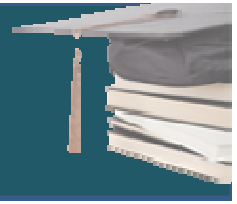

Thanks!