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Abstract：This study considers multiple volume fraction values as constraints and establishes a mathematical model with the objective of minimizing structural compliance (maximizing stiffness) to carry out lightweight design of joints.By analyzing isosurface maps of elements in the joint design domain, the elemental density threshold at which the elements are most efficient in load bearing and the stress distribution is relatively uniform is identified; that is, the topological shape is reasonable. Static analysis is performed on the joints with reasonable topological shapes and compared with the original joint to investigate whether the mechanical performance of the topologically optimized joint is significantly reduced and how effective the weight reduction is. Finally, the topology optimization design of cast steel branching joints under each volume fraction constraint is verified. By comparing and analyzing the mechanical performance of the topologically optimized cast steel branching joints under different volume fraction constraints, the optimal topological form under different volume fraction constraints is determined, the most reasonable target volume fraction is found, and the most suitable new topological configuration is determined.

Keywords: volume fraction; topology optimization; tree-like structure

0 Introduction

Large-span hub buildings widely adopt tree-like bionic structural forms. Such structures generally use integrally cast steel branching joints to realize the convergence and load transfer of multiple members. These joints are integrally cast, with smooth curved surfaces and no welded joints, and their load transfer paths are continuous. They are key load-bearing components in tree-like steel structures [1–4]. Fig.1a shows a typical cast steel branching joint. As a key load-bearing component of the structure, the joint plays a core role in the convergence of multiple members and load transfer, and its mechanical performance and material utilization directly affect the overall efficiency of the structure. Traditional empirical design easily leads to excessive self-weight and significant stress concentration of joints.Topology optimization has become an important technical approach for achieving lightweight joints and rationalized load bearing. Fig.1b shows a typical lightweight-designed joint at Suzhou South High-speed Railway Station, which to a certain extent achieves weight reduction of cast steel joints.



Figure 1a Typical cast steel fork node



Figure 1b Lightweight fork node at Suzhou South Station

At present, topology optimization research on cast steel branching joints mostly uses a single preset volume fraction for calculation.Based on the variable density method, it explores the effects of parameters such as penalty factors, checkerboard suppression, and geometric size constraints on the optimized shape. Some studies combine metal additive manufacturing technology to complete the printing and forming of complex topological entities. Due to the limited samples of empirical analysis, when assuming the volume fraction, this value is not necessarily the most reasonable. Considering only a single volume fraction value as a constraint cannot fully meet the design requirements of cast steel branching joints. Considering multiple volume fraction values as constraints, comparing and analyzing the mechanical performance of cast steel branching joints after topology optimization, and finding the most reasonable target volume fraction are problems that urgently need to be solved.

1 Topology Optimization Theory

According to the degrees of freedom of design variables from low to high, structural optimization can be divided into four categories: size optimization, shape optimization, topography optimization, and topology optimization. Topology optimization is at the highest optimization level. It can re-plan the material distribution and load transfer path within a specified design space without relying on the initial shape, maximizing the lightweight potential. It is the core tool for solving the weight reduction problem of complex cast steel branching joints [5].

1.1 Basic Theory

Continuum topology optimization refers to reallocating material distribution in the design domain through numerical iteration under given joint geometric design domain, external load cases, and boundary constraints, reconstructing the optimal load-bearing skeleton, and reducing redundant material while controlling structural strain energy (compliance), thereby simultaneously improving overall stiffness and material utilization efficiency. The new cast steel joints generated by topology optimization can be directly processed into solid models by combining 3D printing technology, adapting to the integrated forming requirements of complex curved surfaces.

1.2 Mathematical Model

For three-dimensional solid cast steel joints, the most mature solution method in engineering is the solid isotropic material with penalization (SIMP) variable density method. This method discretizes the overall design domain into a large number of

tetrahedral finite elements, introduces the relative density of elements continuously varying in the range of 0–1 as design variables, and assumes that the equivalent elastic modulus of an element and its density satisfy a mapping relationship. Under loads, the density of elements undertaking the main load transfer task approaches 1, while the density of redundant low-contribution elements approaches 0. Intermediate-density elements complete stiffness conversion through an interpolation formula. After iteration, material automatic selection is realized based on the elemental density distribution, generating a clear solid–void topological shape[6]. The topology optimization mathematical model consists of three core elements: design variables, objective function, and constraints. Commercial finite element optimization software completes iterative solutions based on this framework.A general mathematical model for a typical engineering topology optimization problem can be expressed as [7]:

$$\begin{cases} \text{find } X=\{x_1,x_2,x_3,...,x_i\}^T \in \Omega \\ \min\ f(X) \\ s.t.\ g_j(X)\le 0, j=1,...,\mathrm{m} \\ \quad \mathrm{F}=\mathrm{KU} \\ \quad 0\le x_{\min}\le x\le x_{\max}\le 1 \quad (i=1,\cdots,N) \end{cases} \tag{1}$$

In Eq.(1), $X=\{x_1,x_2,x_3,...x_i\}$ represents all elemental density design variables; X lies within the design variable set Ω; $f(x)$ is the optimization objective function;$g_j(X)$ represents the j-th constraint equation, and m is the number of constraint equations; U is the structural displacement vector, F is the external load vector, and K is the overall stiffness matrix of the structure; x_{min} and x_{max} are the lower and upper limits of the design variables, respectively, and i is the number of elements.

Cast steel branching joints bear vertical concentrated loads, and the overall structural stiffness is the core control index. Therefore, the minimum total structural compliance is selected as the optimization objective, and the volume fraction is used as the constraint to establish the optimization model. The design variable is the assumed elemental density, which represents the degree to which the load-bearing capacity of the element is utilized [7]. Its mathematical model is:

$$\begin{cases} \min\ \mathrm{C}(x)=\dfrac{1}{2}U^T KU \\ s.t.\ KU=F \\ \quad V(x)\le V^* \\ \quad 0\le x_{\min}\le x\le x_{\max}\le 1 \quad (i=1,\cdots,N) \end{cases} \tag{2}$$

In Eq.(2), x is the elemental relative density design vector; U is the structural overall displacement column vector;F is the external load vector; C(x) is the total structural compliance; K(x) is the density-related overall stiffness matrix; V(x) is the optimized solid volume; V_0 is the total volume of the original design domain; V^* is the preset volume fraction constraint limit; n is the total number of finite elements; x_{min} and x_{max} are the lower and upper limits of the design variables, respectively, and i

is the number of elements.

2 Finite Element Analysis of the Original Joint

This numerical simulation uses SolidWorks for three-dimensional solid modeling, and selects the most widely used four-branch cast steel spherical joint in engineering as the research object. Finite element preprocessing and topology iteration calculations rely on Altair's HyperWorks platform (HyperMesh preprocessing & OptiStruct solver). Similar mainstream tools include Tosca Structure.

2.1 Establishment of Geometric Model

In large hub buildings, cast steel branching joints are mostly two-branch, three-branch, or multi-branch joints according to the needs of building space. This paper focuses on the most widely used four-branch joint. The geometric parameters and geometric model of the joint are shown in Fig.2.

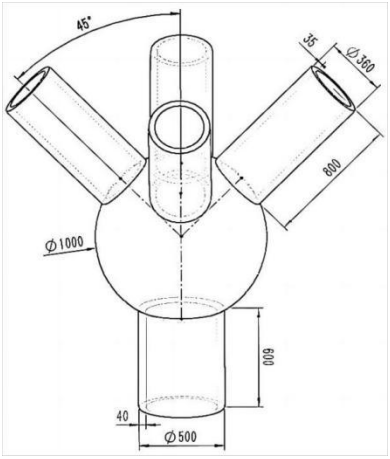


Fig.2 Geometric model of a four-branch cast steel joint

2.2 Model Preprocessing

After exporting the STEP universal format file, it is imported into HyperMesh for finite element preprocessing. During modeling, the component is divided into two regions: the middle spherical region is the topology optimization design domain, and the branching pipes on both sides are non-optimized reserved regions. Material redistribution optimization is performed only on the spherical region. Material properties are assigned to the model, and then meshing is carried out. During meshing, the Max tetra size is set to 20 mm to ensure uniform meshing and stable calculation accuracy in the core spherical region. Table 1 shows the basic information of the finite element models of three types of joints.

Table 1 Summary of finite element models of joints

Total volume		Total mass		Total number of nodes		Total number of elements	
design domain	non-design domain	design domain	non-design domain	design domain	non-design domain	design domain	non-design domain
6.711		5.268		564262		3019235	
5.235	1.476	4.109	1.158	365028	202175	2103296	915939

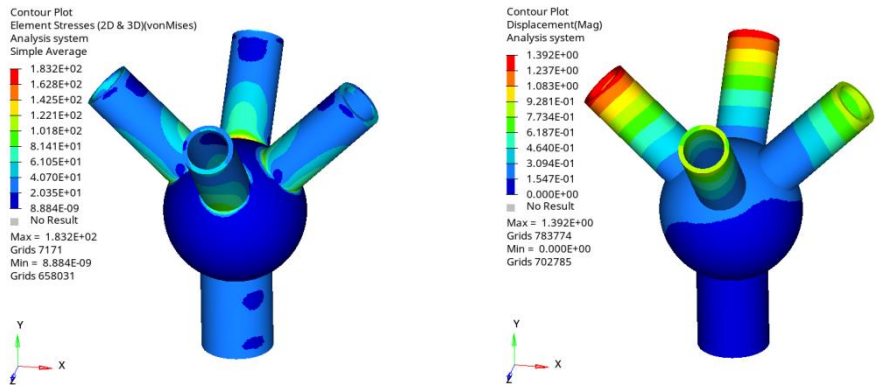
（Note: volume unit is 10^8 mm^3, mass unit is ton.）

Boundary constraints and loads are applied. The bottom of the main pipe is fully constrained in six degrees of freedom, and a vertical downward 1 kN concentrated

load is applied at the top of each branch pipe, simultaneously simulating the coupled loading condition of axial force and additional bending moment in actual engineering.

2.3 Finite Element Analysis

Run the OptiStruct function in the Analysis module of HyperMesh. In the OptiStruct card, select analysis in run options to perform finite element analysis of the original model. The calculation results are shown in Fig.3.



（1—Nodal Von Mises stress/Mpa; 2—Nodal displacement/mm)

Fig.3 Finite element analysis results of the joint

The finite element calculation results show that the maximum von Mises equivalent stress of the four-branch cast steel joint is 183.2 MPa. The high stress concentration area is concentrated in the transition section where the branch pipes intersect the middle sphere. The maximum vertical displacement is 1.392 mm, occurring at the free ends of the branch pipes. The displacement gradually decreases from the branch pipes toward the sphere. The overall stress level in the core spherical region is relatively low, and there is sufficient room for material reduction and optimization.

3 Topology Optimization Design of Cast Steel Branching Joints

Topology optimization design is carried out for four-branch joint models under volume fraction constraints of 30%, 40%, and 50%, respectively. First, the topological shape corresponding to each elemental density threshold is observed to determine a relatively reasonable elemental density threshold range and select a preliminary topology optimization result. Static analysis is then performed on the preliminary results, and the most reasonable elemental density threshold is obtained through comparative analysis of the results, thereby determining the optimal topological shape.

3.1 Parameter Settings

Optimization parameters directly affect the smoothness and numerical stability of the topological configuration. This paper focuses on setting two core parameters: penalty factor and checkerboard suppression.The stiffness penalty factor refers to similar cast steel joint optimization literature. When it is taken as 3.0, the optimized configuration has no fine holes and the curved surface is continuous and full. Therefore, the penalty factor is finally set to 3.0. The variable density method is prone to the numerical defect of periodic density distribution of elements. Global checkerboard suppression is enabled, and the CHECKER control parameter is set to

1.0 to ensure uniform density distribution and continuous smooth boundaries. In this optimization, three gradient volume fraction constraints of 30%,40%, and 50% are set, with the minimum structural compliance uniformly taken as the objective function, and three groups of topology iteration calculations are completed respectively.

3.2 Elemental Density Isosurface Analysis Results

This paper takes the commonly used 40% volume constraint condition in engineering as the research object to analyze the topological forming characteristics of four-branch cast steel joints.With the help of the HyperView post-processing module of HyperWorks software, the topology optimization elemental density results can be intuitively output. In this analysis, the data statistics method is set to simple average, and only the element distribution above the threshold is displayed.By adjusting the density threshold, isosurface contour maps under different conditions can be obtained. Due to space limitations, the image results are not shown one by one in this paper.

The elemental density isosurface can intuitively reflect the material retention law under different thresholds. Different color regions represent effective elements under the corresponding density standard, clearly reflecting the joint topological form. Preliminary trial calculations show that elements with density lower than 0.5 have low material utilization and strong redundancy. Therefore, only three parameters, 0.1,0.3, and 0.5, are selected for comparison in the low-threshold range. When the threshold is greater than or equal to 0.1, the material distribution of the model is basically consistent with the original joint, with no obvious optimization effect; when the threshold is raised to 0.3, the blue region of the model fades, and the overall model appears light blue; when the threshold reaches 0.5, the model turns light green, and the joint initially forms a topological configuration, but the contour features are not yet obvious.

To fully capture the evolution law of the topological structure, five groups of high-density thresholds, 0.6,0.7,0.8,0.9,and 1.0, are further selected for refined analysis. When the threshold is greater than or equal to 0.6, low-efficiency elements are removed, and the topological contour of the joint gradually becomes clear; when the threshold is greater than or equal to 0.7, invalid elements are basically eliminated, and the load transfer path becomes clearer; when the threshold reaches 0.8, high-efficiency load-bearing elements are fully retained, the structural surface is smooth, and the topological forming effect is optimal; when the threshold is greater than or equal to 0.9, the model only retains the high-load-bearing red core elements, and the load transfer characteristics are clear, but the structural surface begins to become rough and local defects are likely to occur; when the threshold is 1.0, the model only retains the most efficient load-bearing elements. Although the load-bearing contribution rate is the largest, the surface roughness problem is significant, which can easily induce stress concentration.

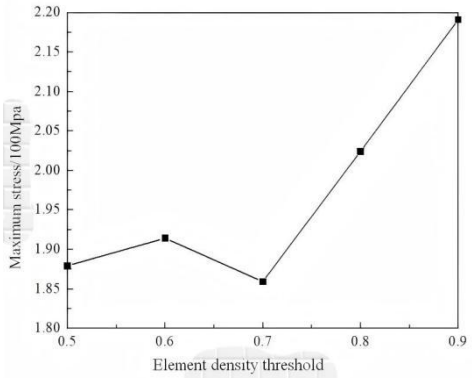
By comparing the topological forming effects corresponding to each threshold, it can be seen that the configuration in the low-density range has a large amount of redundant material, poor lightweight effect, and low engineering applicability. Considering material utilization, forming quality, and structural safety

comprehensively, this paper selects the topological configurations in the density range of 0.5–0.9 for model reconstruction and post-processing, and conducts static performance analysis on the optimized new joints to further verify the mechanical reliability of the optimized configuration.

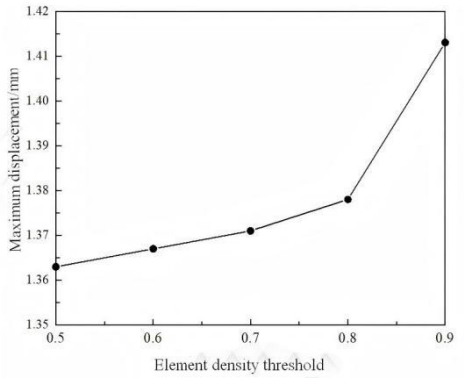
Considering the surface smoothness, material utilization, and stress concentration risk comprehensively, the density threshold range of 0.5–0.9 is selected for subsequent static verification, focusing on comparing the mechanical differences between the two key thresholds of 0.8 and 0.9.

3.3 Static Analysis of Topology Optimization Models

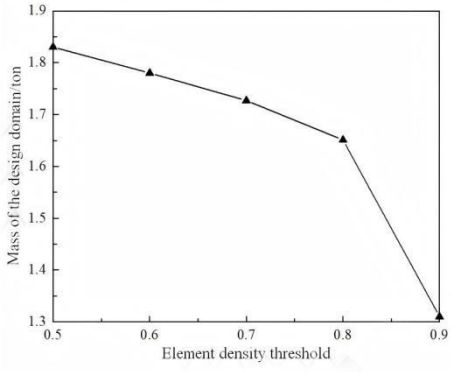
For a selected topological shape, it is necessary to use the post-processing function of HyperMesh software to smooth the model and re-divide the mesh, keep the load magnitude and boundary conditions unchanged, and perform static analysis on the topology optimization joints corresponding to elemental density values from 0.5 to 0.9. The stress and displacement of each joint are collected and organized, as shown in Fig.4.



（1—Variation of maximum Mises stress）



（2—Variation of maximum displacement）



（3—Variation of mass of optimized design domain）

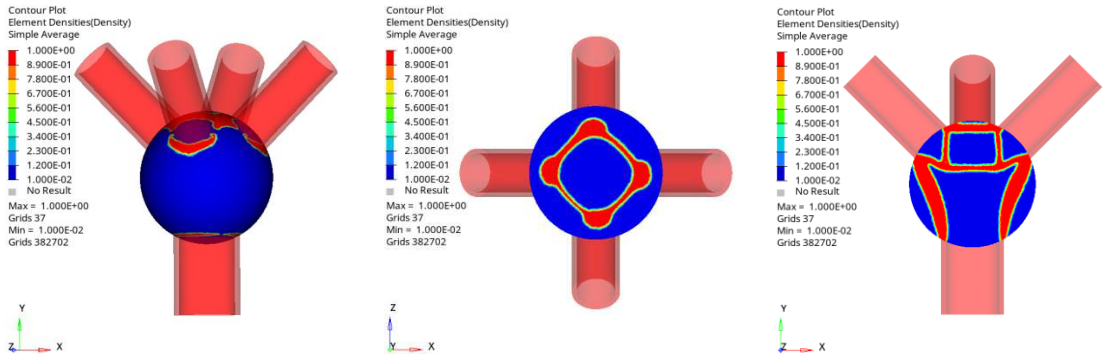
Fig.4 Analysis result charts of topological configurations corresponding to different elemental density thresholds

It can be seen from Fig.4 that when the elemental density threshold varies from 0.5 to 0.7, the maximum von Mises stress does not change significantly, basically distributed around 188 MPa, and the displacement is distributed around 1.360 mm, with a very small variation range. When the elemental density threshold changes from 0.7 to 0.8, the stress increases by 8.87%, and the displacement increases by only 0.5%.

When the elemental density threshold reaches 0.9, the stress increases by 8.25%, and the displacement increases by 2.5%. The safety margin is lower than that when the elemental density threshold is 0.8. The mass of the design domain gradually decreases when the elemental density threshold is from 0.5 to 0.8, and the change is relatively uniform, with an average mass reduction of about 2.8%. When the elemental density threshold reaches 0.9, the mass decreases by 26%. When the elemental density threshold is 0.8, the maximum von Mises stress, maximum displacement, and design domain mass changes are relatively stable, the element distribution is relatively uniform, the topological structure surface has no obvious roughness, and there is no obvious stress concentration. At this time, the lightweight design effect is good, the element weight reduction is obvious, and there is a certain safety margin. When the elemental density threshold is 0.9, the maximum displacement and design domain mass both show obvious abrupt changes, which will produce stress concentration in the topological model and reduce the safety margin. Therefore, the topological shape when the elemental density threshold is 0.8 is taken as the final optimization result. For two-branch and three-branch cast steel joints, by analogy with the four-branch joint, the topology optimization result corresponding to the elemental density threshold of 0.8 is taken as the final topological shape.

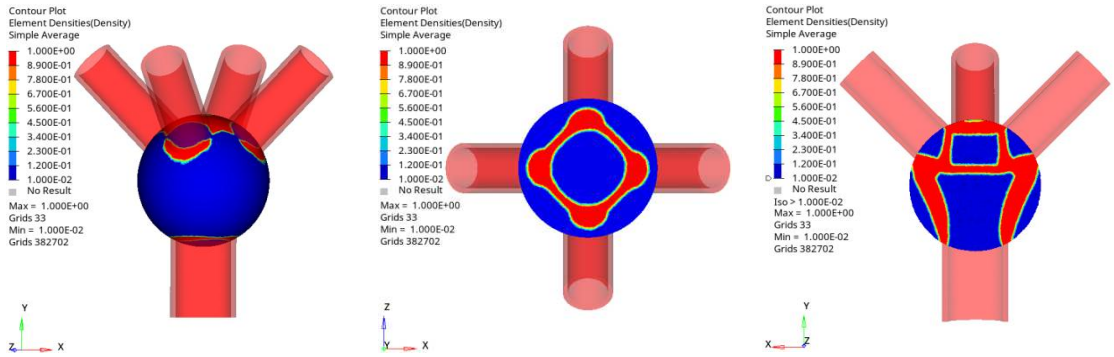
3.4 Elemental Density Static Contour Analysis

Figs.5–7 show the elemental density static contour maps under different volume fraction constraints. As the volume fraction gradually increases, more material is retained. In the overall elemental density contour map, the red high-efficiency elements at the upper and lower ends are separated when the volume fraction is 30%. When the volume fraction reaches 40%, the red elements gradually approach and tend to merge. When the volume fraction reaches 50%, the red elements have completely merged. In the XZ section, the middle load transfer skeleton is initially ring-shaped, and four supporting stiffening ribs are formed at the branch pipes around the ring. Their size is obviously larger than the ring, playing a stiffening role. When the volume fraction reaches 40%, the middle ring becomes thicker, and the cross-sections of the four supporting stiffening ribs formed at the branch pipes around the ring become fuller, gradually forming the main transfer path of axial force. When the volume fraction reaches 50%, the middle ring becomes thicker, and the four supporting stiffening ribs formed at the branch pipes around the ring merge with the ring, forming a common main transfer path. In the XY section, at 30% volume fraction, a load transfer skeleton has just formed, but the size of the skeleton is small; at 40% volume fraction, the skeletons on both sides gradually become fuller; at 50% volume fraction, the skeleton size is larger, and the retained material is the most.



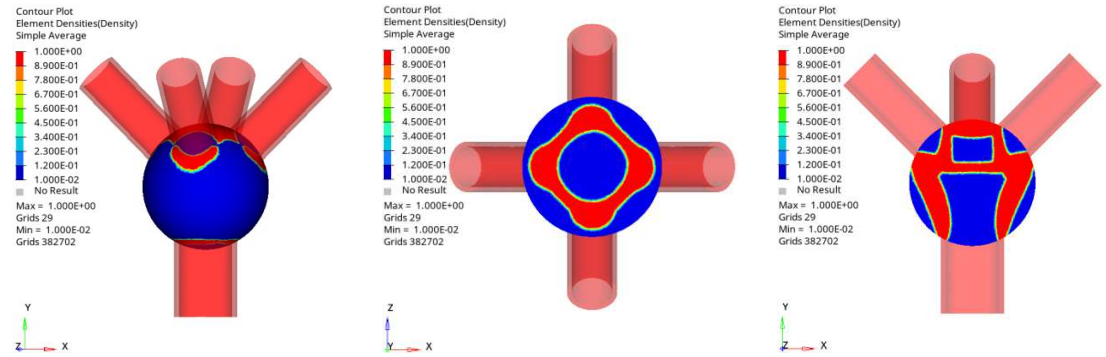
(1—Joint elemental density static contour map; 2—XZ section elemental density static contour map; 3—XY section elemental density static contour map)

Fig.5 Elemental density static contour map with volume fraction 30%



(1—Joint elemental density static contour map; 2—XZ section elemental density static contour map; 3—XY section elemental density static contour map)

Fig.6 Elemental density static contour map with volume fraction 40%

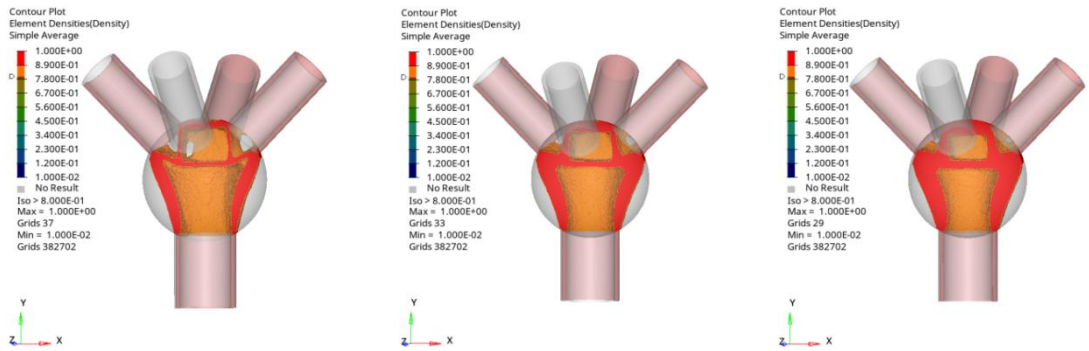


(1—Joint elemental density static contour map; 2—XZ section elemental density static contour map; 3—XY section elemental density static contour map)

Fig.7 Elemental density static contour map with volume fraction 50%

3.5 Determination of Optimal Topological Shape

When the elemental density threshold of topology optimization is 0.8, the obtained topological shape is relatively reasonable. The four-branch joint is topologically optimized under volume fraction constraints of 30%, 40%, and 50%, respectively, and the topological forms under different volume fractions are obtained. To facilitate observation of the internal structure of the topological form, section views of the topological form are output, as shown in Fig.8.



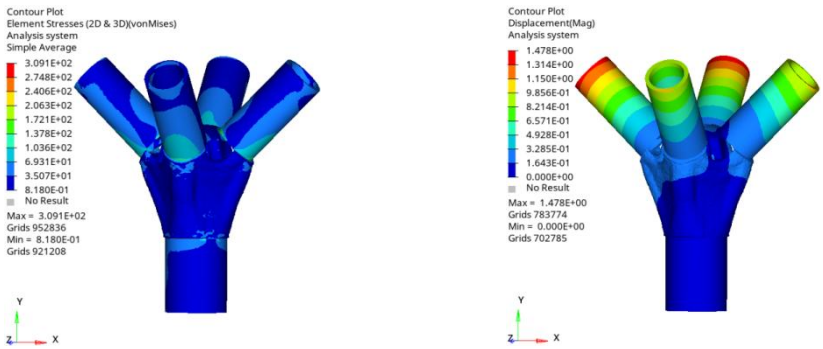
（1—Volume fraction 30%；2—Volume fraction 30%；3—Volume fraction 30%）

Fig.8 Final topological form section views of the four-branch joint under different volume fractions

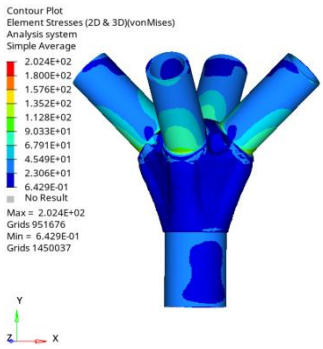
4 Method for Determining the Target Volume Fraction

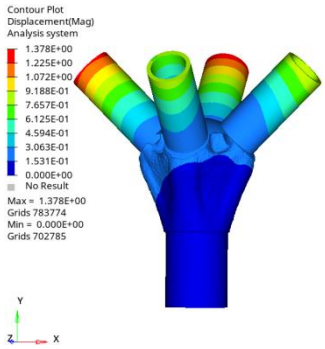
4.1 Finite Element Analysis Results of Topological Configurations

Under volume fraction constraints of 30%,40%,and 50%, the optimal topological shapes of the four-branch cast steel joint are smoothed and re-meshed. With the same loads and boundary conditions as the original joint, the calculation results are shown in Fig.9. Under the 30% volume fraction constraint, the maximum von Mises stress of the four-branch cast steel joint is 309.1 MPa, mainly distributed at the junction between the branch pipes and the middle spherical topological shape, while the stress at other positions is relatively small, and the stress distribution is uneven. The maximum displacement is 1.478 mm, at the free ends of the branch pipes. Under the 40% volume fraction constraint, the maximum von Mises stress is 202.4 MPa, mainly distributed at the junction between the branch pipes and the middle spherical topological shape. The stress distribution is relatively uniform, the material strength is fully utilized, and there is no obvious stress concentration. The maximum displacement is 1.378 mm, at the free ends of the branch pipes, gradually decreasing from top to bottom. Under the 50% volume fraction constraint, the maximum von Mises stress is 191.3 MPa, mainly distributed at the junction between the branch pipes and the middle spherical topological shape. The stress distribution is relatively uniform, with no obvious stress concentration. The maximum displacement is 1.352 mm, occurring at the free ends of the branch pipes, and the displacement in the middle topology optimization part is small.

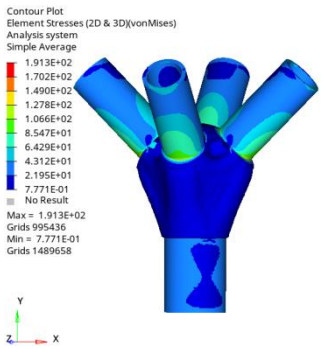


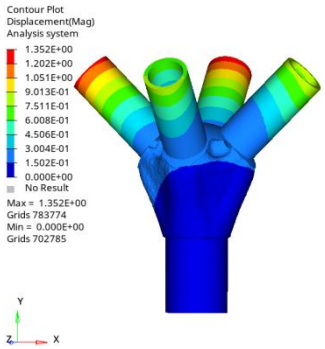
（1—Stress at volume fraction 30%; 2—Displacement at volume fraction 30%）





（3—Stress at volume fraction 40%; 4—Displacement at volume fraction 40%）





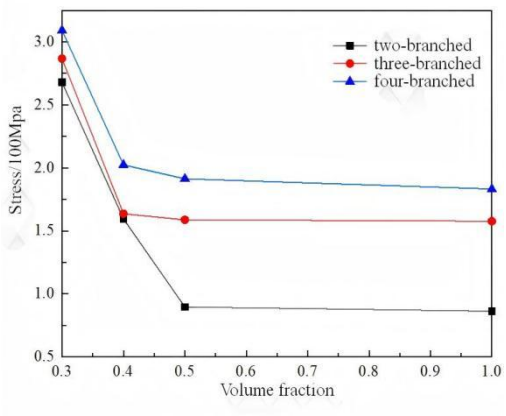
（5—Stress at volume fraction 50%; 6—Displacement at volume fraction 50%）

Fig.9 Static calculation results of the topology optimization model of the four-branch joint

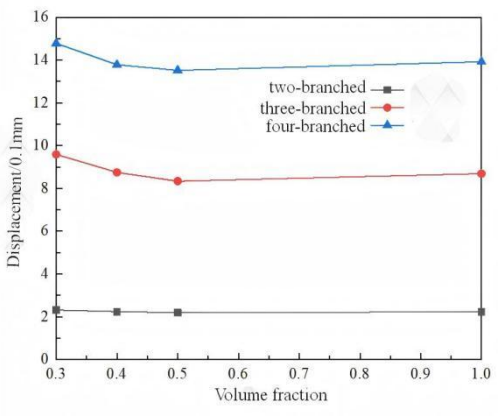
For the four-branch joints under the three volume fraction constraints, the displacement under the 30% volume fraction is 7.26% larger than that under the 40% volume fraction. From 40% to 50% volume fraction, the displacement change is small. The displacement under the 30% volume fraction is slightly larger, and the joint compliance tends to be stable, indicating that the compliance of the topological shape basically converges to the minimum value. The maximum von Mises stress under the 30% volume fraction constraint is relatively large. Because the least material is retained, stress concentration is inevitably generated, and the stress level of individual elements exceeds the stress constraint. The maximum von Mises stress under the 50% volume fraction constraint is relatively small, and the stress distribution is very uniform, but the material consumption is relatively large. Compared with the stress under the 50% volume fraction constraint, the maximum von Mises stress under the 40% volume fraction constraint is slightly increased, the material strength is more fully utilized, the stress distribution is relatively uniform, and the material consumption is also optimized.

4.2 Determination of Target Volume Fraction

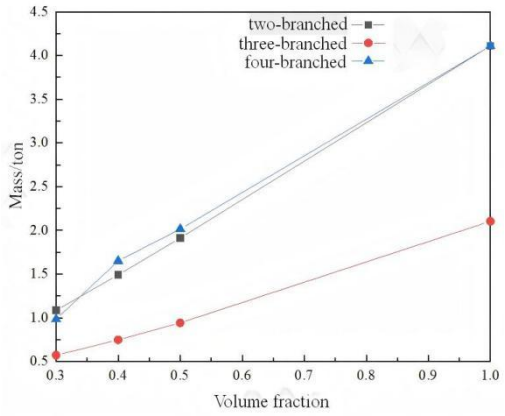
To make the calculation results of the four-branch cast steel joint more statistically reliable, under the same conditions, the calculation results of two-branch and three-branch joints are obtained according to the method for the four-branch joint. The mechanical calculation results of the topological shapes obtained after supplementing the two types of joints are shown in Fig.10. Since the original joint has not been topologically optimized, its volume fraction is set to 1.0 for comparison.



（1—Comparison diagram of maximum Mises stress）



（2—Comparison diagram of maximum displacement）



（3—Comparison diagram of mass in intermediate optimized design domain）

Fig.10 Mechanical performance results of topological shapes under different volume fraction constraints

In Fig.10(1), it can be seen that the maximum von Mises stress of the topological configurations of two-branch, three-branch, and four-branch joints gradually increases as the volume fraction decreases. The stress level variation laws of the three types of joints are basically consistent. When the volume fraction is 30%, individual elements of the three types of joints have a certain stress concentration phenomenon; when the volume fraction is 40% or 50%, the stress distribution is relatively uniform, and the stress changes of two-branch and three-branch joints are smoother than that of the four-branch joint. The stress level at 50% volume fraction is closest to that of the original joint, but the material retention is greater than the former two, and the lightweight design is inferior to the former two; the stress levels at 30% and 40% volume fractions are higher than that of the original joint. From the perspective of stress level, the topological shape at 40% volume fraction is the most reasonable, which not only ensures that the stress result does not exceed the stress constraint, but also realizes the lightweight design of the joint, and the material strength is fully utilized.

In Fig.10(2), while carrying out lightweight design, the joint displacement changes little, and the stiffness is guaranteed. As the volume fraction decreases, the

displacements of the three types of joints gradually increase, and the variation laws remain consistent, proving the authenticity of the topology optimization results. The joint displacements of the topologically optimized configurations of the three types of joints do not change much compared with the original joint, which meets the expected effect.

In Fig.10(3), the mass of the design domain of the three types of joints after topology optimization decreases as the volume fraction decreases, and the variation laws are basically consistent.Under the 50% volume fraction constraint, the two-branch joint is reduced in weight by about 53.4%, the three-branch joint by about 55.2%, and the four-branch joint by about 51%; the three-branch joint has the most obvious weight reduction.Under the 40% volume fraction constraint, the two-branch joint is reduced in weight by about 63.7%, the three-branch joint by about 64.4%, and the four-branch joint by about 59.8%; the three-branch joint has the most obvious weight reduction. Under the 30% volume fraction constraint, the two-branch joint is reduced in weight by about 73.6%, the three-branch joint by about 72.8%, and the four-branch joint by about 76.1%; the four-branch joint has the most obvious weight reduction.

The stiffness changes of the joints under the three volume fractions are small and basically consistent with the original joint. However, the 30% volume fraction constraint topological configuration has a certain stress concentration phenomenon, and the stress distribution is uneven; the 50% volume fraction constraint topological configuration has the most obvious weight reduction, but the topological shape is not light and beautiful enough;the 40% volume fraction constraint topological configuration has uniform stress distribution, the stress level meets the stress constraint conditions, and the weight reduction is relatively obvious,and the topological shape is beautiful. Considering comprehensively, the topological result under the 40% volume fraction constraint is the optimal result, that is, the target volume fraction.

5 Conclusions

(1)Taking the four-branch cast steel joint as an example, new topology optimization configurations with elemental density thresholds of 0.5–0.9 were obtained. By comparing and analyzing the mechanical characteristics of these new configurations, the target elemental density threshold was determined to be 0.8, and the topology optimization result at this time is the most reasonable.

(2) Under volume fraction constraints of 30%, 40%, and 50%, by comparing the mechanical results of the new topological configurations of the four-branch joint under different volume fraction constraints, the target volume fraction was found to be 40%. This analysis method was extended to two-branch and three-branch joints, and it was also verified that a volume fraction of 40% is the most reasonable, which can provide a certain reference for engineering practice.

(3) Due to limited conditions, the loads and boundary conditions in this study are relatively simple. The next step will be to study the topology optimization of cast steel branching joints under other loads and boundary conditions as well as multiple load cases, so as to enrich the theory and practice of topology optimization of cast steel

joints.

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Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author (691221201@qq.com) on reasonable request.

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