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Research on connection structure of aluminumbody bus using multi-objective topology optimization

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Abstract. For connecting Aluminum Alloy bus body aluminum components often occur the problem of failure, a new aluminum alloy connection structure is designed based on multi-objective topology optimization method. Determining the shape of the outer contour of the connection structure with topography optimization, establishing a topology optimization model of connections based on SIMP density interpolation method, going on multi-objective topology optimization, and improving the design of the connecting piece according to the optimization results. The results show that the quality of the aluminum alloy connector after topology optimization is reduced by 18%, and the first six natural frequencies are improved and the strength performance and stiffness performance are obviously improved.

1. Introduction and background

Aluminum body is an ideal method to reduce weight in the development of a new energy bus. Owing to its low density and good mechanical properties, aluminum alloy could gradually replace steel as a dominant material of vehicles; however, due to the limited elastic modulus and poor welding characteristics, the reliability of aluminum body has been a great concern for the vehicle manufacturers.

In order to improve the reliability of aluminum structure, some replaceable connection methods were proposed and applied in the industry including riveted, bolted, bonded and composite connections [1]. Current aluminum body bus is mainly composed of extrusion parts and connected with mechanical joints, the strength, stiffness and longevity could hence strongly be related to the robustness of joint. Several academics and engineers proposed several types of joints to connect the extrusion components, Jia [2] invented a kind of frame connector structure, medium sized jointis used in the position of the bus frame below the window and the side door. Zheng [3] provided a kind of riveted structure of aluminum body. The shearing force of rivet is reduced by setting groove, so as to improve the service life and stability of rivets. Luo [4] released a skeleton connecting piece of aluminum body bus with simple process, high installation efficiency and good connection and fixation effect. However, the comprehensive performance of the joints with practical conditions of aluminum body bus need to be further investigated.

2. Multi objective topology optimization numerical simulation

The SIMP method based on isotropic materials, and no need to introduce microstructures and additional homogenization processes. The relative density of discrete element in the finite element model design space as the design variables, and assuming that the material parameter is constant inside the unit [5]. The material property of discrete element varies with the relative density of unit, and the relation form is shown in formula (1):

$$\begin{cases} E = (a_e)^{\Theta} E_0 \\ K = (a_e)^{\Theta} K_0 \\ M = a_e M_0 \end{cases} \tag{1}$$

In the formula, a_e is relative density of discrete element. E、E_0 is elastic modulus before and after unit optimization. K、$K_0$is the stiffness matrix before and after optimization. M、M_0 is the mass matrix before and after optimization. Θ is penalty coefficient.

2.1. *objective function*

The structural stiffness and the first 3 order low order natural frequencies of aluminum alloy structures under different working conditions are comprehensively considered. The multi-objective optimization problem is transformed into a single objective optimization problem by the compromise programming method.Then in order to transform the objective function into the minimum value problem, ϒ(σ) = -Λ(σ).Finally, the optimization model which satisfies both the stiffness and the natural frequency optimization objective is obtained:

$$\begin{cases} \min P(\sigma) = \left[\psi^2 (\frac{C(\sigma) - C^{\min}}{C^{\max} - C^{\min}})^2 + (1-\psi^2)(\frac{\Upsilon(\sigma) - \Upsilon^{\min}}{\Upsilon^{\max} - \Upsilon^{\min}})^2 \right]^{\frac{1}{2}} \\ s.t. V(\sigma) - \bar{V} \le 0 \\ 0 < \sigma_j < 1 \\ j = 1, ..., l \end{cases} \tag{2}$$

In the formula, $P(\sigma)$ is comprehensive objective function. $\Upsilon^{\max}$ 、 $\Upsilon^{\min}$ is the maximum and minimum value of $\Upsilon(\sigma)$. The meaning of other parameters is consistent with the previous definition.

2.2. *Sub objective weight*

The analytic hierarchy process combines qualitative and quantitative analysis, and solves the multi-objective problem based on strict mathematical theory [6, 7]. According to the problem that the designer wants to evaluate, the decision hierarchy is established. Then, the weights of the factors are solved by the method of paired comparison, and the importance degree between the working conditions is compared. Then the decision matrix is constructed. The weight value of 7 sub objectives is obtained.

$$\Psi = [0.27 \quad 0.13 \quad 0.14 \quad 0.20 \quad 0.09 \quad 0.09 \quad 0.08] \tag{3}$$

3. Multi objective optimization design of connectors

3.1. *Connection structure and load analysis*

In the initial stage of design, the connection structure of height and length is 110mm, width 35.2mm, thickness of 5mm. in the two corners transverse and longitudinal connecting plates respectively arranged on two bolt holes, two holes are 60mm, 25mm from the edge. In the two transverse and longitudinal connecting plates of the corner respectively arranged on two bolt holes. The two bolt holes are 60mm, 25mm from the edge. The material is Al6082, the density is 2.7g/cm3, the elastic modulus is 74Gpa, the Poisson's ratio is 0.3, and the yield strength is 260Mpa.

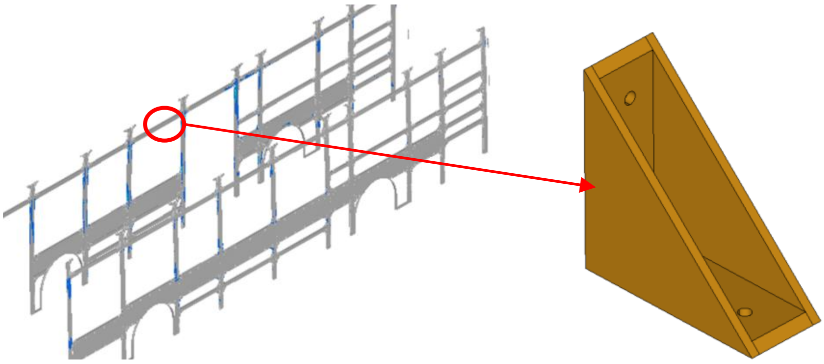

Figure 1. TheOriginal connect model.

The connection in the upper left corner of the first window after the middle door is located as the research object. The force condition is very complicated, and may be affected by several forces at the same time. Such as passenger, body, overhead air conditioning weight and vibration caused by road roughness, engine work, etc. It is difficult to accurately determine the load magnitude due to the influence of pavement condition, vehicle structural parameters and operating conditions. According to the deformation and force condition of the real vehicle and the reference [8], the load condition of the connector is determined. As shown in table 1, the load condition of the connection structure is shown.

Table 1. Finite element model load conditions.

Serial number	Load condition	Working condition description
1	Load condition 1	X force unit 1000N is applied to the model
2	Load condition 2	Y force unit 1000N is applied to the model
3	Load condition 3	Z torque 1×10^6N m is applied to the model
4	Load condition 4	Y torque 1×10^6N m is applied to the model

As shown in figure 2, the load constraint diagram of working condition 1 is shown. The remaining three operating conditions are the same as the condition 1, but the load directions is different.

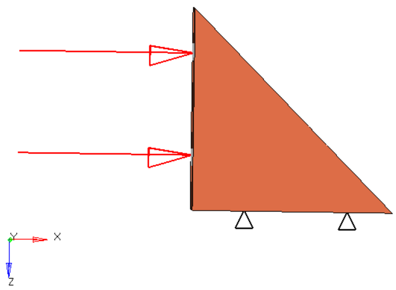

Figure 2. The load and constraint of condition 1.

3.2. Initial design of outer contour

The design of connector structure initial contour shape, is conducive to the follow-up of topology optimization, get connected topology optimum distribution. So the topography optimization identified contour connection is very necessary.

Using HyperMesh software, the compliance values and the first three order natural frequencies of the connectors under four conditions are normalized and weighted. Then the shape of the connection structure is optimized, and the position of the bolt hole is kept unchanged. The optimization results are shown in figure 3. The initial structure of the outer contour of the connector is designed as shown in figure 4. The length and height of the connecting structure are reduced by 10.5mm respectively, and the large blue redundant material in the original connection structure is removed.

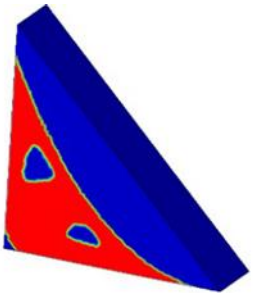

Figure 3. Topography optimization density cloud map.

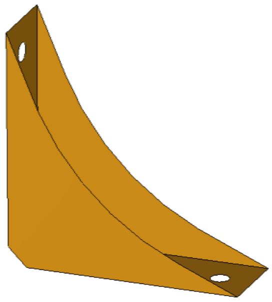

Figure 4. The Outer contourdesign.

3.3. Multi objective topology optimization

Before the topology optimization of the connector is made, the connection before connecting structure is divided into the design of regional and non regional design. non regional design to retain the original model, using shell elements are dispersed, and the design area is filled with solid unit. The optimum design space is shown in figure 5. The hollow area of the connecting piece is used as the topological design space, and the two plate like triangles and the horizontal and vertical connecting plates between the two triangular plates are used as the non optimized design areas.

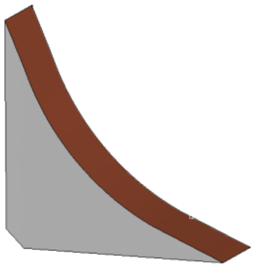

Figure 5. Topology optimization design space.

After defining the multi-objective topology optimization problem, the objective function is calculated, and the results are convergent after 32 iterations. As shown in figure 6, the density profile of the material after the optimization of the aluminum alloy connection structure is shown. It can be seen from the chart, the blue area topological space mainly concentrates in the middle of the connector and at both ends, the two parts should be removed, A area and B area for the Red areas show that the two areas need to consider strengthening member connections on the basis of the original.

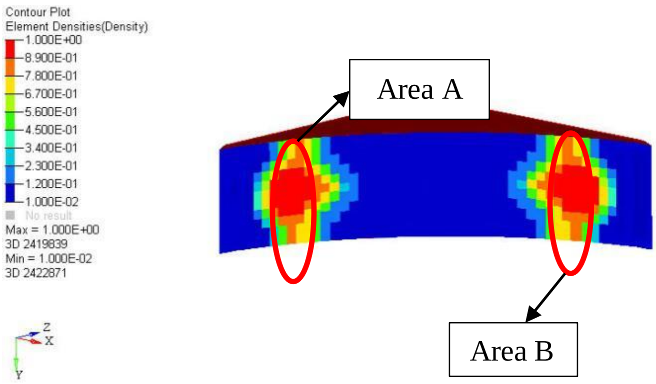

Figure 6. Topology optimization density cloud map.

3.4. Improvement and analysis of connection structure

The material density distribution nephogram of multi objective topology optimization is the reference for the improvement design of the connection structure. In order to ensure the strength of the improved connection will not be reduced and consider the actual structure of the connection. The improved connection structure is shown in figure 7, based on the original connections in the A area and B area were increased floor.

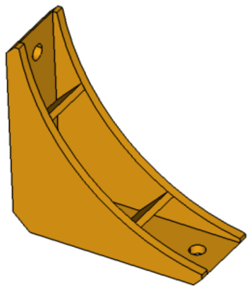

Figure 7. Connection improvement structure.

The quality of the improved connection structure is 0.175kg, which is reduced by 18% compared with the original structure. The inertia release analysis and free modal analysis of the improved aluminum alloy connecting structure are carried out, and the results are shown in table 2 and 3. In order to show the dynamic performance more clearly, the first six order free modal contrast is listed in table 2. According to the table, the first six order natural frequencies of the improved connection structure are slightly increased in addition to the fifth order, and the other five orders increase in varying degrees, and the dynamic characteristics are obviously improved.

Table 2. Comparison of natural frequencies before and after the improvement of Connect.

	1	2	3	4	5	6
Before	617.5	859.7	1008.1	1189.4	1299.2	1426.3
After	637.7	900.6	1137.7	1206.9	1263.7	1593.9

As shown in table 3, the deformation and stress of the improved connection structure under working conditions 1、2、3 are obviously reduced. The stress of the working condition 2 decreases, but the deformation of the working condition increases to some extent. But in general, the stress and deformation are more uniform under different conditions. The maximum stress is reduced from 189.4Mpa to 130.5Mpa. The maximum deformation decreased from 0.36mm to 0.22mm. The stiffness and strength properties are improved obviously after topology optimization.

Table 3. Comparison of the maximum stress before and after the improvement of Connect.

		Before	**After**	**Amplitude of change /%**
1	Maximum deformation /mm	0.39	0.3	-23.1
	Maximum stress /Mpa	159.8	113.01	-29.3
2	Maximum deformation /mm	0.24	0.27	12.5
	Maximum stress /Mpa	129.77	84.48	-34.9
3	Maximum deformation /mm	0.35	0.23	-34.3
	Maximum stress /Mpa	140.4	102.5	-27
4	Maximum deformation /mm	-0.49	-0.38	-22.4
	Maximum stress /Mpa	189.4	130.5	-31.1

4. The strength and fatigue performance of passengercar

The static strength performance of the car body structure has a direct impact on the fatigue life, crashworthiness and vibration characteristics of the aluminum alloy bus. According to the analysis results to verify the design is reasonable. In this paper, the stress distribution characteristics of aluminum alloy body are analyzed based on four typical conditions of bending, torsion, breaking and turning.

As shown in figure 8 the stress distribution of the aluminum alloy bus structure based on the bending condition is presented. From the diagram, the stress level of the front and rear sides and the side of the car body is lower. The maximum stress of the under frame structure is 169.02MPa, which is located at the main longitudinal beam at the center.The maximum stress value of the body structure is 123.91Mpa, located in the upper side of the connecting block. This result is less than the allowable stress of the material, indicating that the strength of the bus under bending condition is enough.

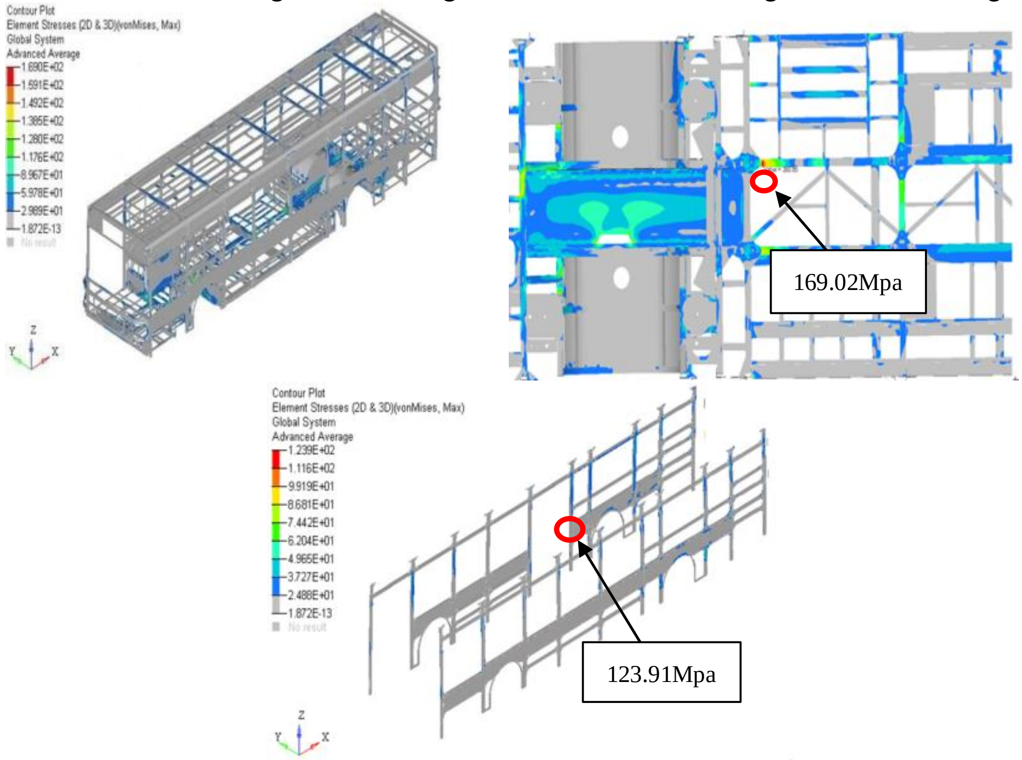

Figure 8. Calculation results of bending conditions.

The maximum stress calculated based on the four typical working conditions is shown in table 4. According to the design requirements of the body strength, the maximum stress of the structure under the limit condition should be less than the allowable stress of the material. From the table, it can be concluded that the topological optimization of the connector can meet the strength requirements of aluminum alloy body structure.

Table 4. Maximum stress distribution of skeleton structure under four typical working conditions.

working condition	Maximum stress and position of underframe	Maximum stress and position of bus body
Bend	**169.02Mpa** Central main longitudinal beam	**123.91Mpa** The connector on the upper middle door
Torsion	**253.82Mpa** Front suspension lower thrust rod	**149.68Mpa** The connector on the upper middle door
braking	**185.08Mpa** Connection between front and middle section of underframe	**150.6Mpa** Connecting slider of the upper skeleton of the posterior segment of the lateral wall
Turning	**238.75Mpa** Front suspension thrust rod support	**126.38Mpa** The connection between side longitudinal beam and side beam

5. Summary
The quality of the aluminum alloy connector after topology optimization is reduced by 18%, and the first six natural frequencies are improved to some extent, and the strength performance and stiffness performance are obviously improved.The improved connector can meet the requirements of strength and reliability of aluminum alloy bus body structure.

Acknowledgments
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Reference
[1] Yongbing L, Yunwu M, Ming L et al. 2016 Advances in Welding and Joining Processes of Multi-material Lightweight Car Body *Journal of Mechanical Engineering* **52(24)** 1-23
[2] Jia B C 2010 A kind of frame connection structure[P] CN CN201020231168.0
[3] Zheng Y P, Lin X, Zhang D G 2016 A kind of riveted structure applied in Aluminum Space Frame[P] CN CN201610333157.5
[4] Luo Z H 2017 Aluminum bus body frame[P] CN CN201621112866
[5] Zhu X Y, Fang Z D, Shen S S, et al. 2011 Multi-objective Topology Optimization for the Control Arm of Vehicle Suspension[J] *Automotive Engineering* **33(02)** 138-141
[6] Yonetani H 2008 Laser-MIG hybrid welding to aluminum alloy carbody shell for railway vehicles *Weld. Int* **46(2)** 43-47
[7] Wu SC, Hu YN, Duan H, Yu C and Jiao HS 2016 On the fatigue performance of laser hybrid welded high Zn 7000 alloys for next generation railway components *Int. J. Fatigue.* **91** 1-10
[8] Hao S H, Hu R, Xu M L et al. 2016 Optimization Design of Roof Frame for Hybrid Aluminium Bus[J] *Automobile Technology* **2016(6)** 11-15