Design of Car Body by the Method of Structural Optimization

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Recent years have seen an increase of the demand for safer, more comfortable railway vehicles. This goal is difficult to achieve with current methods given that some parts of the vehicle structure likely to have an impact during collision cannot be evaluated. Yet, it is indispensable to conduct analyses of the whole of the vehicle, in order to evaluate complex load paths along the whole length of the vehicle body. As such, a structural optimization approach based on FEM analysis was developed to establish a rational car body design method. Zooming in on areas selected during the whole-body structure analysis was used as a basis to build an optimization analysis algorithm. Structural optimization using this algorithm was applied to confirm that this method can be used to reduce the mass and improve the rigidity of railway vehicle car body structures.

Keywords: structural optimization, car body, light-weight, high-rigidity, finite element method, press molding

1. Introduction

Structural optimization is now widely used for machine design, and has become a commonly used CAE (computer assisted engineering) tool in the automobile and airplane industries. On the other hand, even though there are a few examples of this optimization method being applied to railway vehicles, it is not yet widely used in their design.

There are demands to improve the body structure of railway vehicles for various purposes, such as better safety, higher speed and greater ride comfort. Collision safety design is one such demand to improve safety, which tends to add to the weight of a vehicle body structure. As a result, lighter and more rigid structures need to be found. This is where a structural optimization method would be effective to support body structure design.

Previous research on applying structural optimization methods to railway vehicles, with a conventional body frame made of beams and plates to reduce vehicle weight and increase strength, were confirmed for effectiveness [1].

The present research aimed to further reduce the weight of the vehicle by replacing the conventional body structure made of beams and plates with a press-molded structure (of the kind often used to make the inside of cars in the automobile industry) which reproduces the irregularities in the surface of the vehicle body. With a view to establishing a rational method for finding the lightest structure design whilst satisfying railway vehicle requirements of strength and rigidity, this paper examines the introduction of a structural optimization method based on numerical simulation using FEM (finite element method). In addition to devising a practical analytical algorithm, this paper then proposes a press-molded body structure designed by applying the structural optimization method.

2. Structural optimization method

2.1 Overview of structural optimization method

In terms of methods for designing structures based on an original form which has to meet preset conditions, there are two approaches: shape optimization and topology optimization [2]. Shape optimization, based on external shape design variables, and topology optimization, based on internal structure design variables, are derived from combinations of FEM analysis, sensitivity analysis and optimization methods. The optimization method is very versatile because of the large number of design variables that can be used. However, application of a suitable optimization method such as the optimality criteria method [2] is necessary for convergence. In this study, the load transmission path is identified by topology optimization and in turn, the initial form for shape optimization is decided based on this path. An advantage of this method is that numerous limitation conditions such as strength, rigidity, local buckling and geometry limitation etc. can be set. The result of the shape optimization depends on the initial mesh of the FEM analysis. The problem in this approach however is that the mesh must be updated if the element becomes skewed. Nevertheless, this method can restrain shape distortion by considering a load transmission path obtained by topology optimization beforehand which then dispenses with the need to update the mesh model.

2.2 Algorithm of the structural optimization method

An algorithm for structural optimization is proposed to find a design for the existing body structure made of stainless steel which is both light-weight and very stiff. Assuming that press molding will be used to produce the body structure allows greater flexibility for determining its shape. Accordingly, a structural optimization method

Fig. 1 Initial geometric model of whole vehicle

Fig. 2 Algorithm of structural optimization

combining topology optimization and shape optimization was designed. Given the size of railway vehicles, and their complex behavior, it is difficult to evaluate load paths and amount of stress using only a partial model. On the other hand, high loads are applied only to a limited domain, optimization using a whole vehicle body structure model is not effective.

Therefore, a stress analysis based on the initial geometric model of a whole vehicle, shown in Fig. 1, was conducted to calculate the load conditions necessary for structural optimization of the partial domain. Loads specified in the JIS E7106 were applied for the body structure load tests: vertical load, torsional load and car edge compression load. A partial body structure model was then built to apply structural optimization based on the results of the stress analysis and load conditions for a whole-vehicle structure model.

The optimization process making one part of the structure lighter and more rigid also needs to be applied to all the other parts making up the same vehicle. The resulting whole structure, made up from the optimized partial domains, is then subject to a stress analysis. The whole cycle is repeated until the results of this stress analysis satisfy the required criteria. The flow chart illustrating this process is shown in Fig. 2.

2.3 Example of press molded body derived from structural optimization

To verify the structural optimization algorithm proposed in the present study, the method was applied to a simple model of a railway vehicle side window (Fig. 3). The limiting condition was to reduce the mass of the initial form by 70%. Three-dimensional solid elements were used as elements in the analysis model. Load transmission density distribution was obtained through topology optimization to indicate the contribution rate of each load-bearing structural member (Fig. 4). As shown in Fig. 5, the hollow in the normal direction was determined in relation to the scale of load transmission density distribution. In other words, pitch difference and unevenness were set according to the size of the load transmission density. At the same time, the solid elements in the analysis were replaced with shell elements to reflect the sheet structure of the element. The geometric model was then smoothed to take into account large local changes in load transmission density distribution obtained from the topology optimization. Shape optimization was applied next to the smoothed shape to reduce weight and improve rigidity. Three load cases were examined as for the topology optimization. The objective function was defined as achieving maximum rigidity and minimum stress, while the limiting condition for shape optimization was to reduce the mass by 70%. The material coefficients were: elastic coefficient of the stainless steel, 210 GPa, and Poisson ratio, 0.3. The body structure shape obtained through shape optimization is shown in Fig. 6 (a).

Fig. 3 Simple model of side window section

Fig. 4 Distribution of load transmission density

Fig. 5 FEM model for shape optimization

(a) Unevenness after optimization

(b) Distribution of equivalent stress

Fig. 6 Result of shape optimization

Rigidity was improved by transforming the original shape to a curved surface, and the stress distribution in Fig. 6 (b) shows that there are localized areas of high stress. The maximum stress of 235 MPa however, is well below the yield stress (e.g., yield stress 410 MPa of the SUS301L-ST steel) of materials generally used on stainless steel vehicles. Additionally, if the stress has to be further reduced, limitation conditions can be modified and the shape optimization process can be repeated.

3. Stress analysis of a whole-vehicle structure model

3.1 Analysis model

As shown in Fig. 2, the first step in the structural optimization process is a stress analysis of a whole vehicle model structure. FEM analysis is used to evaluate the stress distribution generated when an external force equivalent to body structure test loads is applied to the body structure. Then, a partial domain is selected to apply structural optimization.

In this study, the stress analysis while exerting an external force equivalent to loads used in static load tests on vehicle body structures was carried out by setting the vehicle body structure model of the stainless steel vehicle for conventional lines, as shown in Fig. 1, as an initial shape. The elements to which the analysis was applied were three-dimensional solid elements. The mesh division was made only for the body structure while auxiliary equipment such as under floor devices or air conditioning units were added as mass points.

The purpose of this vehicle body structure model was to derive an optimal body structure through the structural optimization method, therefore, openings such as windows or doorways were modeled beforehand, and each plate constituting the body structure was assumed to be uniform and have a thickness of 30 mm.

3.2 Analysis conditions

The load conditions for the stress analysis were based on load conditions for static load examinations as specified in JIS E7106, while the analysis was conducted under the load conditions indicated in Table 1. Each loading point was specified as follows: vertical load was applied to the entire floor surface, torsional load was applied to the air spring positions, and the car edge compression load was applied to the connector mount. The load applied to the air conditioner unit was assumed to be 7.35 kN and was exerted on the unit mount as a concentrated load.

Table 1 Load condition for one vehicle model

Condition	Load	Load position
Vertical load	392 kN	Entire floor
Torsional load	40 kN · m	Air spring (No.3,4)
Car edge compression load	490 kN	Connector mount

3.3 A domain and load condition of structure optimization

The stress distribution was obtained through this static stress analysis on a whole-vehicle structure model.

In Fig. 7, distribution of the von Mises equivalent stress is shown for the vertical load. This result shows that conspicuously high stress due to stress concentration occurred on the side of the body structure close to the center near the bolster position, particularly in the neighborhood of the corners of the side window section and the doorway. Similarly, high levels of stress were identified around the corners of the side window sections and doorways under torsional loads and car edge compression. No high-stress areas however were found in the areas between open sections, i.e. side windows and doorways. From these results three partial domains bordering openings, as shown in Fig. 8, were selected for structural optimization. The whole vehicle body structure excluding the underframe part was divided into 18 domains.

Zooming is used in structural optimization [3] whereby high load domains are cut out from whole-vehicle structure model to make partial body structure models. Stress analyses are then conducted for each partial body structure model. As for boundary conditions, the stress distribution of the partial body structure model was made to equal to the stress distribution of the whole-vehicle structure model by setting a displacement value for the panel border points on the whole-vehicle structure model as forced displacement.

Fig. 7 Stress analysis result under vertical load (von Mises equivalent stress: MPa)

4. Structural optimization of the partial domains

4.1 Conditions for structural optimization analyses

With respect to all the partial domain models obtained by the stress analysis using a whole-vehicle structure model, the displacement at the edge of each domain was given as a load condition, and topology optimization and shape optimization were conducted applying the structural optimization algorithm. Further, the positive and negative vertical and torsional loads differed on the right and left sides of the model as shown in Fig. 3, therefore load conditions where this difference in load condition was corrected were included, forming a total of five different load conditions used for the structural optimization process.

The load transmission density distribution was obtained through topology optimization for each partial domain under the assumption that the objective function was maximum rigidity while the limitation condition was to reduce mass by 70%. An FEM model was constructed for shape optimization based on the results of the topology optimization, and an analysis was performed. For shape optimization it was assumed that the objective function was maximum rigidity and minimum stress, while the limitation condition was to reduce mass by 70%. The greatest vertical depth of unevenness was set at 30 mm. The press molding process was given the production limitation of avoiding any acute angles in the curved surfaces.

4.2 Results of structural optimization analysis

The form for press molding shown in Fig. 9 was obtained after repeating the structural optimization process several times. The deeper the red, the deeper the hollow in the shape. The shape of the roof at the end of the car was changed only slightly after optimization. It is posited that the reason for this is that this part is located outside the bolster area. The end panel however is subject to significant torsional load, showing clear unevenness in the shape. The analysis confirmed stress distribution in the partial domain models. Figure 10 shows stress distribution when

Fig. 8 Partial domain model for structural optimization

(a) Side window

(b) Doorway

(c) Car edge

Fig. 9 Form for press molding body obtained through optimization

a vertical load was applied to a partial domain model after structural optimization. It shows that the previously concentrated stress was now dispersed. The maximum stress

(a) Side window

(b) Doorway

(c) Car edge

Fig. 10 Distribution of Stress (Vertical load)

on each part was 315 MPa which poses no problem regarding strength.

4.3 Verification of the vehicle body structure

A whole-vehicle structure model was built from the derived partial domains and a stress analysis was conducted again. The final vehicle body structure shape had a dual structure with an outer shell attached as shown in Fig. 11, because of the uneven surface obtained through structural optimization. Following the analysis, the equivalent stress distribution shown in Fig. 12 obtained applying a vertical load showed that there were no longer any areas of concentrated stress on any part of the whole body structure. Similar results were obtained applying torsional and car edge compression loads.

Furthermore, the optimized shape reduced overall mass by 17%, while bending stiffness was improved by 12%, compared with existing stainless steel railway vehicle bodies used on conventional lines.

Fig. 11 Vehicle structure with press molded body

5. Summary

A structural optimization method combining topology and shape optimization processes was proposed to reduce the mass and improve the rigidity of railway car body structures. An optimized body structure was derived using this proposed method. In order to obtain an optimized press-molded body form, which differed from the exist-

Fig. 12 Distribution of equivalent stress on whole-vehicle model

ing vehicle body structure an FEM analysis was made of the whole body structure. Zooming was then applied to increase the effectiveness of the analysis. A structural optimization algorithm was then designed so that topology and shape optimization processes could be applied repeatedly to partial domains of the structure until the require criteria values were satisfied.

Confirmation was obtained that the resulting optimized body structure reduced overall mass by 17%, and improved bending stiffness by 12%.

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