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A study of optimization for automotive parts and structures by using inertia relief

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1. Abstract
The topology analysis method was developed to optimize the part shape and configuration of automotive components [1]. The key point of the method is to embed solid elements in a model made of shell elements for topology optimization. Improvements of static stiffness were verified for a simple cylindrical model, automotive floor model and full vehicle model. However, in addition to static stiffness using constraints, stiffness while driving is required in the body stiffness of a full vehicle. Inertia relief is known as a method for the expression of behaviour while driving.
In this study, stiffness optimizations by using inertia relief were carried out for an automotive full vehicle model. Specifically, the optimized automotive components were the joints linking a side-member and a cross-member. These components are made of steel sheets and have rectangular cross sections.
The results show that the developed topology optimization method, in which solid elements are embedded in a model consisting of shell elements, is valuable in the optimization of automotive rectangular steel sheet components by using inertia relief. The points of difference and similarity between the static stiffness using constraints and the stiffness using inertia relief were clarified by the optimization results.

2. Keywords: Topology optimization, shape optimization, industrial applications, inertia relief

3. Introduction
Environmental issues are rapidly emphasizing the necessity of engineering measures for automobile weight reduction. One such measure is reducing the weight of the body-in-white by using high strength steels, which is effective for reducing the mass of automotive parts. However, thickness reduction by using high strength steels also reduces the stiffness of the part, and the decrease in the rigidity of the part decreases the rigidity of the entire vehicle. In general, topology optimization is known as a technology which improves stiffness without increasing weight [2] [3]. In topology optimization, a design area constructed of solid elements is used, and the effective elements are retained after deleting unnecessary elements during the topology optimization process for the required properties. In the conventional solid element method, the residual shape is commonly complicated, and as the name implies, only solid elements are ordinarily used in the topology optimization method for optimization of cast parts such as an engine block or a lower control arm. On the other hand, in automotive bodies consisting of metal sheets, conventional topology optimization is used as a temporary answer which provides a rough sketch [4], a guide for design from scratch and a method of searching for supersensitive areas of material density in the current shape by using shell elements for the body [5] [6] .

Thus, conventional topology optimization by using shell elements is advantageous when searching for stiffened areas. However, the answer is limited to increasing the material thickness, and the effect is smaller than changing the shape. Topology optimization using solid elements is very effective for creating new shapes but is not used to make new shapes for automotive bodies. The reason for this limited range of use is the difficulty of applying conventional topology optimization to an automotive body, which is mainly composed of thin steel sheets and is normally modeled by using shell elements. For this problem, the topology analysis method was developed to optimize the part shape and configuration of automotive components [1]. The key point of the method is to embed solid elements in a model made of shell elements for topology optimization. Improvements of static stiffness have been verified for a simple cylindrical model, automotive floor model and full vehicle model.

On the other hand, static stiffness using constraint of nodes cannot express deformation while driving [7]. Figure 1 shows the boundary condition and deformation in the static stiffness method [1]. Here, torsional deformation occurred in all parts of the body in the mode in which one point of the front bilateral suspension parts was forced and the other three points were constrained. However, because the automotive body is mounted on the suspension and the displacement of the suspension is not constrained, there is a difference between static stiffness and the condition while driving. For this reason, simulation under the loading condition of driving is necessary. Inertia relief is known as a method for expressing behavior while driving [8]. Inertia relief can solve the deformation while driving without constraint of the suspension parts because the deformation by loading force and the inertia of loading force are calculated in this method.

This paper describes stiffness optimizations for an automotive full vehicle model by using inertia relief, in which solid elements were embedded in the shell elements for topology optimization. Specifically, the optimized automotive components were the joints linking a side-member and a cross-member. These components are made of steel sheets and have rectangular cross sections.

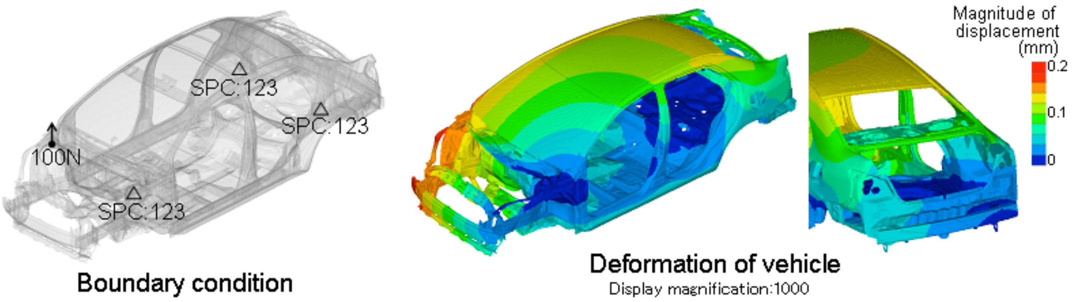

Figure 1: Boundary condition and deformation in static stiffness

4. Stiffness analysis and sensitivity analysis by using inertia relief

4.1. Boundary conditions and deformation of stiffness analysis

A full vehicle model, which is available to the public at the National Crash Analysis Center (NCAC), was used for the stiffness analysis. This model consists of shell elements [9]. Figure 2 shows the boundary conditions for the stiffness analysis compared with static torsion. In static torsion, one point of the suspension was forced by 1000N in the front or rear, and the other points were constrained. The loading conditions for inertia relief were vertical bending in the front or rear caused by passing over a gap, torsion by both sides in the front or rear by lane change, torsion by one side in the front or rear by running aground and horizontal bending in the front or rear by lane change. The solver of the stiffness analysis is NASTRAN2012.

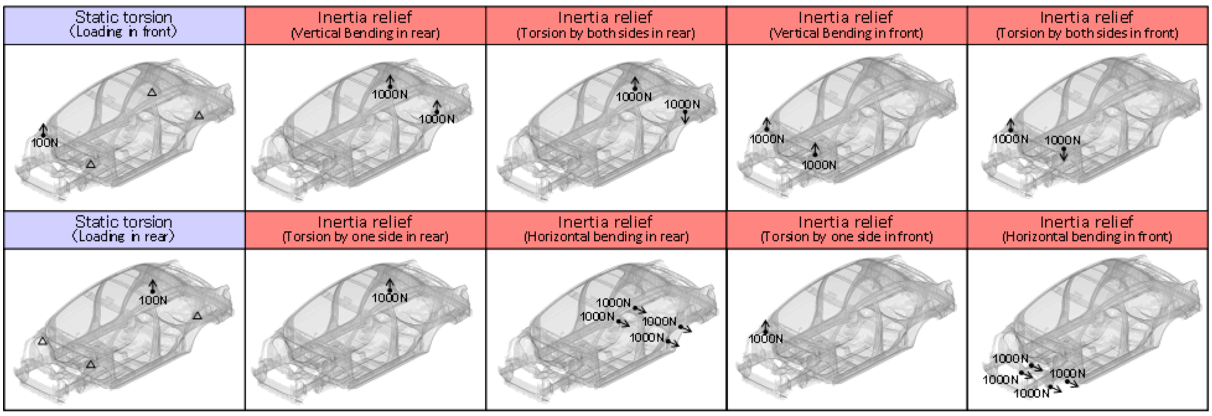

Figure 2: Boundary conditions for the stiffness analysis in this research

Figure 3 shows the deformations in several boundary conditions. The deformation of static torsion is displayed with the magnification of 1000, and that of inertia relief is displayed with the magnification of 300. The length of the vehicle is 4178mm. The results of static torsion in front loading or rear loading show deformation over the entire body. In inertia relief, only the area near the loading point is deformed. For example, under rear loading, the neighbourhood of the rear suspension is deformed and the front of the body is not deformed greatly. Similarly, under front loading, the neighbourhood of the front suspension is deformed and the rear of the body is not deformed greatly because the whole deformation occurs between the loading point and the constrained point in static torsion with constraints, but in inertia relief, the deformation in the neighbourhood of loading mainly occurs by the inertia of the force. It is assumed that the partial deformation of the body calculated by using inertia relief is close to the typical behaviour which occurs during a lane change while driving.

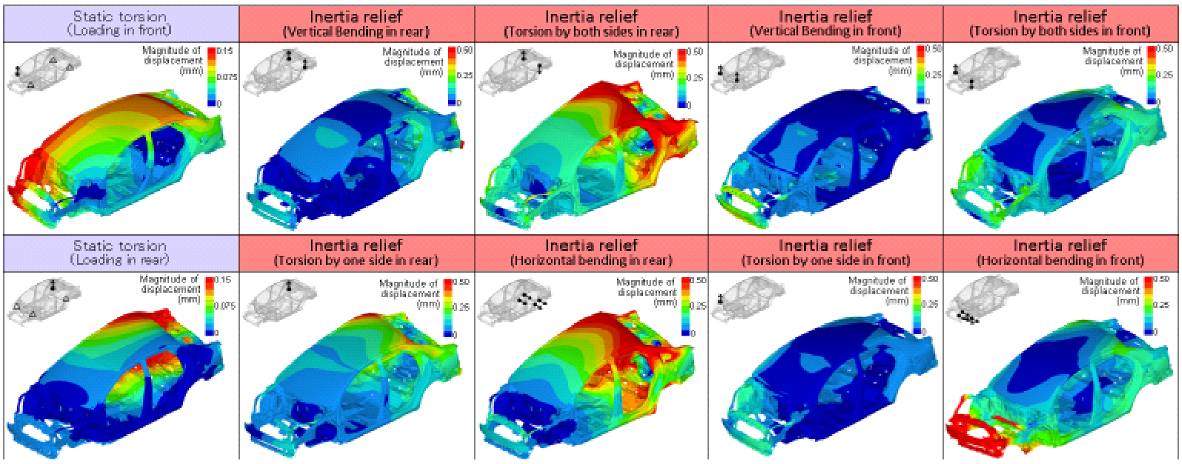

Figure 3: Deformations in several boundary conditions

4.2. Sensitivity analysis of automotive body

Sensitivity analysis of a full vehicle model consisting of shell elements was carried out by topology optimization for several boundary conditions. Figure 4 shows the results of static torsion in front loading, rear loading and complex loading in the front and rear. Figure 5 shows the results of vertical bending in the front and rear, torsion by both sides in the front and rear, torsion by one side in the front and rear and horizontal bending in the front and rear by inertia relief. Figure 6 shows the results of complex loading in the rear, complex loading in the front and complex loading in the front and rear by inertia relief. The objective response was a minimization of compliance, and the constraint function was lower than 25% of the residual volume fraction. In the case of complex loading, the weight of compliance was the same, the objective response was a minimization of the sum of the weighted compliance and the constraint function was lower than 25% of the residual volume fraction. The solver of the topology optimization analysis was Optistruct11. Side panels, roof-outers and window glass are not displayed.

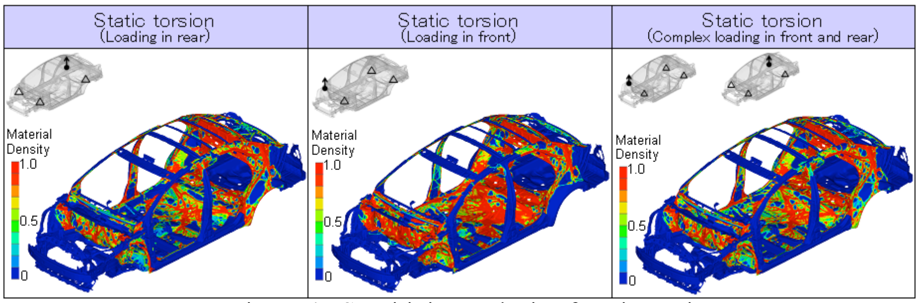

Figure 4: Sensitivity analysis of static torsion

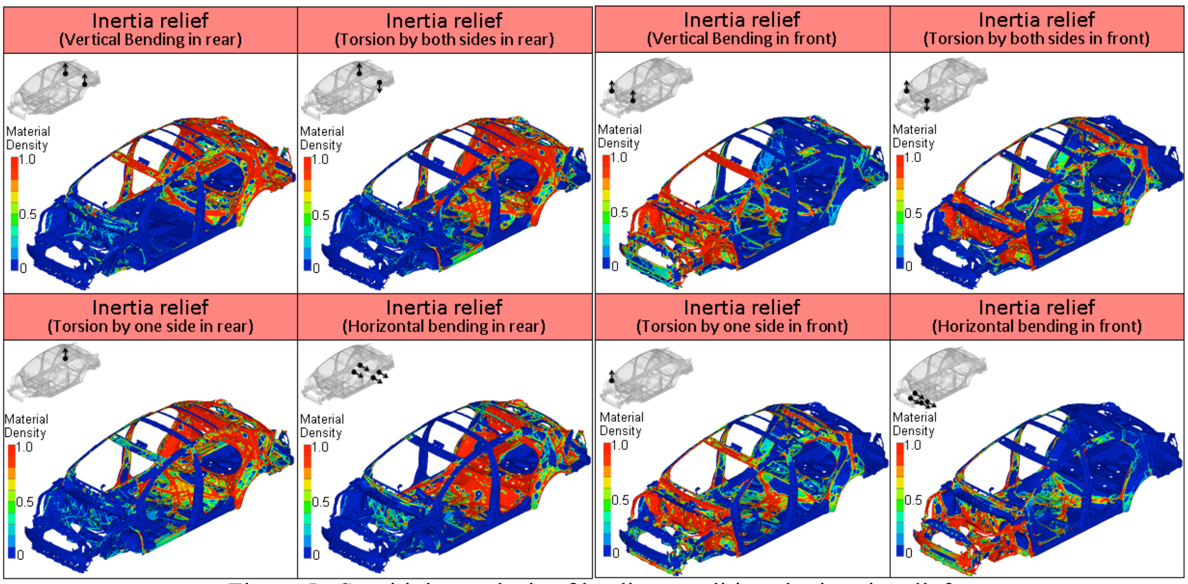

Figure 5: Sensitivity analysis of loading conditions by inertia relief

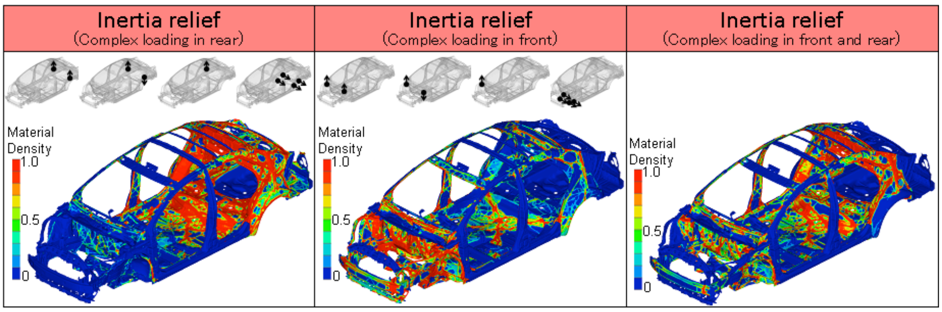

Figure 6: Sensitivity analysis of complex loading conditions by inertia relief

The contour is material density. A large material density area shows a large influence on the stiffness of the automotive body. The sensitivity of the entire body was high in all boundary conditions of static torsion, as shown by Figure 4, because deformation of the entire body occurs in static torsion independent of the loading position. With inertia relief, the sensitivity of the rear side of the body was high in the rear loading conditions, and the sensitivity of the front side of the body was high in the front loading conditions, as shown by Figure 5. This is because the deformation of the neighbourhood of the loading point is predominant in inertia relief. The sensitivity of the rear side of the body was high in the rear complex loading conditions of inertia relief, the sensitivity of the front side of the body was high in the front complex loading conditions of inertia relief and the sensitivity of the entire body was high in the front and rear complex loading conditions of inertia relief, as shown by Figure 6, because inputs from several areas of the body are added in complex loading in inertia relief.

Figure 7 shows the sensitivity analysis of the static torsion and inertia relief in the case of rear complex loading for the selection of the stiffened area. The result is focused in the rear side of the body and the contour is over 0.5. The high sensitivity areas of static torsion are the seat-back, wheel-house, rear suspension, rear side-member and rear cross-member. The high sensitivity areas of inertia relief are the rear floor-member, seat-back, wheel-house, speaker panel, rear suspension, rear side-member, rear cross-member and rear floor-side. The high sensitivity points of inertia relief are larger than those of static torsion because rear side loading was used in inertia relief. Thus, high sensitivity points can be found by using inertia relief, but there are cases in which high sensitivity points are overlooked when using static torsion.

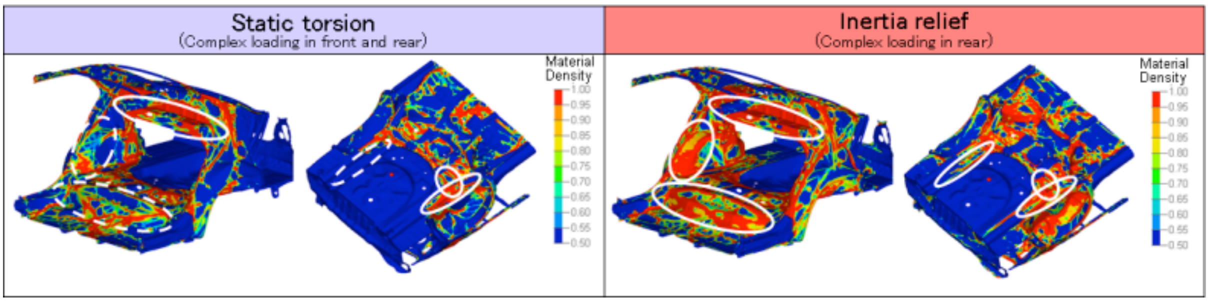

Figure 7: Comparison between static torsion and loading condition by inertia relief

5. Topology optimization by embedded method by using inertia relief

5.1. Difference of residual areas by loading condition of optimization

The validity of the method in which solid elements are embedded in an automotive model made of shell elements for topology optimization by using inertia relief was verified. Figure 8 shows the area where countermeasures are necessary indicated by the sensitivity analysis. Figure 9 shows the original shape with the target area of optimization. The target area was the neighbourhood of the rear cross-member connected with the rear side member, as shown in Figure 10. The end of the rear cross-member was deleted, and the cut edge of the rear cross-member consisting of shell elements was connected with the solid elements of the design area to transmit the load.

The loading conditions of the topology optimization were static torsion in complex loading in the front and rear, vertical bending in the front and rear, torsion by both sides in the front and rear, torsion by one side in the front and rear, horizontal bending in the front and rear by inertia relief and complex loading in the rear and complex loading in the front by inertia relief. The objective response of the optimization was a minimization of the sum of the weighted compliance with the same weight, and the constraint function was lower than 20% of the residual volume fraction. The solver of the topology optimization analysis was Optistruct11.

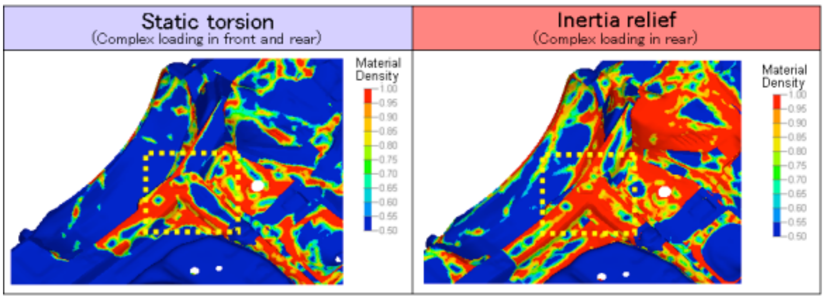

Figure 8: Target by sensitivity analysis

Figure 11 shows the results of the topology optimization for several loading conditions. The residual shape of static torsion was similar to the shape of horizontal bending in the rear by inertia relief. The residual area was the joint linking the cross-member and the side-member and the face of the ground side in the design area. These results show the load path from the loading point to the cross-member and floor by the side-member. The most important area was retained for this load path. The residual area was not only the joint linking the cross-member and the side-member, but also the joint linking the floor and the side-member, and its shape was complicated. This is because the automotive body has a monocoque structure which is made of steel sheets, and the load path is complex because each part of the body plays a role in transmitting loads. Moreover, the conventional material mechanics theory approach cannot solve this load path because the mode of stiffness is not a simple mode such as bending or torsion. On the other hand, the residual shapes for the other conditions were different from the static torsion and the horizontal bending in the rear by inertia relief. These results show that the required shape for stiffness differs depending on the mode of loading.

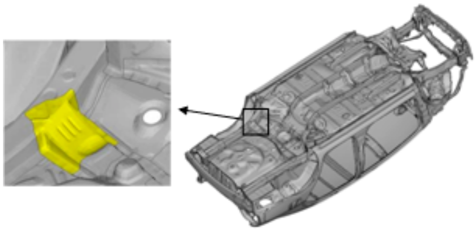
Figure 9: Target area of original shape

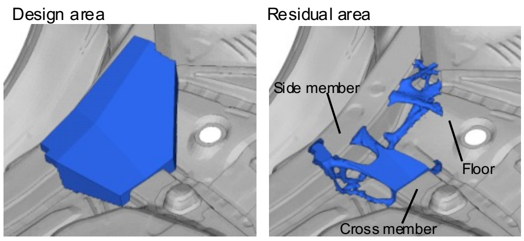

Figure 10: Full vehicle model with embedded solid elements

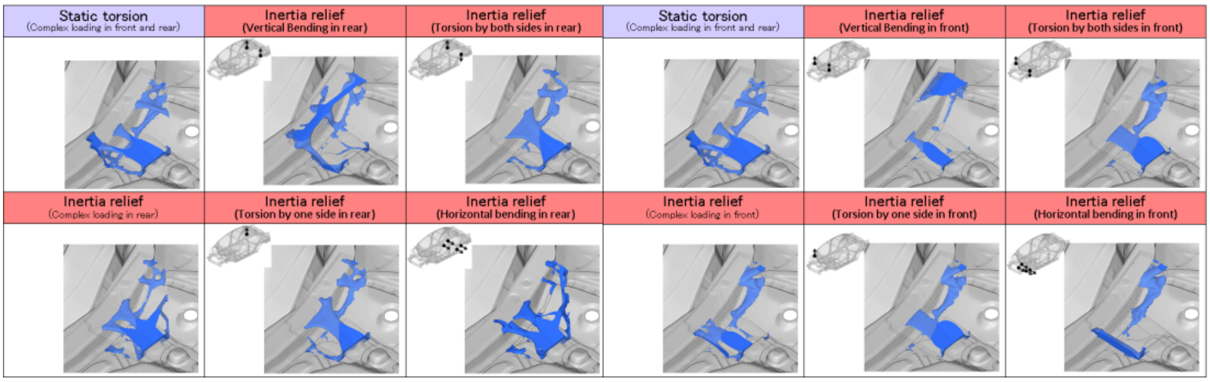

Figure 11: Residual areas of topology optimization for several loading conditions

5.2. Design by using residual shape and effect on mode of stiffness

The new shape designed based on the topology optimization of static torsion and horizontal bending in the rear by inertia relief is shown in Figure 12, together with the original shape. The parts were the joint linking the cross-member and the side-member, the floor and the side-member. The total weight increase in the full vehicle was only 0.1kg.

Figure 13 shows the improvement ratio of stiffness compared with the original shape in the loading condition of static torsion and several inertia relief conditions. Stiffness is calculated by the change of the displacements on the loading point. The solver of the stiffness analysis was NASTRAN2012. The improvement ratios of static torsion and horizontal bending in the rear by inertia relief are larger than those of the other conditions. Thus, the validity of the developed method, in which a design area consisting of solid elements is embedded in an automotive body consisting of shell elements, could be verified by using a full vehicle model. As the improvement ratios of the other conditions were small, these results show that the loading condition used in optimization is important.

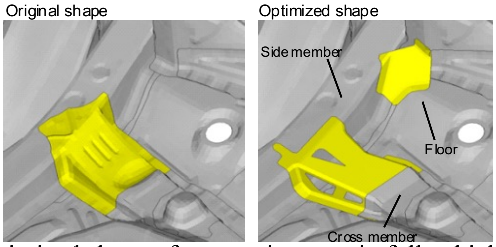

Figure 12: Optimized shape of connecting area in full vehicle model

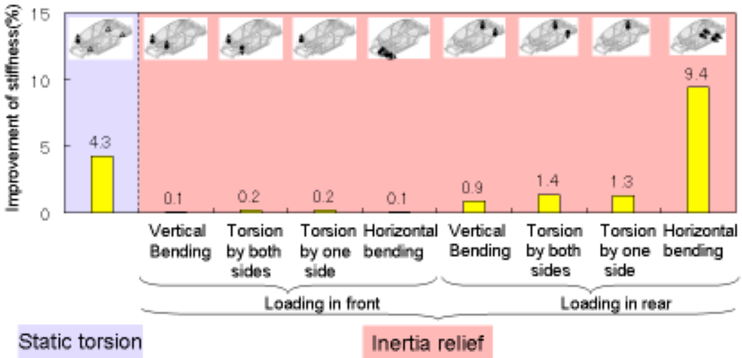

Figure 13: Improvement ratio of stiffness by optimal shape

6. Conclusions

It is clear that the topology optimization method in which solid elements are embedded in the shell elements of an automotive body is effective when using inertia relief for the driving condition.

There is a substantial difference between the static torsion method using constraints and the method of inertia relief. That is, in the static torsion method, deformation occurs over the entire automobile body, whereas in inertia relief, the area near the loading point is deformed.

With the static tension method, the sensitivity of the entire body was high, but with inertia relief, the sensitivity of the loading side of the body was high. Moreover, the sensitivity of the entire body was high in the complex loading conditions of inertia relief because inputs from several areas of the body are added in inertia relief.

The validity of the method in which a design area consisting of solid elements is embedded in an automotive body consisting of shell elements for topology optimization by using inertia relief was verified with a full vehicle model.

7. References

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