

Study on Similarity of Load Path Distribution in Body Structure

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ABSTRACT

Consideration and verification of the way in which load paths will be distributed throughout the structures under various loading conditions is an important element in the design of automotive body structures. Furthermore, given the tendency that load-path distribution becomes denser where coupling rigidity is high irrespective of the loading conditions, it is conjectured that similarities exist in the load-path distributions even under differing loading conditions.

The research discussed in this paper therefore conducted a comparative analysis of two methods for identifying load paths: using U_{sum}^* , which functions as an indicator of the distribution of load paths in body structures, and using stress. The difference between the two methods was clarified, and the distribution of load paths when four different loading conditions were applied to automotive body structures was studied. As a result, it was demonstrated that using U_{sum}^* , load-path distributions can be visually analyzed employing less indicators than was the case when using stress. In addition, the level of similarity of load-path distribution to distribution in other loading conditions was high for torsional loading conditions in which load paths are distributed throughout the structure as a whole.

1. Introduction

Today, given demands for the reduction of the burden on the environment and the realization of greater dynamic performance for increased commercial appeal, the achievement of maximal weight savings is necessitated in addition to the satisfaction of the performance demands made on automotive body structures. When designing high-weight-efficiency automotive bodies, it is important to give consideration to how the loads on the body structures will be transmitted through the structures and the projected performance levels satisfied. Direct identification of where the load paths through which the loads are transferred are located in the body structures is challenging, and at present their location is indirectly estimated using stress or strain⁽¹⁾,⁽²⁾. Because of the existence of areas in which high stresses are generated even when they are not actually functioning as load paths, for example points at which stress concentrates such as areas subject to sudden changes and holes, the identification of load paths according to the magnitude of stress represents a challenge. Furthermore, it is necessary to make a comprehensive judgment on numerous indicators to estimate load paths, including principal stresses, deformation diagrams, and sectional forces.

A method of analysis of load paths within body structures using FEM was therefore proposed. Load paths

can be identified by expressing the strength of connection between load points, constraint points, and arbitrary points on body structures by means of the indicators U^* and $U_{\text{sum}}^{*(3),(4)}$. The use of these indicators offers the advantage of making the load-path distribution easy to understand visually, because there is no rapid change in values, as for example when stress concentrates at holes and points where the structure undergoes rapid change.

When various loads are applied to body structures, load paths are generated within those body structures in response to the loading conditions. At the same time, the majority of load paths tend to be distributed in areas with good coupling to surrounding areas and a high level of rigidity, while there tend to be few load paths in weak areas, irrespective of the loading conditions. In other words, some kind of similarities can be considered to exist in load-path distributions.

It can be indicated that in regions within the body structures in which the load-path distribution displays high levels of similarity, the parts that contribute to load transfer or the parts that do not contribute to load transfer are the same, irrespective of the loading conditions. As a result, if modifications were made to regions that did not contribute to load transfer under one specific loading condition to produce an effectively functioning structure, the structure would also be effective in relation to other loading conditions.

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Because conventional structural analysis involves analysis under each relevant loading condition and the modification of structures or the application of other measures under the respective loading conditions, it can be the case that separate areas of the body structures are subject to modifications. However, the ability to analyze the similarity of load-path distribution under each of the loading conditions in order to identify loading conditions and body areas displaying a high degree of similarity would help to enable the achievement of weight savings by means of the conceptualization of body structures that are effective in the case of multiple loading conditions through the application of appropriate measures in areas displaying high degrees of similarity. This method could be used across a wide range of the body development process, from analyses conducted to obtain a broad grasp of the body structures (for example, the rough framework configuration and load-path distribution within the body structures at the stage of advance review) to detailed analyses of the couplings between components (such as analyses of spot welding points and joins between panels at the detailed design stage).

The purpose of the research discussed in this paper was to demonstrate the validity of the load-path distribution analysis method using U_{sum}^* and to attempt to determine loading conditions for which the load-path distributions displayed a high degree of similarity by using the indicator U_{sum}^* in the analysis of load-path distributions when various loading conditions were applied to automotive body structures.

2. The Indicators U^* and U_{sum}^*

2.1. The Indicator U^* and Load Paths

This section will explain the definition of the indicator $U^{*(3)}$ used in the analysis of load paths within body structures employing finite element analyses. Figure 1(a) shows a schematic diagram of a body structure. Point A is a load point, Point B is a support point, and Point C is an arbitrary point within the structure. The strain energy when an imposed displacement d_A is applied to the structure, U , is expressed by Eq. (1). Here, p_A is the load necessary to displace Point A by d_A .

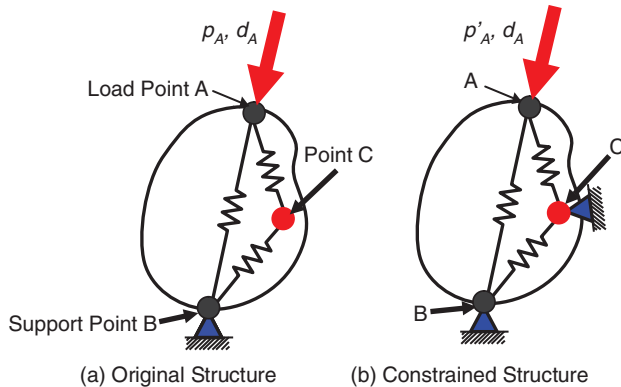


Fig. 1 Strain energy models

$$U = \frac{1}{2} p_A \cdot d_A \quad (1)$$

Figure 1(b) shows the same structure as Fig. 1(a). The arbitrary Point C is constrained, and the load necessary to displace Point A by d_A is p'_A . The strain energy in this case, U' , can therefore be expressed by Eq. (2).

$$U' = \frac{1}{2} p'_A \cdot d_A \quad (2)$$

The indicator U^* at Point C is defined by Eq. (3).

$$U^* \equiv 1 - \frac{U}{U'} \quad (3)$$

Because the value of the strain energy U' is always greater than that of U , U^* takes a value between 0 and 1, and is 1 at the load point and 0 at the support point.

Figure 2 shows a schematic diagram of the distribution of U^* in the structure. The greater the coupling rigidity with the load point within the structure, the greater the value of U^* . In other words, the ridge line of the U^* distribution can be indicated as an area of high coupling rigidity extending from the load point. It is believed that the force acting on the structure is transmitted mainly through the areas of highest rigidity to the coupling point. The main load path therefore follows the ridge line of the U^* distribution and arrives at the support point.

2.2. Load Path Distribution and the Indicator U_{sum}^*

There are multiple load paths other than the main load path. The indicator $U_{\text{sum}}^{*(4)}$, which makes it possible to quantitatively express the status of distribution of the load paths, is therefore introduced.

Figure 3(a) shows a conceptual diagram of U^* when Point A is the load point and Point B is the support point, representing U_1^* , the value of U^* at each node. Figure 3(b) shows a conceptual diagram of U^* when the load point and the support point are transposed, representing U_2^* , the value of U^* at each node. The indicator U_{sum}^* at each node in these cases is defined by Eq. (4).

$$U_{\text{sum}}^* = U_1^* + U_2^* \quad (4)$$

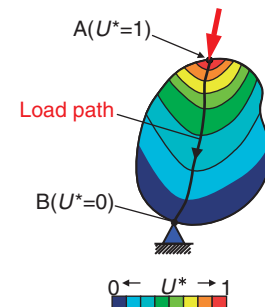


Fig. 2 Image of load path

The conceptual diagram of U_{sum}^* distribution for the whole structure is shown in Fig. 3(c).

Because the load is distributed evenly throughout the structure and the load path distribution is uniform in the one-dimensional spring model shown in Fig. 4, the value of U_{sum}^* is constant at 1.

Figure 5(a) shows an example of the calculation of U^* for a flat plate in which a hole has been opened. Support points are located on one side of the flat plate, and an imposed displacement is applied in the tensile direction on the other side of the plate. Figures 5(b) and 5(c) respectively show the stress distribution and the distribution of U_{sum}^* under the same conditions. Ridge lines which skirt the hole exist in the U^* distribution shown in Fig. 5(a), and it is possible to draw the main load paths from the load points on these ridge lines. By contrast, in the stress distribution shown in Fig. 5(b), stress concentrates at the load points and in the vicinity of the hole, and it is challenging to identify the load paths.

The load paths that extend from the load points to the support points can serve as main load paths, since greater loads can be transferred through them. However, because U^* shows the areas of highest coupling rigidity with the

load points, the magnitude of U^* is the amount evaluated in one direction from the load points, irrespective of whether or not the load paths extend to the support points. Because of this, when forms are complex the load paths become long and complex, and this makes it challenging to judge whether a load path shown by the distribution of U^* extends to a support point. In addition, because the areas identified within the structure are not the only load paths, but load paths are broadly distributed throughout the structure as a whole, an analysis using U^* that is restricted to several main load paths cannot be judged sufficient.

The distribution of U_{sum}^* shown in Fig. 5(c) shows the

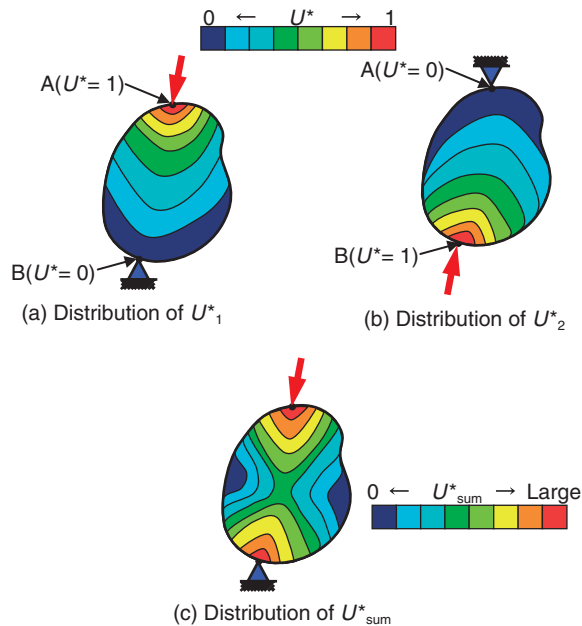


Fig. 3 Conceptual diagram of U_{sum}^*

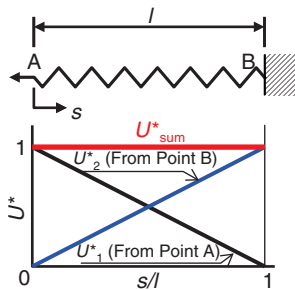


Fig. 4 Diagram for U_{sum}^*

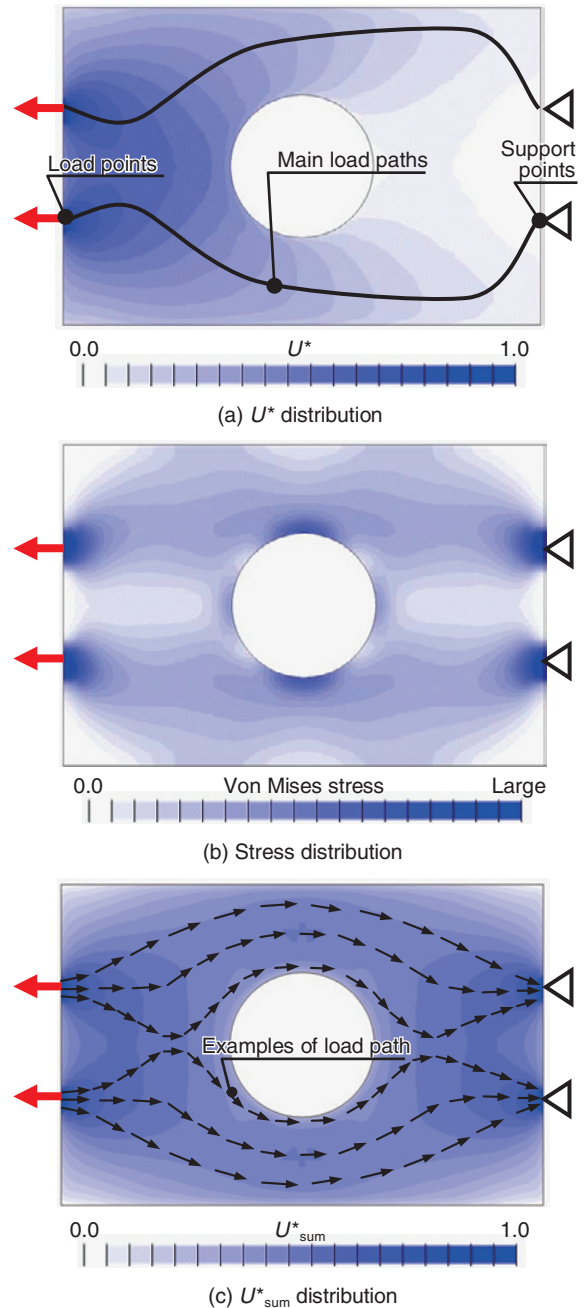


Fig. 5 U^* , stress and U_{sum}^* distribution in plate with hole

strength of coupling from the direction of both the load points and the support points. Because the coupling rigidity with both the load points and the support points is high in areas in which the value of U_{sum}^* is high, there are numerous load paths extending from the load points to the support points. On the contrary, load paths distribute sparsely in areas in which the value of U_{sum}^* is low. Figure 5(c) shows an example of load paths extending from the load points to the support points. Naturally, numerous other load paths could also be represented in this diagram. The distribution of the load paths becomes denser in areas in which the value of U_{sum}^* is high, such as close to the load points and the support points. In this way, the status of distribution of functioning load paths can be expressed visually based on the magnitude of U_{sum}^* .

3. Comparison of Stress Values and U_{sum}^* as Methods of Analysis of Load Path Distribution

3.1. Calculation Model

Figure 6 shows the loading conditions used in the analysis. Four representative loading conditions input from the suspension to the body were used: torsional loading, lateral loading, longitudinal loading, and bending loading. The front damper bases and rear damper bases were basically treated as the load points and the support points respectively, but because a load input using moment cannot be employed in the calculation of U^* in the case of bending loading, the side sill, which possesses high rigidity and displays a low level of local deformation, was treated as the

support point, and bending was reproduced by raising all the damper bases.

3.2. Comparison of Calculation Results

The distribution of stress and the distribution of U_{sum}^* were compared in order to study methods of analysis of the load-path distribution when a load is applied to an automotive body structure. Torsional loading, as mentioned in the previous section, was used as the loading condition.

Firstly, the method of analyzing load paths using stress is discussed. In this method, the flow of forces is estimated by means of distortion diagrams and the direction and magnitude of the principal stress. In the detailed diagram of the area around Part B shown in Fig. 7(b), high

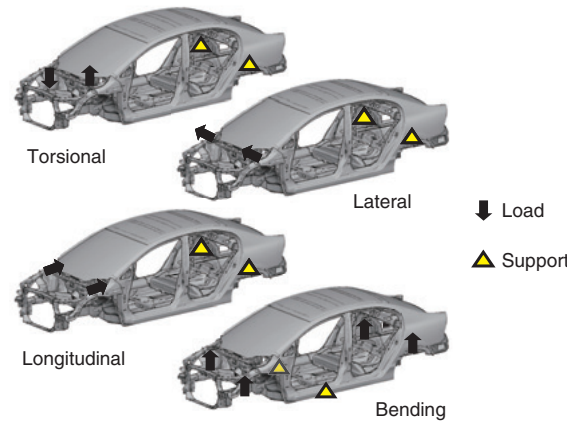


Fig. 6 Load and support conditions

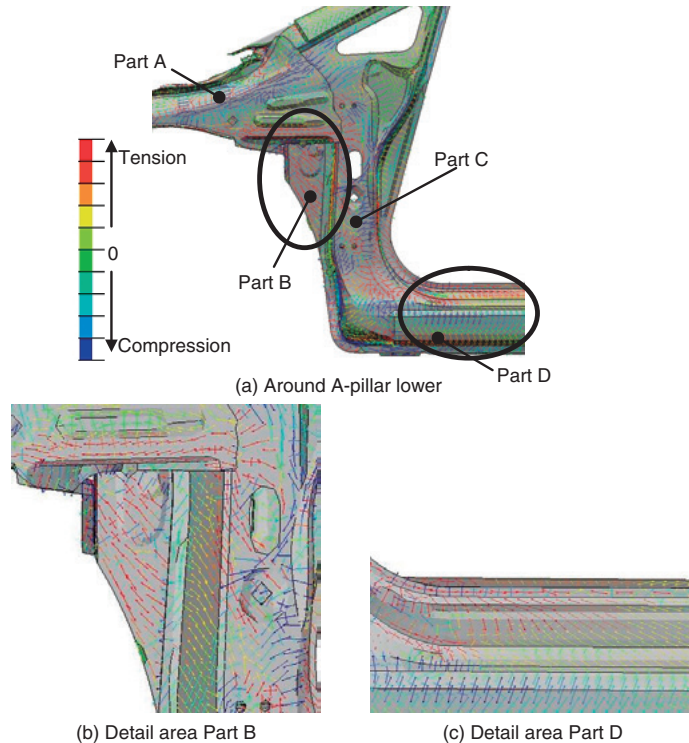


Fig. 7 Principal stress

principal stresses are acting in the tensile direction in the area extending from Part B to Part C, and their directions coincide with each other. It can therefore be conjectured that the load paths extend from Part A toward Part D, via Part B.

It should be noted that a plate has considerably lower bending stiffness in an out-of-plane direction compared to in a shearing direction. As a result, the section of the plate that is subject to out-of-plane bending load can only carry a lower load and thus does not become a main load path. In addition, there is an issue in that whether out-of-plane loads are acting or not is not easily determined by the analysis using principal stress. In order to identify the direction of load acting on the plane, it is necessary to judge whether out-of-plane deformation is occurring using the deformation

diagram or through a comparison of the direction and magnitude of the principal stress between both sides of the plane. These measures are applied to the discontinuous regions based on the understanding of plate thickness and direction of the in-plane stress. Principal stress is high in the detailed diagram of the upper surface of Part D shown in Fig. 7(c), and a strong load appears to be acting on the part. However, the deformation diagram for the cross-section of Part D shown in Fig. 9(a) shows upward displacement of the upper surface of Part D, and can be considered to indicate bending deformation in an out-of-plane direction. Figure 9(b) shows a contour diagram showing the difference between the principal stress on the surface and the reverse surface of the shell elements, formulated in order to verify this bending deformation. Where the surface

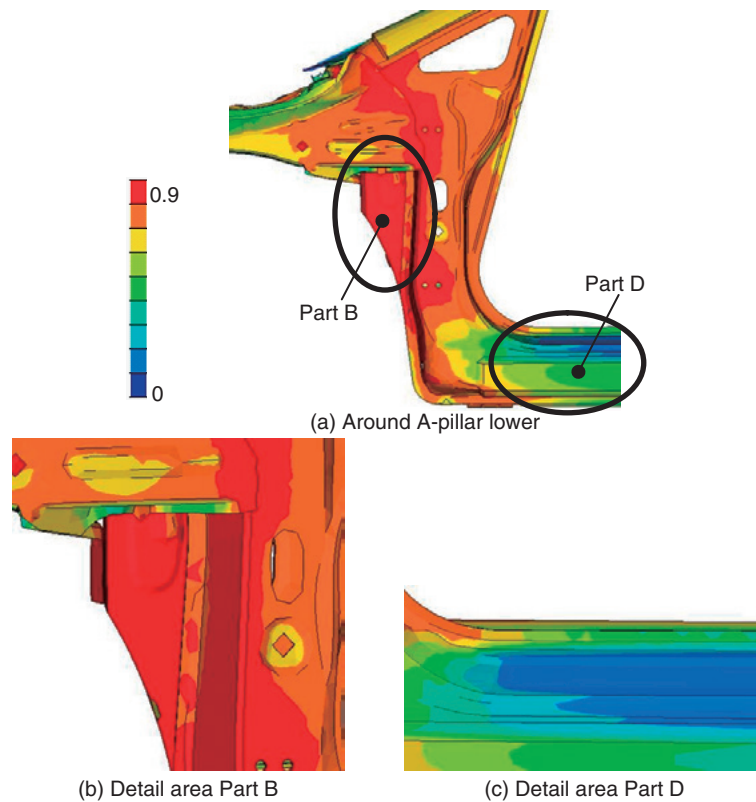


Fig. 8 U_{sum}^* distribution

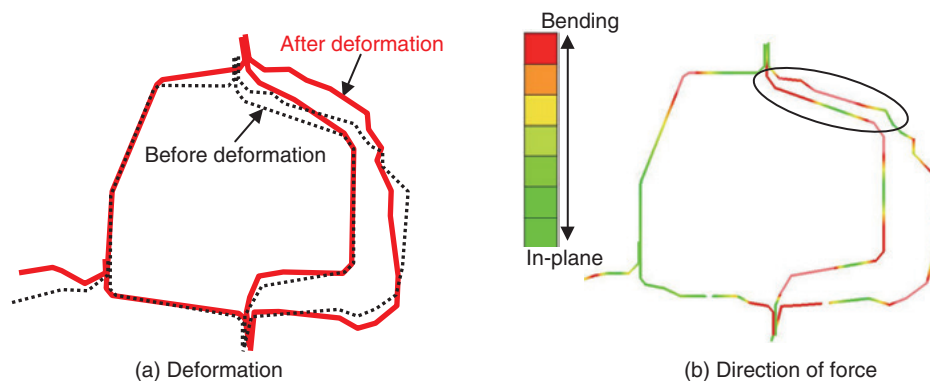


Fig. 9 Section of Part D

is compressed and the reverse surface is stretched due to an out-of-plane bending force, the difference in the principal stresses is high, and this is shown as red in the diagram. The upper surface of Part D (circled in the diagram) shows as red, indicating that a bending force is acting in an out-of-plane direction. Therefore, the upper surface of Part D does not act as a load path.

As the discussion above indicates, when the principal stress is used in an analysis, areas of high stress do not always become load paths, and it is necessary to analyze the nature of the forces by comparing multiple indicators such as deformation diagrams, in addition to judging whether there is sufficient thickness to generate load paths. Therefore, it takes practice and many labor hours to analyze load path distribution using this method and different analysis results may be derived from the same analysis object.

The use of U_{sum}^* , on the other hand, presents the advantage of helping to enable the load-path distribution in the structure to be understood at a glance due to the fact that denser load-path distribution exists at the part with higher U_{sum}^* value.

For example, the area around Part B shown in Fig. 8 (b) displays higher U_{sum}^* value, indicating that load paths distribute densely as in the case of the load path analysis using stress. In the distribution diagram of U_{sum}^* shown in Fig. 8(c), the upper surface of Part D displays a low U_{sum}^* value. The results illustrate the fact that the load path distribution is sparse as in the case of the analysis using stress.

As the discussion above indicates, similar results can be obtained by the load path distribution analysis using U_{sum}^* as those by the analysis using stress, and the analysis using U_{sum}^* can be considered to be valid. In addition, this

method also offers the advantage of making the load-path distribution easy to analyze because it is only required to judge based on the magnitude of U_{sum}^* values instead of the comprehensive judgment based on multiple information as conducted in the analysis using stress.

In addition, the use of stress also presents the issue of concentrations of stress. Figure 10(a) shows the diagram for principal stress tensor of the floor panel. Because the floor panel undergoes shearing deformation under torsional loading conditions, load paths are supposed to distribute throughout the entire floor. However, as the shape of the floor panel is complex due to elements such as beading or holes, concentrations of stress occur and the direction and strength of the principal stress vary with location. Because of this, it is not easy to analyze the distribution of load paths on the floor. By contrast, in the U_{sum}^* distribution diagram, the issue of stress concentration does not occur, and as shown in Fig. 10(b), numerous areas of the floor panel are shown as yellow, making it possible to visually grasp the fact that load paths are virtually uniformly distributed.

4. Similarity of Load-path Distribution in Automotive Structures

4.1. Similarity of Load-Path Distribution

The project went on to compare similarities in the distribution of U_{sum}^* when a variety of loads were applied to automotive body structures.

Figure 11 shows top views, Fig. 12 side views, and Fig. 13 bottom views for the distribution of U_{sum}^* under the loading conditions outlined in the previous chapter. Because the average value of U_{sum}^* differs for each loading condition, the values which are easiest to see for each loading condition have been set as the values for the contour lines.

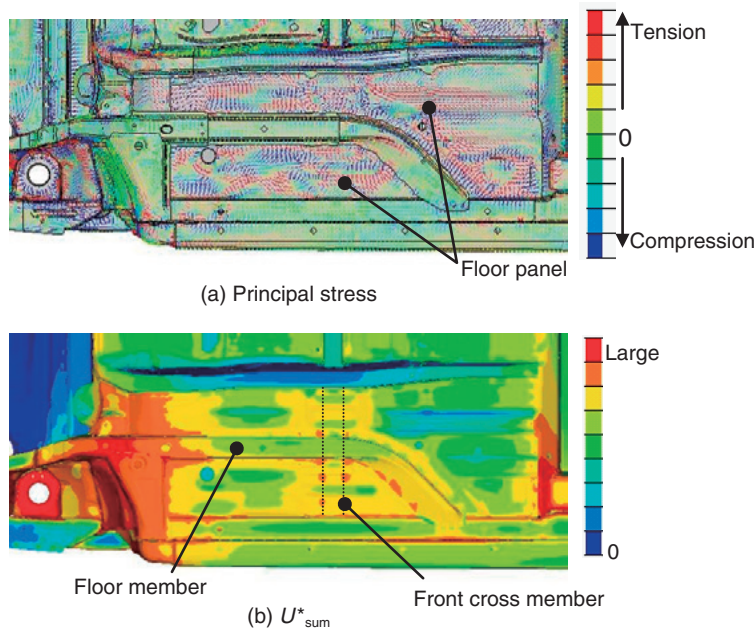


Fig. 10 Front floor

Comparing first the top views shown in Fig. 11, a similarity can be observed between the distribution of U_{sum}^* in the roof section for the torsional loading condition shown in Fig. 11(a) and the lateral loading condition shown in Fig. 11(b). The similarity appears between these two loading conditions because the roof is subjected to the same shearing forces under torsional and lateral loading conditions, while in the case of the other two loading conditions the load path distribution differs, because under longitudinal loading conditions (Fig. 11(c)) the forces act in the direction of bending and under bending loading conditions (Fig. 11(d)) the forces act in an out-of-plane direction.

Next, the side views shown in Fig. 12 will be considered. Under the bending loading condition shown in Fig. 12(d), U_{sum}^* becomes high in the side sill because there is a support point on this member. However, a comparison of the density of the total distribution in the side panel shows a similarity in the distribution of U_{sum}^*

between the torsional loading condition shown in Fig. 12(a) and the bending loading condition shown in Fig. 12(d). In addition, there is a similarity between the lateral loading condition shown in Fig. 12(b) and the longitudinal loading condition shown in Fig. 12(c), in that under both of these loading conditions the values of U_{sum}^* are lower for longitudinal members such as the front pillar lower and the center pillar than for transverse members such as the side sill. However, a detailed analysis of the side sill reinforce, as shown in Fig. 14 indicates that there are differences in the gradation of distribution between the side surface and the top surface for the lateral loading condition (Fig. 14(b)) and the longitudinal loading condition (Fig. 14(c)), and no similarity can be observed between the load-path distributions. The reason for this difference can be explained as follows: taking the direction of the loads acting on the side sill into consideration, under a lateral loading condition the side sill bends in the lateral direction of the vehicle and shearing forces act on the top and bottom

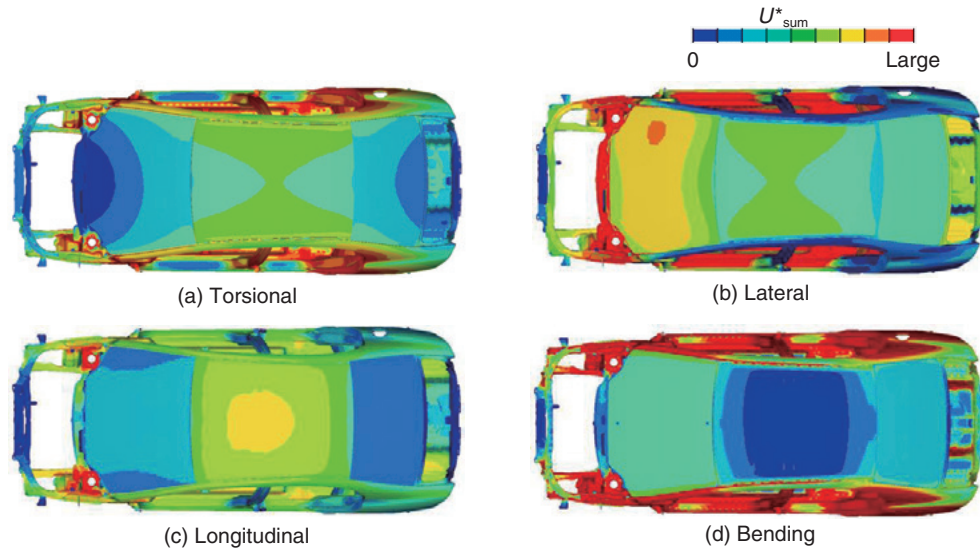


Fig. 11 Top view

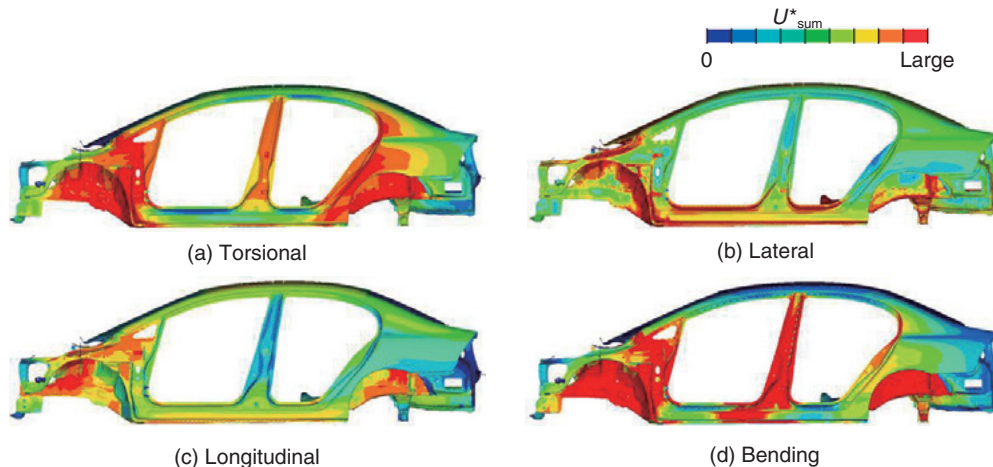


Fig. 12 Side view

surfaces of the side sill, thus generating load paths in these areas; under a longitudinal loading condition on the other hand, the load acts on the side sill in the axial direction, and there is no major difference between the value of U_{sum}^* between the side surface and the top surface of the side sill, with basically identical values displayed across the entire member.

Figure 15 shows the side-roof rail as another

perspective on the side views. Comparing these distributions shows a similarity in the distribution of U_{sum}^* between the torsional loading condition shown in Fig. 15(a) and the longitudinal loading condition shown in Fig. 15(c). Figure 16 shows a diagram of the direction of the loads acting on the side-roof rail at this time. Under a torsional loading condition, forces act on the side-roof rail in the bending and tensile directions, while under a longitudinal

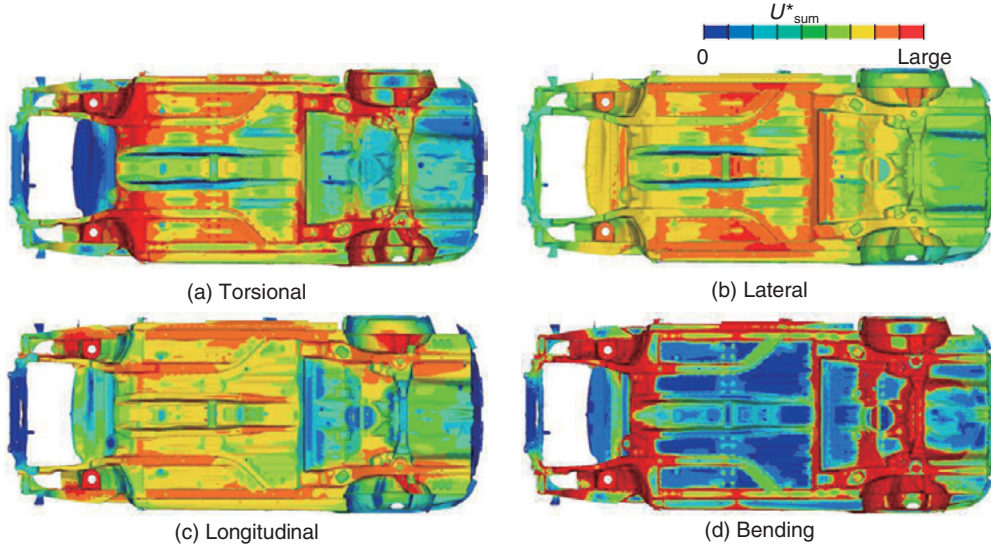


Fig. 13 Bottom view

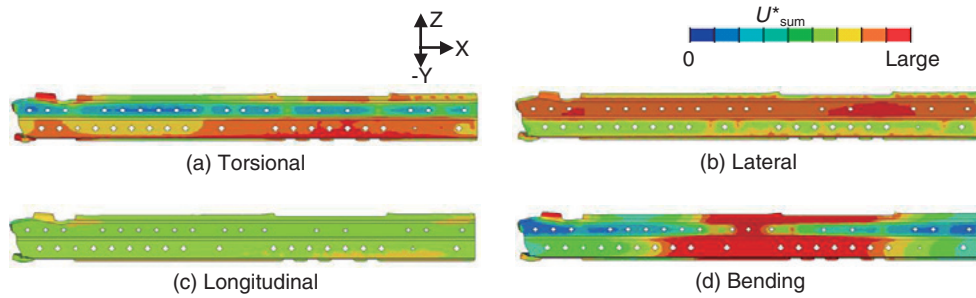


Fig. 14 Side sill reinforce

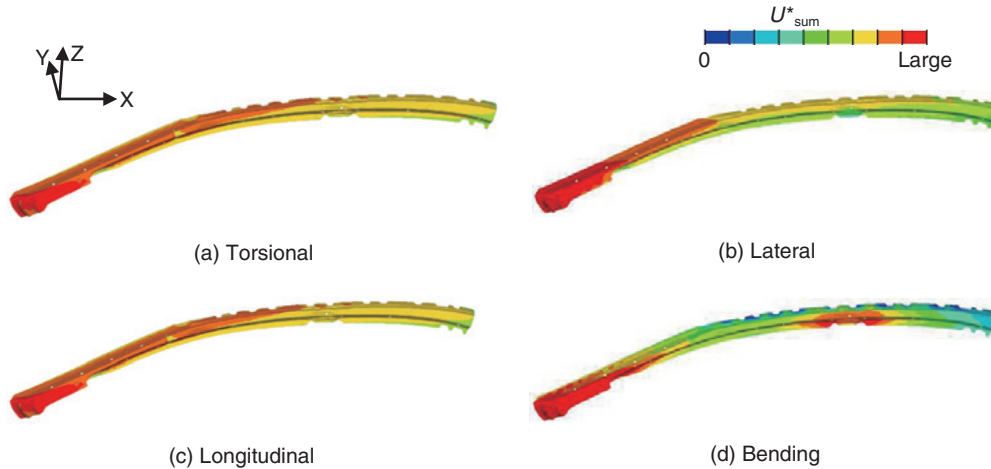


Fig. 15 Side roof rail

loading condition they act in the bending and compression directions. Despite the fact that while the bending direction is the same for both loading conditions, they differ in terms of the tensile and compression directions, because loads act in the axial direction in both cases, the dynamic conditions are identical and there is a similarity in the distribution of U_{sum}^* .

Finally, the bottom views shown in Fig. 13 will be considered. When the distribution of U_{sum}^* is compared for the four loading conditions, no conditions display a high level of similarity for the body as a whole. However, if the focus is restricted to the front floor panel, there is a comparatively high level of similarity between the torsional loading condition shown in Fig. 13(a) and the lateral loading condition shown in Fig. 13(b). A similarity appears between these two loading conditions because shearing forces act on the floor under both torsional and lateral loading conditions. Under a longitudinal loading condition in-plane compression forces and under a bending loading condition out-of-plane bending forces act on the floor, resulting in the difference in the U_{sum}^* distribution.

When the distributions of U_{sum}^* produced by the four loading conditions were compared, the distribution produced by the torsional loading condition was found to display similarities in more members than the distributions produced by the other loading conditions.

4.2. Discussion Regarding Similarities

This section will consider the reason that the torsional loading condition displays a high level of similarity with other loading conditions.

In terms of the direction in which forces act on each part when a torsional load is applied, forces act on transverse members such as the side sills in the bending direction and on longitudinal members such as the center pillars in an axial direction, and shearing loads are generated on each panel. Because of this, U_{sum}^* is high throughout the cabin under a torsional load.

By contrast, under lateral and longitudinal loading

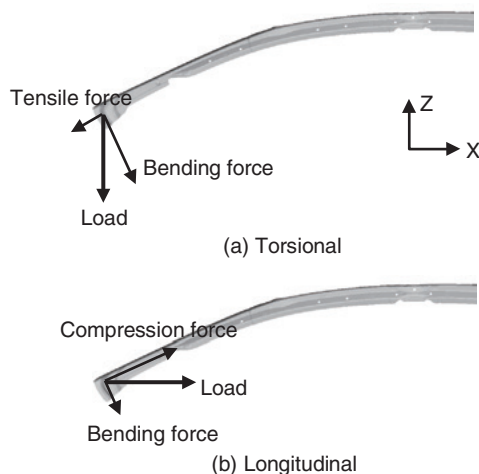


Fig. 16 Image of direction of load on side roof rail

conditions, while a shared point does exist in the fact that there is no principal load path and U_{sum}^* is low in the center pillars, the level of mutual similarity in other members is not particularly high. Taking the direction of the loads acting on the members into consideration, under lateral and longitudinal loading conditions, respectively, the direction of the in-plane forces acting on the floor panels and roof panels is transposed by 90° , and the direction of the axial forces therefore differs. As a result, members displaying high U_{sum}^* and low U_{sum}^* are transposed depending on the loading condition, as observed close to the mid-cross-members and the tunnel frame. Because of this, rather than mutual similarity, these loading conditions display a high level of similarity with the torsional loading condition, under which U_{sum}^* is high throughout the body.

The value of U_{sum}^* is low on the floor and the roof because forces act in out-of-plane directions under a bending loading condition, and load paths are not dispersed through the structures. Given this, the level of similarity between this loading condition and other conditions is low. However, this loading condition matches a torsional loading condition in the fact that principal load paths exist in longitudinal members, and for this reason its level of similarity is high only with a torsional loading condition.

5. Conclusion

- (1) It was demonstrated that similar results can be obtained by the analysis method of load path distribution using U_{sum}^* as those by comprehensive judgments based on the understanding of stress, deformation state, and plate thickness, and that the method using U_{sum}^* is valid as an analysis method for load paths.
- (2) The method based on U_{sum}^* made it possible to indicate the load path state in a structure by using only single indicator and judge the state easily compared to the abovementioned method using stress and the like. As an application example, it was shown that when U_{sum}^* is employed load path distribution throughout the structure can be judged even in a complicated automotive body structure.
- (3) Because load path distribution in the whole structure can be understood at a glance by the analysis using U_{sum}^* , it was made possible to qualitatively grasp the members which display a high similarity in load path distribution under differing loading conditions. As a result, it was shown that the members at which similar loads are acting under differing loading conditions can easily be identified in a complicated automotive body structure.
- (4) It was shown that the torsional loading condition displays a high level of similarity to other loading conditions in terms of load-path distribution. Under this condition, because forces act on each frame members in the bending or axial direction and shearing loads are generated on each panel, load paths are widely distributed throughout all the body structure.

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