Technical Report

Development of Underlying Technologies Contributing to Panel Weight Reduction

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Abstract

Reducing the amount of greenhouse gas emissions is of great importance to protect the global environment, and the adoption of electric vehicles is also accelerating. Under these circumstances, it is crucial to reduce the weight of outer panels and closure parts while minimizing cost increases. This report begins by presenting the underlying technologies for stiffening and reinforcement and their applications that contribute to the weight reduction of panels by thinning, such as hoods and back doors. Door impact beams, positioned inside the door to prevent intrusion during a side crush, are manufactured using high-strength steel sheets by hot stamping or press forming, or high-strength steel pipes, contributing to weight reduction. This report describes examples of our development: applying high-strength steel pipes to door impact beams.

1. Introduction

Following the adoption of the Paris Agreement in 2015, efforts to achieve carbon neutrality have accelerated both domestically and internationally. In October 2020, the Japanese government announced its target of "reducing greenhouse gas (GHG) emissions to net zero by 2050"[1, 2]. In April 2021, an interim target for 2030 was declared, aiming for a 46% reduction compared to 2013 levels, with an aspirational goal of achieving a 50% reduction.[3] To realize these targets, the automotive industry is required to reduce GHG emissions based on Life Cycle Assessment (LCA).[4–7]

Kubo et al. evaluated GHG emissions in LCA for automotive bodies and parts.[6, 7] The assessment was categorized into four stages: (i) material production and processing, (ii) automotive manufacturing, (iii) driving phase (considering fuel production and consumption), and (iv) disposal and recycling. Calculations were performed at the body/part level, and analyses were conducted for each manufacturing process. Their findings indicated that stages (i) and (iii) account for the majority of GHG emissions in LCA, emphasizing the importance of reducing emissions in both stages. They also described case studies on weight reduction using Advanced High-Strength Steel (AHSS)[8], demonstrating that such measures contribute to reducing GHG emissions in stages (i) and (iii), and are effective for lowering life cycle GHG emissions in both Battery Electric Vehicles (BEVs) and Internal Combustion Engine (ICE) vehicles.

It is expected that weight reductions will be achieved for exterior panels and closure parts through the application of advanced materials to exterior panels and crashworthy parts and through shape optimization. As examples of weight reduction related to outer panels, the use of high-strength steel sheets for side outers to lighten surrounding reinforcement parts,[9, 10] as well as thinning of the outer panels themselves, are anticipated. This report first discusses underlying technologies addressing challenges such as stiffness reduction when thinning outer panels like hoods and back doors. In addition, for side-impact crash, door impact beams (DIBs), which absorb the impact through bending deformation, are typically manufactured using ultra-high-strength steel sheets (UHSS), hot-stamped parts, or high-strength steel tubes. This report introduces development cases by Nippon Steel Corporation related to door impact beams made of high-strength steel tubes.

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2. Underlying Technologies Contributing to Hood Weight Reduction

2.1 Lightweight hood structure concept

This section describes underlying technologies addressing issues that arise when thinning both the outer and inner panels for hood weight reduction. **Figure 1** illustrates the concept of a lightweight hood structure. When the outer and inner panels are thinned for weight reduction, a decrease in stiffness and strength characteristics is a concern. To counteract stiffness reduction, an inner structure with a small-pitch supporting the outer panel (small-pitch inner structure) was adopted. Furthermore, to prevent deterioration in strength characteristics such as dent resistance (resistance to permanent deformation when touched by hand) and pedestrian protection performance during frontal crash, the application of high-strength steel sheets to the outer panel was considered.

2.2 Press forming of thin outer panels

Figure 2 shows the appearance of a lightweight hood prototype. Both the outer and inner panels were trial-manufactured using press forming dies and joined at their edges through hemming with mastic adhesive. As an example concept, the prototype employed a 590 MPa-class steel sheet with a thickness of 0.45 mm for the outer panel and a small-pitch inner structure with a thickness of 0.4 mm for the inner panel.

Figure 3 presents the reflection of fluorescent light projected onto the outer panel design area to evaluate surface quality of the lightweight hood prototype. The entire surface, including regions A and B where surface strain tends to occur, was visually inspected. No local distortion of the parallel lines was observed, and no surface strain was detected. These results confirm the potential to maintain high surface quality even with 590 MPa-class steel sheets.

2.3 Performance evaluation of lightweight hood structure

2.3.1 Panel stiffness and dent resistance

Using the lightweight hood prototype shown in Fig. 2, the validity of the underlying technologies was verified by comparing panel stiffness and dent resistance with those of a mass-produced vehicle. In the panel stiffness test (**Fig. 4**, upper left), a hemispherical steel indenter with a curvature radius of R=50 mm was pressed against the outer panel at the points indicated in Fig. 4, upper right, and the applied load and deflection were measured. The evaluation metric was the deflection under a load of 90 N. In the dent resistance test (Fig. 4, upper left), a hemispherical hard rubber indenter with a curvature radius of R=25 mm was pressed against the outer panel at the same points, and the dent depth was measured using a digital dial gauge after unloading. The evaluation metric was the load required to produce a dent depth of 0.15 mm. Figure 4(a) shows the average results for panel stiffness, and Fig. 4(b) shows those for dent resistance. The lightweight hood prototype exhibited performance comparable to that of the mass-produced vehicle in both characteristics.

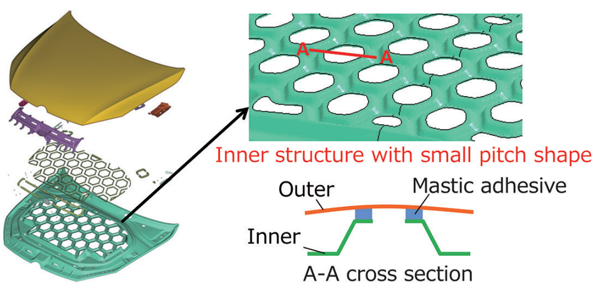


Fig. 1 Concept of lightweight-designed hood

2.3.2 Pedestrian protection performance

Pedestrian protection performance of the lightweight hood structure was evaluated using CAE. The CAE conditions were set in accordance with the pedestrian head protection test of the crash safety performance assessment by the National Agency for Automotive Safety & Victims' Aid (NASVA).[11] The analysis employed LS-DYNA ver. R10.1.0, a general-purpose explicit dynamic FEM solver. A spherical impactor simulating an adult pedestrian's head (diameter: 165 mm, mass: 4.5 kg) was impacted against the hood evaluation surface at an angle of 65° and a speed of 40 km/h. The evaluation metric was the Head Injury Criterion (HIC) calculated from the impactor acceleration.[12] Evaluation points were selected from the hood center with the small-pitch inner structure and the area around the strut tower outside the reinforcement range. The outer panel was made of a 590 MPa-class steel sheet with a thickness of 0.4 mm, and the inner panel was made of a steel sheet with a thickness of 0.4 mm. **Figure 5** shows the HIC values at each evaluation point. Both the hood center and the strut tower area exhibited pedestrian protec-

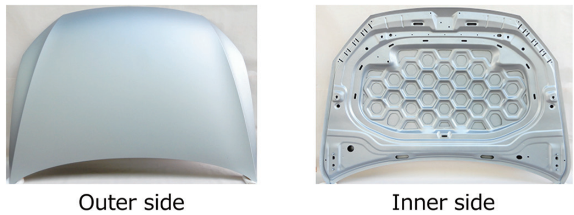


Fig. 2 Appearance of the prototype of lightweight-designed hood

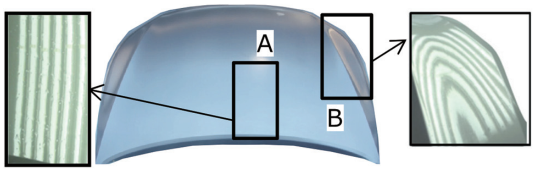


Fig. 3 Surface quality of the prototype of lightweight-designed hood

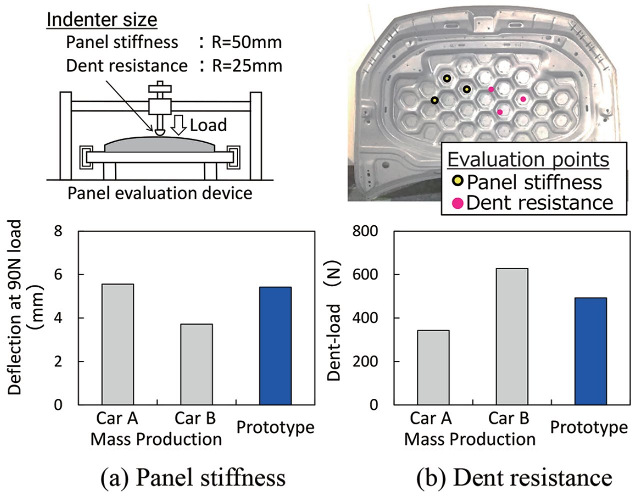


Fig. 4 Comparisons of panel stiffness and dent resistance

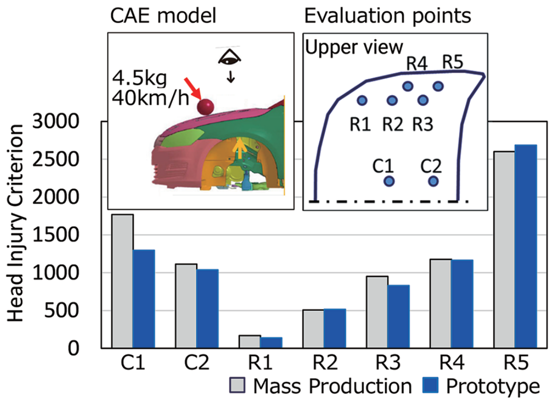


Fig. 5 Pedestrian protection performance

tion performance comparable to that of a mass-produced vehicle.

In summary, the proposed underlying technologies—the small-pitch inner structure and the application of thin high-strength steel sheets to the outer panel—can reduce the decrease in panel stiffness and dent resistance associated with thinning high-strength panels. Furthermore, under the conditions of this prototype, it was confirmed that panel stiffness, dent resistance, and pedestrian protection performance equivalent to those of mass-produced automotive can be achieved.

3. Development of a Lightweight Back Door

3.1 Concept of bridge-type reinforcement structure

In this section, we propose and verify underlying technologies for back door weight reduction. A common countermeasure when thinning outer panels for weight reduction, as shown in **Fig. 6**, is to attach resin sheets partially as reinforcement tools at positions where stiffness is insufficient, followed by curing and foaming the resin during bake coating. However, this method raises concerns about thermal strain during bake coating due to differences in the linear expansion coefficients between the steel outer panel and the resin sheet. Considering these issues and cost implications of existing reinforcement technologies, Nippon Steel developed a steel-based reinforcement method called the "bridge-type reinforcement structure". **Figure 7** illustrates the mechanism of the developed bridge-type reinforcement structure. A straight steel reinforcement member is joined at both ends to the inner side of the outer panel. When an external pressing load acts on the outer panel, the reinforcement member is subjected to tensile force opposing the inward deformation of the outer panel, thereby suppressing its deformation and improving panel stiffness. Since the reinforcement member is straight and joined only at its ends, it does not need to follow the contour of the outer panel, eliminating the need for strict dimensional accuracy. The reinforcement member can be either a steel sheet or wire. Verification results using wire as the reinforcement member are described later; the number and placement of reinforcement members can be adjusted according to the required stiffness performance.

3.2 Effectiveness verification of bridge-type reinforcement structure

An experimental verification of the bridge-type reinforcement structure was conducted using a panel simulating an outer panel, with a curvature radius of R=1 200 mm and dimensions of 400 mm square in a semi-cylindrical shape, as shown in **Fig. 8**. The panel was made of 270 MPa-class steel sheets with thicknesses ranging from 0.4 to 0.7 mm. The reinforcement members were S45C steel wires with a diameter of 2 mm, with both ends bent by 6° over a length of 5 mm in the same direction and bonded to the panel using adhesive. Two conditions were tested: 5 and 15 reinforcement members.

Panel stiffness was evaluated using the stiffness test apparatus shown in Fig. 4 (upper left), with the panel flange constrained. A hemispherical steel indenter with a curvature radius of R=50 mm was pressed against the panel center, and the applied load and deflection were measured. **Figure 9**(a) shows the results for panels with a thickness of 0.4 mm, comparing cases with and without reinforcement members. Increased reinforcement members suppressed deflection and improved panel stiffness. Panels without reinforcement exhibited significant load leaping at low loads, whereas panels with 15 reinforcement members showed no load leaping, and those with 5 members exhibited only minor load leaping. Figure 9(b) compares deflection at 90 N for panels with and without reinforcement members. For example, a 0.4 mm-thick panel with 15 reinforcement members achieved stiffness equivalent to a 0.7 mm-thick panel while maintaining a weight lower than that of a 0.5 mm-thick panel. These results confirm the significant reinforcement effect of the proposed structure. Additionally, CAE analysis of panel stiffness was performed, which was generally comparable to the experimental results, confirming that the reinforcement structure can be easily designed using CAE.

Furthermore, a panel with 15 reinforcement members was held at 170°C for 20 minutes and then air-cooled to simulate the baking paint process. A comparison of surface quality before and after heating confirmed that no visually detectable surface strain occurred.

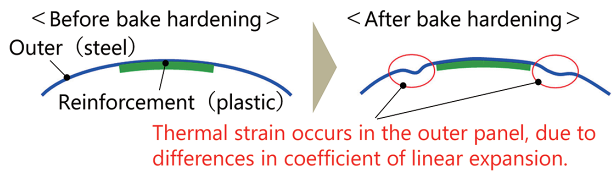


Fig. 6 Problem with reinforcement using resin sheets

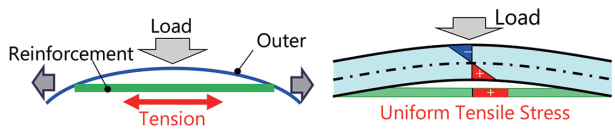


Fig. 7 Mechanism of the developed bridge reinforcement

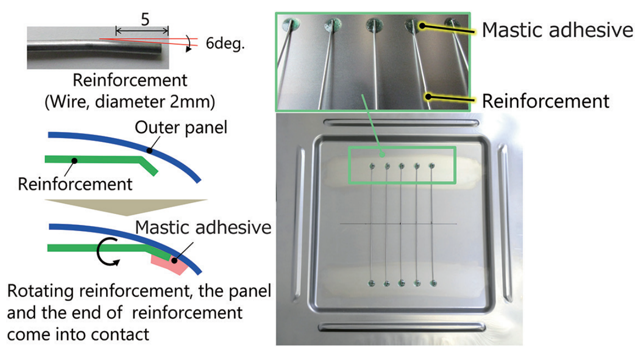
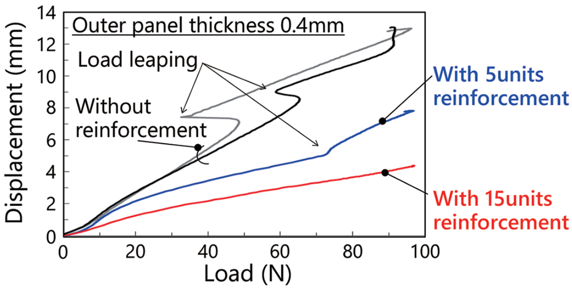
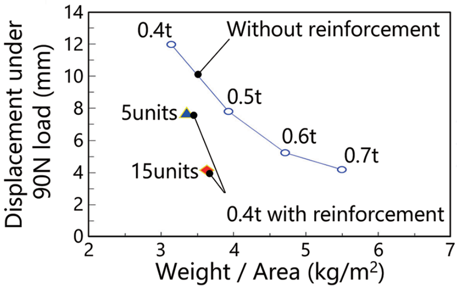


Fig. 8 Appearance of the prototype with a developed reinforcement



(a) Displacement



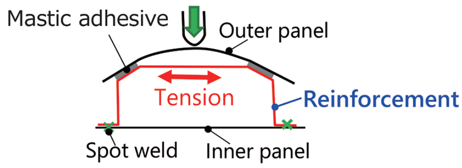
(b) Equivalent performance of panel stiffness

Fig. 9 Effect of developed reinforcement on stiffness improvement

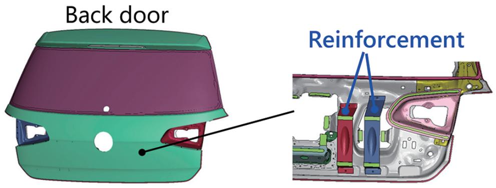
3.3 Application of bridge-type reinforcement structure to the back door

The effectiveness of applying the bridge-type reinforcement structure to a back door was verified using CAE. The back door structure was based on a representative C-segment design. As shown in **Fig. 10**, hat-shaped thin steel sheets were used as the reinforcement members. The flange was spot-welded to the inner panel, and mastic adhesive was applied to the shoulder area to join it to the outer panel. The region between the mastic adhesive joints corresponds to the bridge-type reinforcement. The CAE model compared two conditions listed in **Table 1** to evaluate the stiffness improvement effect of the reinforcement member. In addition to panel stiffness, dent resistance and natural frequency—issues associated with thinning—were also evaluated. Panel stiffness was assessed by pressing a hemispherical steel indenter with a curvature radius of R=50 mm at 98 N and measuring the deflection, with the average value across six outer panel locations used as the metric. Dent resistance was evaluated by pressing the same indenter at 294 N, performing a spring-back analysis, and measuring the residual dent depth, using the average across six locations. Natural frequency was evaluated in the opening/closing motion mode.

Figure 11 shows the evaluation results for panel stiffness, dent resistance, and natural frequency. Panel stiffness is expressed as the inverse of deflection, dent resistance as the inverse of residual dent depth, and natural frequency as the modal value for opening/closing motion, with ratios relative to Model A. Higher values indicate better performance. Model B, which used thinner materials with reinforcement members, exhibited higher panel stiffness and dent resistance than Model A, confirming the effectiveness of the reinforcement members. Natural frequency was nearly equivalent between Models A and B. These results demonstrate that the developed bridge-type reinforcement structure improves not only panel stiffness but also dent resistance and natural frequency, contributing to the lightweighting of panel parts.



(a) Concept of developed reinforcement



(b) Back door with developed reinforcement

Fig. 10 Application of developed reinforcement to back door

Table 1 Verification conditions for the reinforced back door

Model	Reinforcement	Outer panel	Inner panel
A	None	270 MPa 0.60 mm	270 MPa 0.60 mm
B	Some	590 MPa 0.45 mm	270 MPa 0.45 mm

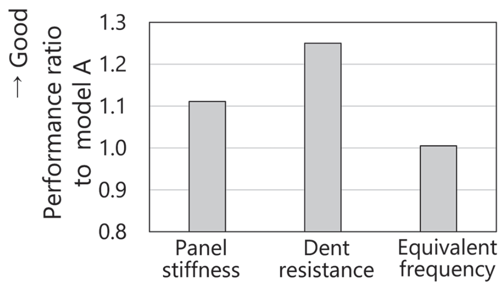


Fig. 11 Results of application to back door (Panel stiffness, Dent resistance, Equivalent frequency)

4. Development of a High-Performance Door Impact Beams

Crash safety requirements are becoming increasingly stringent, and door impact beams (DIBs), which serve to prevent intrusion during side crash (**Fig. 12**), are expected to achieve even higher performance. To meet these demands, further strengthening using hot-stamped or cold-formed ultra-high-strength steel press-formed parts is anticipated.[13, 14] In some automotives, steel tube parts with superior bending strength have already been applied, and efforts are underway to adopt even higher-strength steel tubes to balance crash performance and weight reduction. However, straight tubes generally require additional parts to ensure outer panel reinforcement functionality. To reduce costs by eliminating these additional parts, DIBs made from steel tubes bent accurately to match the outer panel shape are desirable.

Various tube forming technologies have been developed for bending steel tubes, including rotary draw bending, moving roll press bending, cross-section deformation press bending, and Three-Dimensional Hot Bending and Direct Quench (3DQ).[15] Among these, 3DQ is suitable for low-volume, multi-variety production. Conversely, cross-section deformation press bending has been pro-

Fig. 12 Door impact beam

posed as a steel tube bending technology offering excellent productivity and cost efficiency through cold press forming. However, as steel tubes become stronger, increased residual stress after press forming raises concerns about delayed fracture, making residual stress reduction measures critical.

In this section, two processing technologies for manufacturing steel tube DIBs bent accurately to match outer panel shapes are introduced: 3DQ and a new cold press forming method designed to prevent delayed fracture, called the "diameter-reduction press bending process".

4.1 Three-dimensional hot bending and direct quench (3DQ)

3DQ is a process in which a steel tube is continuously fed, locally heated using a high-frequency coil, bent by a robot applying bending moments, and immediately water-quenched, enabling simultaneous forming and quenching. This method offers the following features:[16] (i) Capable of producing closed-section three-dimensional parts with strength exceeding 1 470 MPa. (ii) Hot forming minimizes residual stress and provides excellent shape accuracy. (iii) Die-less forming eliminates the need for dies, and the equipment is compact. (iv) Robot trajectory data can be easily modified.

Therefore, 3DQ enables low-cost production of DIBs with curvatures matching outer panels for low-volume automotive.[17]

4.2 Diameter-reduction press bending process

Figure 13 illustrates the outline and process of diameter reduction press bending method. By designing the die face cross-sectional perimeter smaller than that of the original tube, the entire forming area becomes a compressive field at the forming bottom dead center, promoting relatively uniform plastic deformation over a wide range. This approach aims to enhance shape accuracy and reduce residual stress, thereby improving delayed fracture resistance. The original tube used was a quenched steel tube of 1.5 GPa class (thickness: 2.3 mm, outer diameter: Φ31.8 mm, length: 1 100 mm).

Figure 14 compares CAE results near the bent section. The diameter-reduction press bending process reduced the maximum tensile residual stress by 40% compared to conventional press bending. **Figure 15** shows CAE results for a three-point bending test simulating a collision. The diameter-reduction press bending process achieved higher load than the original tube, indicating improved crash performance. This improvement is presumed to result from increased parts strength due to work hardening and enhanced bending resistance from the convex shape toward the vehicle exterior. **Figure 16** shows the appearance of a prototype produced using the diameter-reduction press bending process. To evaluate delayed fracture resistance, a hydrochloric acid immersion test (pH 1.0, immersion time: 100 hr, solution volume: 5 mL/cm^2, room temperature,

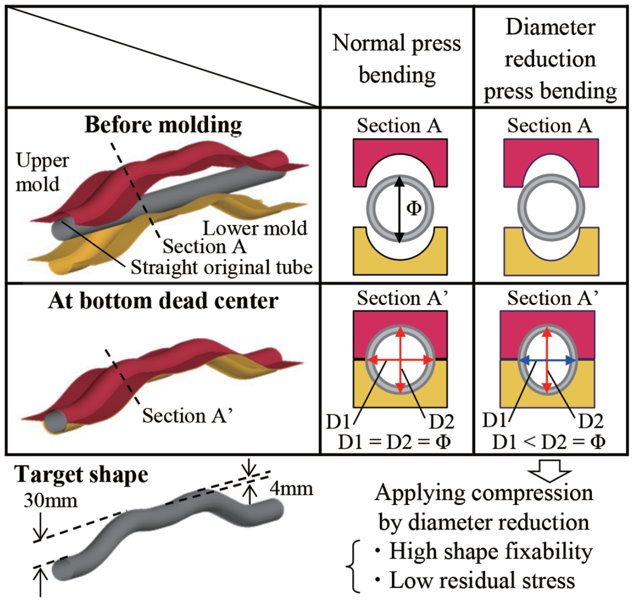


Fig. 13 Outline and process of diameter reduction press bending method

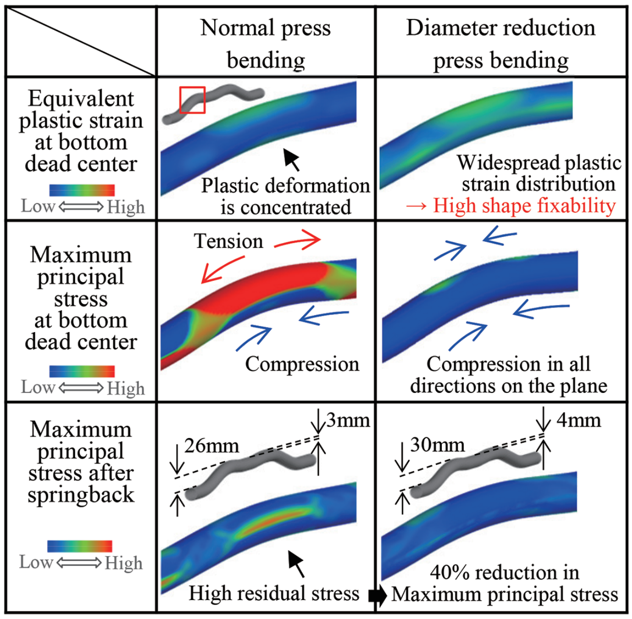


Fig. 14 Comparison of analysis results in the vicinity of the bending area

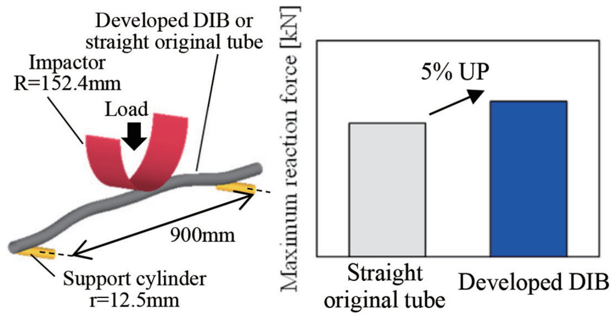


Fig. 15 Calculated maximum reaction force of 3-point bending

Fig. 16 Appearance of prototype produced by the diameter reduction press bending method

N = 3) was conducted using the prototype. No cracks were observed. These results confirm that the diameter-reduction press bending process produces DIBs with excellent delayed fracture resistance and the intended shape.

5. Conclusion

From the perspective of global environmental protection, the importance of reducing greenhouse gas emissions is increasing. Under these circumstances, achieving weight reduction while minimizing cost increases is essential, and thinning outer panels and crashworthy parts within closure parts is an effective approach.

1. Hood: The proposed underlying technologies—the small-pitch inner structure and the application of thin high-strength steel sheets to the outer panel—can reduce the decrease in panel stiffness and dent resistance associated with thinning high-strength panels. Under the prototype conditions presented in this report, it was demonstrated that panel stiffness, dent resistance, and pedestrian protection performance equivalent to those of mass-produced automotive can be achieved.
2. Back Door: Applying the proposed underlying technology—the bridge-type reinforcement structure—was shown to improve not only panel stiffness but also dent resistance and natural frequency, thereby contributing to the lightweighting of panel parts.
3. Door Impact Beam (DIB): Steel tube DIBs bent accurately to match outer panel shapes are desirable for cost efficiency. For low-volume, multi-variety production, Three-Dimensional Hot Bending and Direct Quench (3DQ) technology is suitable. Additionally, for high productivity and cost efficiency, the newly developed diameter-reduction press bending process was introduced, demonstrating excellent shape accuracy and delayed fracture resistance.

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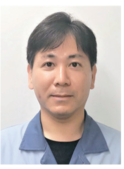

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