NIPPON STEEL TECHNICAL REPORT No. 122 NOVEMBER 2019

Technical Report

UDC 629 . 11 . 011 . 66 : 669 . 14 . 018 . 26

Proposal of New Steel Lightweight Door Structure Applying Frame Reinforcements with Extremely Small Sections

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Abstract

Measures have been actively taken to reduce automobile weight by using thinner steel sheets of higher strength for body structural parts and also for closure parts such as doors. When thin sheets are used for door outer panels, however, panel stiffness lowers, and it is necessary to improve the stiffness. To solve the problem, a new steel lightweight door structure having frame reinforcements composed of members with extremely small cross sections is proposed. This paper reports the basic studies and tests of the proposed door structure.

1. Introduction

Regulations of CO_2 emission from automobiles are enacted in many countries throughout the world as a measure to suppress global warming, and thus, lower fuel consumption is strongly required for cars. Therefore, car builders are striving to reduce body weight by expanding the use of thinner and higher-strength steel sheets for body structural parts to reduce their weight or their number. The need for higher body strength by increasing the use of high-strength sheets is strong also from the viewpoint of collision safety, and new structural design of body frames and related technologies are actively being developed to decrease body weight and improve collision safety simultaneously.

Like body structural parts, measures are taken to reduce weight and improve collision safety also of closure parts such as doors and hoods. In fact, regarding doors, on which the present article is based, there have been many studies of structural improvement and strength increase: for example, hot stamping was applied to the forming of impact beams, the door reinforcing members against side impact, as the first case in Japan[1)], and 1470 MPa grade high-strength steel sheets were used for them[2)]. On the other hand, panel stiffness is required for the outer panels in relation to the sensation of rigidity against hand touch during washing and waxing and the yielding under pressing by fingers, and also the resistance to dents due to pebble strikes, etc. However, panel stiffness and dent resistance are lowered as the thickness of the material sheets decreases.

Although dent resistance increases with higher yield strength of the material, and can be improved by strengthening the steel, higher yield strength leads to more surface deflection during press forming. To solve the problem, bake-hardenable (BH) steel sheets, the yield strength of which is low during press forming and increases through baking of paint coating, has been put into commercial use[3)], significantly contributing to weight reduction through increased use of thinner sheets. Panel stiffness, however, is affected by material thickness[4)], panel shape[5)] and elastic modulus[6)], and therefore, cannot be improved by the use of higher-strength sheets. In addition, design freedom of panel shape is limited since the shape of outer panels is often dictated by artistic design. For these reasons, to decrease the weights of doors by using thinner sheets for the outer panels, reinforcing measures are essential to compensate for lower panel stiffness.

As a measure to further reduce the weight of steel automobile door modules, Nippon Steel Corporation has been studying the use of thinner sheets for door outer panels, and developing reinforcing structures for them. As a result, a new lightweight steel door structure including frame reinforcements for the outer panel composed of members with very small cross sections has been proposed. This paper describes the basic studies for the proposed structure, the evaluation of panel stiffness and side impact performance by FEM analysis and forming test of the frame reinforcement.

2. Outlines of Developed Frame-reinforced Door Structure

When a reinforcement is used to compensate for the lowered panel stiffness of a door outer panel owing to the use of thinner steel sheets, the weight reduction effect of the thinner sheet is reduced by the weight of the reinforcement. To solve the problem, we studied a

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variety of door structures that offer the stiffening function and resistance to side impact, and developed a new door structure wherein long reinforcing members with very small cross sections are arranged on the inner surface of the outer panel to form a lattice frame (the developed structure hereinafter called the frame-reinforced door structure). An example of the developed structure applied to the door of a commercially marketed model is given in **Fig. 1**, and a conventional door structure in **Fig. 2** for comparison (here, the outer panel is omitted). The developed door structure is characterized by the reinforcing members having a small rectangular closed section arranged to form a lattice contacting the inner surface of the outer panel, and the door impact beam responsible for resistance to side impact in the conventional structure is absent.

To minimize weight increase, the frame reinforcement is composed of members made of very thin sheets and having closed hollow sections, and their sectional shape was designed in a square or a rectangle with the longer side in the direction of the body width so as to effectively increase the bend stiffness against lateral force. **Figure 3** shows examples of the cross sections of the frame reinforcements selected for the present study. In addition, since it was necessary for the frame reinforcement to have a high strength to substitute for the side impact resistance of the conventional door impact beam, 1 500 MPa grade steel sheets for hot stamping use were selected as the material. In addition, for the configuration shown in Fig. 1, the designs of some door parts were changed and additional parts were newly included as required to support frame reinforcements.

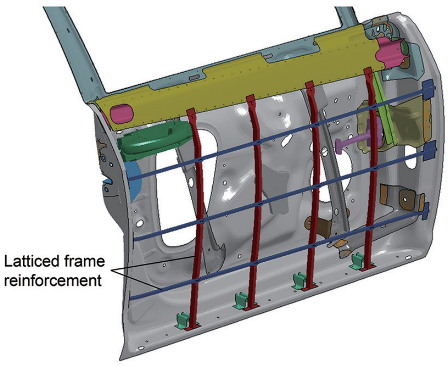

Fig. 1 Example of developed lightweight door structure

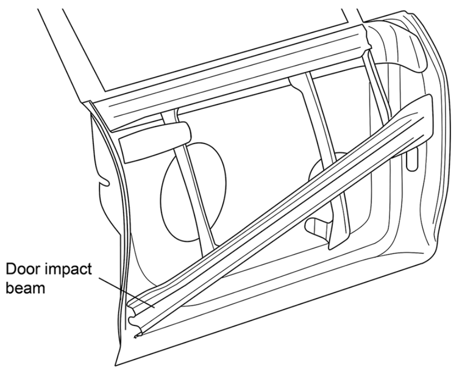

Fig. 2 Schematic illustration of conventional door structure

3. Stiffening Function and Side Impact Resistance of Frame-reinforced Door Structure

The frame-reinforced door structure is required to have the following two functions: a stiffening function to improve the stiffness of the outer panel decreased by the use of a thinner sheet; and the resistance to side impact to compensate for the absence of the conventional member for side impact. Evaluation and verification of these functions of the developed door structure are explained in this Section.

3.1 Evaluation of panel stiffness and side impact resistance by FEM analysis

The developed and conventional door structures given in Figs. 1 and 2 were compared in terms of panel stiffness and side impact resistance by FEM analysis using LS-DYNA, a general-purpose FEM solver for structural analysis. **Figure 4** shows the positions of the indenters assumed for the analysis of panel stiffness, and that of the impactor for the analysis of side impact resistance. In the panel stiffness analysis, a rigid spherical indenter 50 mm in diameter was assumed to indent the outer panel at points A or B in part (a), corresponding to the centers of the rectangles of the lattice defined by the frame members and the rear end line of the outer panel. Point A is the position where panel stiffness is lowest by the conventional structure, and point B is the position where it is lowest by the developed structure according to a preliminary study. The panel stiffness of the conventional structure was evaluated by indenting at point A, and that of the developed structure at points A and B. For panel stiffness analysis, in addition, a restrictive condition was set assuming that frame reinforcements were bonded to the outer panel.

Next, in the side impact analysis, a rigid columnar impactor 150 mm in radius was assumed to strike the door at a position between the middle two vertical members of the frame reinforcement as shown in part (b) of Fig. 4. As a boundary condition, to prevent the door inner panel from displacing toward the cabin inside, a rigid surface was assumed there to be contacting the three zones corresponding to the reinforcements of the A pillar, the B pillar and the side sill on the inner side of the door inner panel. For the analyses of

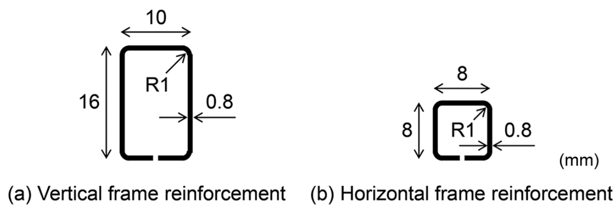

Fig. 3 Basic cross section shapes of frame reinforcement with small section

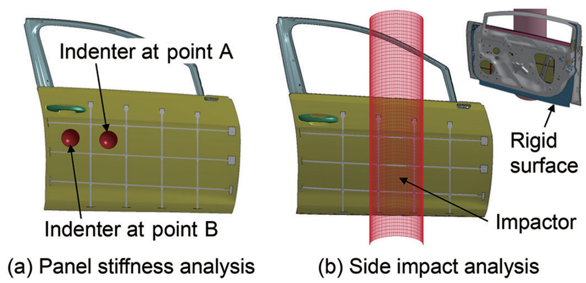

Fig. 4 FE models of panel stiffness analysis and side impact analysis

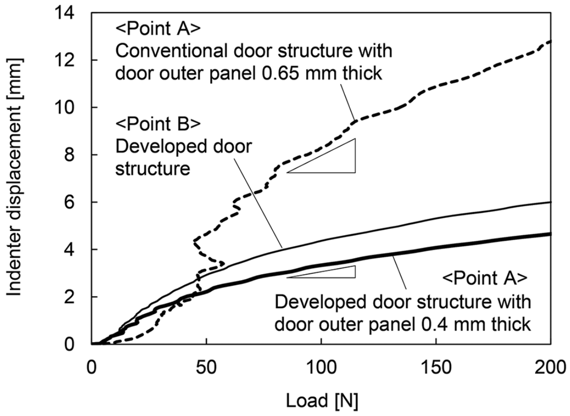

Fig. 5 Load-displacement curves by panel stiffness analysis

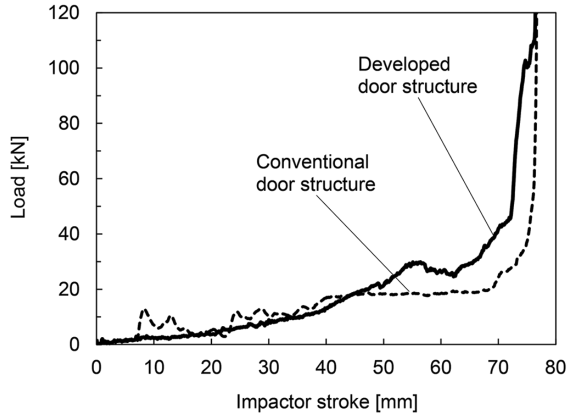

Fig. 7 Stroke-load curves by side impact analysis

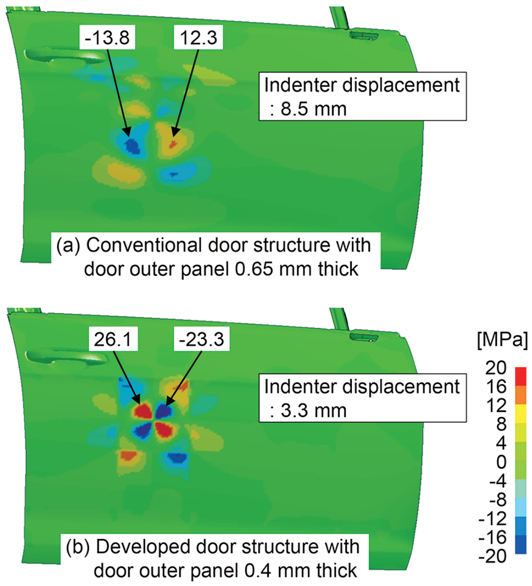

Fig. 6 Calculated in-plane shear stress under load of 100 N at point A

panel stiffness and side impact, a 590 MPa grade high-strength steel sheet 0.4 mm in thickness was used for the door outer panel for the developed structure, and another of mild steel 0.65 mm in thickness for the conventional structure, and the members of the frame reinforcement were assumed to be made of 1 500 MPa grade steel sheets for hot stamping use and formed into the sectional shapes given in Fig. 3.

Figure 5 shows the calculated load-displacement curves obtained through the panel stiffness analysis. With the conventional structure, the loads of the indenters decreased suddenly due to oil canning when the displacement increased from 3 to 4 mm, and in general, the gradient of the curve was greater, which means lower stiffness, than that of the developed structure. With the developed structure, in contrast, there was no sudden decrease in the indenting load corresponding to oil canning, and the gradient of the curve was comparatively smaller, indicating higher stiffness. This seems to indicate that the developed structure exhibits the same or better panel stiffness for the conventional structure even when a door outer panel is as thin as 0.4 mm.

Figure 6 is an analysis of panel stiffness when a indenting load is applied at point A; what is shown here is the distribution of in-plane shear stress in the door outer panel under a indenting load roughly of 100 N. Whereas with the conventional structure, in-plane shear stress is distributed in a wide area around the indenting point, and its absolute value is small, with the developed structure, large in-plane shear stress is concentrated in a limited area defined by the grid square of the lattice. This seems to indicate that by supporting the outer panel with lattice frame reinforcements dividing it into small areas, it is possible to easily obtain tension in the panel plane, which improves the panel stiffness.

Next, **Fig. 7** shows the stroke-load curves calculated in the side impact analysis. In the stroke range of a low load level up to roughly 40 mm, the reactive force is somewhat lower with the developed structure than with the conventional structure, but in the range beyond 45 mm, it is greater with the developed structure, which seems to indicate a high possibility that the developed frame reinforcement exerts the same side impact resistance as that of the conventional door impact beam or better.

3.2 Accuracy verification of panel stiffness analysis

The panel stiffness of the developed door structure was evaluated using a door outer panel specimen formed according to the door of a commercially marketed model different from the one shown in Fig. 1; here, the material was a 440 MPa grade high-strength steel sheet, 0.4 mm in thickness, and two vertical frame reinforcements had been prepared by the forming method described later in Section 4, and attached to the inside surface of the specimen outer panel. **Figure 8** schematically shows the specimen for the panel stiffness measurement; the cross sectional shape of the vertical frame reinforcements was the same as that of Fig. 3 (a). The test was conducted referring to the unitary test method[7] prepared by the Japan Sheet Metal Forming Research Group, using a hemispherical steel indenter 50 mm in tip radius, and the specimen panel was restricted along the front, rear and lower sides with jigs. In addition, the panel stiffness of the specimen was calculated separately simulating the above test condition.

Figure 9 compares the load-displacement curves obtained through the test and the simulation. Both the loads decrease suddenly due to oil canning when the indenting displacement advanced to roughly 8 mm, but up to that point, the two curves agree well with each other. As high accuracy of the analysis of panel stiffness has been confirmed by the above result, the panel stiffness of the developed door structure described in sub-section 3.1 is considered realistic. However, because the panel stiffness of real automobile doors is

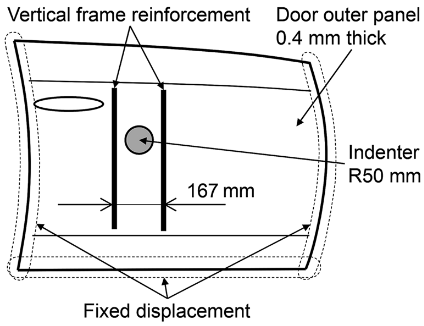

Fig. 8 Schematic illustration of sample for panel stiffness measurement

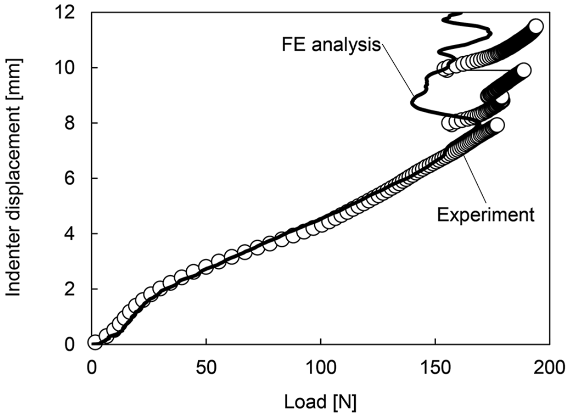

Fig. 9 Comparison of measured and calculated load-displacement curves

likely affected by the arrangement and material characteristics of the mastic sealer[8] and various other factors, we will continue studying it under conditions better reflecting real automobile doors.

4. Method for Forming Frame Reinforcements

A third requirement for the frame-reinforced door structure is establishing from the manufacturing viewpoint a method for forming the long frame reinforcements with small rectangular hollow sections to achieve high strength and dimensional accuracy. The forming methods of thin steel sheets into long parts with rectangular closed sections include roll forming of sheets[9] and bending of rectangular-section pipes[10]. However, since both the vertical and horizontal members of the developed frame reinforcement have to be shaped to follow the inner surface of the door outer panel, it is necessary to change their sectional shapes locally at their crossing points. In addition, for wider freedom of sectional size and sheet thickness, press forming of thin steel sheets using general-purpose press machines was selected in the present study. The selected forming method and the results of the forming test are described below.

4.1 Outlines of forming method

The following three problems are expected in the forming of high-strength thin steel sheets into long parts with small rectangular closed sections as shown in Fig. 3 so that they fit to the sectional shape of a door outer panel: (1) when high-strength steel sheets are cold formed, dimensional accuracy is likely to be poor owing to spring back, and it tends to be worse with thinner sheets; (2) in hot stamping of thin sheets, material stiffness decreases significantly after heating, and as a result, the material sheets may deform during heating in the furnace and transfer after discharge from it, leading to forming problems. Moreover, temperature decreases rapidly owing to air cooling during transfer, and it may be difficult to start the press forming at a temperature adequate for the quenching; and (3) the shape of the rectangular closed section may become irregular during the press forming, and buckling may occur during bending of long parts to the curves of the door outer panel. To solve these problems, a four-process forming method was developed; it consisted of three cold forming processes and one hot bending process as illustrated in the upper frames of **Fig. 10**. A blank sheet is formed into a straight intermediate part with a rectangular closed section through the first three cold forming processes, and then it is bent into desired longitudinal curves through the fourth hot bending process. As it was considered possible to reduce the risk of irregular sectional shape by positioning the two edges so as to butt against each other precisely during the forming into rectangular closed sections, the opposing edges of the blank were formed in the first forming process to have waves in some portions in the length direction such that their tops and bottoms of an edge were staggered to those of the other as shown in **Photo 1**.

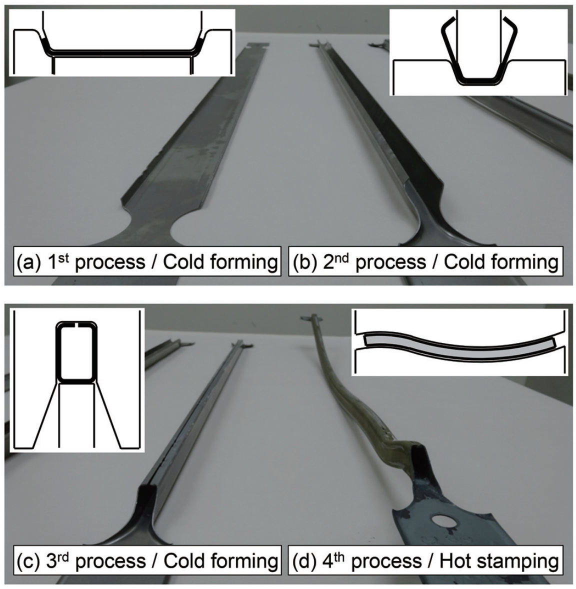

Fig. 10 Processes for forming frame reinforcements with rectangular closed sections

Photo 1 Butting edges having mutually staggered waves

This forming method was effective in solving the above three problems for the following reasons. (1) By limiting cold forming up to the forming of the straight intermediate parts only, 3-dimensional shape accuracy defect is prevented, and then by applying hot stamping excellent in shape fixability at the final stage, it is possible to obtain 1 500 MPa grade high-strength parts. Also, the shape accuracy of the developed method is so high that it is comparatively easy even with thin steel sheets to manufacture reinforcing members that precisely follow the curves of the door outer panel. (2) As intermediate parts with rectangular hollow sections are heated and hot stamped, the stiffness of the parts after heating is far higher than that of flat sheets, and the rate of the air cooling during transfer is expected to be milder. (3) The waves of the butting edges shown in Photo 1 proved effective at preventing the sectional shape from becoming irregular during the forming into the closed section shapes. In addition, longitudinal bending by hot stamping, in which the deformation resistance is low, is expected to suppress buckling during bending even when the material sheets are very thin.

Trial forming of the vertical members of the developed frame reinforcement was conducted according to the above forming method.

4.2 Forming test results

The formed parts shown in the photographs of Fig. 10 are those obtained through processes (a) to (d), respectively. The trial manufacture yielded intermediate and final parts free from cracks, wrinkles and other forming defects and excellent in shape accuracy to follow the section shape of the door outer panel.

Figure 11 shows the temperature change of a formed part measured during air cooling after discharging from the heating furnace for the hot stamping. For the temperature measurement, a thermocouple was attached to a blank 0.8 mm in thickness before the forming at a position corresponding to the longitudinal center on the section inside before the cold forming, then it was formed through the first to third processes. For comparison purposes, a thermocouple was attached to a 0.8-mm thick flat steel sheet and another to a 1.6-mm thick sheet. As is seen in Fig. 11, the temperature drop of the 0.8-mm thick sheet by air cooling was faster than that of the 1.6-mm sheet, but that of the 0.8-mm thick closed-section part was substantially the same as that of the 1.6-mm sheet. Judging from the fact that steel sheets 1.6 mm in thickness are widely used for hot stamping[11)], when the developed forming method is put into commercial manufacture, the problem of the temperature drop due to the air cooling after discharge from the furnace is expected to be solved even when general-purpose equipment for hot stamping is used.

Figure 12 shows the hardness distribution measured at cross sections of a frame reinforcement made by the test forming. Hardness was roughly 450 HV, corresponding to a tensile strength of 1 500 MPa, at all the circumferential positions of sections 1 and 2. This indicates that the forming start temperature and the cooling rate during the holding at the bottom dead point of the hot stamping were adequate for quenching. Although the parts are cooled by the forming die only from the outer side by the developed method, the cooling rate seems to be sufficient for the purpose since the sheet thickness was as thin as 0.8 mm. At section 3, on the other hand, while hardness was approximately 450 HV at most of the measuring positions, it was as low as 370 HV (corresponding to 1 170 MPa tensile strength) locally at some positions corresponding to the outer side of a longitudinal bend.

Next, **Fig. 13** shows the evaluation result of shape accuracy of a vertical reinforcing member of a 1 500 MPa grade steel sheet by non-contact 3-dimensional shape measurement. The figure also shows, for comparison purposes, the shape accuracy of another part of the same frame member, cold formed through all four forming steps using a 780 MPa grade high-strength steel sheet, and photographs of the side views of these two parts. No buckling or other forming defects were found with the cold-formed 780 MPa grade test part, but its curvature was generally small, and it deviated from the design shape significantly. The test part formed through the developed method including hot stamping at the fourth process, in contrast, had markedly smaller dimensional errors, and fitted well to the sectional shape of the door outer panel generally across its length. However, the latter had a local deviation (−0.77 mm) from

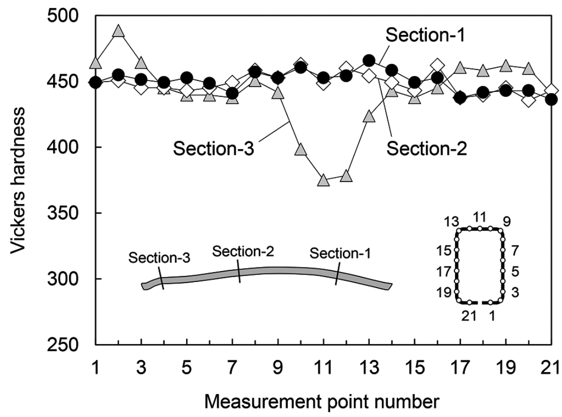

Fig. 12 Vickers hardness distributions in cross sections of trial-formed vertical member of frame reinforcement

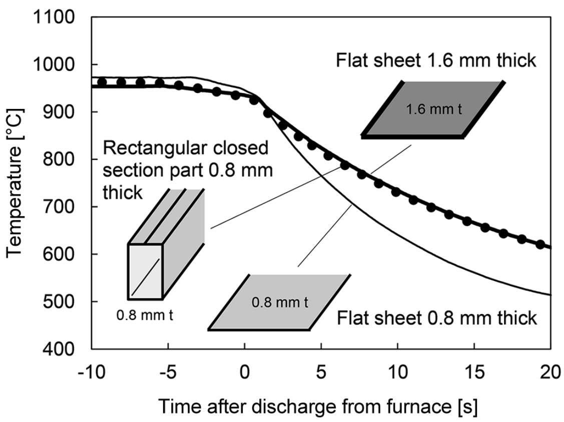

Fig. 11 Air cooling curves for rectangular closed section part

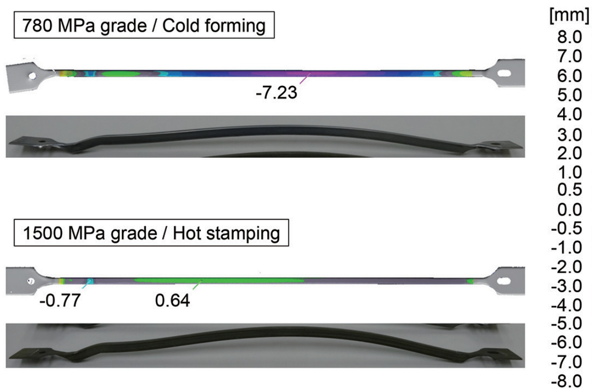

Fig. 13 Shape deviation of trial-formed vertical members of frame reinforcement

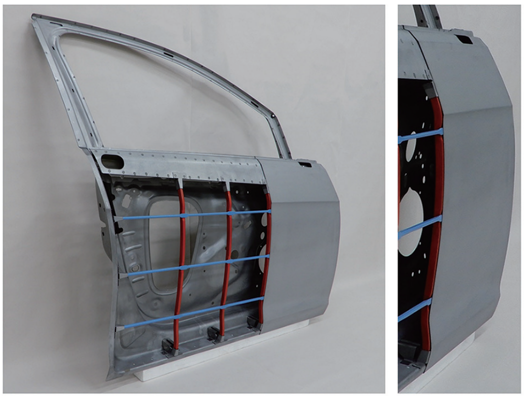

Photo 2 Trial-manufactured steel door of developed structure

the designed shape on the outer side of a longitudinal bend, which resulted from a shrinkage of the outer side of the bend during the bending by hot stamping. This occurred exactly at the same position where hardness was low in section 3 in Fig. 12; it is presumed that, in this portion, the cooling rate during the holding at the bottom dead point was low because of the shrinkage, and sufficient hardness was not obtained. The quenching hardness of this portion can be increased as designed by modifying the die shape taking the shrinkage into consideration.

The vertical and horizontal members of the frame reinforcement were manufactured by the developed forming method, and a door of the developed structure was assembled for trial purposes by fitting the frame to the other, separately manufactured parts of the door shown in Fig. 1; note that the outer panel of this trial door was made of a 0.65-mm thick sheet of mild steel. The door thus manufactured is shown in **Photo 2**. The vertical members of the frame reinforcement fitted well to the sectional shape of the door outer panel, which verifies practical applicability of the developed forming method for the manufacture of the frame reinforcement using thin steel sheets for hot-stamping use as the material.

5. Conclusions

A new frame-reinforced door structure for automobiles was developed aiming at decreasing weight and realizing the same or better outer panel stiffness and side impact resistance of the door as those of the conventional structure even with a significantly thinner outer panel. By FEM analysis, the outer panel stiffness and side impact resistance of the door by the developed structure were evaluated, and a method for forming the members of the frame reinforcement was developed through forming tests. The following results were obtained through these studies:

1) It is highly likely through panel stiffness analysis that, by the developed structure, the same panel stiffness of the door outer panel as that of the conventional structure, or better, is maintained even when the steel sheet of the outer panel is as thin as 0.4 mm.
2) It is highly likely through side impact analysis that, by the developed structure, the same side impact resistance as that of the conventional structure, or better, is maintained even without the door impact beam.
3) Trial production has clarified that it is possible to manufacture the high-strength members of the frame reinforcement at a high shape accuracy to fit to the shape of the door outer panel by the developed forming method, which consists of cold forming of flat blanks into straight intermediate parts with a closed rectangular section and then bending them by hot stamping so as to follow the sectional shape of the outer panel.

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