

Structural Design for Battery Protection of Electric Vehicles and Crash Performance Evaluation Techniques

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Abstract:

JFE Steel is engaged in proposing component designs utilizing steel materials. This report presents structural design technologies focused on battery protection in electric vehicles. Two types of steel-reinforced side sill structures were developed as alternatives to aluminum extrusions, achieving both weight reduction and crash performance. Additionally, a large steel battery case was designed to be lighter than conventional aluminum cases while maintaining equivalent crash safety. In crash performance evaluation, testing techniques simulating actual vehicle behavior were established, contributing to component designs that address small overlap and frontal impacts. These achievements support enhanced EV safety and the realization of cost-competitive vehicle structures.

1. Introduction

Battery electric vehicles (BEV) are being developed in countries around the world from the viewpoint of environmental preservation, and their share in total automobile unit production has increased in recent years¹⁾. Since it is important to secure a long driving range in BEVs, these vehicles frequently have a structure in which a heavy, large-capacity battery pack is installed under the floor²⁾. Since the requirements for management of deformation of the battery pack in collisions are stricter than those in conventional EVs, makers tend to adopt a strong, tough battery pack enclosure structure. However, this also increases the vehicle weight. On the other hand, vehicle lightweighting is necessary to extend the driving range. To meet this need, materials with a low specific weight, such as aluminum, are often used in various parts, but com-

pared with steel materials, the cost of aluminum is high, and its lightweighting effect is small due to its low Young's modulus. Thus, the applicable vehicle types and parts tend to be limited. Moreover, steel materials also have the advantages of a low material production cost and lower CO₂ emissions in the manufacturing process³⁾.

Based on these considerations, it is extremely important to reduce the weight of frontal-impact energy absorption (EA) components such as the front side member and bumper reinforcements, side-impact EA components such as side sills and their internal structures, and battery packs to a level equal to or less than the weight of conventional parts by using steel materials, which offer overwhelming advantages in terms of material cost and CO₂ emissions.

This paper introduces original steel sheet structural designs, evaluation techniques necessary when evaluating crashworthiness, and a newly-developed material which was evaluated by those techniques developed by JFE Steel.

2. Design of BEV Battery Protection Structure

2.1 Side Sill Inner Structure

2.1.1 Issues of Aluminum Extrusions and Purposes of Research

As described in the Introduction, since a large-capacity battery pack is installed under the floor of BEVs, one issue is the small EA zone in pole side impact (i.e., a lateral collision against a pole). In the pole side impact test, the vehicle body, inclined 75° with respect to a stationary pole, collides with the pole

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at a speed of 32 km/h. Since the side sills play an important role in EA, a side sill structure for absorbing pole impact is necessary. An increasing number of BEVs use lightweight, high-rigidity aluminum alloy extrusions (aluminum extrusions) as side-sill reinforcement members. Since the sectional rigidity (flexural rigidity) of extrusions can be adjusted within a single part, the same part can simultaneously perform multiple functions such as load transfer and EA, contributing to reduction of the number of individual parts. Extrusions also have a uniform cross section, which has the advantage of uniform crashworthiness regardless of the position. However, the uniform cross section of extrusions also has the disadvantage of increasing part weight because reinforcement is provided at points where it is not needed.

This chapter describes the development of steel side-sill reinforcement structures that provide weight efficiency and crashworthiness performance equal or superior to aluminum extrusions for two types of automobiles in which aluminum extrusions are now used.

2.1.2 Performance Evaluation of Aluminum Extrusions and Development Targets

As vehicles in which aluminum extrusions are applied, a European C-segment vehicle (vehicle A) and an American D-segment vehicle (vehicle B) were investigated. (Note: C-segment and D-segment are vehicle classifications indicating compact and large family automobiles, respectively.) In vehicle A, the battery pack and floor cross members are arranged along the width direction of the aluminum extrusion inside the side sill, and it was thought that the load in a pole impact collision is transferred from the side sill to these components. In vehicle B, only the floor cross members were arranged in the width direction of the aluminum extrusion. Therefore, in this structural design, the larger part of the pole impact force is transferred to the floor cross members, and force is not transferred to the battery pack. The weight of the side sill components of vehicles A and B were 22.5 kg and 14.2 kg, respectively.

First, a side-sill module crash analysis simulating a pole side impact test with a full car was carried out to evaluate the pole side impact performance of vehicles A and B. In anticipation of verification testing with an automotive crash simulator, which is described in the following, this analysis was designed on the premise that a punch simulating the pole is impacted into a stationary side sill. **Figure 1** shows the side-sill module models. Finite element method (FEM) models of the side sills were prepared based on the results of measurements of actual side-sill parts. In the crash analysis, material models having the same strength level as the material strength obtained by an investigation of the

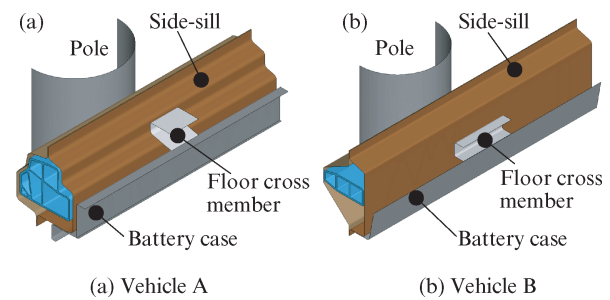


Fig. 1 Crash analysis models

actual structures were used. As the jig used to fix the side sills, simplified partial rigid models of the geometry of the battery pack and floor cross members were prepared.

In the crash analysis, the contact reaction force generated between the side sill and the punch until the speed of the punch impacted on the side sill reached 0 km/h was evaluated. The punch simulating the pole had a semicircular columnar shape with a diameter of 254 mm, and was impacted directly on the floor cross member at an initial speed of 32 km/h and an initial kinetic energy of 30 kJ. This initial kinetic energy was determined based on the deformation of the side sill in a full-car crash analysis.

The analysis results confirmed that in both vehicle A and vehicle B, only the side sill absorbed the impact energy of 30 kJ. Based on the above, the target weights of the steel sheet structures for vehicle A (developed structure A) and vehicle B (developed structure B) were not more than 22.5 kg and not more than 14.2 kg, respectively. For battery pack protection, the target for maximum intrusion was not more than 100 mm so that the punch did not come into contact with the battery pack.

2.1.3 Lightweight Reinforcement Structure Utilizing Bulkheads

Figure 2 shows developed structure A. Here, a center plate with a cross section divided into 2 parts was added inside the side sill, and hat section members were arranged along the longitudinal direction on both sides of the center plate. At parts where additional reinforcement was needed, rigidity was increased while avoiding weight increases by arranging bulkheads inside the hat section members. To simultaneously satisfy both high strength and lightweighting, 1 470 MPa material (thickness: 1.0 mm) was applied in the hat section members, 1 180 MPa material (thickness: 1.6 mm) was applied in the bulkheads, and 1 470 MPa material (thickness: 0.8 mm) was applied in the center plate. To suppress variations in crashworthiness due to increased load transfer and the impact position, the positions of the bulkheads were on a linear extension of the respec-

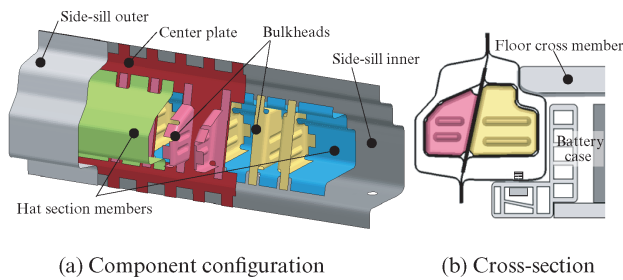


Fig. 2 Developed side-sill structure A

tive floor cross member and between those positions. In the side-sill inner and outer of the developed structure, the same 1.5 GPa grade (thickness: 1.6 mm) hot-stamped material as in the original structure was applied. As a result of these changes, the weight of developed structure A was 22.3 kg, achieving a weight reduction of 0.2 kg from the original structure. The results of a crash analysis of developed structure A showed that the maximum intrusion was 92 mm, which also achieved the target for crashworthiness.

2.1.4 Reinforcement Structure with Fewer Parts Using Frame with Closed Cross Section

Since the load transfer path of vehicle B was different from that of vehicle A, a new internal structure was designed. **Figure 3** shows developed structure B. To increase the flexural rigidity of the two sides of the vehicle and disperse loads, a “double square” (H) cross section with weight efficiency was adopted. The weight efficiency of the double square cross section is explained in detail in the following section. Hat section members were arranged on the inner side of this cross section so that the axial direction of the members was oriented in the vehicle transverse direction, and EA performance was improved by welding the pairs of flanges together to form a continuous hat section member structure so that loads can also be transferred in the vehicle longitudinal direction. In addition, double square members were also arranged on the inner side of that structure, creating a structure that transfers the loads dispersed in the initial stage of a collision to the floor cross members along those members. Although the reinforcing structure consists of 4 parts, the 2 double square section members have the same shape, and the continuous hat section members consist of members with the same shape, with the two and bottom members inverted. Thus, this reinforcing member substantially consists of only 2 types of parts. Since the reinforcement in vehicle B consisted of the 3 members, the number of parts was almost the same as in the original vehicle. The materials applied were 1 180 MPa grade GA (1.8 mm) in the double square section members and 980 MPa grade GA (1.4 mm) in the continu-

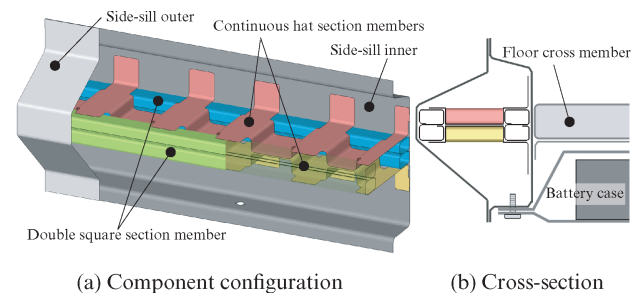


Fig. 3 Developed side-sill structure B

ous hat section members. The bending rigidity of the double square section members was improved by continuously joining the abutting parts by laser welding. The continuous hat section members were assembled by spot welding, joined with the double square section members by arc welding, and joined with the side sills by spot welding. As a result, the weight of the developed structure B was the same as the original structure (14.2 kg). The results of the crash analysis of developed structure B showed that the maximum intrusion was 79 mm, also achieving the target for crashworthiness.

2.2 Structural Design of Battery Case

2.2.1 Design Concept

In recent years, aluminum extrusions, castings and flat-rolled materials have increasingly been used as component parts of battery cases⁴⁾. An aluminum battery case was also used in the above-mentioned vehicle A. This section reports the development of an original battery case with a steel battery case structure (steel battery case) that can accommodate the same battery capacity as in vehicle A, while also achieving lightweighting and the same level of crashworthiness.

Figure 4 shows the design concept of the developed product for side impacts. As mentioned above, the body structure of vehicle A is designed to transfer the force of a side impact from the side sill to the battery pack and floor cross members. The side frame has a structure that receives the force input to the battery pack and transfers that force to the cross members. This is also the same as in the developed structure.

Other properties required in battery cases include a waterproof property to prevent battery fires. To secure the waterproof property, the battery housing is a tray produced by drawing a single steel sheet, and the tray flanges are flat to ensure sealability with the top cover. In addition, the punch radius R and plan-view corner radius R are designed to be as small as possible to achieve a large battery capacity.

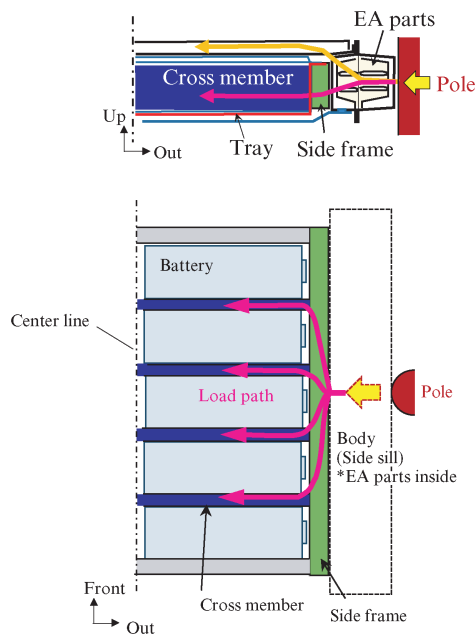


Fig. 4 Structural design concept for side impacts

2.2.2 Structural Design of Impact Absorbing Part

The cross members and side frame are the main structural parts in side impact collisions. Therefore, a basic study of those parts was carried out with the aim of designing a cross-sectional geometry that achieves high load-bearing capacity with thin steel sheets.

First, the basic study of the cross member will be explained. The structural investigation of vehicle A showed that this part was an aluminum casting with a cross-sectional width of 15 mm, height of 100 mm and part length of 605 mm. Assuming the same part external dimensions in a steel cross member, the cross section for obtaining a high load-bearing capacity in a long, slender part were studied. **Figure 5** (a) shows the cross-sectional geometries of the aluminum casting cross member (YS: 140 MPa) of vehicle A and the steel cross member studied here. In the steel member, in addition to the normal hat section, a closed cross-sectional shape with a convex shape in the center of the vertical wall (the developed shape) was also studied. A closed cross-sectional forming technique which makes it possible to form this developed shape with a conventional press machine was also developed⁶⁾, but a detailed explanation is omitted in this paper. Part models with a constant cross section and a length of 650 mm were prepared for these two cases (steel members with conventional hat section and with closed section) and the aluminum casting member of vehicle A. The steel sheet was a 1 180 MPa grade steel sheet (YS: 895 MPa) with a thickness of 1.0 mm. As shown in Fig. 5 (a), the component weights of both steel cross

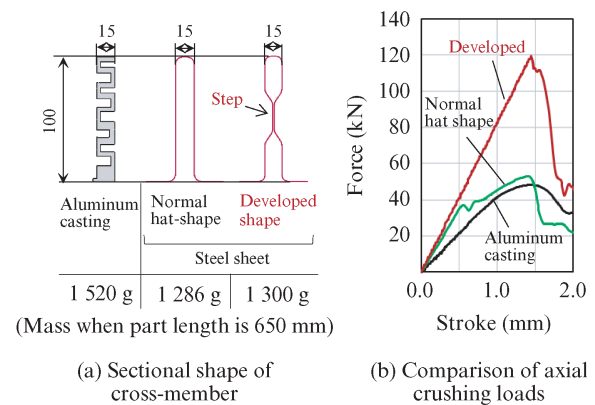


Fig. 5 Basic analysis of cross member crash performance

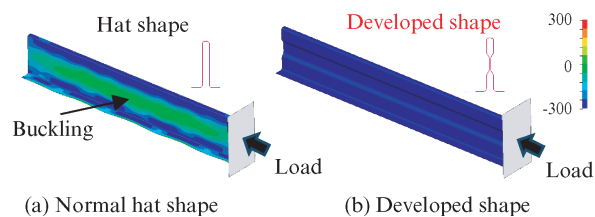


Fig. 6 Comparison of stress distribution between normal hat shape and developed shape

sections studied here is approximately 15% lighter than the aluminum casting. Crashworthiness was evaluated by an axial crushing deformation analysis by fixing one end of the part and pressing the other end at the rigid wall at a rate of 100 mm/s.

Fig. 5 (b) shows a comparison of the reaction force (axial crushing load) during axial crushing deformation. Although the maximum force of the normal hat section is similar to that in vehicle A, the results confirmed that the maximum load of the developed shape is improved by a factor of 2.3 times. **Figure 6** shows the axial stress distribution under pressing by 1 mm. In the hat section, elastic buckling occurs and stress decreases, but in the developed shape, compressive stress is generated uniformly, and the cross section is used effectively.

Next, the basic study of the side frame will be explained. The side frame receives bending load in a collision, but since the frame is installed in the limited space between the side sill and tray, which are auto body parts, a geometry that obtains an effective reaction force in the narrow design space is desirable. In vehicle A, aluminum extrusions with a width of 25 mm are arranged in the 35 mm space in the vehicle width direction between the side sill and the battery housing, and these extruded parts are supported by 4 cross members at 260 mm intervals in the vehicle longitudinal direction.

For the steel side frames, cross sections with good load efficiency were studied by varying the width (W) and height (H) of the single square section and double

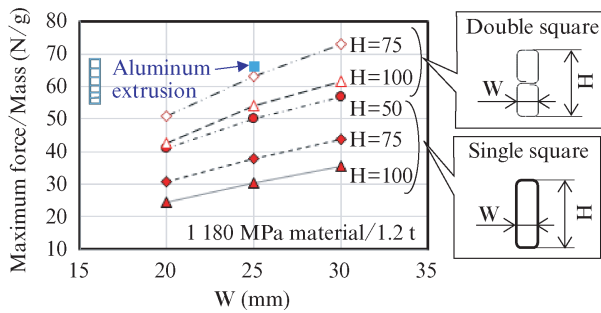


Fig. 7 Study of effective part geometry for three-point bending performance

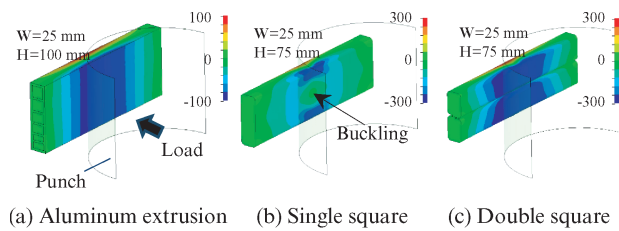


Fig. 8 Comparison of stress distribution during three-point bending test

square sections shown at the right in Fig. 7. Part models with a constant cross section were prepared, and a three-point bending analysis with a span of 260 mm was conducted. The rotation of ends was not restrained, and translation of one side was restrained. A rigid column with a diameter of 200 mm was made to impact on the part at a speed of 500 mm/s, and the reaction force was evaluated. The steel sheet was a 1 180 MPa grade steel sheet with a thickness of 1.2 mm.

Fig. 7 shows the relationship between the part geometry and the value obtained by dividing the maximum force generated in the members under three-point bending deformation by the part mass (maximum force/mass, i.e., mass efficiency for maximum force). The abscissa shows the width W of the part, and results were arranged for each section height. For comparison, mass efficiency of the aluminum extrusions of vehicle A is also shown. Fig. 7 shows that double square section provides higher mass efficiency for maximum force than the single square section. Both sections display higher mass efficiency for maximum force when the width is large and the height is small, and the double square section with a width of 25 mm and height of 75 mm provides substantially the same mass efficiency as the aluminum extrusion.

Figure 8 shows the longitudinal stress distribution in the initial stage of bending (punch displacement: 2.5 mm) of the aluminum extrusion and the steel single square and double square sections with the width of 25 mm and height of 75 mm. Compressive stress is

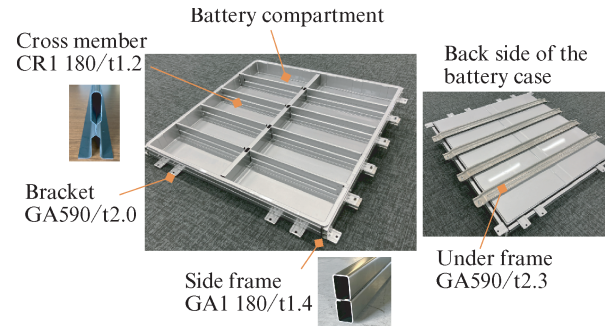


Fig. 9 Prototype of steel battery case enclosure

generated uniformly in the aluminum extrusion owing to its large thickness and multiple partition walls (bulkheads). On the other hand, in the single square section, elastic buckling occurred and decreased in stress. However, in the double square section, force is efficiently shared because stress is generated in the sides due to the partition in the center of the cross section. This analysis demonstrated the effectiveness of the double square section design.

2.2.3 Trial Manufacture of Battery Case

Cross members and side frames were designed based on the study in the previous section. To provide a safety factor, a 1 180 MPa grade steel sheets with a thickness of 1.4 mm was used in the side frames. The side frames were bolted to the tray via brackets. These brackets also have the function of fastening the side sills, which are side parts of the auto body. The cross members were spot welded to the tray, and an under-frame that supports the battery pack as whole was designed and installed under the battery case, considering its heavy weight. Since the deep-drawn tray is a very large part, it cannot be formed by the conventional single drawing process. Therefore, crack- and wrinkle-free trays were obtained by forming using a pre-forming technology⁵⁾, which is an original technology developed by JFE Steel.

Figure 9 shows the steel battery case that was trial-manufactured by assembling all the component parts. This battery case achieved a 2 kg weight reduction from the aluminum case structure of vehicle A. Finally, a pole side impact analysis was carried out with a full-car model. Figure 10 shows the cross section of deformation when the input kinetic energy becomes zero. As in vehicle A, contact between the battery case and the battery inside it did not occur with the steel battery case, and crashworthiness was the same as that of the aluminum battery case, satisfying the development target.

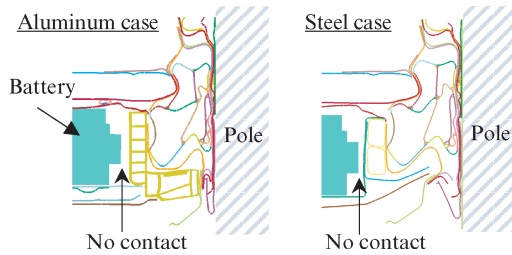


Fig. 10 Comparison of aluminum and steel battery cases in a full-car pole impact simulation

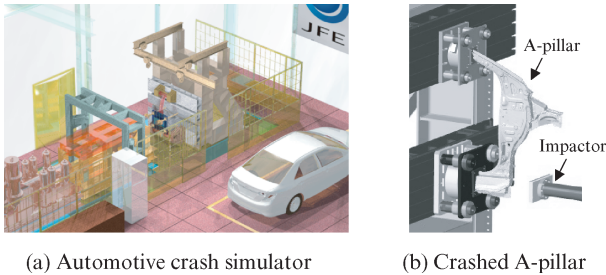


Fig. 11 A-pillar crash test by automotive crash simulator

3. Crashworthiness Evaluation Technologies and New Material Design

3.1 Overview of Automobile Crash Simulator

With growing awareness of automobile safety, the automobile safety performance evaluation standards established by various countries are also becoming stricter by the year. In performance evaluations, crash tests are conducted using one vehicle, but the cost is high and preparations require considerable time. Since there are many design changes during vehicle development, particularly in the initial stages, performing tests each time a change is made would result in increased costs and delays in development. Therefore, a process in which vehicle performance is divided into modules, performance is evaluated at the module level in tandem with performance design, and the performance of the full vehicle is evaluated by the aggregate of those results is continuing to become the main stream in recent years.

To respond to these needs, in 2017 JFE Steel introduced the automotive crash simulator shown in Fig. 11 (a). This system can simulate crashes at arbitrary speeds from 0.1 to 100 km/h. The simulator has a test specimen installation space with a height of 2 000 mm and width of 1 500 mm, allowing testing of various types of parts as well as large-scale modular components, enabling evaluations in response to future safety performance evaluation standards.

3.2 Crashworthiness Evaluation Technology Simulating Actual Vehicle Deformation Modes

As one important requirement for evaluation tests of single-part units and modules, it is necessary to reproduce the actual crash deformation behavior of the full car. JFE Steel is developing various evaluation techniques for this purpose, as described below.

3.2.1 Evaluation of A-Pillar Simulating Small Overlap

The small overlap test is an automobile crashworthiness evaluation test. One type of offset crash test is a frontal crash test at 64 km/h conducted with an overlap of 25%, which is more severe than the conventional method, assuming strong partial frontal impact. Since larger force is applied to the outside of the vehicle than to the front side members, which are expected to absorb the energy of a frontal crash, the full car shows behavior in which the tires are pushed toward the back of the car, and impact is applied to the lower part of the A-pillar. Fig. 11 (b) shows a crash test of an A-pillar reproducing this condition. By using this technique, it was possible to study the optimum structure of the A-pillar corresponding to the small overlap test.

3.2.2 Evaluation of Front Side Member Simulating Frontal Crash

In frontal crashes, transferring a large ratio of the kinetic energy of the vehicle occupants to the auto body via restraining devices such as seatbelts is advantageous for occupant injury criteria⁷⁾, and increasing the vehicle deceleration rate in an initial stage of the crash is effective for improving the kinetic energy transfer ratio⁸⁾. To increase vehicle deceleration, it is necessary to generate a high load in the front side members, where force is applied in the initial stage of the crash. High strength members are effective for this purpose. On the other hand, in case a sudden decrease in the load occurs during a collision, the decrease in the vehicle deceleration will lead an increase in occupant injury criteria. For this reason, a large fracture that causes a load decrease is not permissible. Therefore, a test that can evaluate fracture occurrence due to crash deformation is necessary. In addition, since high-voltage components, fuel piping and the like, which may cause a serious accident if damaged, are arranged in the area around the front side members, it is necessary to control the deformation mode so as to avoid damage due to contact with the side members in a crash. For this reason, the side members are designed to avoid contact with protected parts by inducing “dog-leg” shaped deformation at 2–3 places by providing notches in the

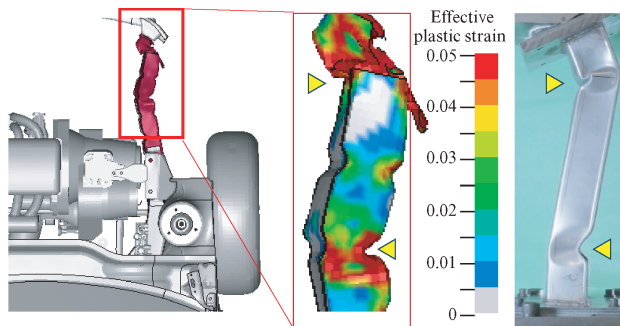


Fig. 12 Comparison of front side member deformation mode

bend line, design of the part geometry with a bead set in the top part, etc.

Based on the above, reproduction tests were conducted with a bead set at the targeted buckling position to reproduce the dog-leg shape necessary in evaluations of front side members. The specimen geometry simulated that of a C-segment vehicle, and had a hat section shape with a width of 170 mm and height of 70 mm and a length of 500 mm. As test speeds, the parts were evaluated at a static speed of 0.01 km/h and high speed of 64 km/h. **Figure 12** shows the analysis results and test results at 64 km/h. Since the dog-leg shape was also obtained in the reproduction test, it was clear that the crashworthiness of the front side members can be evaluated by the developed evaluation technique.

3.2.3 Evaluation of Bumper Reinforcement Simulating Offset Frontal Crash

Since BEVs are equipped with a large-capacity battery to extend the driving range, the vehicle weight is heavier than that of conventional gasoline-powered automobiles. Since the force generated in a collision is proportional to the vehicle weight, deformation resistance in high-strength parts is effective. For performance evaluations of bumper reinforcements, in addition to the three-point bending test, the ODB (Offset Deformable Barrier) simulation test is conducted as a one frontal crash evaluation technique. In the ODB test, the driver's side (40% overlap ratio to the full-car width) of the test vehicle is impacted against an aluminum honeycomb barrier fixed to a rigid wall. Since the impact force is concentrated in one front side member, preventing fracture of the bumper reinforcement itself or the point where it is connected is one challenge. In a full car, deformation occurs when force is concentrated in one of the two front side members. Therefore, in tests under the ODB condition, deformation of the ODB was simulated by applying force with the impactor offset from the center to the front side member side.



(a) 980 MPa Conventional DP (b) 980 MPa JEFORMA™ Type 2

Fig. 13 Crash test results of front side member simulated parts



Fig. 14 1700 CR bumper reinforcement

3.3 Material Design Contributing to Battery Protection Performance

3.3.1 Front Side Member Applying JEFORMA™ Type2

Figure 13 shows the results of a crash test of simulated front side member parts produced using a 980 MPa grade general-purpose DP steel sheet and JEFORMA™ Type2. In the general-purpose DP steel sheet, fracture occurred in the buckling deformation area, but fracture did not occur with JEFORMA Type2. This showed that JEFORMA Type2 provides excellent bendability and crash fracture resistance when compared with the general-purpose DP steel sheet.

3.3.2 Cold-Rolled 1 700 MPa Grade Steel Sheet Bumper Reinforcement

Using a cold-rolled 1 700 MPa grade steel sheet (hereinafter, 1700CR) which was newly developed by JFE Steel, a bumper reinforcement was trial-manufactured with the aim of simultaneously satisfying cost reduction and lightweighting. **Figure 14** shows the trial-manufactured 1700CR bumper reinforcement. This part was studied based on the geometry of a hot-stamped 1.5 GPa grade steel sheet bumper reinforcement of a commercially-available vehicle. Since fracture during impact was a concern, as described above, the parts was evaluated by a three-point bending test and a test under the ODB condition.

From the results of the three-point bending tests of the 1700CR and the hot-stamped 1.5 GPa evaluated by the automotive crash simulator, very small cracks were observed in the deformed portions of both parts, but because these did not lead to a large fracture, there

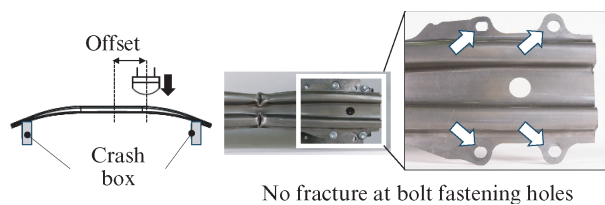


Fig. 15 ODB test condition and fastening area after test

were judged to be no problems in terms of crashworthiness. Next, when the generated moments were compared, the maximum value of the 1700CR increased by approximately 8% from that of the hot-stamped part. This was attributed to the fact that the 1700CR has a higher yield stress than the hot-stamped material. This difference is equivalent to 0.5 mm of the part thickness (weight reduction of 200 g per vehicle), indicating that lightweighting is possible.

Next, a test under the ODB condition was performed. This test evaluated whether fracture occurs at the bolt fastening holes of the bumper reinforcement and crash boxes. The crash boxes were parts taken from the same commercially-available vehicle. **Figure 15** shows the results. Fracture was not observed at the bolt fastening holes, showing that the newly-developed 1700CR can be applied to bumper reinforcement. Thus, these tests confirmed that the new product can satisfy both lightweighting by sheet thickness reduction and cost reduction.

4. Conclusion

This paper introduced structural designs and technologies for the characteristic battery protection struc-

tures of BEVs, beginning with advancing crashworthiness requirements. JFE Steel believes that the pursuit of performance improvement and lightweighting in this field will continue to evolve in the coming years, and is committed to contributing to better automobile manufacturing in the future by always anticipating trends, and cooperating with auto makers based on an accurate understanding of customer needs.

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