Technical Report

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“Katachi” Solution

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Abstract

Nippon Steel & Sumitomo Metal Corporation has been widely applying the design technology of light -gauge steel structures developed through the R&D for building structures to a large variety of steel structural systems in many fields. Since better solutions for effective utilization of steel can be proposed by controlling shapes, we call the technology as “Katachi” solution. “Katachi” is a Japanese word with broader meaning of member shapes and structural configurations. This report shows some of the activity examples on low-rise residential housing, electric home appliances, OA equipment, food cans, freight containers, ships and solar systems. Various approaches and potential of “Katachi” solution are introduced.

1. Introduction

In the field of residential buildings, Nippon Steel & Sumitomo Metal Corporation has studied steel-framed houses (**Fig. 1**) and similar structures [1, 2] composed of cold-formed light sections of thin steel sheets since 1994. Once the structural problems related to buckling and local deformation are adequately solved, the use of the products brings about various advantages unique to light sections of different shapes, and in view of this, the company has tackled such R&D subjects as the torsion assessment of structural members of large width-to-thickness ratios, buckling design methods, etc., aiming at wider use of new section shapes that combine structural rationality and ease of use (see **Fig. 2**). Besides the above, the company has expanded the application of such design approach from housing structures [3] to various other structures of electric appliances, OA devices and others. Since the essence of the expanded design approach is to work out new solutions in the use of steel materials, focusing on the shape or form (“katachi” in Japanese) of the object in question, this approach has been named the “Katachi” solution. [4, 5] This paper presents the basic philosophy of the “Katachi” solution, some examples of its application, and its potential.

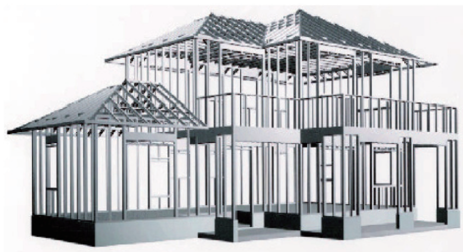

Fig. 1 Skelton of steel framed house

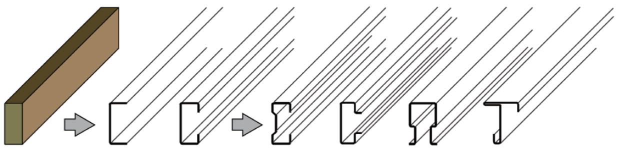

Fig. 2 Various shapes using cold-forming technology (optimization from lumber and conventional steel sections)

2. How to Improve Object Shape

Owing to the advancement of computer-aided engineering (CAE), stiffness, strength, and other performance aspects of a structure can be accurately predicted by formulating detailed finite element models without performing structural tests. Various methods are available for working out shape improvement; such advanced CAE methods as topology optimization [6] have been used for aircraft and automobile design. These technologies are very effective, especially in the design of solid pieces such as metal castings. On the other hand, in building structural design, it is necessary to disclose the flow of design work to show that the structure conforms to applicable laws and regulations, and to this end, structural members and component structures are often modeled in design studies as simple bars and frameworks, respectively. Use of such simplified models makes it easier to understand the mechanisms through which

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stiffness and strength of the components show, although the evaluation accuracy is somewhat lower than that with finite element models. The "Katachi" solution is characterized by working out improvements in the overall or partial shape of an object by understanding and analyzing its structural mechanisms on the basis of comparatively simple mechanical models and making use of various methods of numerical analysis and optimization.

3. Application Examples and Methods of Shape Improvement

The structures to which the "Katachi" solution is effectively applied can be divided into the following three: bars and frameworks; panels and boxes; and cylinders (see **Fig. 3**). How the method is applied to obtain solutions is explained below based on simple and easily understandable examples.

3.1 Improvement of bars and frameworks

(1) Improving local buckling strength of columns by use of octagonal section

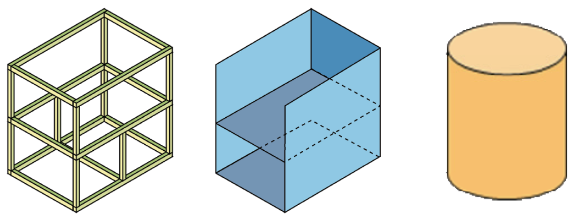
A square hollow section (**Fig. 4** (b)) is more prone to local buckling as the wall thickness decreases,[1, 2] and as a measure to decrease the width-to-thickness ratio, stiffeners as seen in Fig. 4 (c) are often provided along the center lines of the side walls, but this lowers productivity. As an alternative, Nippon Steel & Sumitomo Metal has proposed to make the column section octagonal (Fig. 4 (d)) to reduce the wall thickness. For example, in the case of a square hollow section, 90 × 90 mm^2 in size and 2400 mm in length for low-rise buildings, the relationship between the dimension D (mm) in Fig. 4 (d) and the axial compressive strength P (kN) of a column changes, as shown in **Fig. 5**. The graphs indicate that for different wall thicknesses, there is an optimum value of D at which the axial compressive strength is largest. This is a simple and effective solution for the sectional shape based on the analysis of buckling mechanisms.

(2) Replacing aluminum extruded sections with roll-formed steels

Sometimes aluminum structural members have very complicated sectional shapes: for example, **Fig. 6** (a) shows an aluminum column used for OA desks and the like. Based on the "Katachi" solution, a steel column composed of four cold-formed sheets (Fig. 6 (b)) is proposed as a substitute. Since the specific density and the Young's modulus of steel are roughly three times those of aluminum, respectively, when the steel column is designed to obtain the same axial stiffness, the weight of the steel column becomes equal to that of the aluminum one. However, in the case of aluminum extrusion, there is a lower limit to the material thickness for manufacturing technical reasons, and sometimes the structural performance may be excessive for required functions. In such a case, steel columns are lighter than aluminum ones, because thinner sheets can be used (see **Fig. 7**).

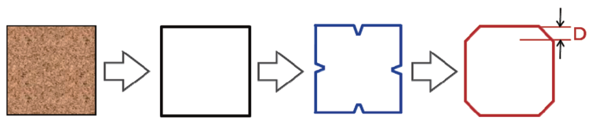
(3) Improving torsional stiffness of framework by rearrangement of members

To improve the performance of a framework, besides changing the sections of component members, changing their arrangement is also effective. For example, to improve the torsional stiffness of a framework as given in **Fig. 8**, an effective measure is to enhance the torsional stiffness of the bottom panel. In this relation, Nippon Steel & Sumitomo Metal has made it clear that a rhombus frame (as



(a) Framework (b) Box (c) Cylinder

Fig. 3 Simplified structural models



(a) Lumber (90 mm × 90 mm) (b) Square box (c) Ripped box (d) Octagon shape

Fig. 4 Shape optimization from lumber and conventional steel section

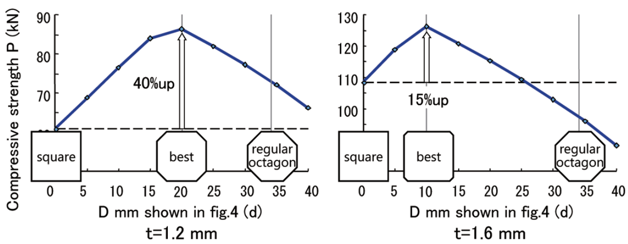
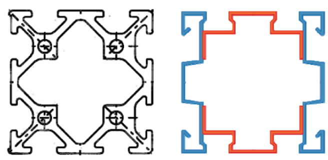


Fig. 5 Comparison of compressive strength (□ 90 mm×90 mm, L=2 400 mm)



(a) Alminum (b) Steel

Fig. 6 Sections of member

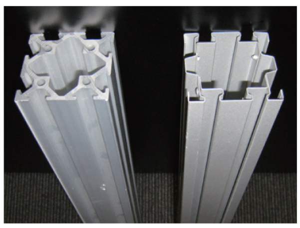
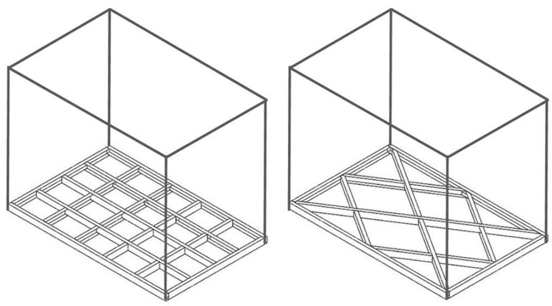


Fig. 7 Alminum (left) and steel (right)



(a) Rectangle shape (b) Diamond shape

Fig. 8 Member arrangement for structural base panel

shown in Fig. 8 (b)) is more resistant to out-of-plane torsion than a common lattice frame (Fig. 8 (a)) and clarified the mechanism by which such torsion resistance is increased, especially when the component members are channels or similar of open sections. Based on this and other related findings, the company has established a design tool for optimally arranging frame members capable of proposing the most adequate member arrangement for a base panel of whatever shape a customer has in mind. This tool employs a genetic algorithm [7] to optimize a ground structure [8] that a designer draws up. It can be used in combination with other programs; it is possible, by using a topology optimization program (see **Fig. 9**), to obtain hints for improving the arrangement of frame members in a flexible manner, and then, by using the frame arrangement optimization tool (see **Fig. 10**), obtain more specific member arrangement in consideration of the sectional shapes and restrictions on their manufacture, etc.

3.2 Improvement of panels and boxes

(1) Analysis of properties required for body panels for electric and electronic devices

Corrugated panels are often used for building walls and roofs (see **Figs. 11** and **12**). The corrugation shape is designed to maximize mainly the stiffness and strength against out-of-plane bending. The body panels of electric appliances, OA devices, and the like are also required to be resistant to out-of-plane bending. While it is possible to increase the bending strength of a panel by using steel sheets of a higher strength, the bending stiffness, which is governed by Young's modulus, cannot be improved by increasing the material strength, and a separate measure has to be taken to improve out-of-plane stiffness. The properties required for panels are significantly different in building structures and the bodies of electric appliances, whereas in building structures, torsional forces are borne by the framework; therefore, wall and roof panels are required to withstand out-of-plane forces only in appliances and OA devices; both forces are borne by the body panels. Therefore, studies were conducted for developing checkered embossment steel sheets (to have the trade name of Latis®) having high stiffness against both out-of-plane bending and torsion.

(2) Development of checkered embossment steel sheets, Latis®

To enhance the torsional stiffness of a flat panel, it is necessary to increase the out-of-plane bending stiffness in two directions in the panel plane normal to each other (directions X and Y in **Fig. 13** (a)). With a corrugated sheet, the bending stiffness in direction X parallel to the corrugation is sufficiently high, and the torsional stiffness is improved by increasing the bending stiffness in direction Y, in right angles to direction X. This leads to the idea of superposing a corrugation pattern on another, in right angles to each other, as shown in Fig. 13 (b). However, in the course of the development studies, it was confirmed through finite element analysis that simply arranging truncated square pyramids in a plane would lead to stress concentration at the joints where the pyramid corners met. Thus, the joints between concaves and convex of the checkered embossment sheets were optimally designed to mitigate the stress concentration and significantly increase out-of-plane bending stiffness and torsional stiffness (see **Fig. 14**).

(3) Optimum positions of body panel joints

In a box structure for an electric/electronic device body, the configuration of component panels is determined by the functional requirements of the device, and there is little room for structural variety. On the other hand, the positions of panel joints do not significantly affect the device function, and there is much room for change to optimize the structural performance. The shear resistance of a shear wall of a steel-framed house, for instance, can be enhanced by

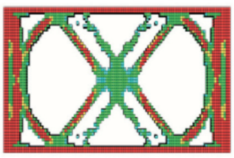


Fig. 9 Example of study using topology optimization method

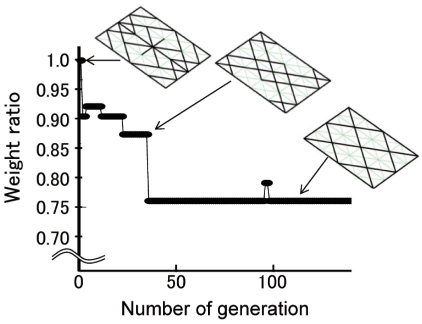


Fig. 10 Genetic algorithm optimization

Fig. 11 Corrugated sheet roof

Fig. 12 Corrugated sheet wall

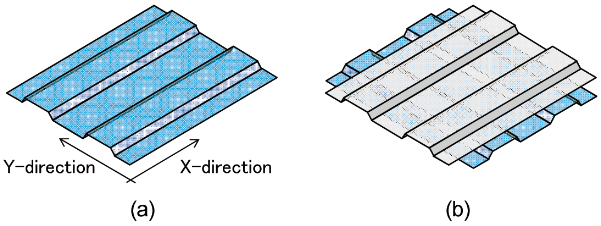


Fig. 13 Corrugated sheet (a) and structure image of double layer corrugated sheet (b)

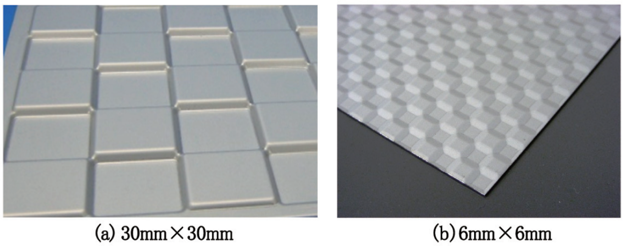


Fig. 14 Example patterns of checkered embossment panel

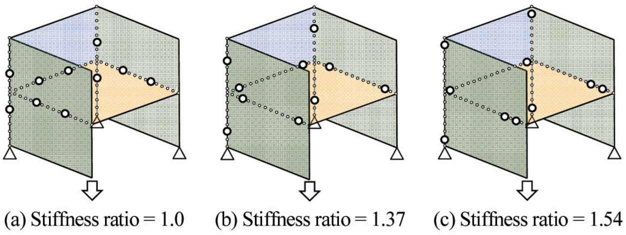


Fig. 15 Optimization of connection arrangement for box structure

fixing the wall panel to the framework with self-tapping screws at positions as close to the four corners as possible. This is because the shear stiffness of the panel against horizontal force is obtained as the sum of the multiplication products of the distances of the fixing points to the wall center and the shear stiffness at each of the fixing points.

Applying the above to a structure consisting of four panels, each 150 × 150 mm^2 in size, simulating a device body as shown in **Fig. 15**, the stiffness can be improved as seen in parts (a) and (b) by changing the joint positions. Further, supposing this as an optimization problem having an objective function for increasing the stiffness without increasing the number of joints, the genetic algorithm mentioned earlier[7] can be applied, and another improvement in which the joints are optimally arranged under given conditions is obtained as shown in part (c) of Fig. 15. Here, it was confirmed that the stiffness of the structure was enhanced by arranging two joints near each of the two front corners of the horizontal panel. Such stiffness improvement study is practically effective for box structures where panel joints are positioned discretely.

3.3 Cylindrical structure —Decrease in sheet thickness of food cans through improvement of side-wall corrugation

One of the key issues about cylindrical structures of thin sheets is how to prevent the buckling due to the axial compressive force illustrated in part (a) of **Fig. 16** and the force normal to the circumference (negative pressure) shown in part (b). It is necessary for the cans for coffee drinks or pineapples to stand the vertical force at stacking (resistance to axial compression) and the negative pressure at the cooling after thermal sterilizing of the ingredients (paneling strength). Corrugation of can bodies is effective for increasing the paneling strength (see **Fig. 17** (a)), and this measure is used in various types of food cans. The larger the corrugation height, the greater the paneling resistance, but since this increases the deviation of the body material from the vertical line of loading, the resistance to the axial compression decreases.

By analyzing these structural characteristics of cylindrical bodies, Nippon Steel & Sumitomo Metal has proposed a measure to satisfy these mutually conflicting requirements. The essence of the measure is to change the corrugation waves from triangular to trapezoidal. By this, the second moment of an area is increased and the wave height is decreased, which minimizes the deviation of the body material from the line of loading and increases the resistance to axial compression (see **Fig. 18**). It has been confirmed, that this change brings about a 10% weight reduction of a pineapple can 150 mm in diameter. An advantage of the "Katachi" solution is that for efficient shape improvement study, it evaluates the performance of a structure using simplified structure models as shown in Fig. 17 (b) in combination with finite element analysis.

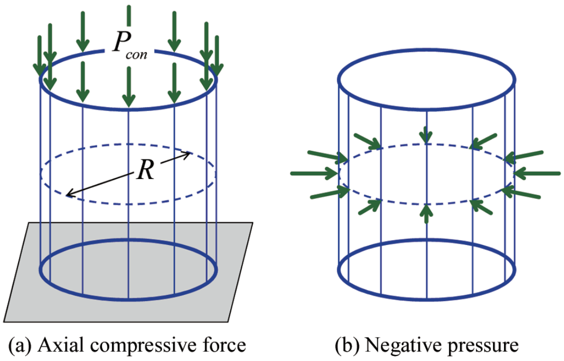


Fig. 16 Required strength of cylinder

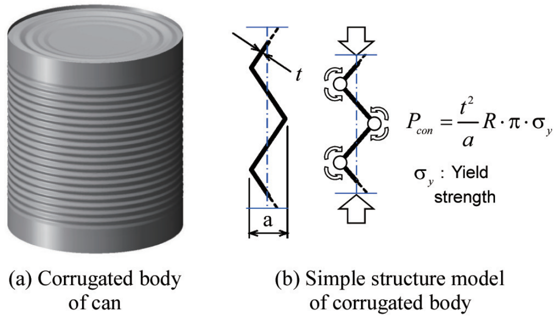


Fig. 17 Corrugated can body and simplified model of corrugation

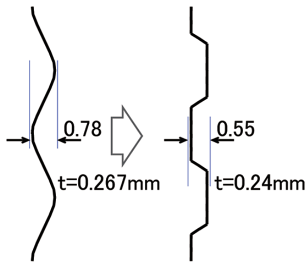


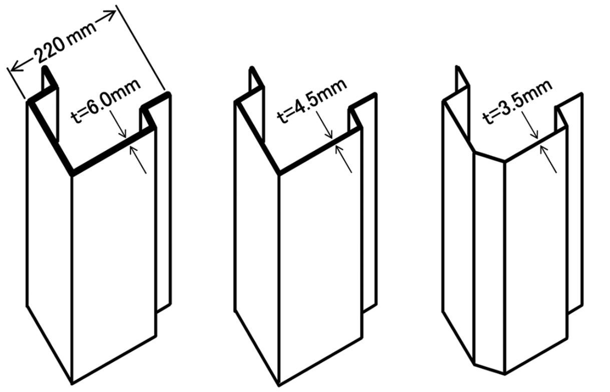
Fig. 18 Optimization of corrugation shape

4. Wider Applications

Some application examples of the "Katachi" solution in the fields of building structures, OA device bodies, etc. have been presented above. This approach can be effectively applied more widely.

(1) Weight reduction of corner posts of freight containers

There is a column of Ω shape, as shown in **Fig. 19** (a), at each of the four corners of a marine freight container (**Fig. 20**). When these containers are stacked in piles, the columns, or corner posts, undergo heavy compressive loads. To reduce the container weight, it is



(a) YS = 400 N/mm² t = 6.0 mm (b) YS = 550 N/mm² t = 4.5 mm (c) YS = 700 N/mm² t = 3.5 mm

Fig. 19 Corner post of freight container

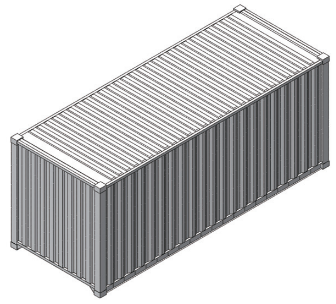


Fig. 20 Freight container

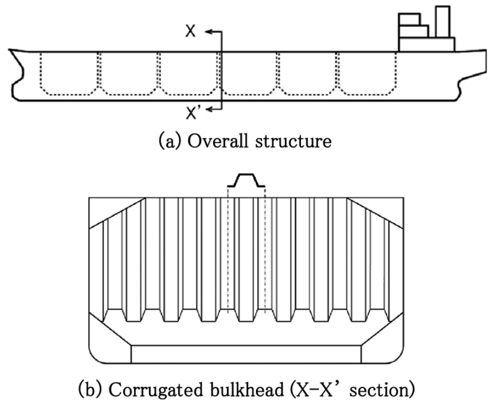


Fig. 21 Schematic illustration of bulk carrier

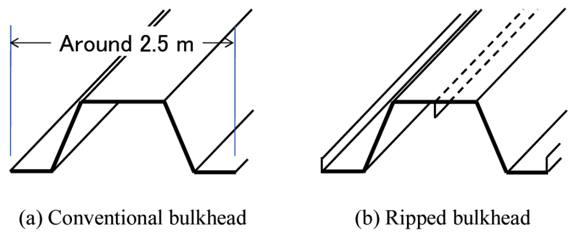


Fig. 22 Example of optimization study for corrugated bulkhead

necessary to decrease the thickness of the base steel while maintaining the compressive strength of the posts. Increasing the yield strength (YS) of the steel is effective for the purpose, but it is not always possible to reduce the sheet thickness by simply increasing the YS. According to a study on the weight reduction of a corner post shown in Fig. 19 (a), the sheet thickness can be decreased from 6.0 to 4.5 mm when the YS is increased from 400 to 550 N/mm², but even if the YS is increased yet further, it is impossible to decrease the sheet thickness any further (Fig. 19 (b)) for the fear of local buckling, which occurs depending on Young's modulus. However, applying the idea of the octagonal section mentioned earlier and changing the section as shown in Fig. 19 (c), it is possible to decrease the width-to-thickness ratio while preventing local buckling. As a result, it becomes possible to increase the YS to 700 N/mm² and decrease the material thickness to 3.5 mm. This example shows that the weight of the post is reduced by about 40% by combining the use of higher-strength sheets and change in the section shape. As given above, the "Katachi" solution offers an effective tool for solving the problems of decrease in stiffness (or decrease in elastic buckling strength) while using higher-strength materials.

(2) Thickness reduction of corrugated bulkheads of bulk carriers

The cargo holds of large ships such as bulk carriers [9] are divided into several sections by providing corrugated bulkheads, as illustrated in **Fig. 21**. To lower the center of gravity in order to stabilize the ship against lateral winds and waves, these sections are filled with water when the ship is empty of cargo, and thus the bulkheads are required, among others, to withstand the pressure of the water. The load condition on the bulkheads is substantially the same as that of the corrugated roof panels (such as shown in Fig. 11) under the weight of snow, but the material thickness is totally different; while the thickness of roof sheets is about 1 mm, the plates used for ships' bulkheads are sometimes more than 20 mm thick. On the other hand, where the width of the flat parts of a corrugated roof panel is about 50 mm, the same of a bulkhead is as large as approximately 1 m and the width-to-thickness ratios of the two are nearly the same.

A corrugation wave of a ship's bulkhead is mostly as shown in **Fig. 22** (a). To improve its structural strength in order to prevent local buckling due to hydraulic pressure, it is effective to provide a vertical rib along the centerline of each flat part. It is calculated that in the example given in Fig. 22 (b), the bulkhead weight can be reduced by about 8% with the ribs, while it is necessary to separately check the fatigue strength of welded joints and other problems. What is essential here is that as far as buckling resistance is concerned, a ship's bulkhead made of heavy plates 20 mm in thickness is from the viewpoint of the "Katachi" solution—a thin-sheet structure having a large width-to-thickness ratio—and can be viewed in the same manner as a roof panel 1.0 mm in thickness, which makes it easier to work out a proposal for thickness reduction.

(3) Shape improvement of pipe pilings

A philosophy similar to that of the corrugation design for food can bodies has been applied to the shape of dimpled pipes.[10] As seen in **Fig. 23**, small depressions are formed in hot at regular intervals on the surface of dimpled pipes. In appreciation of good adhesion with cement or soil around them, these pipes are used mainly for pilings. The philosophy for defining the relationship between the depression depth and the axial strength of the pipe is based on that for the can-body corrugation shown in Fig. 17 (b).

The columns of square hollow sections for steel-framed houses and the Ω-section corner posts for freight containers, corrugated roof panels and bulkheads for cargo ships, food cans and steel pipe pilings are apparently altogether different from each other, but when viewed from the standpoint of shape, or from "katachi" approach,

Fig. 23 Pipe with surface dimples (left), and application example as foundation pilings for solar panels (right)

similar natures can be found; the same ideas can be applied for the improvement of both. Identifying similarities and differences in the shapes and functions of objects of different fields and applying the same improvement measure for one to another are the advantage and attractiveness of the “Katachi” solution.

5. Future Prospects

As a steelmaker, Nippon Steel & Sumitomo Metal has developed the technologies of steel manufacturing, and those for joining (welding, caulking, fastening, etc.) and forming (stamping, roll forming, hydraulic forming, etc.) steel materials. The “Katachi” solution presented herein adds a new point of view to the capability of the company to propose and offer customers solutions for more efficient and economical use of steel materials.

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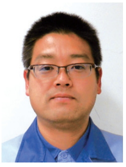

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