Technical Report

"Katachi" Solution —Five Approaches for Structure Weight Reduction and Some Examples—

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Abstract

Nippon Steel 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 the "Katachi" solution. "Katachi" is a Japanese word broadly meaning member shapes and structural configurations. This report shows the process of finding better solutions, the concept of analyzing deformation and five approaches for development with various examples.

1. Introduction

Nippon Steel Corporation has been focusing on the development of steel utilization technologies in parallel with the development of steels themselves. Particularly, we have systematized the designing technology with sheet structures through developing the technologies of utilizing steel sheets with a thickness of about 1.0 mm as framework members for low-rise buildings by taking initiatives including the promotion for the revision of laws to popularize the technology. We have made efforts to apply these ideas and technologies not only to the building field, but also to home appliances, OA equipment and various other structures. These ideas and technologies are collectively called the "Katachi" Solution ("Katachi" means "shape" in Japanese). The study examples and possibilities of the "Katachi" Solution were introduced in our previous report[1]. In 2020, the Japanese government announced major policy shifts toward carbon neutrality and highlighted a new material saving (structure weight reduction). We think that more weight reduction efforts are required of our customers who handle various structures. Following the previous report[1], we once again focus on the "Katachi" Solution as a means of reducing the weight of structures and introduce more specific concepts and methods.

2. Purposes of "Katachi" Solution

The "Katachi" Solution is a group of technologies that reduce the weight of structures by improving their shape and is designed to enhance the performance of structures without increasing their weight or to reduce the weight of structures while maintaining their performance. Here, we define two structural properties, or strength and stiffness, and explain them in the P-δ relationship diagram of **Fig. 1**. P on the vertical axis is the force (N) acting on the structure and δ on the horizontal axis is the deformation (mm) of the structure. The values of points ① to ③ on the vertical axis are the maximum strength of the structure and the slopes α and β are the stiffness of the structure. The strength of the structure can be increased from point ① to point ② by increasing the strength of the structural steel. There are no steels that can increase the stiffness of the structure from α to β. We must increase the thickness and dimensions of structural parts. The main purpose of the "Katachi" Solution is to derive measures to increase the stiffness of the structure without in-

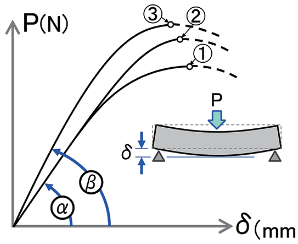

Fig. 1 Two types of structural performance (strength and stiffness)

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creasing the size of the structure as much as possible. We can also expect to improve the buckling strength and fatigue strength by increasing the stiffness and restricting the deformation.

3. Study Process

The main study flow of the "Katachi" Solution is shown below.

3.1 Construction of abstraction model

The progress of computers and software is generalizing the execution of numerical simulation and computer-aided engineering (CAE) of complex structures and the concept of digital twins for structures. When we evaluate only the performance of a structure, it is better for us to calculate it as an entire complicated system. When we study a structure for its significant improvement, we may be unable to find the target or policy of the improvement if we calculate the entire complicated system as it is. The "Katachi" Solution not only targets the entire complex system, but also studies the structure using the abstraction model, which is a model with characteristics of the structure derived from abstraction. Specific calculations are conducted through utilizing a group of design tools originally developed by Nippon Steel, based on general-purpose finite element analysis (FEA) and evolutionary computation[2, 3, 4] involving iterative calculations, among other matters.

3.2 Substructure extraction and "deformation separation"

When we conduct structural analysis on an abstraction model, we can see substructures (parts and elements) that contribute to the stiffness of the entire structure among the elements that make up the structure. Which substructure contributes varies infinitely with the object of study. When a torsional force acts on a box-shaped structure as shown in **Fig. 2**, for example, the side panel may become a key. In this example, we extract the side panel as an object of study, understand that two deformation modes, or out-of-plane bending and in-plane shear, occur in parallel and grasp that the former is dominant. We can consequently derive that increasing the out-of-plane flexural stiffness of the side panel is one of the measures to improve the performance of the entire structure. In the "Katachi" Solution, this analysis method of separating deformation modes and seeking improvement measures is called "deformation separation".

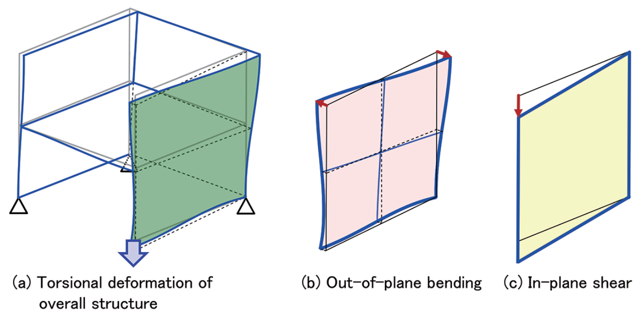


Fig. 2 Abstract model with clarified structural feature and deformation of substructure (side panel)

3.3 Study of improvement based on five viewpoints

There are various improvement measures based on the characteristics of the structure. The "Katachi" Solution proposes a study based on five viewpoints: [1] thickness combination, [2] cross-sectional shape, [3] frame arrangement, [4] connection arrangement and [5] embossment arrangement. The five viewpoints are outlined in **Fig. 3**. In the next chapter, we will concretely introduce the ideas and examples of the respective viewpoints.

4. Five Improvement Viewpoints and Study Examples

4.1 Thickness combination

Improvements that optimize the thickness of structural elements

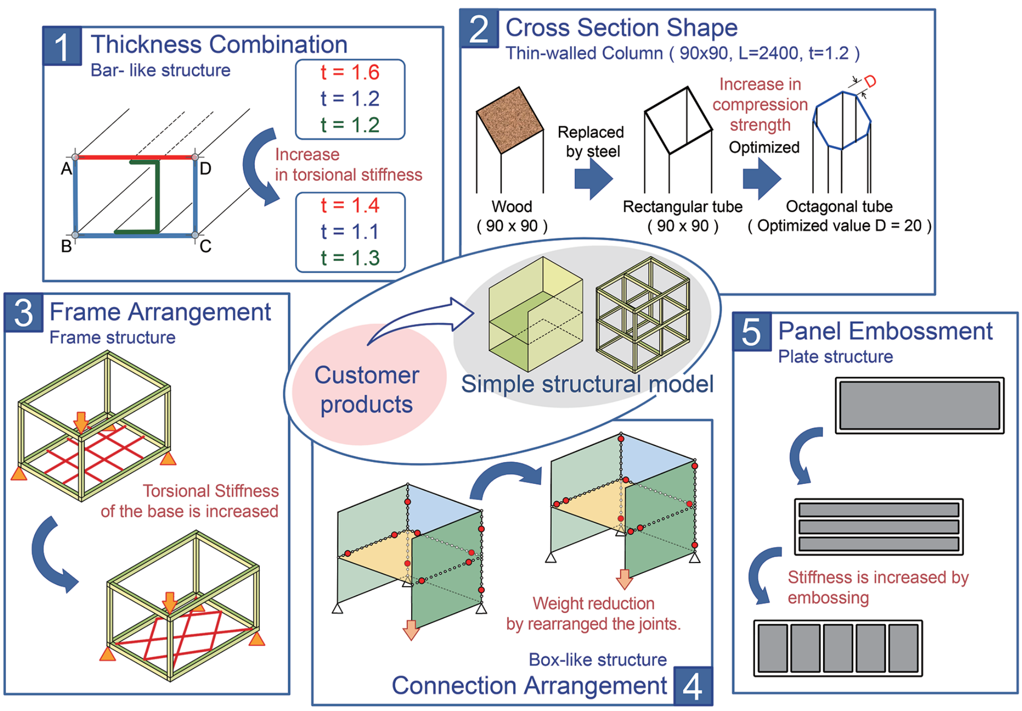


Fig. 3 Five approaches for improvement in the "Katachi" Solution

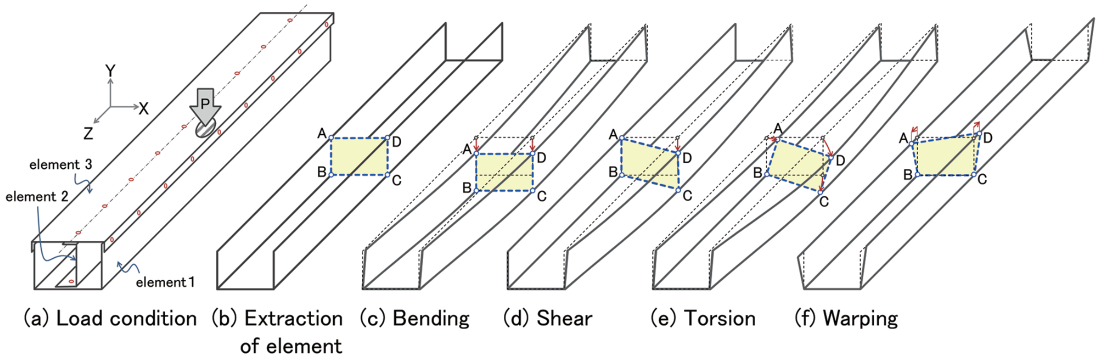


Fig. 4 Load conditions and multiple deformations

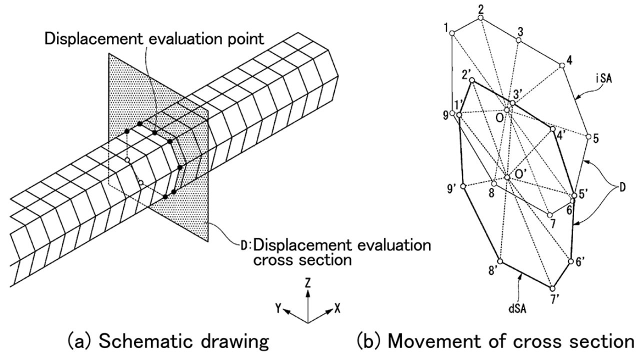


Fig. 5 Method to understand the deformation mode of the structure[5)]

without changing their shape are widely and commonly conducted. In the case of a long box-shaped structure (box beam) as shown in **Fig. 4**, we have confirmed that the torsional stiffness of the box beam may be improved by about 30% when the thickness of each element is changed as shown in Fig. 3[1]. There are four main deformation modes that occur in this box beam: bending, shear, torsion and warping as shown in Fig. 4. If the shear mode (d) is predominant, measures are required to prevent the center cross section (A-B-C-D section in Fig. 4) from deforming into a parallelogram. However, such measures cannot stop the torsion mode (e). This is because in the torsion mode, the center cross section (A-B-C-D section in Fig. 4) has little deformation but mainly rotates. Because the corrective measures vary with the deformation mode in this way, deformation separation plays a significant role.

For the technology for the deformation separation of such structures, refer to Reference 5). As shown in **Fig. 5**, the deformation separation technology can extract the deformation mode of the cross section iSA by comparing the cross section iSA arbitrarily set by the designer with the cross section dSA after deformation.

4.2 Cross-sectional shape

Regarding the cross-sectional shape of members, the case of the octagon in Fig. 3[2] also introduced in the previous report[1)] is easy to understand. Based on the deformation separation results of the box beam in the previous section, we can consider multiple options as shown in **Fig. 6**, for example. The short arrows in Fig. 6 indicate screwed or spot-welded joint points. Of the options (a) to (c) in Fig. 6, which one is better depends on the detailed conditions and cannot be specified. We can conduct some trials, though. If the deformation of the left vertical panel of element 1 turning down to the right side becomes conspicuous, for example, we can improve the partial shape focusing on the left corner (circled in Fig. 6) or change the assembly method of elements 1 and 3. It is important to separately consider the overall deformation of elements 1 to 3 and the local deformation mode of the respective elements.

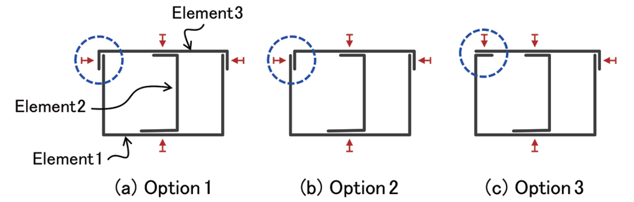


Fig. 6 Configuration options of cross-section for long box-shaped member

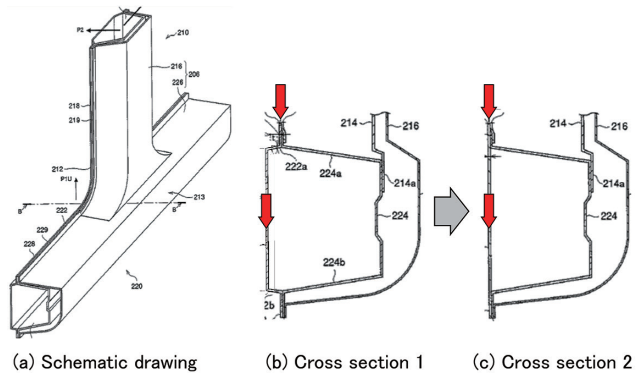


Fig. 7 Example of improvement proposal in the cross-sectional shape for automobile side sill[6)]

As a good example of cross-sectional shape improvement, an improvement plan[6)] for an automobile side sill is shown in **Fig. 7**. Through the analysis of the force flow from the pillar (vertical member in Fig. 7(a)) to the sill (horizontal member in Fig. 7(a)) and the deformation mode, we found that the stiffness of the joint between the sill and the pillar can be increased by reducing the width of the sill as shown in Figs. 7(b) and 7(c).

4.3 Frame arrangement

One of the effective means for increasing the stiffness of a structure is to increase the torsional stiffness of the parts called the base panels which are installed on the bottom surface of the structure. As introduced in the previous report[1)], it is easy to understand the cases[4, 7)] in which the frames that make up the base panel are arranged diagonally as shown in Fig. 3[3]. In this example, the effect of the frame is particularly large when its cross section is channel shaped. In the channel shape, the torsion (e) and warping (f) shown in Fig. 4

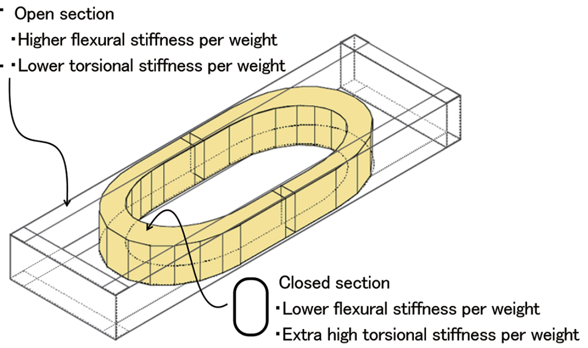


Fig. 8 Example of combining open sections and closed sections in order to take advantage of the structural significance of both[8, 9)]

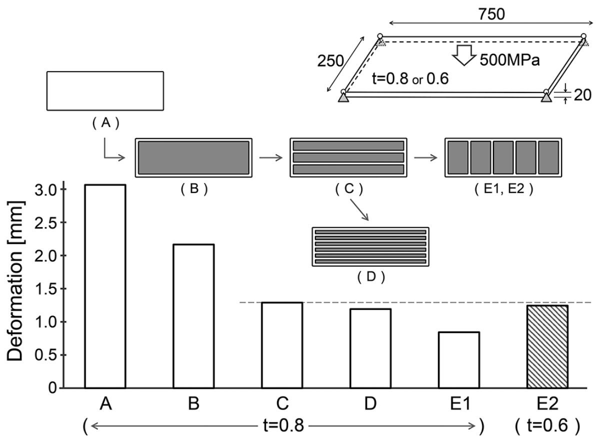


Fig. 9 Relationship between the orientation of embossment and central deformation
A: No embossment (t = 0.8)
B: Wide overall embossment (t = 0.8)
C: Three embossments along the long side (t = 0.8)
D: Six embossments along the long side (t = 0.8)
E1: Five embossments along the short side (t = 0.8)
E2: Five embossments along the short side (t = 0.6)

are likely to occur, so that the stiffness of the frame tends to decrease enormously. In the example of Fig. 3[3], the frames are diagonally arranged to utilize the mechanism whereby the frames restrain each other's torsion and warping.

As this example shows, preventing the component frames from torsioning is effective in increasing the torsional stiffness of the base panel. To achieve this, it is better to utilize a closed cross section like a pipe instead of an open cross section like a channel shape. This can be understood by comparing the Saint-Venant torsion constant and the warping torsion constant of both. It is recommended to check these constants while designing the structure . Moreover, as shown in **Fig. 8**, we have confirmed that structures combining the characteristics of both the open and closed sections[8 ,9)] achieve high weight reduction efficiency in some cases, such as when the four sides around the base panel are configured with open cross sections and an annulus made from a closed cross section pipe is arranged in the base panel.

4.4 Connection arrangement

In the case of a box-shaped structure, the torsional stiffness can be particularly increased by improving the arrangement of the connections as shown in Fig. 3[4]. As introduced in the previous report[1)], this is an application of the findings that the shear stiffness of a shear wall of a steel-framed house can be increased when drive screw joints between the wall panel and steel frame are concentrated at the four corners of the wall panel. Nippon Steel has studied these conditions with analysis tools based on mathematical optimization technologies[2, 3, 4), etc]. For box structures where multiple joints are discretely arranged, we can obtain practical measures for improving their stiffness.

4.5 Embossment placement

The Young's modulus of steel is about 205 GPa. It is difficult to change that value significantly. Unfortunately, we cannot increase the flexural and torsional stiffness of steel sheets by improving steel mechanical properties for now. This is one factor that hinders the application of high-strengthened steel. When the steel sheet is reduced in thickness by utilizing its high strength, its flexural stiffness decreases, resulting in deteriorated vibration characteristics and buckling. Embossing the steel sheets in patterns is a general and effective method for countering such problems. Here we introduce that the direction of arranging the embossments has an enormous impact on the improvement effect. The case shown in Fig. 3[5] is explained in **Fig. 9**. Figure 9 compares the maximum value of deformation when an evenly distributed load of 500 Pa (about 50 kg/m^2) is applied to a 750×250 mm panel flanged 20 mm at the circumference. We can see that when the steel sheet thickness is 0.8 mm, the deformation of the panel E1 with the embossments arranged in the short side direction is 30% or more smaller than that of the panel C with the embossments arranged in the long side direction. When the 0.8 mm thick panel C with the embossments arranged in the long side direction and the 0.6 mm panel E2 with the embossments arranged in the short side direction are compared, we can see that both are almost the same in their deformation. In other words, when the embossed arrangement is rotated by 90°, the sheet thickness can be reduced from 0.8 mm to 0.6 mm while maintaining the flexural stiffness. Although this method is quite a simple example, it certainly provides benefits and has been applied to washing machines[10)] and air conditioner outdoor units, among other appliances.

Embossments can be freely arranged on the top and side panels that cover the internal parts. The arrangement of embossments is limited in the internal chassis where many electrical components are mounted. In this case, a phase optimization tool or the like can be used. It is often difficult to understand the relationship between the embossments and their improvement effect obtained as an analysis result. Some ingenuity is required here. For example, **Fig. 10** shows a trial model of a chassis where embossments are arranged in a complicated manner. The effect of embossing can be shown as in **Fig. 11**. The vertical axis shows an index of the contribution the embossments made to the improvement of stiffness and presents a relative value of the reciprocity of the deformation. Under the bending condition (flexural condition) where a concentrated load is applied at the center shown in Fig. 11, the contribution of embossments ㉖ and ㉗ placed on the short side is extremely high. Under the twisting condition (torsional condition), the contribution of embossments ①, ⑥, ⑲ and ㉔ diagonally placed is high. Such an examination seems to be a matter of course when we look at the results, but it is important to quantify and organize all of them.

Through these studies, we proposed panels embossed in checkered patterns (**Fig. 12**)[11)] to increase the stiffness in a well-balanced manner against flexural and torsional forces. These ideas and shape

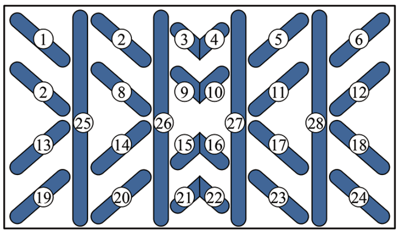


Fig. 10 Embossment arrangement for trial studies

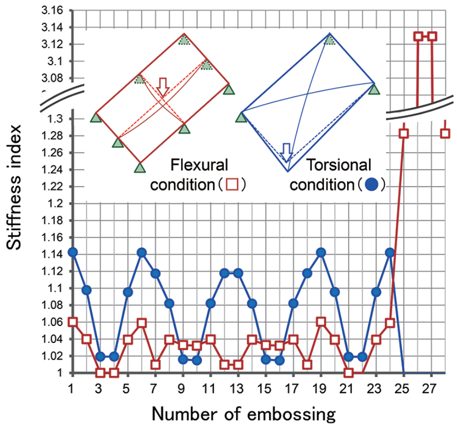
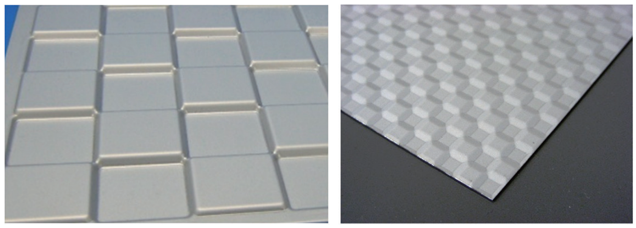


Fig. 11 Example of stiffness evaluation results



(a) 30mm x 30mm (b) 6mm x 6mm

Fig. 12 Press forming samples of checker embossment panel[11)]

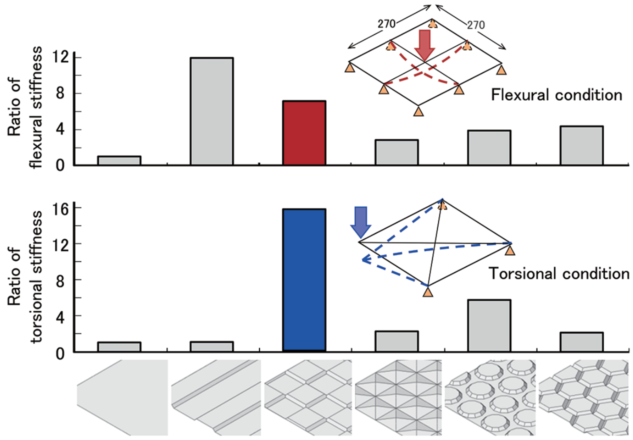


Fig. 13 Comparison of flexural and torsional stiffness

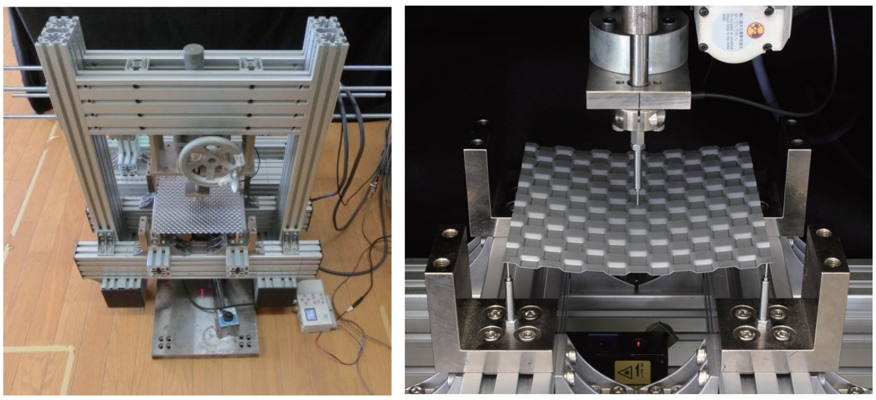
features are mentioned in the previous report[1)]. The checkered embossed patterns are particularly effective in improving the torsional stiffness. The magnitude of this effect becomes obvious when compared with the other embossed patterns (**Fig. 13**).

5. Structure Experiment Technology

One of the basic technologies of the "Katachi" Solution is structure experiment technology that can simulate actual phenomena with high accuracy. Nippon Steel has a variety of loading units from large ones with a maximum load capacity of 80 MN to small ones that can evaluate small structural elements and chassis as shown in **Fig. 14**. Structure experiments often focus on the magnitude and speed of the force to be applied. The method of properly fixing the test object to the test equipment is also important. Setting these boundary conditions is key to simulating actual phenomena in both structure experiments and numerical simulations. We have accumulated expertise as we have evaluated superhigh-rise buildings, low-rise houses, large bridges, piles, sheet piles and other underground structures, automobile white bodies, OA equipment and home appliance housings, and many other structures. As we mutually utilize such accumulated expertise across different fields, we can conduct proper structure experiments and hence can perform numerical simulations that accurately reproduce the actual situations.

6. Conclusions

The development of computers and software now allows us to evaluate the characteristics of structures by numerical simulation and computer-aided engineering (CAE) without conducting structure experiments. We cannot, however, automatically obtain shape improvement ideas conducive to weight reduction. We can derive feasible ideas only after separating and analyzing in detail the defor-



(a) Overall view of the device (b) Bending test of embossment panel

Fig. 14 Small test equipment for evaluating the structural elements of home appliance housings and the structural chassis

mation modes while considering the characteristics and load conditions of specific structures. Before we utilize mathematical optimization and artificial intelligence, we must develop tools to handle such technologies and connect them to concrete and effective solutions. To that end, we should endeavor to improve structure using the viewpoints proposed in the "Katachi" Solution. Nippon Steel will continue to strengthen its comprehensive proposal capabilities by combining steel material technologies with many steel utilization technologies such as the "Katachi" Solution.

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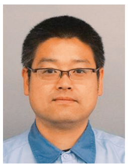

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