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# Development of All Laser Welded Honeycomb Structure for Civil Transports

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## Abstract

***An all-laser-welded stainless-steel honeycomb structure was developed for civil transports. This honeycomb panel consists of corrugated sheets, face sheets and flanges. These flanges are important for manufacturing curved surface panels and enable joining panels to panels in the field. A laser-welding process was applied to manufacture this honeycomb panel. Laser welding features highly controllable depth penetration, which eliminates welding bead on the honeycomb panel external surface. Therefore, this panel has high corrosion resistance and a sturdy appearance. This honeycomb panel was employed in a prototype of a high-speed freight ship as a national project. It is also being applied in a prototype commuter train and is being examined by the East Japan Railway Company.***

## 1. Background

Honeycomb panels have been used for containers, vessels and vehicles for transportation as lightweight, high-rigidity and high-strength materials. A honeycomb panel is composed basically of a core and two sheets fixed on both its sides. Honeycomb panels are classified according to the shape of the core into a hexagonal type having a core in a honeycomb shape, a truss type having a corrugated core and so on, and are made of various materials such as an aluminum alloy, steel, titanium and a composite material. These varieties of honeycomb panels are used for different applications according to their characteristics.

However, the facts such as the following have been pointed out as the problems of conventional honeycomb panels: a curved panel entails complicated manufacturing processes and high production costs as a consequence; special inserting joints, tools or procedures are required for joining panel-to-panel or to a structural member of a different kind, so field workability is poor; and corrosion resistance and weldability are poor in the case of an aluminum alloy panel.

In order to solve the above problems, Nippon Steel Corporation developed a laser-welded stainless steel honeycomb panel as schematically shown in **Fig. 1**. It is composed of a core, internal and external sheets and flanges arranged at the four end faces; the flanges constitute one of the main features of the developed honeycomb panel. The principal achievements regarding the developed panel are as follows:

(1) The developed honeycomb panels were used and evaluated in the prototype vessel of a next-generation high-speed freight ship called “Techno Super Liner: TSL” (see **Fig. 2**) developed as a national project under promotion of the then Ministry of Transport (now the Ministry of Land, Infrastructure and Transport). The development project was concluded in 1993.

(2) The panels were used for the structures of the prototype cars of a next-generation commuter train named “AC Train” (type E993-1, see **Fig. 3**) of East Japan Railway Company. The prototype train is being tested as of June 2003.

(3) The manufacturing technology of the developed honeycomb panel

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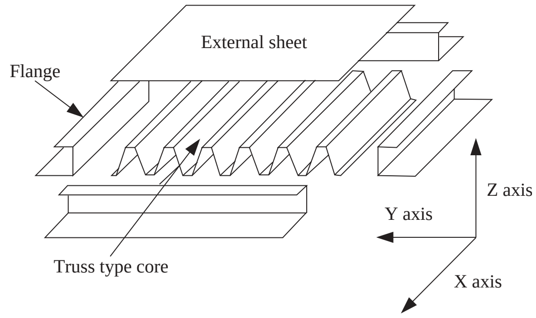


**Fig. 1 Schematic illustration of laser-welded stainless steel honeycomb panel**

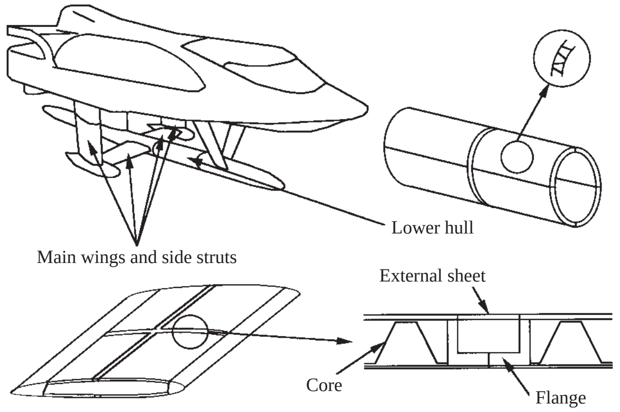


**Fig. 2 Schematic illustrations of prototype vessel of TSL and portions constructed with developed honeycomb panel**

**Fig. 3 Prototype cars of AC train constructed using developed honeycomb panels**

has been established through the above applications and in addition, the technology for optimum design and service life estimation of the panel using computer simulation has been developed.

The advantages of the developed honeycomb panel are as follows:

(a) It is made of stainless steel, which is better in corrosion resistance, weldability and recyclability than an aluminum alloy. In addition, the carbon dioxide emission at the production of stainless steel is only about 1/3 that of an aluminum alloy.

(b) A quadratically curved panel can be manufactured as easily as a flat panel as a result of use of a truss type core.

(c) A flange for joining to another panel or a structural member of a different kind is provided as an integral component at each end face of a panel unit, and therefore joining work can be done without requiring special tools.

(d) Laser welding is used for welding the panel components together. By controlling the penetration depth in welding an external sheet to a core, a panel excellent in appearance can be manufactured without weld marks on the external sheet surface.

This paper describes the structure, fabrication techniques and mechanical properties of the honeycomb panels used for the TSL prototype vessel and the AC train.

## 2. Characteristics and Mechanical Properties of Honeycomb Panels for TSL Prototype Vessel

### 2.1 Outline of TSL and portions constructed with honeycomb panels

Under the TSL project, a high-speed freight ship that could cruise stably at 93 km/h was developed as a means to stimulate a modal shift in freight transportation from land to sea. It was promoted as a national project by the then Ministry of Transport, and its prototype vessel was developed by a project team of leading Japanese shipbuilders. The vessel was designed as a hydrofoil ship consisting of an upper hull housing a cargo hold, a crew space and a main engine, and a lower structure composed of a submerged body (or a lower hull), hydrofoils and side struts. The laser-welded stainless steel honeycomb panels were used for the lower structure. High dimensional accuracy and light weight are required of hydrofoils, which generate the lift to support the whole vessel. For this reason, a hydrofoil had been manufactured conventionally from a solid metal plate using an NC-control milling machine to realize a dimensional accuracy in the order of 10 μm, but this method was impossible to achieve the weight reduction required for the TSL vessel. For this reason, laser-welded stainless steel honeycomb panels having curved shapes were used for the hydrofoils and the lower hull as shown in **Fig. 4**.

### 2.2 Characteristics and mechanical properties of honeycomb panels for TSL

**Table 1** shows the main specifications of the honeycomb panels used for the TSL prototype vessel. The material is SUS 317J2L highly resistant to corrosion in seawater and produced through TMCP rolling to increase the yield point load. The most significant characteristic of the developed honeycomb panel is that the core and flange are welded together by laser welding in order to prevent stress concentration to the internal and external sheets at the discontinuity of the core at an end face. The welding of a core with a flange was impossible by conventional welding methods, even in the case of laser welding, because the difference in heat capacity between the two was too large. As a measure to solve the problem, the laser paste welding method was employed to reduce the difference in heat capacity. By the method, (i) a groove was cut in the surface to be

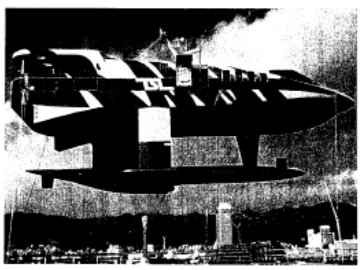

**Fig. 4 Prototype vessel of TSL with hydrofoils fabricated using developed honeycomb panels**

**Table 1 Main specifications of honeycomb panels for prototype vessel of TSL**

| External sheet | Internal sheet | Core | | | |
|---|---|---|---|---|---|
| | | Shape | Thickness | Pitch | Trapezoid upper base length |
| 2.0mm | 1.0mm | Truss type | 0.4mm | 24.3mm | 7.0mm |

welded of a flange, and the groove was filled with a paste composed of Ni powder and an organic solvent, (ii) the core sheet to be welded was set in the groove, (iii) the paste was sintered by irradiating a beam of continuously oscillated YAG laser, and then (iv) the core was finally welded to the flange.

The method is schematically shown in **Fig. 5**. The laser oscillator used for the welding was a continuous YAG laser oscillator, and its power output was 189 W at the work point. Welding tests were carried out setting the groove width at 0.6 and 0.8 mm and changing the scanning speed of the laser beam. **Table 2** shows the results of tension shear tests of the joints between the core and flange (see **Fig. 6**) that were welded by the laser paste welding method. The breaking strength was 235 to 307 MPa, and the ratio (Ts/Ys) of the breaking strength (Ts) of the weld joints to the yield strength (Ys) of the core material was 0.68 to 0.89. Although the breaking strength of the weld joints was lower than that of the material steel sheet, it was about 70 to 90% of its yield strength; thus the weld joints were judged to have sufficient strength. A continuously oscillating $CO_2$ gas laser (see **Table 3** for main specifications) was used for welding the core to the internal and external sheets. The half-penetration welding method, by which no weld marks were left on the external sheet surface, was employed to weld the core to the external sheet, which would contact seawater. The welding of the core to the internal sheet was done by the penetrating welding method from the internal surface of the panel.

The above welding methods are schematically shown in **Fig. 7** and sectional photos of welded joints in **Fig. 8**. As seen in the upper part of Fig. 8, the penetration into the external sheet by the laser irradiation from the core side is limited to approximately 1/3 of its thickness. Tests of different penetration depths into external sheets were carried out changing welding speed. The results of tension shear tests of the external sheet/core joints are shown in **Fig. 9**. The breaking strength at a welding speed of 4.5 m/min or less was close to 883 MPa, the breaking strength of the material steel sheet. Honeycomb panels were fabricated employing these three welding methods, and their mechanical property items listed in **Table 4** were tested. Among these test items, the results of the tensile test of joints are explained below.

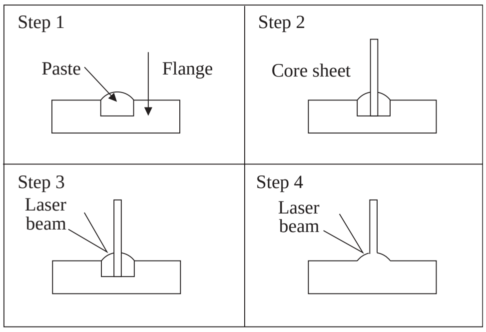


**Fig. 5 Schematic illustration of laser paste welding method**

**Table 2 Tension shear test results of joints welded by laser paste welding method**

| Groove width | Welding speed: 0.6m/min | | Welding speed: 0.8m/min | |
|---|---|---|---|---|
| | Breaking strength | Ts/Ys | Breaking strength | Ts/Ys |
| 0.6mm | 235MPa | 0.68 | 290MPa | 0.84 |
| 0.8mm | 307MPa | 0.89 | 300MPa | 0.87 |

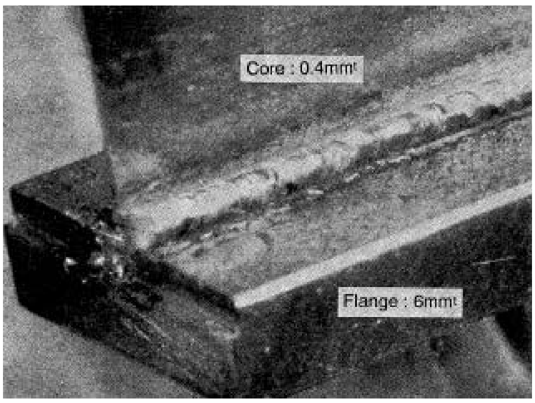


**Fig. 6 Joint welded by laser paste welding method**

**Table 3 Main specifications of $CO_2$ gas laser oscillator**

| Type | Wave length | Max. output | Beam mode |
|---|---|---|---|
| Unstable type | 10.6μm | 15kW | TEM01* |

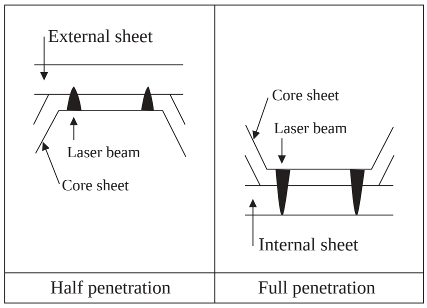


**Fig. 7 Schematic illustration of laser welding methods**

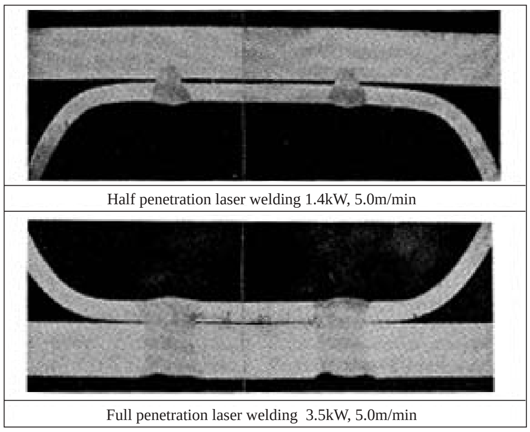


**Fig. 8 Laser-welded joints**

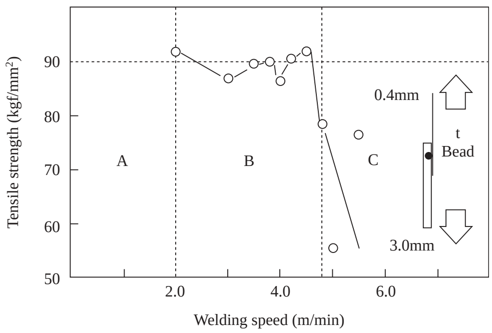


**Fig. 9 Tension shear test results of joints between core and external sheet**

**Table 4 Evaluation items of mechanical properties**

| | Static properties | Fatigue properties |
|---|---|---|
| X axis direction | Compressive<br>Tensile<br>Bending | –<br>Tensile<br>Bending |
| Flange in X axis direction | Tensile | Tensile<br>Bending |
| Y axis direction | Compressive<br>Tensile<br>Bending | –<br>Tensile<br>– |
| Flange in Y axis direction | Tensile | Tensile |
| Z axis direction | Compressive<br>Tensile | Tensile<br>– |

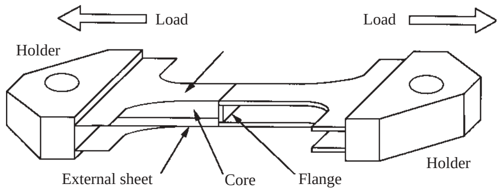


**Fig. 10 Schematic illustration of tensile test piece**

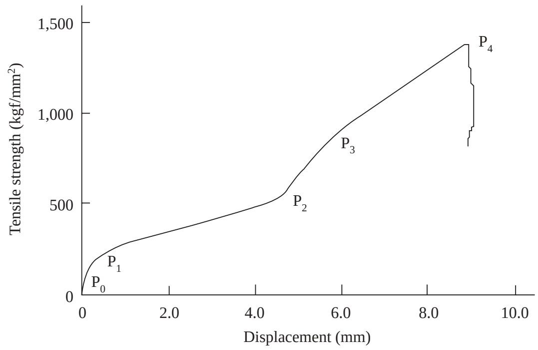


**Fig. 11 Load-displacement diagram**

**Fig. 10** schematically shows a test piece used for the test. A test piece consisted of a panel portion and two flat sheets simulating a structural member of a different kind. The panel portion was composed of a core, internal and external sheets and a flange, and included the joint between the core and the flange, those between the core and the internal and external sheets and those between the internal and external sheets and the flange. The load-displacement curve obtained through the test is shown in **Fig. 11**. In the figure, $P_0$-$P_1$ is the elastic region, $P_1$ the yield point, $P_2$ the breaking point of the core-internal sheet joint, $P_3$ the breaking point of the core-flange joint, and $P_4$ the breaking point of the flange-internal sheet joint. Yield stress and maximum stress were calculated by dividing the yield point load and maximum load, respectively, by the sectional area of the portion composed of the core and the internal and external sheets. As a result, the average of the yield stress was 475 MPa, and that of the maximum stress was 554 MPa. The required yield stress of the honeycomb panel was 42 MPa, and thus it was confirmed that the mechanical properties of the honeycomb panel satisfied required conditions.

## 3. Characteristics and Mechanical Properties of Honeycomb Panels for AC Train

### 3.1 Outline of AC Train and portions constructed with honeycomb panels

The AC Train is a prototype, next-generation commuter train developed by East Japan Railway Company aiming at reducing life-cycle costs, enhancing transportation quality and causing less environmental loads. Among a variety of new technologies employed in the development, the laser-welded stainless steel honeycomb panel was used as a measure to reduce the structural weight of the cars and the costs of construction.

Conventionally, the structure of a railway vehicle had been composed of columns, beams and outer panels and because of a great number of components involved, there were limitations to the reduction of vehicle weight and component management costs and the simplification of fabrication processes. To solve the problems, prefabricated panels have come to be used for the structure of a railway vehicle. Although panels of extruded aluminum alloy sections have been used for limited express train cars, the aluminum panels are not economical for commuter train cars, which have a higher number of doors. In view of this, a method was worked out whereby different portions of a vehicle structure were fabricated as panel units, and honeycomb panels of stainless steel sheets, which were corrosion-resistant in bear use and easily recyclable, were considered effective for many of the panel units.

In this background, application of the laser-welded stainless steel honeycomb panel to the structure of a railway vehicle was studied, and it was used for the prototype train of the AC train for the purpose of evaluating its mechanical properties and examining the methods and costs of structure construction. The prototype AC train consists of five articulated cars as shown in **Fig. 12**, and four types of structures of different materials and construction are used in it for comparison purposes. Use of high-rigidity members for side walls enhances the rigidity of a whole vehicle structure and for this reason, the stainless steel honeycomb panels were used for most of the side walls of the intermediate cars as shown in **Fig. 13**.

### 3.2 Mechanical properties of honeycomb panels for AC Train

A honeycomb panel was composed of a truss type core, internal and external sheets and flanges. **Table 5** shows its main specifica-

**Fig. 12 Consist of prototype AC train**

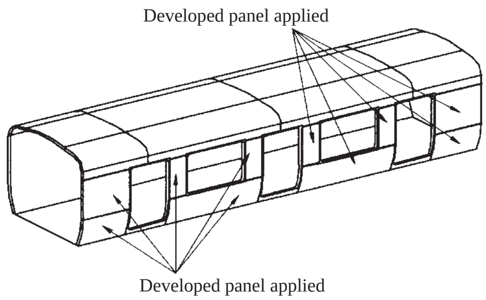


**Fig. 13 Portions of AC train vehicle where developed honeycomb panel was used**

**Table 5 Main specifications of honeycomb panels for AC train**

| External sheet | Internal sheet | Core | | | |
|---|---|---|---|---|---|
| | | Shape | Thickness | Pitch | Hight |
| 1.0mm | 0.8mm | Truss type | 0.4mm | 49.2mm | 36.2mm |

tions. Although the thickness of the external sheet initially indicated by the client was 0.8 mm, it was increased to 1.0 mm at a specification definition stage in consideration of required mechanical properties and accidental events such as bouncing of ballast of a rail bed and poking with an umbrella or the like at a station. In consideration of required characteristics, YAG laser spot welding was used for fabricating the panels to reduce thermal strain of welding work, and the penetration depth of welding was so controlled as to secure sufficient strength and good appearance of the external sheet. The panels were fabricated in the following four steps: (i) welding of an external sheet to flanges, which had been formed beforehand in accordance with a designed curvature of a panel; (ii) spot welding of a core to the external sheet using pulsed YAG laser by so controlling heat input as not to cause welding marks on the external sheet surface; (iii) welding of an internal sheet to the core that had been welded to the external sheet; and (iv) welding of the internal sheet to the flanges.

**Fig. 14** shows the welding work of the second step. The laser beam is transmitted from an oscillator through an optical fiber to a work head, which is mounted on an NC work table as seen in the photo to travel over the panel under fabrication. The bright portion in the photo is the plasma induced by the irradiation of the laser beam from the work head. The main specifications of the laser oscillator and the beam transmission and condensation optical systems are shown in **Table 6**.

As the typical mechanical properties of the honeycomb panels, their static and bending fatigue properties are described below. **Fig. 15** shows an outline of the test and the shape of a tested panel. For the purpose of examining the influence of the core shape and the welding pitch over the bending properties of a panel, static tests were carried out under the conditions marked with ○ in **Table 7**. The Young's modulus of a panel was calculated from displacement, load, the geometrical moment of inertia, the span between supports and the shape of the loading portion. The point of inflection of a load-displacement curve was defined as the elastic limit, and its highest point as the maximum load.

The test results are shown in **Tables 8 to 10**. The Young's modulus decreased from 20,612 to 16,651 kgf/mm$^2$ as the upper base length of the trapezoid of the core increased. This is because the shape of the core trapezoid has influence over the restriction between a core and internal and external sheets. With respect to the welding pitch, the fluctuation of the Young's modulus depending on the welding pitch was only 5% at the largest, and the fluctuation was attributed to natural error. The maximum load increased as the welding pitch decreased and the upper base length of the core trapezoid increased. The elastic limit did not change in correlation with the welding pitch or the upper base length of the core trapezoid, but its fluctuation was as large as 31%. This is presumably due to a slight twist of tested panels. Fatigue properties of the panels were tested under the condition of a core trapezoid upper base length of 12.5 mm and a welding pitch of 5 mm. The tested panels withstood $5 \times 10^6$ cycles of repetitive loads at a stress ratio of 0.1, that is from a maximum load of 75 kgf to a minimum load of 7.5 kgf.

The shape of the panels was finally decided based on investigations of static and repetitive tensile properties, static compression properties and static shear properties.

The honeycomb panels fabricated in accordance with the above specifications were supplied to Tokyu Car Corporation, and assembled at the company's plant into vehicle structures through welding panel-to-panel and to window frames and door frames; no modifications to existing plant facilities were required for the assembly work. **Fig. 16** shows a side wall unit of a car about 5 m in length. The honeycomb panels were used for both the sides of a door frame and the

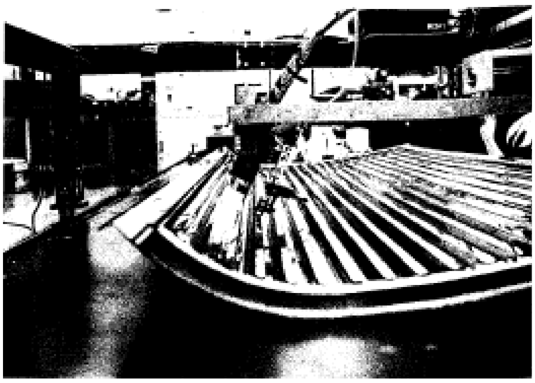

**Fig. 14 Core and external sheet of developed panel during welding work**

**Table 6 Main specifications of laser oscillator and optical systems for beam transmission and condensation**

| YAG laser oscillator | | Transmission optical system | | Condensation optical system |
|---|---|---|---|---|
| Wave length | Output | Type | Core diameter | Magnification |
| 1.06μm | 400W | SI type | 800μm | 0.5 |

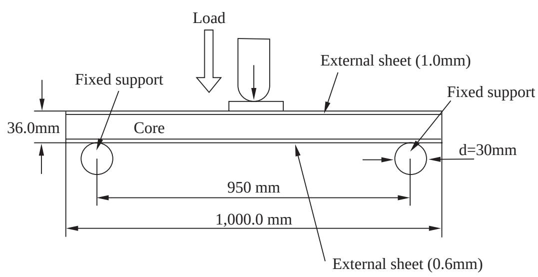


**Fig. 15 Schematic illustration of bending property test**

**Table 7 Specifications of tested panels**

| | Trapezoid upper base length (mm) | | |
|---|---|---|---|
| Welding pitch (mm) | 7.5 | 10.0 | 12.5 |
| 5.0 | × | ○ | × |
| 3.3 | ○ | ○ | × |
| 2.5 | × | ○ | × |

**Table 8 Young's modulus** (kgf/mm$^2$)

| | Trapezoid upper base length (mm) | | |
|---|---|---|---|
| Welding pitch (mm) | 7.5 | 10.0 | 12.5 |
| 5.0 | – | 17,689 | – |
| 3.3 | 20,612 | 17,537 | 16,651 |
| 2.5 | – | 16,952 | – |

**Table 9 Maximum load** (kgf)

| | Trapezoid upper base length (mm) | | |
|---|---|---|---|
| Welding pitch (mm) | 7.5 | 10.0 | 12.5 |
| 5.0 | – | 341 | – |
| 3.3 | 331 | 361 | 382 |
| 2.5 | – | 372 | – |

**Table 10 Elastic limit** (kgf)

| | Trapezoid upper base length (mm) | | |
|---|---|---|---|
| Welding pitch (mm) | 7.5 | 10.0 | 12.5 |
| 5.0 | – | 178 | – |
| 3.3 | 117 | 190 | 179 |
| 2.5 | – | 168 | – |

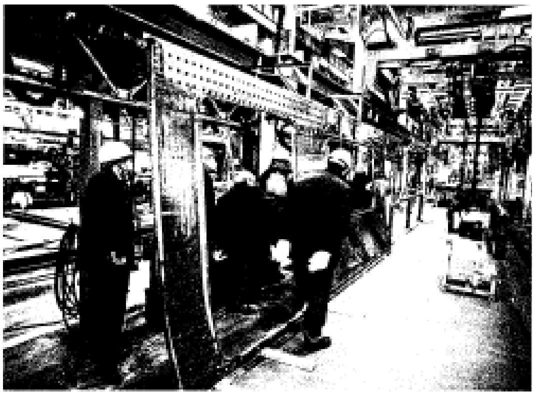

**Fig. 16 Side wall unit of AC train**

side wall below a window frame. After the photographed scene, the side wall units were assembled with the panels of the roof, floor and ends to form a complete car structure, which was then subjected to static and fatigue tests of mechanical properties. In the test of fatigue properties, steel weights were laid on the floor to cover the whole area to simulate the weight of a full load of passengers and repetitive loads were imposed by an actuator, and the amount of strain was measured. In addition to these tests using the structure of real cars, the properties of the structure were also analyzed using computers.

## 4. Summary

A laser-welded stainless steel honeycomb panel has been developed, and its fabrication methods and technologies for the design and structural analysis of the panel including the estimation of its service life have been established. The principal achievements regarding the developed panel are as follows:

(1) Actual applicability of the panel has been evaluated and verified through application to the prototype vessel of a next-generation high-speed freight ship that was developed under a national project.

(2) The panel was also used for the structure of the prototype cars of a next-generation commuter train (AC Train, type E993-1) and the cars are being run for performance test purposes.

(3) The technology for the optimum design of the honeycomb panel by computer simulation has been established.

The laser welding method employed for the fabrication of the panel is characterized by excellent controllability of heat input, and is capable of forming sound weld joints of 30μm thin stainless steel foils to 1-inch thick heavy steel plates. It has been reported that laser welding is applicable also to nonferrous materials such as intermetallic compounds. New types of honeycomb panels for a wide variety of applications will surely be worked out through combinations of new materials such as intermetallic compounds, a laser welding method that does not damage their properties and the technologies of design and structural analysis of the panels.

## 5. Acknowledgement

The authors express their sincerest gratitude to the staff of East Japan Railway Company and Tokyu Car Corporation for their cooperation.