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# Corrosion Environment and Durability of Steel-Framed Houses

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**Abstract:**

***In order to clarify the durability of steel-framed houses, we measured corrosion environment and corrosion rate of coating indoors using steel framed experimental houses, we researched the durability between coated steel sheets for frames as well as joint areas between sections and plywood, and we researched adhesion of coated steel sheets and wooden materials. This study has shown that there is a mild corrosion environment indoors with a very low rate of coated steel sheet corrosion and that the durability of each joint area is adequately secured.***

## 1. Introduction

To clarify the durability of steel-framed houses, it is important to investigate the corrosion resistance of coated steel sheet shapes (hereinafter referred to as coated steel shapes) to be used in frames and the durability of self-tapping screw connections. Quantification of the environment where such coated steel shapes and screw connections are used and determination of their corrosion rate are also important.

Nippon Steel Corporation has studied the durability of steel-framed houses[1-4] as part of the steel-framed house promotion activities of the Kozai Club. Nippon Steel measured the corrosion environments of experimental steel-framed houses and the corrosion rate of metal coatings, and investigated the durability of connections between coated steel shapes and of connections between coated steel shapes and plywood, and the adhesion between coated steel sheets and wooden materials.

The results obtained are described in this report. They can be not only applied to steel-framed houses, but also used for the substitution of steel for the component parts of prefabricated houses and wooden two-by-four houses.

## 2. Corrosion Resistance of Zinc-Coated Steel Sheets and Corrosion Environment of Steel-Framed Houses

The zinc-coated steel sheets used in the frames of steel-framed houses have excellent long-term corrosion resistance, so that they have been used in large amounts as outdoor building materials. Several sets of atmospheric exposure test results have been published for zinc-coated steel sheets in outdoor environments. Some of those results are summarized in **Table 1**[5]. From **Table 1**, it can be seen that zinc-coated steel sheets with a zinc coating weight of 550 g/m$^2$ have an estimated life of 50 years in most parts of Japan.

Among the environmental factors that have a great impact on the atmospheric corrosion of zinc-coated steel sheets are increased humidity, rainfall, sulfur oxides, and fine sea salt particles. In indoor locations where the zinc-coated steel sheets are less susceptible to these environmental factors, their corrosion rate is naturally lower than in outdoor locations. For example, the corrosion rate of cold-rolled steel sheets in an air-conditioned room is reported to be 1/1000 of that measured outdoors[6].

When quantifying the life of steel-framed houses, it is thus of extreme importance to measure the indoor corrosion environment and determine the corrosion rate of coated steel sheets in the indoor environment. Tujikawa et al. measured the corrosion environments inside of houses by using atmospheric corrosion monitor (ACM) sensors[7,8], and reported that the indoor corrosion rates of iron and zinc are extremely low. Nippon Steel has been measuring indoor corrosion environments and corrosion rates in a monitor house built in the seacoastal area of Futtsu-shi, Chiba Prefecture, and in another monitor house built in the rural area of Kugino-mura, Kumamoto Prefecture. The measurement results of the monitor house in Futtsu-shi are reported below.

The environmental measurements included the analysis of deposits (chloride ions, sulfate ions and nitrate ions) by ion chromatography, the determination of sulfur oxides by the lead dioxide

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Table 1 Summary of exposure test results[5)]

| Environment | | | Annual corrosion weight loss ($g/m^2/y$) | | Estimated life |
|---|---|---|---|---|---|
| Atmospheric environment | Example of area | Exposure site number | Range | Estimate | 550g/m$^2$ |
| Place with little artificial pollution (this applies to most parts of Japan) | Rural area Inland area | 1, 5, 6, 12, 26, 27 | 4 - 16 | 10 | 50 years |
| Place with much artificial pollution (heavily populated area) | Urban area | 2, 7, 8 | 3 - 18 | 15 | 33 years |
| | Industrial area | 3, 8, 11 | 8 - 19 | 15 | 33 years |
| Place with high concentration of fine sea salt particles (area within about 2 km of sea coast line) | Seacoastal area | 4, 10, 13, 17, 19, 20, 21, 23 - 25 | 11 - 21 | 20 | 25 years |
| | Area with high concentration of fine sea salt particles | 20, 22, 26 | 15 - 37 | 30 | 16 years |
| Place subjected to direct action of sea water | Splash area | 14, 16 | 34 - 104 | 70 | 7 years |

Table 2 Analysis of deposits in and out of steel-framed house

| Position | $Cl^-$(mg/m$^2$) | $NO_3^-$(mg/m$^2$) | $SO_4^{2-}$(mg/m$^2$) | $SO_3$* |
|---|---|---|---|---|
| Exterior wall of first floor | 5.2 | 1.5 | 0.3 | 0.005 |
| Eaves soffit | 47.5 | 11.2 | 32.5 | 0.042(Instrument shelter) |

*Sulfur trioxide determined by lead dioxide method, mg/(day·100 cm$^2$ $PbO_2$)

method, and the measurement of the corrosion environment of the monitor house by ACM sensors installed in various parts of the monitor house. Hot-dip galvanized steel sheets, hot-dip Zn-5%Al alloy-coated steel sheets (hereinafter abbreviated as the Zn-5%Al alloy-coated steel sheets), and hot-dip 55%Al-Zn alloy-coated steel sheets (hereinafter abbreviated as the 55%Al-Zn alloy-coated steel sheets) were exposed in and out of the monitor house and tested for corrosion rates by a precision chemical method[9)].

The deposits within the exterior wall of a Japanese-style room on the first floor and in an outdoor instrument shelter were analyzed by ion chromatography. Sulfur oxides deposited in the same areas were determined by the lead dioxide method. The results are given in **Table 2**. When chloride ions are taken as an example, their deposit weight in the wall is about one-ninth of that in the outdoor location. The sulfate ions and sulfur oxides that have a large effect on the corrosion rate of zinc are far smaller in the wall than in the outdoor position. This suggests that steel-framed house walls constitute a mild corrosion environment.

The daily average quantity of electricity, Q (C/day), measured in each wall by the ACM sensors was of the order of $10^{-4}$ after 2 years. In light of the relationship between the corrosion rate of zinc-coated steel sheets and the quantity Q of electricity obtained in joint experiments of the Kozai Club (see **Fig. 1**)[10)], the corrosion rate of hot-dip galvanized steel sheets is estimated at a very slow 1 g/m$^2$/y. The actual corrosion rates of various types of zinc-coated steel sheets are comparatively shown for wall (in) and outdoor (out) positions in **Fig. 2**. The corrosion rate of each type of zinc-coated steel sheet in the walls was much slower than outdoors, being about one-tenth or less of that measured outdoors.

The above results indicated that the steel-framed house presents a mild corrosion environment and that the corrosion rate of various types of zinc-coated steel sheets is slow enough in the steel-framed house.

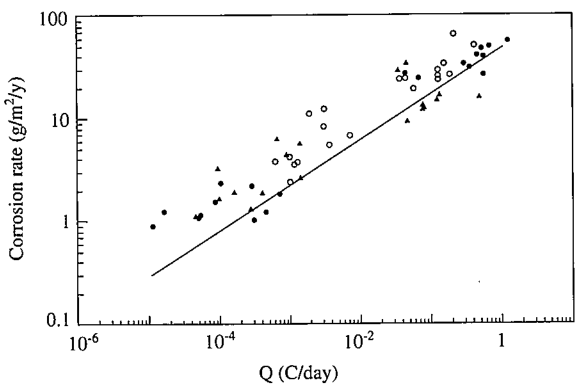


**Fig. 1 Relationship between corrosion rate of galvanized steel sheet (Z27) and ACM sensor output[10)]**

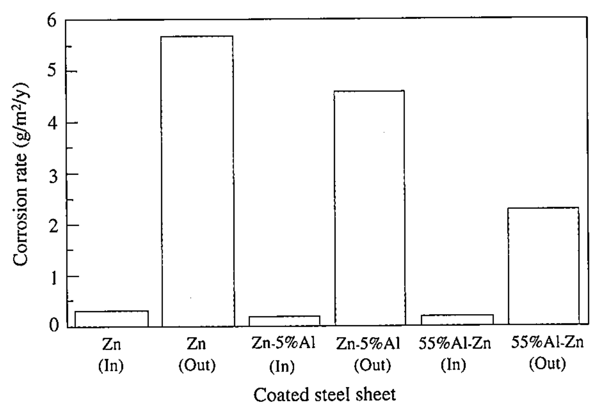


**Fig. 2 Corrosion rate of coated steel sheets exposed in and out of steel-framed house**

## 3. Durability of Joining Methods Applicable to Steel-Framed Houses

### 3.1 Connections between steel shapes

The steel-framed house is a wooden two-by-four house whose studs and nails are replaced by zinc-coated steel sheets and self-tapping screws, respectively. At the factory, steel frames are fabricated and assembled to such a degree that the task of construction can be reduced at the site. Besides self-tapping screws, clinching and riveting are also considered applicable as joining methods at the factory.

The Kozai Club has conducted many tests on the durability of self-tapping screw connections between steel shapes. It is already known that a zinc coating thickness of 20 $\mu$m assures practically satisfactory durability.[1,3-4] Other joining methods have not been studied yet, however. The shear strength of connections made by joining methods other than self-tapping screws was measured, and the durability of such connections was compared with that of self-tapping screw connections.

The experiments used 0.6-mm thick and Z18 coating weight zinc-coated steel sheets, and employed clinching and one-side riveting as joining methods. The one-side rivets were 4 mm in diameter and electrogalvanized to a thickness of 20 $\mu$m. The self-tapping screws were 4.2 mm in diameter and electrogalvanized to a thickness of 20 $\mu$m.

The shape of a shear test specimen is shown in **Fig. 3**. The specimen consisted of two 150 × 60 mm steel sheets overlapped by 85 mm and connected at two points as shown in **Fig. 3**. The maximum shear strength of the connection was measured before and after a corrosion accelerate test, and the durability of the connection was investigated. A shear force was applied to the connection by applying a tensile force to each end of the specimen shown in **Fig. 3**, and the resultant shear strength of the connection was measured.

The accelerated corrosion test was the cyclic corrosion test (hereinafter abbreviated to CCT) whose conditions are shown in **Table 3**. The CCT shown in **Table 3** is a kind of CCT that simulates an outdoor environment. One 1-day cycle consists of salt spraying, drying, wetting, and freezing. This experimental study performed the CCT for eight weeks and evaluated the shear strength of the specimens every two weeks.

The maximum shear strength of the specimens measured as an index of durability is shown in **Fig. 4**. The flat portions of the

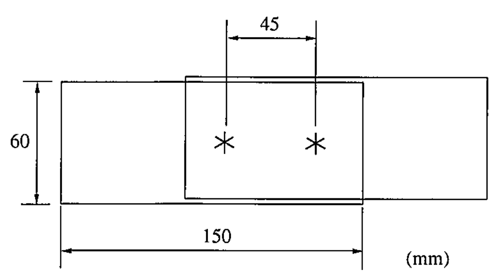


**Fig. 3 Shape of shear test specimen**

**Table 3 Conditions of cyclic corrosion test**

| | |
|---|---|
| Salt spraying (5%NaCl, 35°C, 6 h) ⇒ 1 h ⇒ Drying (70°C, 60%RH, 4 h) ⇒ 2 h ⇒ Wetting (49°C, 95%RH, 4 h) ⇒ 2 h ⇒ Freezing (–20°C, 4 h) ⇒ 1 h ⇒ | 24 h/cycle |

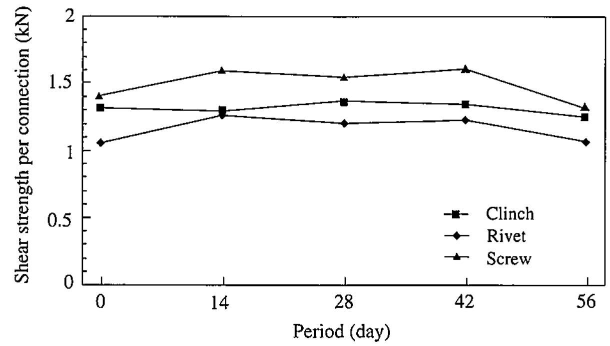


**Fig. 4 Change with time in shear strength (Z18)**

specimen made of hot-dip galvanized steel sheets developed red rust after two weeks of the CCT, and lost all of the hot-dip galvanized coating and developed red rust throughout after four weeks of the CCT. This means that eight weeks of the CCT is a test duration two to four times longer than the life of the hot-dip galvanized steel sheets.

The clinched specimens showed no appreciable change in the shear strength through eight weeks of the CCT. The failure mode of the connection in each specimen showed no difference before and after the corrosion test. The one-side riveted specimens showed a slight drop in the shear strength after eight weeks of the CCT. The failure mode of the connection in each specimen was the failure of the steel sheet base metal. No difference was observed before and after the CCT. The formation of red rust was observed on the rivets after the CCT, but the rivets did not fail in the shear strength test of the specimen. The maximum shear strength of the self-tapping screw-connected specimens slightly declined after eight weeks of the CCT. The failure mode of the connection in each specimen was the failure of the steel sheet base metal. No difference was observed before and after the CCT. The self-tapping screws developed red rust after two weeks of the CCT and had red rust formed throughout after four weeks of the CCT. The self-tapping screws themselves did not fail in the shear strength test of the specimens.

Actual coated steel sheets are at the end of their life when they lose the coating, and are used no more. The clinched and one-side riveted specimens showed no decline in the shear strength when red rust formed on the coated steel sheets. It was thus made clear that the durability of the connections made by clinching and one-side riveting is maintained during the life of the coated steel sheets, like the self-tapping screw connections.

### 3.2 Self-tapping screw connections between steel shapes and structural plywood

The steel-framed house has connections between steel shapes and structural plywood used for walls and floors, in addition to connections between steel shapes used for studs. These connections account for about 60 percent of all connections, so that their durability is also important. The self-tapping screw connections between steel shapes and structural plywood had their shear strength and pull-out strength measured and their durability investigated.

**Fig. 5** shows a shear strength test specimen. The specimen had 9-mm thick structural plywood and 1-mm thick Zn-5%Al alloy-coated steel sheet (Y18) overlapped and connected with two self-tapping screws, which were driven from the plywood side. **Fig. 6** shows a pull-out test specimen. The specimen had 9-mm thick structural plywood and 1-mm thick hot-dip Zn-5%Al alloy-coated

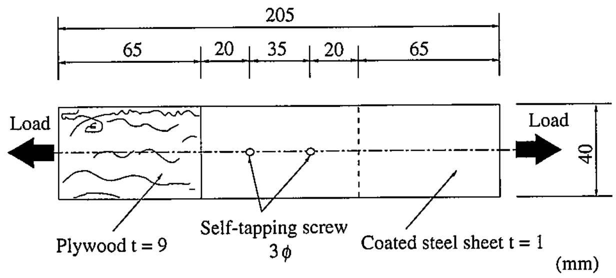


**Fig. 5 Schematic of shear strength test specimen**

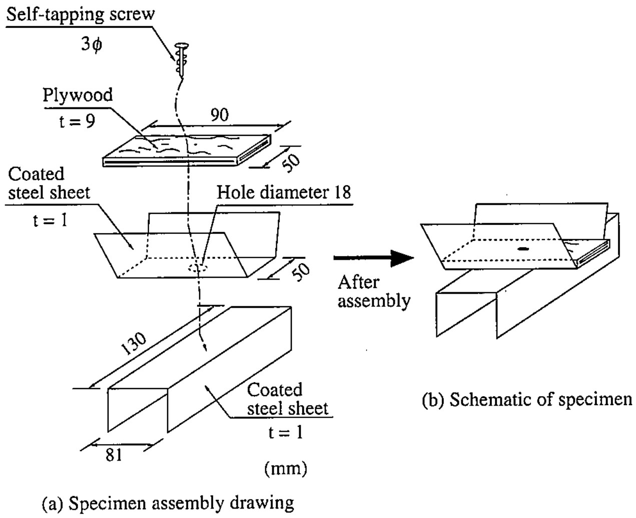


**Fig. 6 Schematic of pull-out strength test specimen**

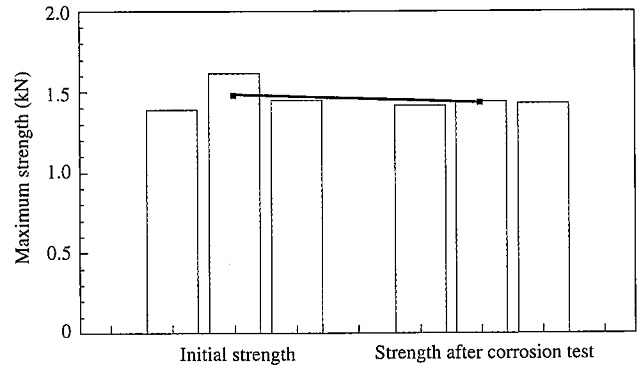


**Fig. 7 Shear strength test results of connections**

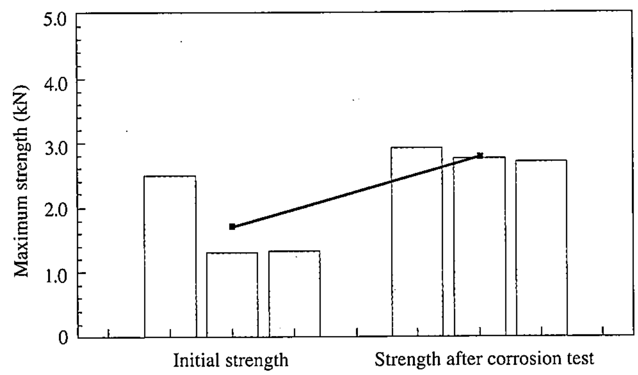


**Fig. 8 Shear strength test results of connections**

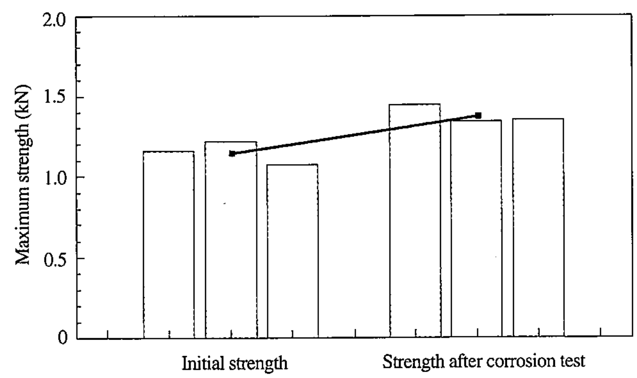


**Fig. 9 Pull-out strength test results of connections**

steel sheet overlapped and connected with a self-tapping screw, which was driven from the plywood side in the same way as for the shear strength test specimen. Between the structural plywood and the coated steel sheet was inserted a coated steel sheet bent to lift the plywood during the pull-out test. The bent coated steel sheet had an 18-mm hole drilled at the center of the connection to have no effect on the pull-out strength.

The conditions of the CCT[11] used to evaluate the durability of the specimens are shown in **Table 4**. The CCT shown in **Table 4** is a kind of CCT simulating an outdoor environment and consists of three cycles per day of salt spraying, drying and wetting. Corrosion resistance evaluation specimens were placed with the coated steel sheet surface (screw tip side) tilted at 20° with respect to the vertical line, so that the coated steel sheet was exposed to the salt spray during the cyclic corrosion test. The CCT was carried out for 60 cycles. After the corrosion test, each specimen was tested for strength and was also cross-sectionally observed to investigate the corrosion condition of the self-tapping screw connection.

The maximum shear strength of the specimens per self-tapping screw and the stiffness of the specimens in the shear strength test are shown in **Figs. 7** and **8**, respectively. The maximum pull-out strength of the specimens in the pull-out strength test is shown in **Fig. 9**. The stiffness of the specimens in the shear strength test is defined as the secant stiffness at the point where a 0.5-kN force was applied to a self-tapping screw according to the relationship between the load per self-tapping screw and the displacement shown in **Fig. 10**. The respective values did not appreciably change before and after the corrosion test.

**Table 4 Conditions of cyclic corrosion test[11]**

| | |
|---|---|
| Salt spraying (5%NaCl, 35°C, 2 h) ⇒ Drying (60°C, 30%RH, 4 h) ⇒ Wetting (50°C, 98%RH, 2 h) ⇒ | 8 h/cycle |

In this experiment, the maximum strength was used to compare the shear strength. The allowable strength of a wall in an actual steel-framed house depends on the performance of the entire wall, so that the allowable strength per self-tapping screw is not clear. Based on an analysis conducted elsewhere by the authors, the slip displacement at the screw connections in the bearing walls is estimated around 0.5 mm when the walls are at the allowable strength. From this information and **Fig. 10**, the shear force acting on the screw

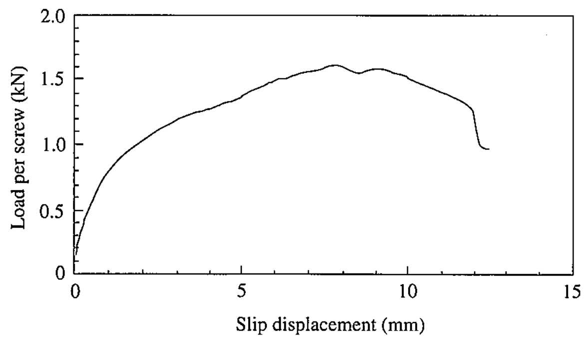


**Fig. 10 Relationship between load and displacement in shear test**

connection is much smaller than its ultimate strength and about 1/2.5 of the strength when the walls are at the allowable strength. This suggests that the effect of corrosion is fairly small on the strength of the bearing walls in steel-framed houses.

The specimens after 60 CCT cycles had red rust formed on the entire self-tapping screw surfaces. The coated steel sheet was covered with white rust, red rust was formed in some positions, and the coating was almost entirely lost. At the beginning and after 60 CCT cycles, the bearing failure of the plywood occurred with increasing load in the shear strength test, and was followed by the gradual inclination of the self-tapping screws. In the pull-out strength test, the bearing failure of the plywood developed with increasing load and was followed by the pull-out failure of the self-tapping screws.

**Fig. 11** shows the cross-sectional observation of a self-tapping screw connection between plywood and coated steel sheet. The area enclosed with the white line in **Fig. 11** was examined by an X-ray microanalyzer (CMA). The CMA results are shown in **Fig. 12.** For both the coated steel sheet and self-tapping screw, the corrosion of zinc was predominant, and little corrosion of the base steel was observed. It is thus presumed that the joint strength between the coated steel sheet and the self-tapping screws is not changed before and after the corrosion test.

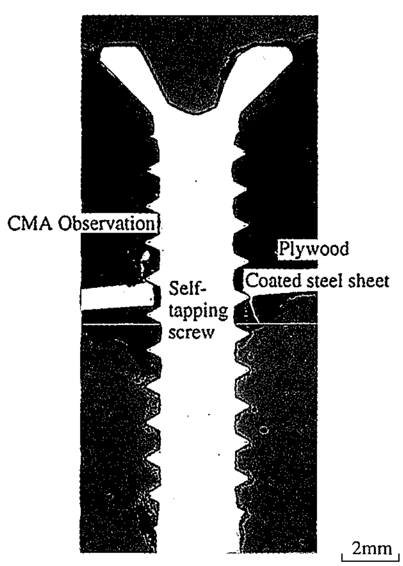


**Fig. 11 Cross-sectional photograph of self-tapping screw connection (after 60 JASOM609 cycles)**

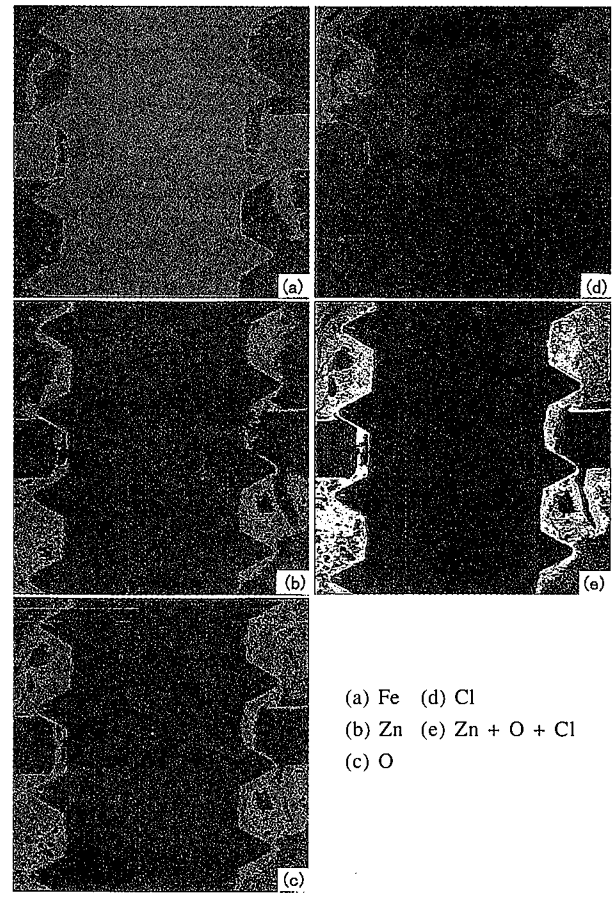


**Fig. 12 CMA observation results of cross section of self-tapping screw connection (after 60 JASOM609 cycles)**

The above-mentioned results show that the bearing failure of the plywood is a predominant failure mode in both the initial condition and the corroded condition where the coated steel sheet is presumed to be at the end of its life with the coating consumed. Both the shear strength and the pull-out strength are thus considered to have remained almost the same before and after the corrosion.

### 3.3 Adhesion between coated steel sheet and wooden material

Prefabricated parts call for coated steel sheets and various boards (wooden materials) to be properly connected by using self-tapping screws and adhesives. The durability of self-tapping screw connections is fully maintained to the end of life of coated steel sheets as discussed in the preceding chapter. Few studies are reported about the adhesion between coated steel sheets and wooden materials. The adhesion between coated steel sheets and wooden materials was studied by using general panel adhesives.

Hot-dip galvanized steel sheets (Z27), Zn-5%Al alloy-coated steel sheets (Y18), and 55%Al-Zn alloy-coated steel sheets (AZ150) were used as coated steel sheets. Each measured 0.8 mm in thickness. Plywood (5 mm thick), Douglas fir (5 mm thick), particle board (20 mm thick), and plasterboard (12 mm thick) were used as wooden materials. A two-part epoxy adhesive and a one-part urethane adhesive were used as adhesives. Each is used for the adhesive joining of panels in houses.

The tensile shear test based on the bond strength specified for wall boards in JIS A1613 was conducted as adhesion test. The repeated boiling test specified in JIS K6852 and the salt spray test specified in JIS Z2371 were performed as adhesive connection durability tests. The failure of specimens was classified into the following six modes. WB: failure in the wooden material, SB: failure in the coated steel sheet, WAF: interfacial separation of the wooden material, SAF: interfacial separation of the steel sheet due to a cause other than corrosion, COR: failure of the steel sheet due to corrosion, and CF: cohesive failure of the adhesive.

The adhesion in the initial condition and after the repeated boiling test did not differ among the types of coated steel sheets tested. Taking the hot-dip galvanized steel sheet as an example, the test results with the epoxy adhesive and the urethane adhesive are shown in **Figs. 13** and **14**, respectively. The failure modes of the specimens were the cohesive failure of the adhesive (CF) and the failure of the wooden material (WB). Each specimen did not have interfacial separation of the coated steel sheet. It was thus found that the coated steel sheet and the wooden material can be properly connected by a general panel adhesive.

As examples for wooden material and adhesive, Douglas fir, which is the strongest of the wood materials, and epoxy adhesive, which has a high cohesive force, were used. The change with time in shear stress and the failure modes after the salt spray test are shown in **Figs. 15** to **18**. Each coated steel sheet decreased in the shear stress in proportion to the duration of the salt spray test. The failure mode was initially the cohesive failure of the adhesive. The entry of water increased the interfacial separation of the Douglas fir, and the failure resulting from corrosion of the coated steel sheet beneath the adhesive increased in frequency. The difference in the drop of strength between the coating types corresponded to the difference in the progress of corrosion at the interface between the

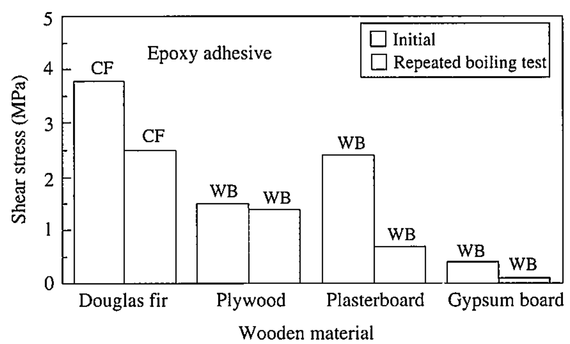


**Fig. 13 Adhesion between hot-dip galvanized steel sheet and wooden material**

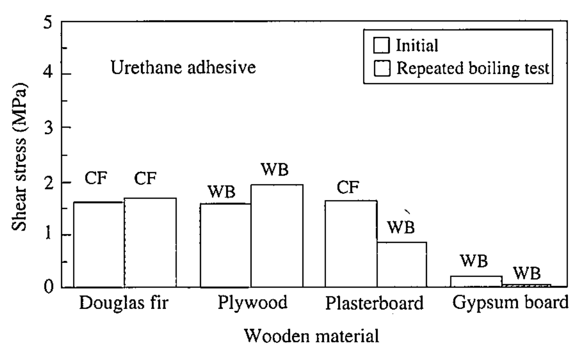


**Fig. 14 Adhesion between hot-dip galvanized steel sheet and wooden material**

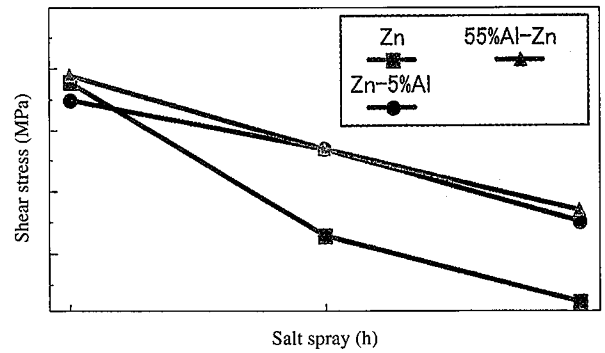


**Fig. 15 Adhesion between coated steel sheet and Douglas fir after salt spray test (epoxy adhesive)**

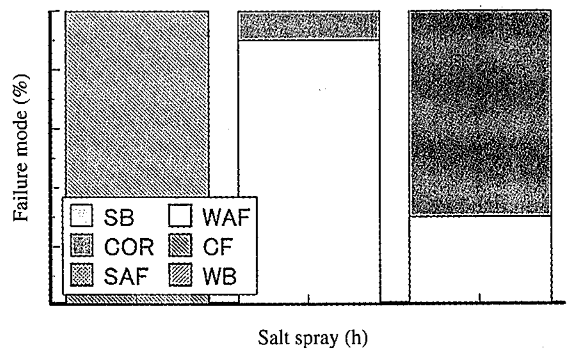


**Fig. 16 Failure modes of adhesion test specimens (hot-dip galvanized steel sheet/Douglas fir)**

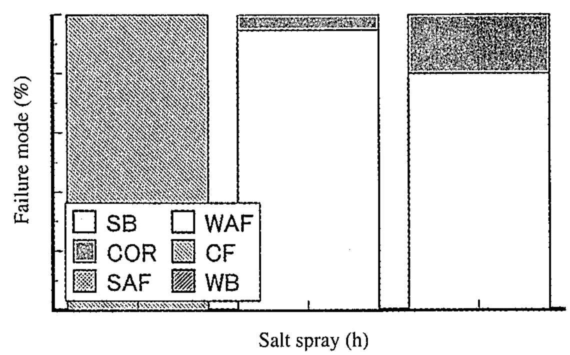


**Fig. 17 Failure modes of adhesion test specimens (Zn-5%Al alloy-coated steel sheet/Douglas fir)**

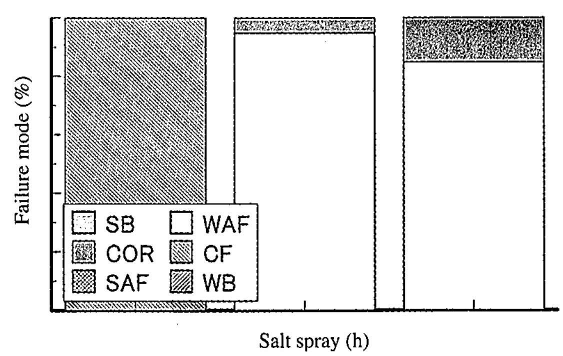


**Fig. 18 Failure modes of adhesion test specimens (55%Al-Zn alloy-coated steel sheet/Douglas fir)**

adhesive and the coating. For 240 hours or more of the salt spray test, the highly-corrosion resistant 55%Al-Zn alloy-coated steel sheet and Zn-5%Al alloy-coated steel sheet retained high shear stresses. These tendencies did not substantially change when the urethane adhesive was used and when any other wooden material was used. As described in Chapter 2, the actual steel-framed house is a far milder corrosion environment than the salt spray environment. The adhesive connection durability of the hot-dip galvanized steel sheet is at a practically satisfactory level.

It is confirmed that the coated steel sheets for steel-framed houses and wooden materials are adequately bonded with common adhesives for panels, and that the Zn-5%Al alloy-coated steel sheet and the 55%Al-Zn alloy-coated steel sheet are excellent in terms of adhesive connection durability under the salt spray condition. Thermal cycling test, indoor exposure test, and outdoor exposure test are under way as additional adhesive connection durability tests. The results of these tests will be reported on another occasion.

## 4. Conclusions

Nippon Steel has been measuring the environments of steel-framed houses, performing the exposure test of materials in steel-framed houses, and investigating the durability of connections made by joining methods applicable to steel-framed houses. The results obtained to date may be summarized as follows:

(1) The corrosion environment measurement results of monitor houses with ACM sensors show that the steel-framed house constitutes a mild corrosion environment where the corrosion rate of various zinc-coated steel sheets is fully low.

(2) When connections were made by clinching and one-side riveting and tested for durability, the specimens that were degraded to such a degree as to have rust formed throughout the coated steel sheet surface did not decline in maximum shear strength. This means that the durability of these connections is retained until the end of life of the coated steel sheet, like self-tapping screw connections.

(3) The connections between steel shapes and structural plywood did not appreciably deteriorate in shear strength and pull-out strength, even in the corroded condition in which the coated steel sheet is presumed to have reached the end of life with the coating lost. This means that the durability of these connections is retained until the end of life of the coated steel sheet.

(4) The coated steel sheets and wooden materials used in steel-framed houses can be properly connected with general panel adhesives. The Zn-5%Al alloy-coated steel sheet and the 55%Al-Zn alloy-coated steel sheet are excellent in terms of the durability of adhesive connections.

### References


1) Sakumoto, Y.: The Journal of the Surface Finishing Society of Japan. 45, 859 (1997)
2) Nakamura, K., Nomura, H., Yamamoto, S., Matsumoto, M., Tsujikawa, S.: Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan. 22211, 1996, p. 421
3) Yamamoto, S., Matsumoto, M., Nakamura, K., Nomura, H., Tsujikawa, S.: Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan. 22211, 1996, p. 423
4) Sakumoto, Y.: Zairyo-to-Kankyo. 46, 274 (1997)
5) Goto, H.: Lead and Zinc. 27, 23 (1990)
6) Nagai, T., Udo, Y., Henmi, Z.: Journal of the Japan Institute of Metals. 49, 860 (1975)
7) Tsujikawa, S.: The Iron and Steel Institute of Japan forum, 9452, 1997, p. 1
8) Motoda, S., Suzuki, Y., Shinohara, T., Kojima, Y., Tsujikawa, S., Oshikawa, W., Itomura, S., Fukushima, T., Izumo, S.: Zairyo-to-Kankyo. 43, 550 (1994)
9) Matsumoto, M.: Japan Society of Corrosion Engineering Symposium, 111, 1996, p. 26
10) Working Group on Durability, Committee on Steel-Framed Houses, the Kozai Club: Research and Discussion on Coated Steel Sheets Durability in Steel-Framed Houses. p. 42
11) JASO Technical Paper TP-91001