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Durability of 11%Cr Stainless Steel "JFE410DH" for Building Structure Use[†]

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Abstract:

The durability of 11% Cr stainless steel "JFE410DH" has been investigated by exposure tests and accelerated tests for structural materials of steel structural houses. As the type of corrosion about stainless steel is localized corrosion (pitting), the end of lifetime is defined as the point when the maximum pit depth reaches 10% of the thickness. Because the base steel has good anti-corrosion property, the lifetime of JFE410DH (2.3 mmt) is estimated at more than 100 years without coating or painting in the indoor environment. The cut edge or the weld is free from repair and maintenance. JFE410DH is approved as structural materials for long life dwelling houses by the Minister of Land, Infrastructure and Transport, therefore JFE410DH is expected to be used for long life dwelling houses.

1. Introduction

Before 1993, stainless steel was not approved under the Building Standard Law of Japan. As a result, the main applications of stainless steel as a building material were in interior/exterior materials, panels, and roofing, and there were few examples of use as a structural material. On September 30, 1994, "stainless building structures" received general certification based on the standard in Article 38 of the Building Standard Law. Subsequently, in June 2000, the Building Standard Law and its Enforcement Order were revised, and stainless steel was introduced in the Enforcement Order as a structural material[1)]. JIS G 4321 (2000), "Stainless steel for building structure," provides for four types of austenitic stainless steel (SUS304A, SUS304N2A, SUS316A, SCS13AA-CF).

JFE Steel undertook the development of chromium stainless steel structural materials, and received certification for JFE410DH (former name: R410DH, 11%Cr steel)[2)] under Article 37 (certification of structural materials) of the Building Standard Law in January 2002. Because its mechanical properties are on the same level as SN400 rolled steel material for general building structures (JIS G 3136), structural design is possible in the same manner as with the general steel materials used conventionally in steel frame buildings.

In 2000, the "Housing Quality Assurance Act" came into effect with the aims of securing quality in housing and protecting the interests of housing purchasers and others, and the "Housing Performance Indication System" was established. The Housing Performance Indication System and the Japan Housing Performance Indication Standards[3)] include a "grade of countermeasure regarding deterioration (structural material)" as an evaluation of countermeasures for reducing deterioration of materials. Performance grade 3, which is the highest rank, means that materials conform to the requirements of housing with a long-life, 100 year life expectancy. Under this standard, the period until housing reaches the limit of its useful life spans 3 generations (75–90 years). Conventionally, under the standard for grade 3 in steel structural houses, corrosion prevention which combines a painting specification of the necessary standard and coating or plating of the steel material was necessary

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for each thickness of steel material. Repair treatment of welds and cut edges is also necessary.

If JFE410DH is used as a structural material for long-life, 100 year housing, the authors believed that painting and other corrosion prevention measures could be omitted because the material itself possesses satisfactory corrosion resistance. This paper describes the results of an investigation of the durability of JFE410DH in atmospheric exposure tests and accelerated tests, prediction of its service life in housing environments, and judgment of its suitability as a structural material for 100 year housing.

2. Experimental Method

2.1 Exposure Tests

2.1.1 Test specimens

The test materials used were JFE410DH and a comparison steel, SUH409L. The chemical compositions of the specimens are shown in **Table 1**. The shape and dimensions of the specimens, test periods, and number of pieces tested were as follows.

(1) Flat plate, 50 mm × 150 mm, 3 years and 4years, 1 piece
(2) Flat plate, 50 mm × 100 mm, 1 years, 1 piece

2.1.2 Exposure conditions

Exposure tests were conducted at the following two locations, which have different environments.

Exposure site A: Kawasaki-cho, Chuo-ku, Chiba City, Chiba Pref. (1 km from coast);
The amount of airborne sea salt particle:
0.2 mg · dm^{-2} · day^{-1}
Exposure site B: Nii Hama-cho, Chuo-ku, Chiba City, Chiba Pref. (10 m from coast);
The amount of airborne sea salt particle:
0.4 mg · dm^{-2} · day^{-1}

The 3 and 4 year test periods were begun in May 2000, and the 1 year test, in October 2001. The tests were conducted with the test specimens facing south and inclined 30° from the horizontal.

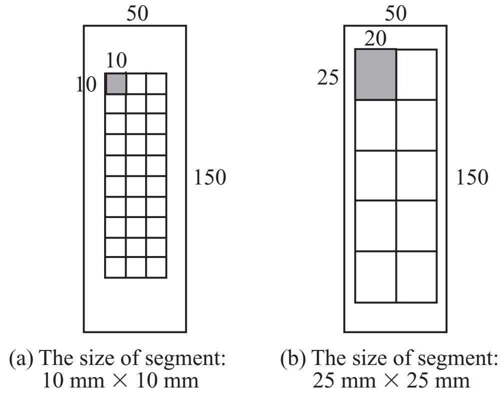
2.1.3 Evaluation items

After exposure, the corrosion product was removed by immersing the specimens in a 10–20% aqueous solution of diammonium hydrogen citrate at 70°C, followed by washing with water (brushing). The maximum pit depth (maximum penetration depth) was then measured. As shown in **Fig. 1**, with the 4 year test specimens, cutting was performed in two ways, either by dividing the central area of the specimen into 30 segments with a size of 10 mm × 10 mm (1 cm^2) or 10 segments with a size of 20 mm × 25 mm (5 cm^2). The maximum pit depth in each segment was measured with a microscope (confocal laser scanning microscope 1LM21W; manufactured by Lasertec Corp.). The maximum pit depth in each segment was arranged by Gumbel distribution4), and the maximum pit depth with a possibility of occurrence in a 150 cm^2 specimen was estimated, assuming a return period of 150 for the 1 cm^2 segments and 30 for the 5 cm^2 segments. This value was defined as the maximum pit depth. In these calculations, the extreme value analysis program EVAN-II of the Japan Society of Corrosion Engineering (editor) was used. With the specimens for the 3 year test, 15–18 segments (10 mm × 10 mm) were cut, and measurements and arrangement of the data were performed in the same manner to obtain the maximum pit depth with a possibility of occurrence in a 150 cm^2 specimen. With the 1 year test specimens, 28 segments (10 mm × 10 mm) were cut from the center of the test sample, and measurements and arrangement of the data were performed in the same manner to obtain the maximum pit depth possible in a 150 cm^2 specimen.

Table 1 Chemical compositions of the specimens

(mass%)

Type	C	Si	Mn	Cr	N	Others
JFE410DH	0.01	0.2	1.5	10.9	0.01	Cu: 0.3
SUH409L	0.01	0.2	0.3	10.9	0.01	Ti: 0.2



(a) The size of segment: 10 mm × 10 mm (b) The size of segment: 25 mm × 25 mm

(unit: mm)

Fig. 1 Schematic diagrams of specimens and segmentations for measuring pit depth

2.2 Evaluation of Initial Rust Resistance of Cut Edge

2.2.1 Test specimens

As test materials, JFE410DH, a hot-dip zinc-coated steel sheet (Z27), and a carbon steel sheet (SS400) were used. The sheet thickness was 2.3 mm in all cases. The specimens were sheared to 60 mm × 150 mm so as to form a downward burr.

2.2.2 Exposure conditions

Exposure tests were conducted at exposure site C (Kawasaki-cho, Chuo-ku, Chiba, Chiba Pref.; 1km from coast) outdoor and indoors (simulating a residential environment). The amount of airborne sea salt particles was 0.2 mg · dm^{-2} · day^{-1} in the outdoor environment and 0.003 mg · dm^{-2} · day^{-1} in the indoor environment.

2.2.3 Evaluation items

Evaluations were conducted by visual inspection of rust development on the specimen surface and cut edges.

2.3 Evaluation of Durability of Weld

2.3.1 Test specimens

Two specimens containing butt-welded joints were prepared by semi-automatic metal active gas arc welding. The specimen dimensions were 60 mm × 180 mm. Welding was performed using a Y309L wire (0.03mass%C-23mass%Cr-14mass%Ni) and CO_2 shielding gas. An accelerated corrosion test was performed with one specimen in the as-welded condition, and with the other, after removing the temper color and spatter adhering to the welding zone with a wire brush.

2.3.2 Conditions of accelerated test

A cyclic corrosion test was performed, in which 1 cycle consisted of (1) spray (artificial seawater, 35°C, 4 h), (2) drying (60°C, 2 h), and (3) wetting (50°C, 95%RH, 2h). The test was conducted up to 20 cycles. Specimens were held in the test chamber so that the weld bead was perpendicular, and the entire specimen was placed at 20° to the vertical.

2.3.3 Evaluation items

After the accelerated test, the corrosion product was removed, and the specimens were cut into segments as shown in **Fig. 2**. The maximum pit depth was then measured in each segment.

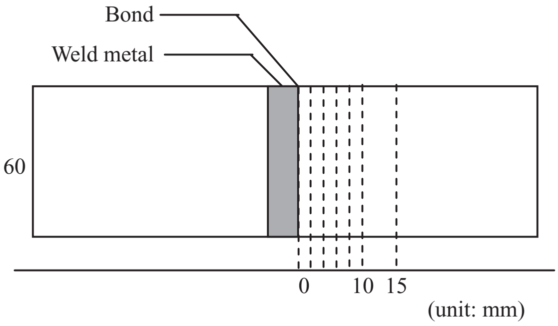


Fig. 2 Schematic diagrams of welded specimens and segmentations for measuring pit depth

3. Results

3.1 Durability of Base Material

The cross section of JFE410DH after exposure for 3 years is shown in **Photo 1**. Pitting corrosion can be observed, and it can be understood that the corrosion type is local corrosion.

The maximum pit depth after the exposure test is shown in **Table 2**. The maximum pit depth of JFE410DH after exposure for 4 years was 53.6 μm at location A and 220.9 μm at location B. The maximum pit depth of SUH409L, which is also an 11% Cr steel, was on the same order as in JFE410DH. With JFE410DH, the relationship between the maximum pit depth D (μm) and test duration t (years) is approximated by $D = A \cdot t^n$ (here, A is a constant, and $n = 0.6$) and is shown in **Fig. 3** (details are discussed in chapter 4).

3.2 Initial Rust Resistance of Cut Edge

The surface appearance of the cut edges of the various specimens after exposure is shown in **Photo 2**. With JFE410DH, after outdoor exposure for 1 week, virtually no development of rust could be observed on either the surface or the cut edge. With Z27, red rust could be observed on part of the cut edge, and with SS400, red rust was observed on both the surface and the cut edge. In indoor exposure for 1 month, no rust was observed on JFE410DH, either on the surface or at the cut edge, whereas Z27 showed red rust on the cut edge and SS400 showed red rust on both the surface and the cut edge. With SS400, rust development at the cut edge after indoor exposure for 1 month was on the same level as after outdoor exposure for 1 week. However, with Z27, rust development in indoor exposure was remarkable. This is considered to be due to the fact that sacrificial protection by zinc did not function to the edge because the effect of rainfall was slight and wet time was short.

The test results described above demonstrated that the initial rust resistance of cut edge of JFE410DH is

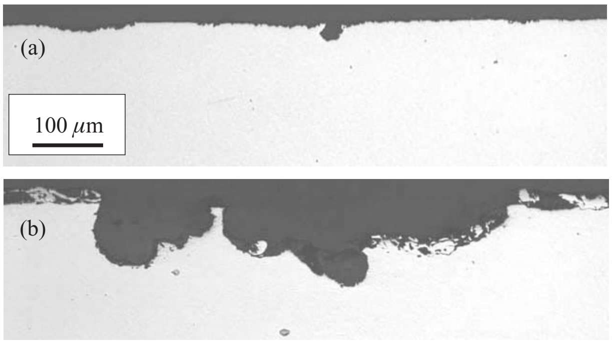


Photo 1 Cross section of JFE410DH after exposure for 3 years at (a) location A, (b) location B

Table 2 Maximum pit depth after the exposure test

(μm)

Location	Specimen	Test duration (year)			
		1*	3*	4*	4**
A	JFE410DH	44.2	52.5	53.6	45.0
	SUH409L	—	55.9	72.9	71.8
B	JFE410DH	150.6	175.5	220.9	224.7
	SUH409L	—	165.7	163.8	162.6

*Size of segment: 10 mm × 10 mm
**Size of segment: 20 mm × 25 mm

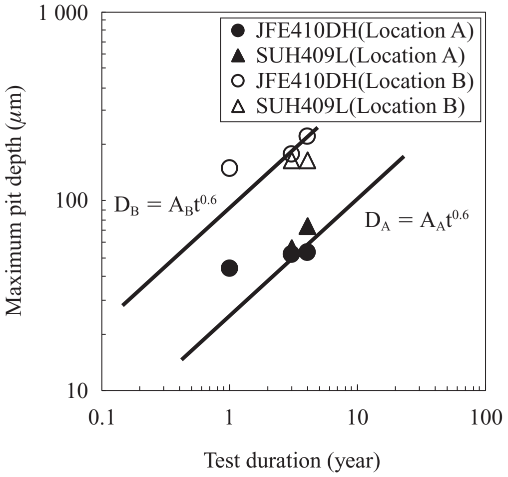
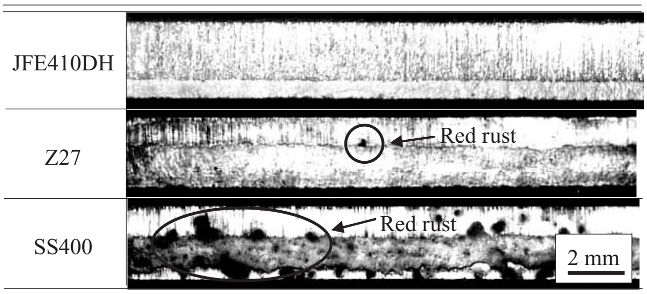
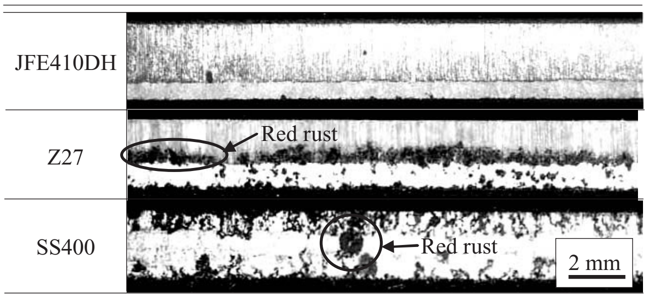


Fig. 3 Maximum pit depth after the exposure test



(a) Out door for a week



(b) In door for a week

JFE410DH: 11%Cr stainless steel
Z27: Hot-dip zinc-coated steel sheet
SS400: Carbon steel sheet

Photo 2 Surface appearance of the cut edges after exposure

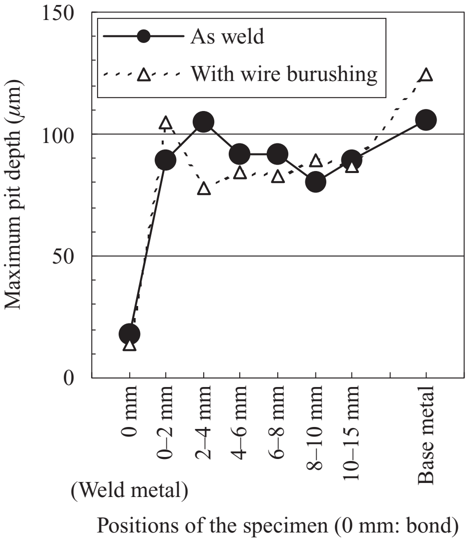


Fig. 4 Maximum pit depth of the weld specimens after the accelerated test

superior to that of zinc-coated steel.

3.3 Durability of Weld

The maximum pit depth of the weld specimens after the accelerated test is shown in **Fig. 4**. Irrespective of whether conditioning (removal of spatter and temper color) with a wire brush was performed or not, progress of corrosion in the vicinity of the weld was not observed. From this, the durability of welds of JFE410DH is considered to be equal to that of the base metal.

4. Discussion

4.1 Life Evaluation Equation

Based on the results of a 10 year exposure test of various types of stainless steel (SUS316, SUS304, SUS434, SUS430, SUS410), Yoshii et al.[5)] reported that corrosion (pit depth, corrosion loss) of stainless steel progresses in proportionate to the mth power of exposure duration, as shown by the following equation:

$$h = a \cdot t^{1/m} \tag{1}$$

where h is the degree of corrosion (pit depth, corrosion loss), t is time (elapsed years), and m and a are constants.

Similarly, Muto et al.[6)] reported that the pitting corrosion behavior of stainless steels (Type 409, Type 430, Type 304, etc.) in atmospheric environments shows the following relationship between maximum pit depth D (μm) and test time t (years):

$$D = A \cdot t^{n} \tag{2}$$

where D is maximum pit depth (μm), t is test time (y), A

is a constant (μm), and depends on chemical composition and the environment, *n* is a constant and depends on the environment.

In the present report, Eq. (2) is applied as a life evaluation equation for JFE410DH.

4.2 Evaluation of Life of JFE410DH in Residential Environments

4.2.1 *n* value and *A* value

In the following, the useful life of JFE410DH (thickness: 2.3 mm) in residential (indoor) environments will be calculated.

The limit condition (end-of-life) of general steel materials is defined as a condition in which 10% of the material thickness has been lost to corrosion[3]. In the case of stainless steel, which is characterized by local corrosion (pitting), end-of-life is defined as a condition in which the maximum pit depth is 10% of the material thickness. This means that end-of-life for a member (open section shape) with a thickness of 2.3 mm is a condition in which the maximum pit depth has reached 115 μm. If the values of *A* and *n* in Eq. (2) are known, it is possible to obtain the duration *t* (y) until the maximum pit depth reaches 115 μm, in other words, the service life of the material. If the value of *A* is considered to be a function *A* (*T*) of the exposure duration *T* (y) obtained from the exposure data (maximum pit depth) for a duration of *T*, from Eq. (2):

$$A\ (T) = D / T^{n} \quad \cdots\cdots (3)$$

where *D* is the maximum pit depth for exposure duration *T*, and n is a constant. As values of n for 11% Cr steel, Muto et al.[6] reported 0.57 (severe marine environments) and 0.21 (industrial environments), and a value of 0.51 (severe marine environments)[7], which was calculated from weight loss average penetration depth data present by Schmitt et al.[8], has also been reported, among others. In the present report, a value of 0.6[7] is used, as the possibility of adaptation to a wide range of environments from coastal to rural districts has been shown.

Table 2 shows *A* (*T*) obtained from the maximum pit depth at various test times *T* at exposure sites *A* and *B*. (For example, *A* (*T*) obtained from the data for a 4 year exposure test at location A is $53.6/4^{0.6} = 23.3$.)

4.2.2 Deterioration environment (Amount of deposited sea salt)

Deterioration due to corrosion of stainless steel occurs more easily as the amount of deposited sea salt increases. Therefore, in this research, the deterioration environment was defined not by the amount of airborne sea salt particles, but by the amount of deposited sea salt.

Oshikawa et al.[9] reported that the maximum amount of deposited sea salt indoors in steel-structural prefabricated housing located in Nogi-cho, Tochigi Pref. is on the order of 1×10^{-3}g/m^2. Similarly, Matsumoto et al.[10] reported that the maximum amount of deposited sea salt indoors in steel-framed housing in Hachioji City, Tokyo and Kukino Village, Aso-gun, Kumamoto Pref. is approximately 1×10^{-3}g/m^2. Referring to the above-mentioned data in the literature, the upper limit of deposited sea salt in residential environments was set at 3×10^{-3}g/m^2 in order to secure a safety factor, and an environment in which the amount of deposited sea salt is 3×10^{-3}g/m^2 or less was assumed as a precondition.

4.2.3 Life evaluation (Estimation of useful service life)

Using the exposure data, a life evaluation was made as follows.

The environmental data from the exposure test shown in section 3.1 are for airborne sea salt particles (airborne sea salt). Therefore, using the relational equations for the amount of deposited sea salt W_s (g · m^{-2}) and airborne sea salt F_s (mdd: mg · dm^{-2} · day^{-1}) proposed by Shinohara et al.[11], as shown below, the airborne sea salt was converted to deposited sea salt. The results are shown in **Table 3**.

$$\log W_s\ (\mathrm{g \cdot m^{-2}}) = 1.52 \log F_s\ (\mathrm{mdd}) - 0.104 \quad (F_s \geqq 0.2)$$

$$\log W_s\ (\mathrm{g \cdot m^{-2}}) \fallingdotseq 0.346 \log F_s\ (\mathrm{mdd}) - 0.963 \quad (F_s < 0.2)$$

Figure 5 shows the obtained amount of deposited sea salt W_s (g · m^{-2}) on the x-axis, and the coefficient *A* (*T*) shown in Table 3 on the y-axis, plotted on a log scale. Assuming that a linear relationship exists between the log of the amount of deposited sea salt W_s (g · m^{-2}) and that of the coefficient *A* (*T*) (μm), the coefficient *A* in a residential environment (amount of deposited sea salt) is obtained by extrapolation, and the life of the material is estimated. When the coefficient *A* at $W_s = 0.003$ g/m^2 is calculated by extrapolating along a straight line obtained by joining the 1 year data points, which are the maxi-

Table 3 Coefficient, A(T) calculated from exposure test

(μm)

Location	F_s (mdd)	W_s (g/m^2)	Test duration (year)		
			1	3	4
A	0.2	0.07	44.2	27.2	23.3
B	0.4	0.2	150.6	90.8	96.2

F_s: The amount of airborne sea salt
W_s: The amount of deposited sea salt

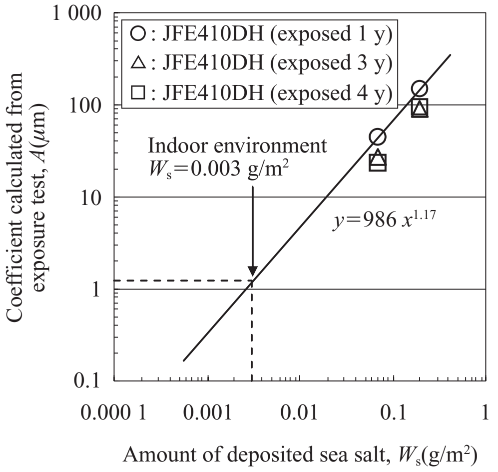


Fig. 5 The relationships of W_s to $A(T)$ on a log scale

mum of the coefficient A (T) at the exposure sites A and B in Fig. 5, the result is A = 1.1 (μm). Accordingly, the service life t (y) of JFE410DH (material with thickness of 2.3 mm or more, open section shape) is obtained as follows.

If Eq. (2) is solved for t,

$$t = (D / A)^{1/n}$$

Substituting the maximum pit depth D = 115 (μm), which is the end-of-life condition, the coefficient A = 1.1 (μm) for residential environments, and the constant n = 0.6,

$$t = (115 / 1.1)^{1/0.6}$$
$$= 2\ 320 \geqq 100$$

From the above, it is considered that the useful life of JFE410DH (material with thickness of 2.3 mm or more) in residential environments exceeds 100 years without surface treatment.

Based on the research results presented above, an application for Approval of Special Evaluation Methods was made to The Building Center of Japan, to the effect that JFE410DH conforms to performance grade 3 (structural materials, etc. for long-life 100 year housing) under the Japan Housing Performance Indication Standards. The content of the tests in the application included:

(1) Outdoor exposure test results and method of estimating long-term life
(2) Effect of finishing and effect of material thickness
(3) Corrosion resistance of welds
(4) Galvanic corrosion resistance

In all cases, there were no problems. Life of more than 100 years was certified, and certification by the Minister of Land, Infrastructure and Transport was obtained, dated June 7, 2005.

5. Conclusions

With the aim of applying 11%Cr stainless steel JFE410DH for building structures to steel structural houses, the durability of this product was evaluated in atmospheric exposure tests and accelerated tests. The following conclusions were obtained.

(1) Because JFE410DH possesses excellent corrosion resistance, the useful service life of members with a thickness of 2.3 mm or more in residential environments exceeds 100 years, even without surface treatment such as zinc coating or painting.
(2) The initial rust resistance of cut edge of JFE410DH is superior to that of zinc coated steels.
(3) Because welds possess the same level of corrosion resistance as the base metal in the as-welded condition, repair treatment of welds is not necessary.
(4) Certification that JFE410DH conforms to requirements for structural materials for long-life 100 year housing (performance grade 3 under the Japan Housing Performance Indication Standards) was received from the Minister of Land, Infrastructure and Transport. In the future, use in long-life housing applications is expected.

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