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Performance of “JFE FRAME KIT”†

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Abstract:

“JFE FRAME KIT” is the structural system which includes structure design and building materials for the high-performance housing. This article explains the outline of structural performance such as strength, stiffness and deformation capacity, that are evaluated through the full scale loading test of braced panel fire-resistant structure, insulation specifications and the result of measurement of the model house of recommended insulation specifications are discussed along with structural performance.

Photo 1 “JFE FRAME KIT”

1. Introduction

A series of major earthquakes exceeding 7 on the seismic intensity scale have struck Japan in recent years, including the Hyogo Nanbu Earthquake (1995) and Niigata Chuetsu Earthquake (2004), and massive Tokai and Nankai earthquakes may occur in the future. Due to heightened anxiety regarding these natural disasters, interest in the seismic performance of housing is also high. Therefore, JFE Steel developed “JFE FRAME KIT” (**Photo 1**) as structural steel materials for low-rise buildings such as housing, offices, stores, and other structures of 3 stories or less. The advantages of this product include high durability (long life) and excellent seismic performance.

This paper presents an evaluation of the rigidity, strength, and deformation performance of “JFE FRAME KIT” based on a structural loading test of braced panels, an outline of its fire-resistance structure, and an outline of its heat insulation/anti-sweat specifications and the results of performance verification with a model house of the recommended heat insulation specifications.

2. Features

“JFE FRAME KIT” uses steel materials in the construction system members in the frame construction (skeleton system) method, combining the freedom of floor-plan design of frame construction and the reliability of steel frame construction. Because all members used are manufactured from hot dip zinc coated steel sheets, high durability is secured. All connections, including the columns and beams, are bolt connections using metal fittings developed by JFE Steel. Welded joints are frequently used in the connections in general steel frame structures, imposing a heavy load on welding control, but in contrast, no welding processes are used with “JFE FRAME KIT,” in either the steel frame fabrication process or during erection at the site. This is a factor in securing uniform performance of products.

Unlike industrialized housing, “JFE FRAME KIT” is a one-of-a-kind steel construction method. Therefore, structural design drawings and documents are necessary

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when making applications for building construction, and shop drawings are necessary during fabrication of the steel frame. However, all types of data are prepared efficiently by an integrated system which includes the design and fabrication processes, beginning with the proprietary design support program "AI-FRAME" developed by JFE Steel. The fact that the product is supplied as a set, including the structural steel materials, structural calculation documents, structural drawings, etc., is also a major feature of "JFE FRAME KIT."

3. Structural Performance of Braced Panels

3.1 Performance Evaluation Method

In "JFE FRAME KIT," seismic loads, wind loads, and other horizontal loads are all borne by braced panel load-bearing walls, which comprise vertical braces, the columns on the two sides, and the upper and lower beams. Structural safety technical appraisals of braced panels including connections were carried out using full-scale models in accordance with the Building Letter "Technical Regulations for Structural Strength Performance of Low-Rise Steel Frame Structures"[1) issued by the Building Center of Japan, and "Documents of Performance Evaluations for Approvals under Article 1.3.1 of the Enforcement Regulations of the Building Standard Law (Steel Frame Buildings and their Parts)[2)]. A test specimen and the loading apparatus are shown in **Fig. 1**. The experimental parameters were the brace diameter, beam connection method, sheet thickness of the columns, and sizes of the upper and lower beams. As loading conditions, after cyclic loading comprising story drift ±1/200 rad × 1 time, ±1/100rad × 2 times, and ±1/50 rad × 1 time, loading was applied up to 1/12.5 rad and the fact that there was no failure of the bolted connections or excessive local deformation was confirmed.

3.2 Outline of Results of Performance Evaluation

Figure 2 shows the load-deflection curve (hysteresis loop) for a continuous beam model and a segmented beam model of standard test specimens (brace M20, column sheet thickness; 3.2, upper beam: BH-250 × 99 × 4.5 × 4.5, lower beam: H-100 × 100 × 6 × 8). All specimens showed stable hysteresis characteristics of the slip type due to yielding of the brace, which is a characteristic of tension braces.

Figure 3 shows the rigidity, allowable strength, strength, and Ds-value (structural characteristic coefficient) when modeled as an energy equivalent bilinear curve (skeleton curve). The Ds values in the experiments were from 0.29 to 0.33. However, as a design value, a

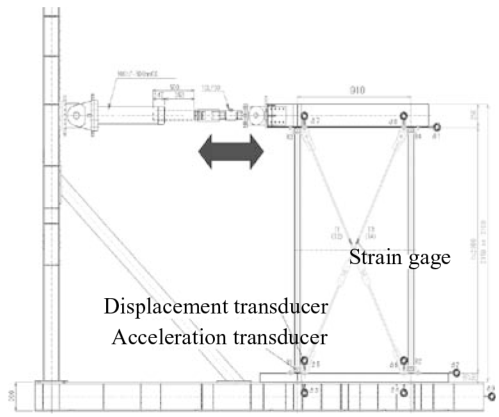


Fig. 1 Apparatus of braced panel test

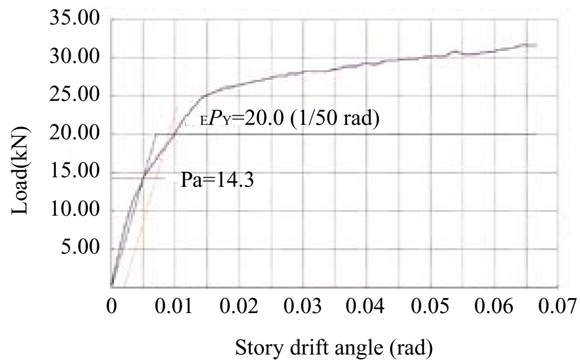
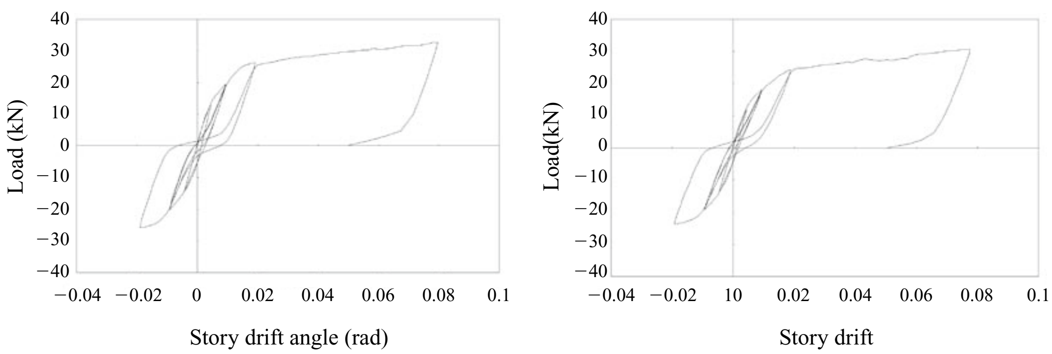


Fig. 3 Skeleton curves of braced panel



Panel-1

Panel-2

Fig. 2 Load-deflection curve

conservative value of 0.35 is adopted in all cases. The fact that the coefficient of damping is on the order of 7% has been confirmed from vibration tests of actual buildings[3).

4. Outline of Fire-Resistance Structure

4.1 Background of Development

In order to expand the applications of "JFE FRAME KIT" to urban housing and 3-story multi-family housing, JFE Steel developed Japan's first membrane fire-resistance structure using ALC 100 mm (ALC: autoclaved light-weight concrete) and other products. Subsequently, the 2 × 4 wood-frame construction industry obtained fire-resistance certification and entered the market for fire resistant buildings. In response to this move, JFE Steel developed a JFE-type fire-resistance structure (membrane fire proof construction bearing wall/composite fire proof construction beam (sprayed fireproof and membrane fireproof)) using ALC 50 mm in order to improve the competitiveness of "JFE FRAME KIT," and obtained the approval of the Minister of Land, Infrastructure and Transport in February 2006. The approval of the membrane fire proof construction bearing wall and composite fire proof construction beam (fire-resistive covering thickness: 25 mm, specific gravity: 0.2) was the first in Japan.

4.2 Outline of Structure

An outline of the fire-resistance structure using ALC50 is shown in **Fig. 4**. This fire-resistance structure has the following three features: (1) reduction of the thickness of the fire-resistive covering (exterior material: ALC, 100 mm→50 mm, interior material: fire-resistant gypsum plaster board, 15 mm × 2→12.5 mm × 2, beam: sprayed slag wool, 30 mm→25 mm· γ0.3→0.2), (2) simple construction method (installation of fire-resistant gypsum plaster board: drilling tapping screws→installation using adhesive in combination with stapler; fire-resistant sealing material is not used), (3) satisfies both room temperature heat insulation and anti-sweat performance requirements (in order to secure anti-sweat performance based on inorganic wall cavity insulation, additional insulation (including organic heat insulation) is applied). Although (1) and (2) reduce the heat insulation property and non-damage ability, and (3) is generally disadvantageous for fire-resistance because the structure contains flammable organic insulation, safety is secured by optimizing the total structure.

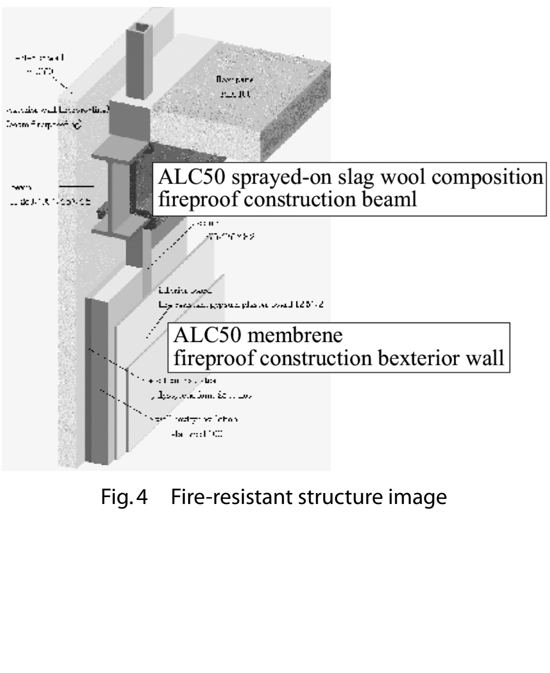


Fig. 4 Fire-resistant structure image

4.3 Specification of ALC50 Membrane Fire-Resistance Exterior Material

A membrane structure is adopted using the exterior material and interior material as a fire-resistive covering, and fire-resistive coverings of the columns and beams are omitted.

The exterior material is ALC 50 mm, and the approved range has been set so that all designs can be adopted, including designs that makers may possibly produce in the future. Both vertical and horizontal installation are possible. The specification does not use fire-resistant sealing material at joints in the ALC.

The interior material is a double layer of fire-resistant gypsum plaster board. The under layer is installed by drilling tapping screws, while the top layer is installed with tapping screws or using a combination of an adhesive (vinyl acetate resin adhesive) and stapling. As the adhesive method, full-surface coating was adopted, and not the general buttering method.

In the wall cavity insulation, slag wool 32K (kg/m^3) or higher was adopted, giving priority to fire-resistance performance. Glass wool and organic heat insulation are not used.

Because it is necessary to secure anti-sweat performance in cold climates, the possible range of additional heat insulation materials includes polystyrene and phenolic resin (phenol-formaldehyde) foam, in addition to slag wool and glass wool. The standard thickness is 25 mm, but because this is not necessary in warmer climates, a specification with no additional insulation is also included in the authorized range.

4.4 Specification of ALC50 · Sprayed Slag Wool Composite Fire Proof Construction Beam

Because residential-type exterior materials have a small clearance with columns and beams and it is not possible to perform fire-resistive covering work on the outdoor side of beams, ALC50 · sprayed slag wool composite fire proof construction beams were adopted.

The exterior material part is common with the outside wall, and fire-resistant sealing material is not used. In consideration of workability, the specification of the sprayed slag wool is set lower than in the existing construction method, at a thickness of 25 mm and density of 0.2. Special reinforcement is not necessary at joints with the sprayed slag wool.

Because beams act as heat bridges, the web part on the outdoor side of the beams is filled with 50 mm of slag wool 32K to prevent condensation on the indoor side under room temperature conditions. As in the exterior walls, combined use with additional insulation is possible. The applicable insulating materials are the same those as for the exterior walls.

4.5 Outline of Fire Resistance Test Results

In the 1 hour fire resistance test (loaded heating) of exterior walls, the main judgment standards are maximum temperature rise at back side: 180°C or less, average: 140°C or less, maximum axial shrinkage: h/100 mm (31.5 mm) or less, maximum axial shrinkage rate: 3h/1000 mm/min (9.45 mm/min) or less (where h: initial height of the test specimen) in a test with a total time of 4 hours, comprising heating for 1 hour and natural cooling for 3 hours. Under the same conditions, the judgment standards for beams are maximum deflection: $L$2/4 000 $d$mm (200.1 mm) or less, and maximum deflection rate: $L$2/9 000 $d$mm/min (11.6 mm/min) or less (where L: beam span, d: beam depth).

The conditions of the specimens after the loaded heating tests are shown in **Photo 2** (exterior bearing wall outside), **Photo 3** (exterior bearing wall inside), and **Photo 4** (composite fire proof construction beam). The tests were conducted by the General Building Research Corporation of Japan.

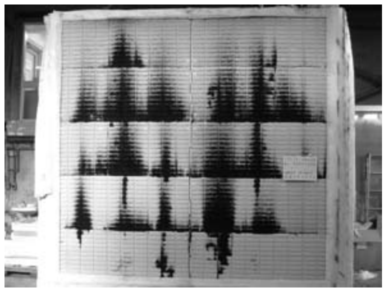


Photo 2 Bering wall specimen (Out-side)

Photo 3 Bering wall specimen (In-side)

Photo 4 Beam specimen

In the exterior wall (outside) test, there were no particularly large changes during heating. After an elapsed time of 5–18 min following the end of heating, fire occurred on the heated side from the joints in the ALC. This fire burned out in about 1 hour. On the back side from the heated surface, no problems were observed with the exception of slight cracking of the material used to finish the joints in the interior gypsum board. Overall, no major damage was observed. The maximum and average temperature rise at the back side were 65°C and 45°C, respectively, maximum axial shrinkage was 0.26 mm, and the maximum axial shrinkage rate was 0.44 mm/min.

In the exterior wall (inside) test, delamination of the gypsum board occurred several minutes before the end of heating. However, the temperature of the steel obtained from measurements of out-of-plane displacement and axial shrinkage was on the order of 360–400°C, indicating that temperature rise was suppressed in comparison with previous experimental results, which showed a steel temperature exceeding 500°C. With the exception of slight cracking around the heads of the tapping screws, which was attributed to thermal expansion of the screws, no problems were noted in the exterior ALC. The maximum and average temperature rise at the back side were 43°C and 34°C, respectively, maximum axial shrinkage was 0.12 mm, and the maximum axial shrinkage rate was 0.36 mm/min.

In the test of the composite fire proof construction beam, no harmful damage of the fire-resistive covering was observed. Maximum deflection was 34.9 mm, and the maximum deflection rate was 1.3 mm/min. As reference values, the measured temperature of the steel was maximum: 446°C and average: 343°C, which were basically in agreement with the results of a prior trial calculation.

5. Outline of Heat Insulation and Anti-Sweat Specification

Where the seismic performance and durability of the steel frame are concerned, "JFE FRAME KIT" amply satisfies the standards of the Japan Housing Finance Agency (formerly known as the Housing Loan Corporation) and the conditions for performance labeling in the Housing Quality Assurance Act. However, considering the fact that energy saving performance cannot be secured by the steel frame itself, and also from the viewpoint of maintaining the durability of the steel materials, appropriate heat insulation/anti-sweat design are necessary. Many of the builders and house makers who are customers for "JFE FRAME KIT" are mainly involved in wood-frame housing construction, and thus lack the requisite know-how for heat insulation design/construction of steel frame buildings, making it extremely difficult for these customers to perform the design work independently. The following describes the basic thinking on heat insulation/anti-sweat specifications for "JFE FRAME KIT," and presents an outline of the results of measurements with a model house.

5.1 Heat Insulation/Anti-Sweat Specifications

The general method of heat insulation in housing is cavity insulation, in which the interior space in the walls is filled with an inorganic fiber heat insulating material, represented by glass wool and slag wool. However, in steel frame buildings, prevention of heat loss due to the heat bridge effect and prevention of condensation, or "anti-sweat" performance are indispensable considerations. From the viewpoint of securing energy saving performance and preventing heat loss, in heat insulation for housing, the recommendations for design and construction prior to the Ministry of Construction's Government Notification No. 998 (Next-Generation Energy Saving Standards) of 1999 presented a specification[4)] requiring heavier heat insulation in general parts in structures containing heat bridges, such as steel frames, considering heat loss from heat bridges. However, the effect of metal heat bridges becomes increasingly pronounced when higher insulation is applied in cavity insulation, and in cases where the thickness of the insulation is simply increased, and depending on the method of additional insulation, this can have the undesirable effect of promoting condensation. Therefore, great care is necessary in selecting the heat insulation specification. To avoid this problem, with "JFE FRAME KIT," the specifications for cavity insulation and outer insulation are determined based on a 2-dimensional heat transfer/moisture permeability simulation, using AMeDAS weather data. However, because outer insulation is desirable in steel frame buildings from the viewpoint of heat insulation and anti-sweat performance, an outer insulation/ventilation method of construction using a plastic-based heat insulating material has been established as the recommended heat insulation specification for "JFE FRAME KIT." In this connection, because it is generally difficult to designate the structural heat bridges in steel frame buildings, the heat insulation standards in the above-mentioned recommendations for design and construction in the Ministry of Construction's Energy Saving Notification of 1999 provide only a method of outside insulation, and do not specify methods of cavity insulation[5)].

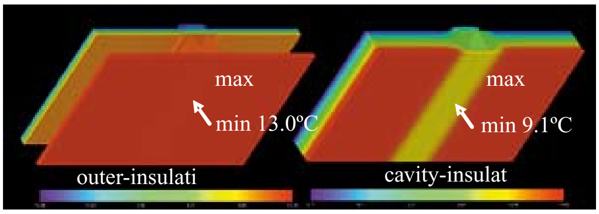


Fig. 5 Result of 3D heat transfer simulation

In order to compare cavity insulation and outside insulation, a 3-dimensional heat transfer simulation was performed assuming an outside air temperature of −4.7°C (minimum value for region IV; Moka City, Ibaraki Prefecture), and indoor conditions of 15.0°C and 70% relative humidity (indoor dew point temperature: 9.6°C). The results are shown in **Fig. 5**. Here, the thermal resistance of the cavity insulation material was set at 1.88 m^2K/W, which is more than 2 times that of the outside insulation (0.89 m^2K/W). However, due to the effect of the heat bridge, the coefficient of heat transmission of the cavity insulation, at 0.89 W/m^2K, is greater than the 0.80 W/m^2K of the outside insulation. As a result of the remarkable decrease in cavity insulation performance at the heat bridge, the indoor surface temperature falls below the dew point temperature, which means that condensation occurs on the indoor surface. However, with outside insulation, there is virtually no heat bridge effect, and consequently, the indoor surface temperature is approximately uniform.

5.2 Verification with Model House Using Recommended Heat Insulation Specification

In order to prevent condensation due to heat bridges, in addition to outside insulation, a foundation insulation method of construction is recommended with "JFE FRAME KIT." With foundation insulation construction methods which do not provide ventilation holes in the foundation, it is generally thought that the crawl space environment is stable throughout the year, and there is low risk of condensation on indoor surfaces in winter due to cooling of sills and column footings, or of condensation in the crawl space due to the influx of hot, humid air into the cool crawl space during the rainy season and summer. On the other hand, because this structure makes it difficult to remove the moisture that evaporates from the foundation concrete in the initial stage of construction, it has been pointed out that the humidity in the crawl space tends to increase approximately 1–2 years after construction, depending on ventilation of the indoor air.

To verify the performance of the outside insulation/foundation insulation construction method, the indoor environment and crawl space environment of a "JFE FRAME KIT" house with outside insulation and foundation insulation were measured over a period of 1 year. An outline of the results is presented here.

5.2.1 Outline of model house

The object of measurements was a house (Sumeru SI: skeleton infill) with outside insulation and foundation insulation, which was constructed in Nagoya City, Aichi Prefecture. The model house (non-resident) was completed in January 2006. A view of its external appearance is shown in **Photo 5**.

In the object house, ALC 50 mm was applied directly to the exterior walls, and folded steel plates were used in the roof. As outside and foundation insulation, 25 mm of extruded polystyrene foam was applied externally, and 200 mm of glass wool was laid in the ceiling.

As interior materials, with the exception of the second floor ceiling, utility, and first floor Japanese-style room spaces, the model house was left in unfinished skeleton form with the structural members visible. On the second floor, half of the entrance foyer formed a well, and the structural materials, wall studs, and substrate (shina plywood) for the exterior were left unfinished. Thus, the entire indoor area on the second floor was an open space. A view of the entrance well is shown in **Photo 6**.

Photo 5 Model house exterior

Photo 6 Interior

5.2.2 Measurement items

Measurements, including preparatory measurements, were carried out from January 14, 2006 to February 9, 2007. The main measurement items were as follows.

(1) Temperature and humidity conditions and condensation in crawl space of model house with foundation insulation: Crawl space air temperature, Humidity, Surface temperature of slab concrete
(2) Interrelationship between indoor environment and crawl space in model house with outside insulation and foundation insulation: Air temperature (center of living room space, lavatory), Humidity (center of living room space, lavatory), 1st floor floor-surface temperature (Japanese-style room, lavatory)
(3) Condensation on steel materials: Temperature of steel materials (center of living room, 2nd floor floor-beams, exterior wall, 2nd floor floor-beams)
(4) Measurements of test environment: Outside air temperature, Humidity (measured on the north side of the building)

5.2.3 Measurement results

(1) Indoor Environment

The outside air temperature and temperature and humidity in the living room and crawl space are shown in **Fig. 6**. The indoor surface temperature and dew point temperature are shown in **Fig. 7**.

Because the model house has high insulation and air-tightness, the highest air temperature in summer was at maximum 2–4°C lower than the outside air, even without air-conditioning. In winter, the indoor temperature was always higher than the outdoor temperature, being 2–6°C higher even at the time of the daily low air temperature. Daily fluctuations in temperature were also small. The floor surface temperature was low in summer and high in winter, and daily fluctuations were extremely slight. The temperatures of the beams of the steel frame were substantially the same as room temperature, and because the steel temperature trended higher than the dew point temperature, condensation did not occur.

Humidity generally trended at around 60–70% and was extremely stable in comparison with the changes in the outdoor humidity.

(2) Crawl Space Environment

The temperature and humidity in the crawl space are shown in **Fig. 8**. The crawl space temperature showed a stable trend, being around the daily low outside air temperature in summer and around the daily high

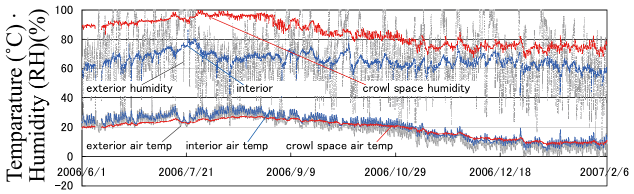


Fig. 6 Trend of air temperature and humidity

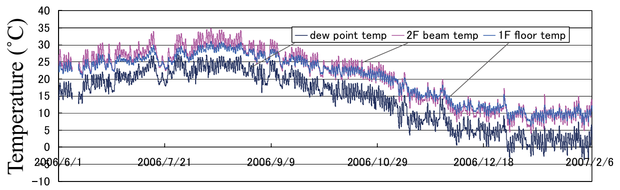


Fig. 7 Relations of surface temperature and dew point temperature

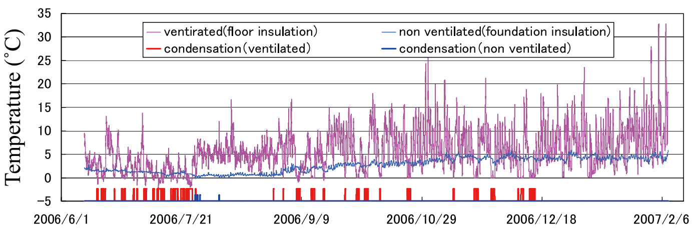


Fig. 8 Compare of crawl space temperature and humidity

outside air temperature in winter. Although crawl space humidity exceeded 90% in August, it gradually decreased thereafter. In the crawl space environment, the effect of the indoor environment is greater than that of the outside air, and the temperature and humidity in the crawl space varied depending on air-conditioner operation. Figure 8 also show the results of a trial calculation for a model with ordinary crawl space ventilation (case in which water vapor in the outside air flows into the crawl space). With conventional construction, the frequency of condensation in the crawl space was higher than with the foundation insulation method, and crawl space condensation generally occurred in June and July.

5.2.4 Durability of crawl space

The condition of the crawl space 1 year after the completion of construction is shown in **Photo 7**. The “JFE FRAME KIT” members, nuts, and bolts all show a metallic luster, and rust cannot be observed. Similarly, no rust was observed on the unit bath supporting columns, hardware related to the equipment, or nuts and bolts. Partial white rust could be seen on the adjustment nuts and bolts of the steel bunch and the sleeper seats, but there were no problems in the steel bunch itself.

Photo 7 Crawl space view one year later

The screws connecting sleeper seats and wood materials were also lustrous and free of problems. No mold or decay of the wood was observed.

6. Conclusions

This paper has described the features of “JFE FRAME KIT.” The safety of buildings using this construction method was confirmed from the following study and development.

(1) Regarding structural performance, strength, deformation performance, and the fact that no breakage of bolt connections or excessive local deformation occurs were confirmed in a cyclic loading test with a full-scale model.

(2) For fire-resistance performance, a membrane fire proof construction bearing wall and composite fire proof construction beam using ALC50 and sprayed slag wool were developed. These members have been approved by Japan’s Minister of Land, Infrastructure and Transport.

(3) For heat insulation/anti-sweat specifications, recommended standards are set by region, considering the effect of heat bridges. Performance was verified with a model house, and excellent durability was confirmed.

In the future, the authors plan to carry out technical development aiming at further improvement of the seismic performance and livability of “JFE FRAME KIT.”

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