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Thermal Insulation and Thermal Bridge of Steel-Framed Walls

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Abstract

This study is on the thermal insulation properties of cavity insulation in walls of steel-framed houses. In the walls with cavity insulation, thermal bridges of the light-weight sections increase the overall thermal transfer and the possibility of surface condensation inside and outside the walls. To examine the thermal insulation characteristics, thermal transmission property tests were conducted considering the plate thickness, shape, material type, etc. as experimental parameters. The tests showed that the thermal transfer distance and the thermal conductivity of material affected the thermal insulation characteristics. It was also shown that the cavity insulation increased the possibility of surface condensation.

1. Introduction

The steel-framed house is based on wooden two-by-four construction but the members are replaced by zinc-coated light-gauge steel channels (hereinafter referred to as light-gauge steel). Since steel transfers heat more readily than wood, the light-gauge steel members may serve as thermal bridges. Because of the thermal bridges, it is feared that the amount of heat transmission is increased and the durability of the wall and interior finish is decreased by the occurrence of condensation. It is thus imperative to ensure the thermal insulation performance of walls and to develop techniques for preventing the occurrence of condensation. The thermal insulation performance of walls is one of the housing loan criteria established by the Goverment Housing Loan Corporation. It is also a subject that has come to be discussed from the viewpoint of life cycle assessment (LCA) in recent years and is regarded as a problem that must be tackled.

Few findings are published on the thermal bridge phenomenon in the walls of steel-framed houses built with light-gauge steel studs of 1.6 mm or less in thickness. The items to be considered in the design of steel-framed houses regarding the thermal bridge phenomenon are not made clear, either. It is thus important to collect and analyze data on the thermal bridge and to establish the thermal insulation specifications for steel-framed houses.

2. Research Trends Related to Thermal Insulation and Condensation Prevention of Steel-Framed Houses

In foreign countries, techniques are already developed and commercialized for slitting light-gauge steel studs and so on to increase the heat transfer distance and alleviate the effect of the thermal bridge phenomenon[1]. The climate in Japan where it is hot and humid in summer is different from that in the United States and Canada where the steel-framed houses have been developed. Therefore it may be difficult to apply the steel-framed house techniques developed in these countries directly in Japan. In Japanese prefabricated steel-framed houses where thicker steel members are used, a thermal insulation material is placed between a steel member and other sheathing materials to cut off the heat transfer and alleviate the effect of the thermal bridge. This type of technique is difficult to directly apply in steel-framed houses of the 2×4 construction, because it may increase the number of parts and decrease the load carrying capacity of bearing walls.

Research on the thermal insulation and condensation prevention of steel-framed houses in Japan is performed by the Thermal Team of the Steel House Committee in the Kozai Club (hereinafter referred to as the Thermal Team). The targets of the activities are the establishment of thermal insulation specifications for steel-framed houses and the acquisition of approval by the Goverment Housing Loan Cor-

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poration. Issues to be discussed include the assurance of thermal insulation performance to meet new and old energy codes, and the assurance of condensation prevention performance in the walls. For these targets, various studies have been conducted, based on numerical analysis and measurement in monitor houses, among other things[2-6]. As a result of these efforts, the exterior thermal insulation method that meets the thermal insulation and condensation prevention requirements of the Goverment Housing Loan Corporation in December 1997.

Typical temperature measurements taken in a monitor house are shown in **Fig. 1**. The steel-framed house is located in Kumamoto Prefecture, Japan, has a total floor area of 135 m^2, and is two storied. The thermal insulation specification consists of 25-mm thick thermal insulation boards applied to the outside surface of each exterior wall. The values given in Fig. 1 are the measured temperatures of the inside and outside surfaces of a wall on the north side of the first floor (see **Fig. 2**) on January 5, 1997. The dew-point temperature calculated from the temperature and humidity values of the wall is also shown in Fig. 1. The outside surface temperature (a) of the thermal insulation material greatly varies, but the temperatures (b, c) of the light-gauge steel stud positioned inside the thermal insulation material vary to a small degree. The comparison with the dew-point temperature indicates less possibility of condensation. The measurements made in summer are similar and indicate the occurrence of no condensation in summer. These results indicate that the exterior thermal insulation effectively works against condensation in the wall throughout the year.

3. Positioning of This Study

At present, exterior insulation is being recommended as a standard insulation specification for steel-framed houses. Since exterior insulation is inferior to cavity insulation in cost and recognition in Honshu, the mainland of Japan, there are demands for applying the cavity insulation to steel-framed houses. When cavity insulation is adopted, the light-gauge steel studs become thermal bridges as indicated by an infrared image of an interior wall surface shown in **Fig. 3**. Unlike with exterior insulation, localized, low-temperature portions are consequently created, calling for careful consideration on the prevention of condensation. The cavity insulation may, however, be applied directly if its characteristics are clarified and application areas are limited.

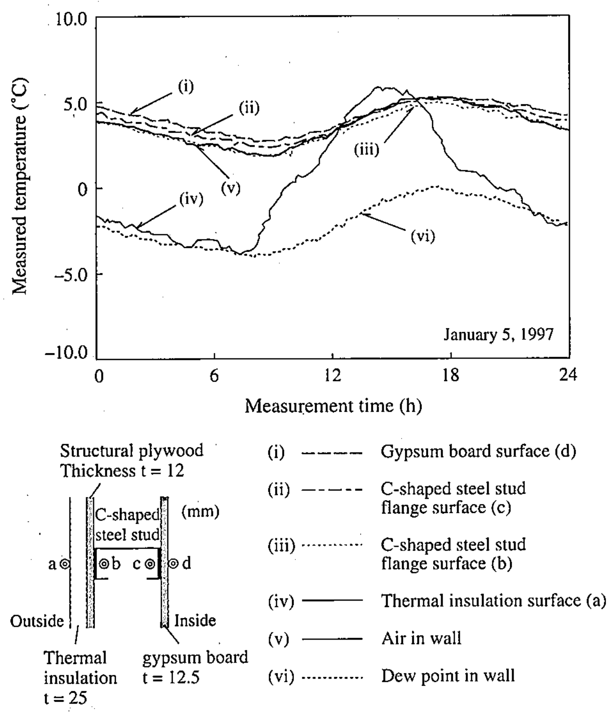


Fig. 1 Temperature measurements in monitor house

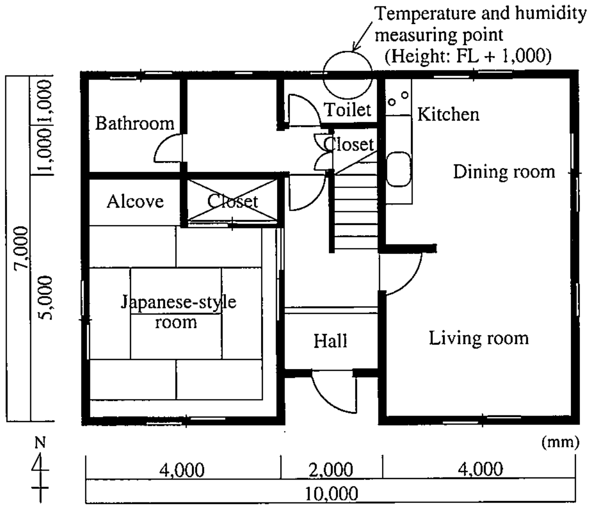
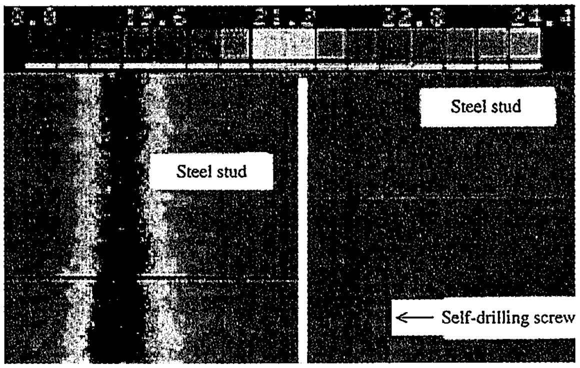


Fig. 2 First-floor plan of monitor house

Few findings are available about the thermal bridge phenomenon of cavity-insulated walls constructed of light-gauge steel studs of 1.6 mm or less in thickness, therefore, it is an important issue to be studied. Aimed at the application of cavity insulation to steel-framed houses, this study is conducted to gain data on the heat transmission coefficient of walls and the inside and outside surface temperatures of walls, and investigate the effects of stud thickness, shape, material and other parameters on the thermal insulation performance and condensation prevention performance.

4. Experiments on Heat Transmission Coefficient and Temperature Distribution of Walls

This experimental study was conducted to obtain data on the heat transmission coefficient of cavity-insulated walls and the inside and outside surface temperatures of cavity-insulated walls, clarify the effect of each parameter, and discuss the possibility of condensation



Cavity insulation **Exterior insulation**

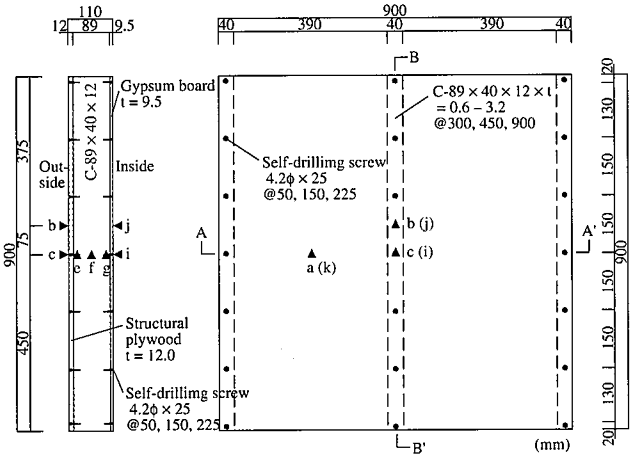
Fig. 3 Interior wall surface temperature distribution

occurring on the inside and outside surfaces.

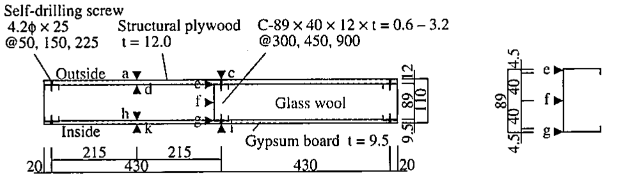
4.1 Description of test

A typical test specimen is schematically illustrated in **Fig. 4**. Three light-gauge steel studs (C - 89 × 40 × 12 × t = 1.0) were arranged at a spacing of 455 mm. Structural plywood (12.0 mm thick) and gypsum board (9.5 mm thick) were fastened to the light-gauge steel studs with self-drilling screws (4.2 mm in diameter and 150 mm in spacing). The resultant wall was filled with glass wool 10 kg/m^2 density (for a thickness of 100 mm) as basic specimen No. 1. The positions a to k where thermocouples were installed are marked by the solid triangle (Δ) in Fig. 4. The thermocouples were attached to the web surface of the light-gauge steel studs, the surfaces of the structural plywood and gypsum board, and the heads of the self-drilling screws.

As listed in **Table 1**, the parameters of the specimens are: 1) thickness of the studs (specimens Nos. 2 to 5); 2) spacing of the studs (specimens Nos. 6 and 7); 3) spacing of the screws fastening the structural plywood and gypsum board to the studs (specimens Nos. 8 and 9); 4) shape of the studs to confirm the effect of the heat transfer distance (specimens Nos. 10 and 11); and 5) material of the studs to confirm the effect of the thermal conductivity of the material (specimens Nos. 12 and 13). Specimen No. 10 has slit openings in the web of each light-gauge steel stud as shown in **Fig. 5** by referring to the examples[7,8] of thermal insulation studs overseas. The slit openings account for about 30% of the total web surface area. Specimen No. 11 has the web of the light-gauge steel stud bent into Σ form as shown in **Fig. 6** to change the heat transfer distance. Specimens Nos. 12 and 13 has C-shaped studs made of stainless steel (SUS304) and aluminum alloy (Al), respectively, as compared with carbon steel of the basic specimen, in order to change the thermal conductivity of the studs. Specimen No. 14 is a specimen where the light-gauge steel studs of the basic specimen are replaced by 2×4 wooden studs. Only one of each type of specimen was prepared.



(a) Section B-B'　　(b) Elevation



(c) Section A-A'　　(d) Thermocouple positions

Fig. 4 Schematic of specimens No. 1 to No. 11

Table 1 Specimens and parameters

No.	Stud thickness (mm)	Stud spacing (mm)	Screw spacing (mm)	Stud shape	Stud material
1	1.0	450	150	C	Carbon steel
2	0.6	450	150	C	Carbon steel
3	1.4	450	150	C	Carbon steel
4	2.3	450	150	C	Carbon steel
5	3.2	450	150	C	Carbon steel
6	1.0	300	150	C	Carbon steel
7	1.0	900	150	C	Carbon steel
8	1.0	450	50	C	Carbon steel
9	1.0	450	225	C	Carbon steel
10	1.0	450	150	C, slit	Carbon steel
11	1.0	450	150	Σ	Carbon steel
12	1.0	450	150	C	SUS
13	1.0	450	150	C	Al
14	2 × 4	450	150	■	Wood

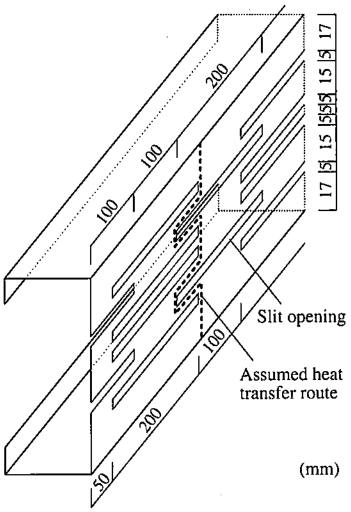


Fig. 5 Schematic of C-shaped steel stud with slits in web

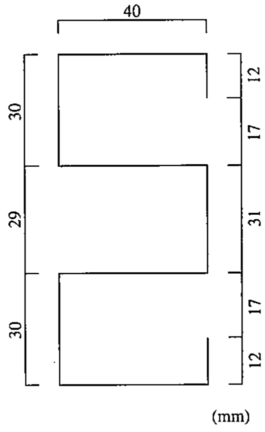


Fig. 6 Cross section of Σ-shaped steel stud

The specimens are not provided with exterior finishes or with air flow layers between the exterior finish and structural plywood, in order to accentuate the effect of each parameter on the heat transmission coefficient and the outside and inside surface temperatures of the walls. The space inside of the web of each light-gauge steel stud is not filled with the glass wool (not shaded in Fig. 4) conduct the test on the safe side.

The specimens were tested as described in JIS A1420. Such a temperature gradient was created as to maintain the structural plywood side (exterior side) at 10°C and the gypsum board side (interior side) at 30°C. The heat transmission coefficient and the surface temperature of each specimen were measured under this temperature gradient. Essentially, it is considered best to set the structural plywood side at about –5°C by simulating the winter temperature condition in Japan. Because of the cooling capacity of the constant-temperature chamber used, however, the structural plywood side was set at 10°C.

4.2 Test results and effect of parameters

The measured heat transmission coefficients and surface temperatures of various parts are given in **Table 2**. Since the temperature of the test chamber somewhat deviated from the preset temperature from experiment to experiment, the surface temperatures listed in Table 2 were normalized by proportional calculation to 10°C and 30°C.

The heat transmission coefficient is shown by parameter in **Fig. 7**. The heat transmission coefficient of each specimen constructed of metal studs is larger than that of specimen No. 14 constructed of 2×4 wooden studs. From Fig. 7, it is clear that the heat insulation of the walls can be improved by changing the thickness, spacing, shape, and material of the studs. The test results by parameter may be summarized as follows.

1) Effect of stud thickness

A stud thickness of 2.3 mm or more makes the heat transmission coefficient about 8% higher than a stud thickness of 1.4 mm or less. This tendency can be confirmed from the surface temperature measurements shown in **Fig. 8**(a). The greater the thickness, the smaller the change in the temperature between the points e, f and g of the stud and the greater the heat transfer through the wall.

When the stud thickness is 2.3 mm or more, the heat transmission coefficient increases with increasing stud thickness. When the stud thickness is 1.4 mm or less, the heat transmission coefficient decreases with increasing thickness. The cause for this difference is not fully indentified. The difference in the heat transmission coefficient between the two thickness groups is quite small, that is, 0.01 to 0.02 kcal/m^{2}h°C. Therefore, one possible cause may be a measurement error.

2) Effect of stud spacing

The heat transmission coefficient increases by 0.12 to 0.17 kcal/m^{2}h°C as the stud spacing decreases from 900 mm through 450 mm to 300 mm. The heat transmission coefficient increases by about 25% with the addition of a stud. As shown in Fig. 8(b), however, the surface temperatures of the different parts of the wall are approximately the same despite the difference in the stud spacing. Increasing the number of studs simply reduces the heat insulation performance of the wall.

3) Effect of screw spacing

The heat transmission coefficient changes by a mere 0.01 kcal/m^{2}h°C as the spacing of the sheathing fastening screws changes. The

Table 2 Measured values of surface temperature and heat transmission coefficient

No.	Heat transmission coefficient (kcal/m^{2}h°C)	Surface temperature (°C)												
		Outside	a	b	c	d	e	f	g	h	i	j	k	Inside
1	0.64	10.0	10.9	14.6	15.0	11.8	19.0	21.2	22.9	28.5	26.2	26.5	29.2	30.0
2	0.66	10.0	11.3	14.1	14.9	12.4	19.3	21.5	23.6	28.7	26.2	26.7	29.2	30.0
3	0.63	10.0	11.0	14.4	15.3	12.2	20.1	21.7	23.2	28.7	26.4	26.5	29.1	30.0
4	0.69	10.0	10.8	14.8	15.5	11.9	20.3	21.5	22.7	28.6	25.5	25.6	28.9	30.0
5	0.70	10.0	11.0	14.9	16.9	12.4	20.8	21.8	22.6	28.5	24.7	25.5	28.8	30.0
6	0.81	10.0	11.1	13.9	14.8	12.3	19.5	21.1	22.9	28.8	26.6	26.6	29.3	30.0
7	0.52	10.0	10.8	—	—	11.6	—	—	—	28.7	—	—	29.1	30.0
8	0.62	10.0	11.1	15.1	16.0	12.1	19.2	21.3	22.8	28.7	26.2	26.0	28.8	30.0
9	0.65	10.0	10.8	14.6	16.1	12.0	19.7	21.4	23.2	28.8	26.6	26.1	29.0	30.0
10	0.54	10.0	11.2	13.1	14.0	11.9	15.5	20.2	25.2	28.4	27.2	27.8	29.0	30.0
11	0.58	10.0	11.0	13.9	14.9	12.3	18.2	21.2	24.0	28.8	26.7	26.7	29.1	30.0
12	0.55	10.0	11.0	13.4	13.6	12.2	18.1	21.1	24.2	28.7	26.9	26.8	28.9	30.0
13	0.73	10.0	10.6	14.7	15.1	11.8	20.4	21.5	22.9	28.8	25.8	25.4	29.0	30.0
14	0.43	10.0	11.0	11.7	11.8	12.0	13.5	20.1	26.5	28.6	28.3	28.4	29.1	30.0

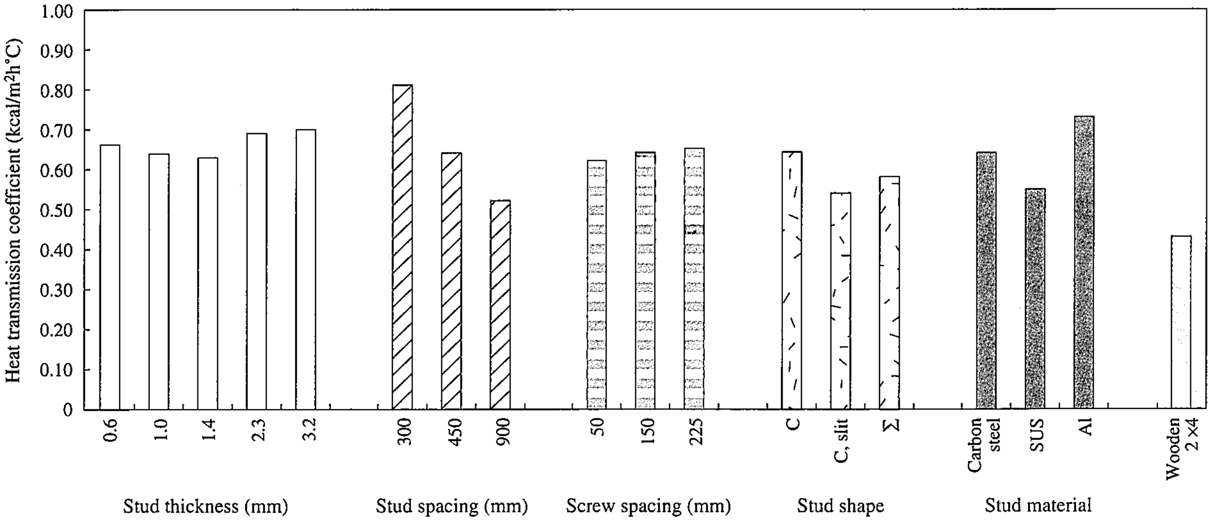
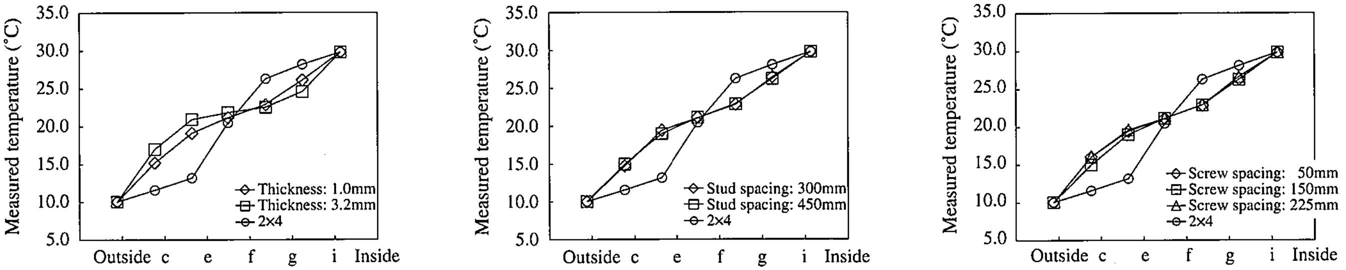
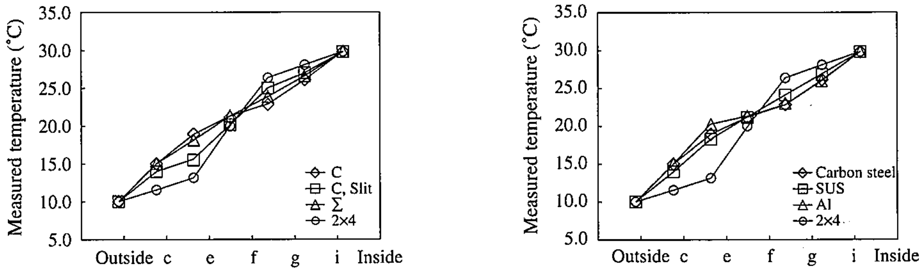


Fig. 7 Heat transmission coefficient by parameter



(a) Effect of stud thickness (b) Effect of stud spacing (c) Effect of screw spacing



(d) Effect of stud shape (e) Effect of stud material

Fig. 8 Surface temperature by parameter

specimens change in the surface temperature with the screw spacing only to a small degree as shown in Fig. 8(c). From these results, it may be said that the spacing of the sheathing fastening screws does not affect the heat insulation performance of the wall much.

4) Effect of stud shape

When the specimen is constructed of C-shaped light-gauge steel studs slit in the web, the heat transmission coefficient decreases by about 15% as compared with that without web slits. When the specimen is constructed of light-gauge steel studs formed into the shape Σ, the heat transmission coefficient decreases by about 10% as compared with a specimen with C-shaped studs. The heat transfer distance of the specimen having C-shaped studs with web slits and of the specimen with Σ-shaped studs becomes about 3.25 and 1.90 times longer than that of a specimen having C-shaped studs without web slits. This means that the heat transmission coefficient decreases with increasing heat transfer distance. A similar tendency can be confirmed from the temperature measurements shown in Fig. 8(d). As the heat transfer distance increases, the temperature change between the points e, f and g of the stud increases. Slitting the web of each C-shaped stud brings the temperature distribution closer to that of the specimen with 2×4 wooden studs and reduces the heat transfer of the wall.

5) Effect of stud material

When the specimen is constructed of stainless steel (SUS) studs, its heat transmission coefficient decreases by about 15% as compared with a specimen constructed of carbon steel studs. When the specimen is constructed of aluminum alloy (Al) studs, its heat transmission coefficient increases by about 15% as compared with a specimen constructed of carbon steel studs. The stainless steel, carbon steel, and aluminum alloy are related by the thermal conductivity λ (kcal/mh°C) in the following order: stainless steel ($\lambda = 13$) < carbon steel ($\lambda = 46$) < aluminum alloy ($\lambda = 175$). This means that the heat transmission coefficient of the specimens increases with increasing thermal conductivity of the studs. A similar tendency can be confirmed from the surface temperature measurements shown in Fig. 8(e). The temperature change between the points e, f and g increases for the stainless steel (SUS) studs with smaller thermal conductivity and decreases for the aluminum alloy (Al) studs with larger thermal conductivity.

4.3 Condensation on inside and outside surfaces of walls

As discussed above, the heat transmission coefficient and the thermal insulation performance of the walls can be decreased and improved, respectively, by changing the thickness, shape, and material of the studs. This in turn, however, may increase the stud temperature differences in the wall and cause the low-temperature portions of the wall to fall below the dew-point temperature. Therefore, the possibility of condensation occurring on the plaster board surface and the stud surface in the wall is verified here.

Fig. 9 shows the relationship between the heat transmission coefficient of the wall and the temperature difference from the inside room temperature for typical specimens. The temperature differences are calculated at point i (screw head) where the temperature of the gypsum board surface becomes the lowest and at point e where the stud surface temperature becomes the lowest. The values of specimen No. 15 given in Fig. 9 are the test results of the exterior-insulated specimen illustrated in **Fig. 10**, conducted separetely from this research. The exterior insulation board has a thickness of 25 mm and thermal conductivity l of 0.034 kcal/mh°C. Because of its relatively low grade of thermal insulation specification, specimen No. 15 has a measured heat transmission coefficient of 0.82 kcal/m^{2}h°C, the lowest thermal insulation performance among the specimens.

From Fig. 9, it can be confirmed that as the heat transmission coefficient decreases and the thermal insulation performance improves, the effect of low-outdoor temperature portions on the interior finish surface diminishes, the difference between the plaster board surface temperature and the inside room air temperature decreases, and condensation becomes less likely to occur. On the other hand, with increasing the thermal insulation performance the difference between the stud surface temperature and the inside room air temperature increases, and the potential of condensation on the stud surface increases.

Assuming both insides of the room and wall have a temperature of 20°C and humidity of 50% in winter, the dew-point temperature is about 9.3°C. This means that condensation occurs in the positions where the temperature difference is lower than 10.7°C as shown in

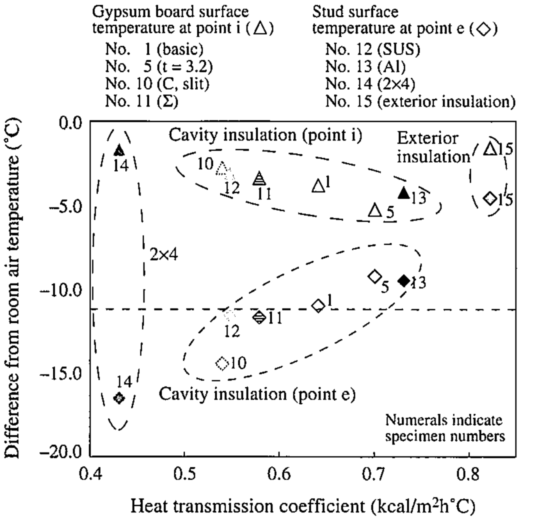


Fig. 9 Heat transmission coefficient and difference between surface temperature and room air temperature

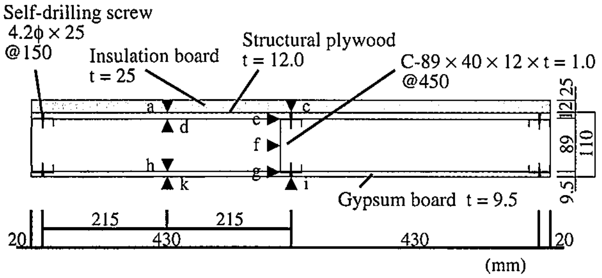


Fig. 10 Cross section of specimen No. 15

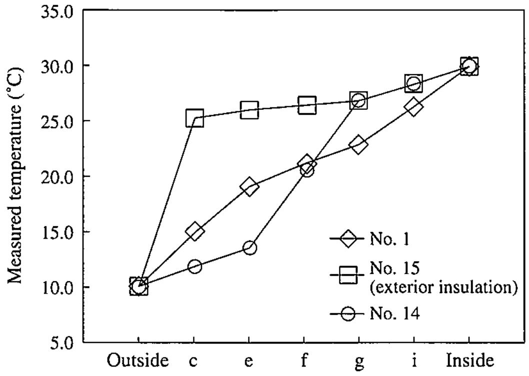


Fig. 11 Surface temperature of wall with exterior insulation

Fig. 9. If this criterion is applied to the test results, condensation does not occur on the plaster board surface, but occurs on the stud surface of the specimens whose thermal insulation performance is improved by using studs of different shape or material. The similar tendency also occurs for the specimen constructed of 2x4 wood studs. Since the wood studs are highly hygroscopic, however, there is a great possibility that the condensation problem will not surface.

For specimen No. 15, the thermal insulation positioned at the outside (cold side) of the studs obstructs the heat flow, and the stud surface temperature is far higher than that of specimen No. 1 with cavity insulation as shown in **Fig. 11**. The temperature difference of specimen No. 15 from the inside room air temperature shown in Fig. 9 is small enough to eliminate the possibility of condensation.

It should be noted with the cavity insulation specification that even if the thermal insulation performance of a wall is improved by using studs of different shape or material in this way, condensation on the stud surface cannot always be prevented. The test results of specimen No. 15 indicate, however, that a 25-mm thick insulation board of somewhat low grade can substantially improve the anti-condensation performance of a wall if applied to the exterior side of the wall. Given this fact, the combined use of exterior insulation and cavity insulation may be promising and studied as a future issue for investigation.

5. Conclusions

This study has found that the heat transmission coefficient of a cavity-insulated wall can be reduced by changing its heat transfer distance or thermal conductivity with the use of studs of appropriate shape or material. It should be noted, however, that the stud surface temperature may drop below the dew-point temperature at the same time.

Only typical wall portions have been studied in this experimental work. The wall corners where the effects of thermal insulation and condensation prevention appear markedly will have to be investigated in the future.

The temperatures in the monitor house of Kumamoto prefecture shown in Figs. 1 and 2 were measured in a joint research project by six steelmakers (Kawasaki Steel, Kobe Steel, Nippon Steel, Sumitomo Metal Industries, Nisshin Steel, and NKK) in the Kozai Club.

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