Heat Bridge Effect of Composite Sandwich Walls of Steel Plates and Concrete

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ABSTRACT

Composite sandwich walls of steel plates and concrete are considered to have possible applicability to main structures of nuclear power plants. This structure is fabricated by placing concrete between two steel plates with steel-studs, shear reinforcing bars and web plates in the wall in order to fasten the steel plates on both sides of the wall together and to connect the plates to concrete. It is considered that heat transfers from fire-exposed surface of the wall to unexposed surface through steel members which form heat-bridges in case of fire.

To examine the heat transfer and temperature distribution in the walls with heat bridges, a heat transfer analysis was performed. Then, heating tests by using small-scale models were carried out.

The results obtained showed that after two hours of heating up to close to 1000℃ (specified heating the temperature) on the fire-exposed wall surfaces, the maximum temperatures on the other side of the wall surfaces of 20cm thick specimens were about 100℃, which were much lower than the ignition temperature of wood, 260℃. The temperature within 75 % of the total cross sectional area of the walls did not exceed 400℃.

KEYWORDS : heat bridge effect, composite sandwich wall, shear reinforcing bar, steel-stud, web plate, concrete, heat transfer, temperature distribution

INTRODUCTION

Composite sandwich walls of steel plates and concrete are fabricated by placing concrete between two steel plates and made to be structural members which carry applied loads including seismic load. In order to fasten two steel plates together and to connect the plates to concrete, steel-studs, shear reinforcing bars and web plates are welded to the plates as shown in Fig. 1.

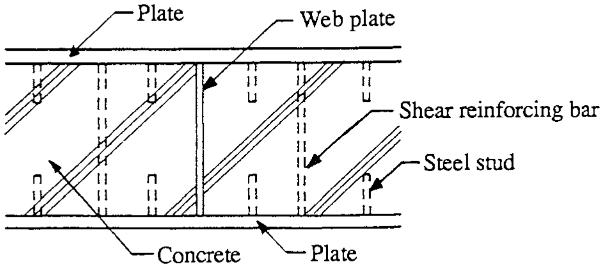

FIGURE 1 Cross section of composite sandwich wall

Composite sandwich walls are considered to have applicability to main structures of nuclear power plants, expecting thinner thickness of walls and reduction of cost of construction by prefabricating of wall elements and embedding pipes and equipments.

However, from the view-point of fire resistance design, some problems should be solved for application to real structures, because steel plates without fire resistive coating are intended to use for wall surfaces. Another problem to be solved is heat bridge effect of the steel-studs, shear reinforcing bars and web plates in concrete. Therefore, the following two most important phenomena should be clarified.

1) Heat transfer from fire-exposed surface plates in fire compartment to unexposed surface plates of the other side through steel-studs, shear reinforcing bars and web plates in concrete.
2) Strength reduction of concrete around heat-bridges by the influence of high temperature caused by heat transfer.

In order to investigate on these two phenomena, heat transfer analysis was made, then heating tests of heat bridges in concrete using small-scale models were carried out. The results obtained made it possible to predict temperature distribution in cross section of each specimen for the fire resistance design of composite sandwich walls of steel plates and concrete.

HEAT TRANSFER ANALYSIS

Heat transfer analysis was made preceding to heating tests to obtain information on the behaviour of heat-bridges in concrete and to design specimens. Analysis models of heat-bridges such as steel-studs, shear reinforcing bars and web plates are simplified to four kinds of models as shown in Fig. 2. Calculation method of unsteady heat transfer analysis was conducted by three dimensional finite element method.

Conditions and Assumptions for Analysis

1) Each model for analysis is one-fourth of the specimen taking symmetry of the specimen into account.
2) Standard heating temperature-time curve according to JIS-A-1304 is used for the heating temperature.
3) Air temperature of unexposed side of models to fire is kept constant at 15℃.

4) Coefficient α of heat transfer is obtained from Eq. (1) and Eq. (2)[1].
5) Specific heat and heat conductivity of concrete and steel is obtained from formula[2] as shown in Fig. 3 and 4. However, when T≧800℃, specific heat of steel is read from the figure in reference (3).
6) The dispersion and evaporation of water contained in concrete during heating are not considered.
7) Bond between steel and concrete is assumed to be perfect.

$$\alpha_c = \begin{cases} 5 & (T \leqq 300K) \\ 0.02T - 1 & (300K \leqq T \leqq 800K) \\ 15 & (800K \leqq T) \end{cases} \quad (1)$$

$$\alpha = \alpha_c + \frac{5.67 \times 10^{-8} \varepsilon}{T_f - T_1} \left(T_f^4 - T_1^4 \right) \quad (2)$$

Where α_c : coefficient of heat transfer by convection
T_f : temperature of fire (K)
T_1 : temperature of the wall surface (K)

$$\varepsilon = \frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_1} - 1}$$

ε_f : emissivity of flame (=0.4)
ε_1 : emissivity of the wall surface (=0.8)

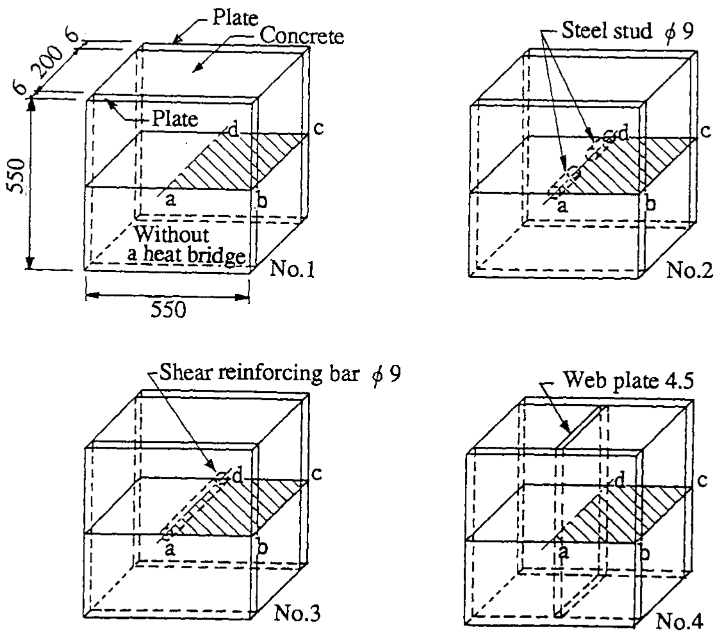

FIGURE 2 Models employed for analysis

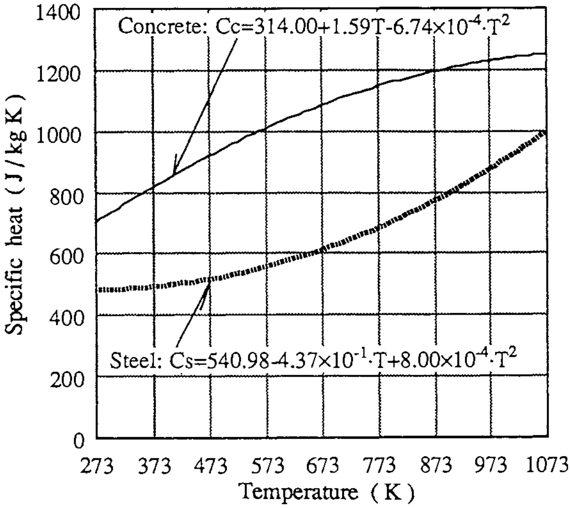

FIGURE 3 Specific heat of concrete and steel
(When T≧1073K, specific heat of steel is read from the figure in reference (3))

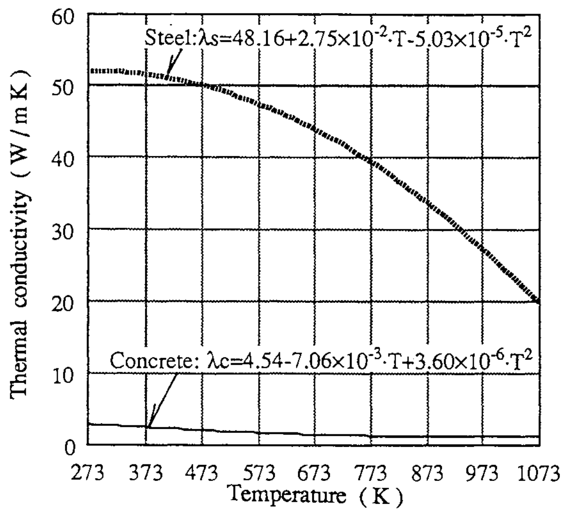

FIGURE 4 Thermal conductivity of concrete and steel

Results of Analysis and Discussions

The contour curves of the temperature distributions obtained by heat transfer analysis on a,b,c,d-planes in the models shown in Fig. 2 are shown in Fig. 5.

The influence of heat-bridges on temperature in concrete was larger in the neighbourhood of heat-bridges such as a steel-stud, a shear reinforcing bar and a web

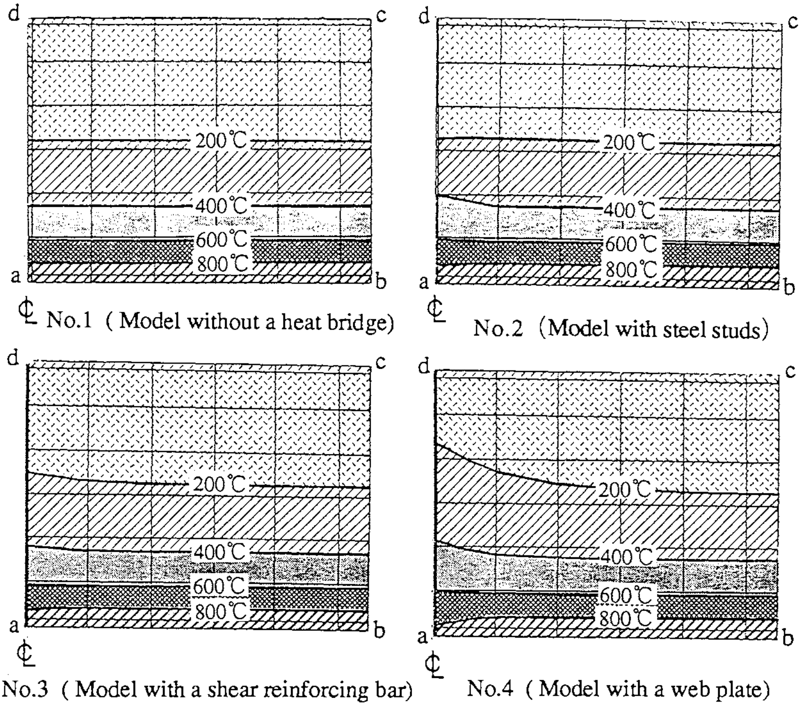

FIGURE 5 Contour curves of temperature distributions by analysis
(At 120 minutes after heating)

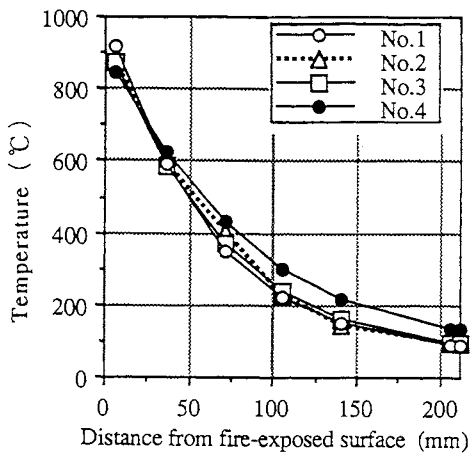

FIGURE 6 Temperature distributions by analysis
(At 120 minutes after heating)

plate, in accordance with the amount of steel. It was not noticeable, however, at locations farther than 15cm from a-d axis in the models. This fundamental result showed that the dimensions of specimen for heating tests should be more than 30cm long and wide, and a heat-bridge should be placed at the center of the specimens.

The temperature distribution in each model is shown in Fig. 6. It can be said that the heat transfer from fire-exposed surface to unexposed surface was the greatest in the model with a web plate. Temperature on the unexposed surface was higher in order of model with a web plate, a shear reinforcing bar and a steel-stud. The influence of a web plate to temperature at the unexposed surface was 18% higher than the model without a heat-bridge. In this case, the temperature was 150℃, which is lower than the ignition temperature of wood, 260℃.

HEATING TEST

Specimens

Specimens are designed by taking the results of heat transfer analysis into account. Analysis showed that the dimensions of 550 mm long×550 mm wide is large enough for the specimens for heating test, considering the influence of heat transfer through a steel-stud, a shear reinforcing bar and a web plate in concrete. The shape and dimensions of the specimens are shown in Fig. 7. In each specimen, the axis of the heat bridge was located on the line between the centers of two surface plates. The grades of steel used for surface plates, a steel-stud, a shear reinforcing bar and a web plate, and mechanical properties of concrete are shown in Table 1 and Table 2, respectively.

Test Method

Each specimen was placed in the furnace chamber and exposed to fire for two hours in accordance with the standard heating temperature-time curve prescribed by JIS A-1304. Heating test method is shown in Fig. 8. The temperatures in a specimen were measured at 25 points by using K-type thermocouples.

TABLE 1 Grades of steel for specimens

Members	Grades of steel
Surface plate	SM490A(t=6mm)
Reinforcing bar (steel-stud, shear reinforcing bar)	SS400B(Φ=9mm)
Web plate	SS400(t=4.5mm)

TABLE 2 Properties of concrete

Age (day)	Compressive strength (MPa)	Tensile strength (MPa)	Specific gravity	Water content (wt.%)
58	31.0	2.5	2.24	7.36

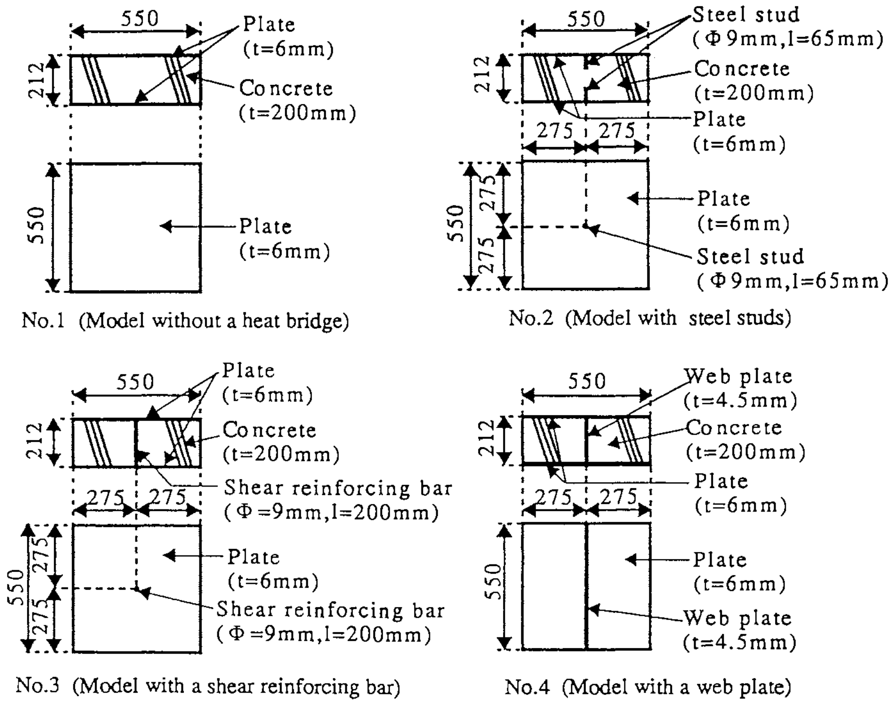

FIGURE 7 Specimens

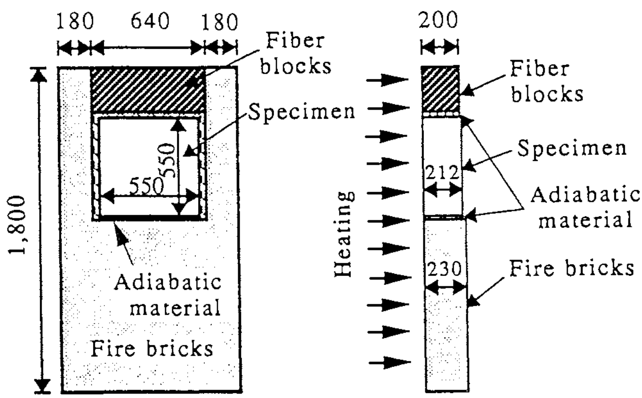

FIGURE 8 Test method

TEST RESULTS AND DISCUSSIONS

The temperature-time curves for each specimen are shown in Fig. 9. In this figure, for example, the curve 6 mm in the figure shows the temperature change on the inner surface of fire-exposed plate, and the curve 206 mm shows that of the inner surface of unexposed plate and so on. These points where temperatures were measured are along the central axis (a-d axis in Fig. 2), i.e. the axis of a heat-bridge, as shown in Fig. 7.

Comparing No.1 specimen with other specimens in Fig. 9, it can be said that heat transfers evidently from the fire-exposed plate to the unexposed plate through heat-bridges. Though No.2 specimen has a discontinuous heat bridge of steel-studs, it has higher temperatures at the points of 36 mm and 71 mm from fire-exposed surface than those of No.3 specimen with a continuous heat-bridge of a shear reinforcing bar. The reason for this phenomena can be explained that heat did not flow and was stored around the discontinuous steel-stud on the fire-exposed side in concrete. No.4 specimen with a web plate showed the largest heat-bridge effect.

Concerning No.3 and No.4 specimens, it was observed that the temperature of the heat-bridge farther than 71 mm from fire-exposed surface remained constant at 100℃ at ten minutes after heating began. It is considered that water or steam between steel and concrete or in concrete was dispersing or evaporating and taking latent heat of water from concrete.

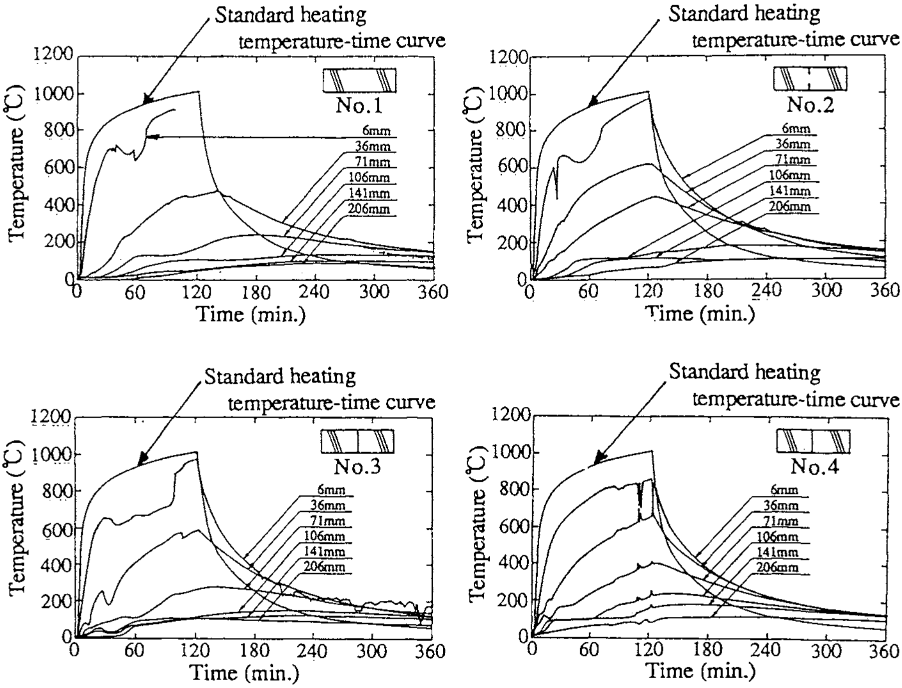

FIGURE 9 Temperature-time curves in specimen

At four hours after heating was stopped, the temperatures on the central axis (heat bridge axis) of each specimen converged between 100℃~200℃.

The temperature curves along the central axis (a-d axis) of the specimens at 120 min. and 330 min. after the start of heating were compared with those obtained by analysis as shown in Fig. 10 and Fig. 11. The temperatures measured in the tests were lower than those obtained by the analysis except for the neighbourhood of fire-exposed surface and showed steeper curves downward. And the temperature within 75 % of the total cross sectional area of the wall including the unexposed surface plate did not exceed 400℃. Comparing No.2 specimen with a discontinuous heat-bridge to No.3 specimen with a continuous heat-bridge, No.2 specimen has higher temperature than No.3 within the distance from fire-exposed surface to the end of a steel-stud (at the distance 71 mm from fire-exposed surface). It is considered that heat was stored around the steel-stud because of the discontinuity of the heat- bridge. In No.3 specimen, heat transferred smoothly through the heat bridge. The specimens with heat bridges of any type showed higher heat transfer from fire-exposed surface to unexposed surface and dispersion of heat in concrete than the one without the heat-bridge. The specimen No.4 with a web plate shows the largest heat-bridge effect.

The temperature of the unexposed plate surface of each specimen obtained by the test was about a half of that by analysis, and it converged to 100℃ at 330 min. after heating. The maximum value of it did not exceed 200℃, which was lower than the ignition temperature of wood, 260℃.

Fig. 12 shows the influence of the heat transfer through a heat-bridge of each specimen to the heat-flow through concrete at 120 min. after heating was started. It can be seen that No.1 specimen without a heat-bridge has uniform distribution of temperature

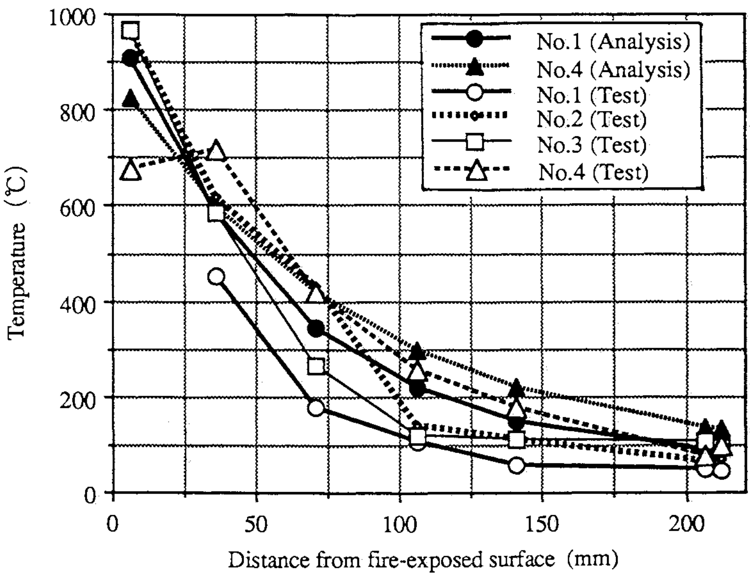

FIGURE 10 Temperature distributions along a-d axis
(At 120 minutes after heating)

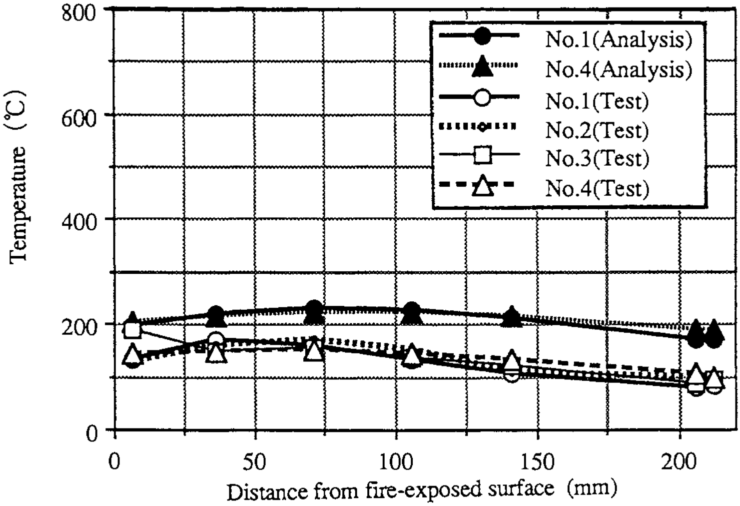

FIGURE 11 Temperature distributions along a-d axis
(At 330 minutes after heating)

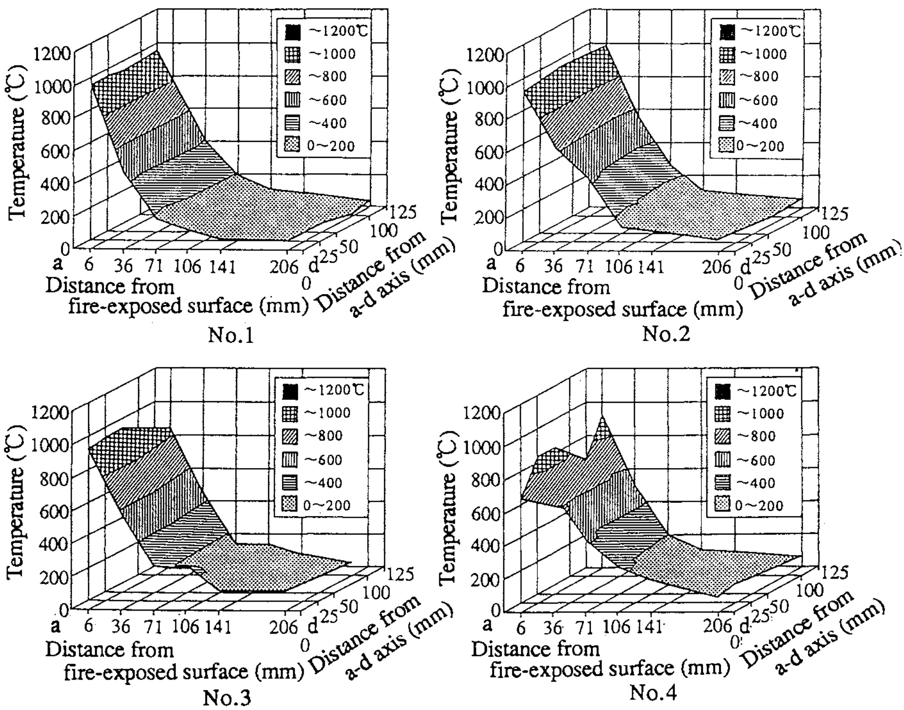

FIGURE 12 Contour curves of temperature distributions by test
(At 120 minutes after heating)

orthogonal to a-d axis (the heat-bridge axis) in specimen. On the other hand, regarding No.2, No.3 and No.4 specimens, heat-bridges affect the temperature distribution in concrete. However, the influenced region was limited up to 12.5 cm from the heat-bridge axis. The temperature near the fire-exposed surface of No.4 specimen was lower than those of other specimens. It is considered that the web plate effectively transferred heat from fire-exposed plate to the unexposed plate. The effect of heat-bridge to temperature of unexposed surface is relatively large, however, the absolute value was about 100℃.

The explosive failure of concrete was not observed during heating test. Steam began to come out from each specimen at 10~30 min. after heating has been started, and the evaporation continued until the end of heating. The weight of No.3 specimen just after the heating test was 7.40 kgw lighter than that before the test. The initial water content of concrete was 7.36 % by weight and the weight of concrete enclosed by plates is 135.5kg, therefore it means 74.2 % of water by weight in concrete evaporated.

CONCLUSIONS

The analysis and the heating tests of the small models of composite sandwich walls of plates and concrete with heat-bridges were carried out and the following conclusions can be obtained.

1) The analysis which did not take the effect of moisture in concrete into account gave higher temperatures in cross section of the walls than those measured in the heating tests, i.e., the analysis gave a temperature distribution which lie on safe side from the viewpoint of fire safety design. The temperatures of unexposed plate obtained by the heating tests were about a half of those obtained by the analysis.

2) The temperature within 75% of the total cross sectional area of the wall including the unexposed surface plate did not exceed 400℃, after two hours of heating up to close 1000℃ on the fire exposed wall surface.

3) The walls with heat-bridges showed higher heat transfer from fire-exposed surface to unexposed surface and dispersion of heat in concrete in accordance with the amount of steel, than the one without the heat-bridge. In this case, the web plate in the wall transferred heat most effectively. However, if the depth of the wall is thicker than 20cm, the temperature of the unexposed surface does not exceed 100℃ for two hours of fire exposure, which is lower than the ignition temperature of wood, 260℃.

4) The wall without a heat-bridge has uniform distribution of the heat-flow. On the other hand, regarding the walls with heat-bridges, heat-bridges affect the temperature distribution in concrete. However, the influenced region in concrete was limited up to 12.5 cm from the heat-bridge axis.

5) Though the water content of concrete enclosed by steel was 7.36% and high, the explosive failure of concrete was not observed during heating test. The evaporation continued until the end of heating.

6) Since the water plays an important role in temperatures and behaviour in case of concrete enclosed by steel such as composite sandwich walls of plates and concrete, further studies on effect of moisture are needed.

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