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Development of the Fire-Protective System (Membrane System) Using Fire-Resistant Steel for Cooperative Houses

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Abstract

Fire-resistant steel for building structure (FR Steel) is the one whose high-temperature intensity is improved by adding alloy elements (e.g. molybdenum) with heat-resistance enhancing ability. At 600°C, the steel has a yield point over 2/3 of the specification value at room temperature, which is long-term permissible stress. On the other hand, a fire temperature reaches about 1,000°C in the case of a fire in a building with a lot of inflammables such as a house, therefore, applying FR steel to this kind of building could not omit insulating shield, rock wool for example. With cooperative houses as our target, we have developed steel-framed construction using FR steel without fire-resistant shield and its fire-resistance designing method, which makes use of the thermal insulation effects of the interior materials (walls and ceilings).

1. Introduction

Strength of the steel used in steel-framed building lowers by heat during fires. In steel-framed buildings for many and unspecified persons (special construction: Article 27 of the Buildings Standard Law of Japan) and built in town areas (Article 61 and 62 of the same Law), steel-frame protection by fire protection, rock wool for example, are required by the Law. The fire protection partly contributes to hampering the competitiveness of steel-framed buildings in terms of not only construction costs, but also shortening construction period and work environment of spraying (labor shortage, scattering to surrounding areas or curing). Recently there have been many attempts to adopt steel frame itself into building designs. The realization of steel-framed construction without fire protection has been awaited in this respect.

Fire-resistant steel for building structure (FR steel) was developed in 1988 in response to these needs. At high temperature, the yield strength of this steel is greater than that of conventional steels. At 600°C, the steel has the yield strength over 2/3 of the specified yield strength at room temperature, which is allowable stress for long time loading (equivalent to the permissible temperature being 600°C). That enables omitting fire protection for buildings with only a few inflammables, such as multistory parking space or atrium, whose steel-frame temperature will not exceed 600°C even during a fire. On the other hand, a fire temperature goes well over the permissible temperature of FR steel (about 1,000°C) during a fire in a building with a lot of inflammables such as a house, therefore, applying FR steel to this kind of building can not omit fire protection.

Inside a house, interior materials (noncombustible materials) such as walls and ceilings are installed. Although their thermal insulation effects can be expected, the materials are not used as fire protection of steel-frame members. Since gaps form at joint sections of the interior materials when they are heated by a fire, conventional steel

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(permissible temperature: 350°C) is difficult to secure the required performance (steel-frame temperature should be below 350°C at specified fire heating).

Fire protection is obligated for cooperative houses (higher than three stories) by Article 27 of the Buildings Standard Law of Japan. Our target in this development is to omit fire protection by applying FR steel superior in high-temperature performance to columns and beams and using the thermal insulation effects of the interior materials (the FR Steel Fire-Protective System (Membrane System) hereinafter).

2. Characteristics of FR Steel

High-temperature strength of FR steel is further improved by adding alloying elements with heat-resistance improving ability (e.g. molybdenum). **Fig. 1** shows temperature dependency of the strength of FR steel (NSFR400) and conventional steel (SS400). The yield strength (YP) of conventional steel decreases almost linearly with increasing temperature. At around 350°C, it decreased to 2/3 (157 N/mm^2) of the specification at room temperature. FR steel, on the other hand, has less tendency of decrease in YP than conventional steel. At 600°C, it maintains higher than 2/3 YP of the specification at room temperature. As for tensile strength (TS), both conventional steel and FR steel show almost similar tendency, but FR steel at 600°C is about twice as strong as conventional steel.

3. Fire-resistant Designing Method

Fig. 2 shows the fire-resistant designing flow of the fire-protective system (membrane system) using FR steel. Since house fires have virtually the same as the standard time-temperature stipulated in Notification of the Ministry of Construction No. 2999 (standard time-temperature hereinafter), this fire-resistant designing does not estimate fire performance (estimation of fire temperature or fire duration) but adopts standard time-temperature. To prevent fire spreading (performance to prevent fire spreading to adjacent sections), the performance of fire retarding division (in specified fire heating, the performance to keep the temperature of non-fire sections below 260°C, the ignition temperature of wood) is confirmed by fire endurance test or heat transmission analysis.

Although this fire-resistant designing can be applied to all cooperative houses regardless of the number of stories, this report explains the conformation method of destruction prevention performance taking an example of cooperative houses of lower than four stories (required fire endurance time: 1 hour).

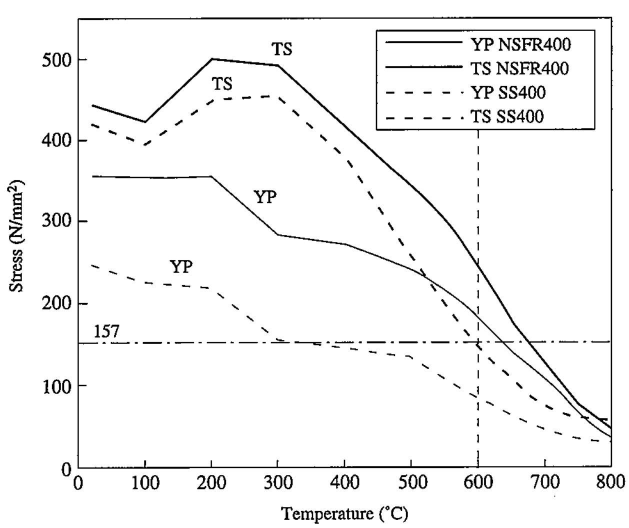

Fig. 1 Temperature dependency of high-temperature strength

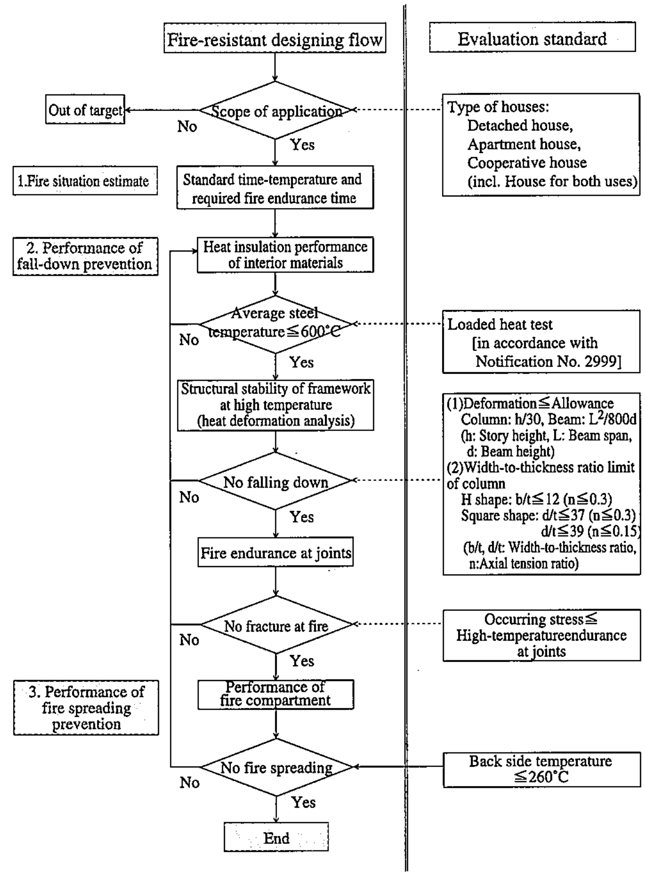

Fig. 2 Fire-resistant designing flow

4. Thermal Insulation Performance of Interior Materials

The thermal insulation performance of interior materials is confirmed by the loaded heat tests stipulated in Notification of the Ministry of Construction No. 2999. The followings are the results of the loaded heat tests of columns and beams.

4.1 Test specimens

Two test specimens were prepared: thermally insulated columns and beams for walls and ceilings using plaster board frequently used in cooperative houses (Membrane system hereinafter). In order to enhance thermal insulation performance of walls and ceilings, the reinforced plaster board stipulated in JIS A 6901 (plaster board hereinafter). Because such columns and beams not fit within walls and ceilings (beams in stairwell, for example) can be assumed, two test specimens were also prepared, whose columns and beams are directly surrounded by plaster board (surrounding type hereinafter). **Table 1** shows test conditions, **Table 2** the mechanical properties of FR steel used in the tests (column: STKR400-FR, beam: SM400-FR) at room temperature and 600°C, and **Table 3** the moisture content and the specific gravity of the plaster board.

4.1.1 Column

The shape of the membrane system specimen is shown in **Fig. 3**. At the center of the specimen frame, FR-steel column (□ – 125×125×3.2, STKR400-FR) is set up and to the inner walls plaster

Table 1 Test condition

Kinds of test		Interior materials	Test number	Code	Test place
Column	Membrane	Reinforced plaster board (thickness 15 mm)	2	CM1,2	Japan Testing Center for Construction Materials
Column	Surrounding type	Reinforced plaster board (thickness 15 mm)	2	CE1,2	General Building Research Corporation
Beam	Membrane	Reinforced plaster board (thickness 12.5 mm×2)	2	BM1,2	Japan Testing Center for Construction Materials
Beam	Surrounding type	Reinforced plaster board (thickness 15 mm)	2	BE1,2	Japan Testing Center for Construction Materials

Table 2 Mechanical properties

Kind		Yield point (N/mm^2)		Tensile strength (N/mm^2)	Elongation (%)
		Room temperature	600°C		
Column	STKR400-FR (3.2mm)	424	214	478	23
Beam	SM400-FR (4.5mm)	362	184	470	35
	Standard rate	More than 245	More than 157	More than 400	More than 23

Table 3 Moisture content and specific gravity of plaster board

Kind		Kind of plaster board (thickness)	Moistrure content	Specific gravity	Dryness situation
Column	Membrane	Reinforced plaster board (thickness 15 mm)	0.20%	0.78	7-day drying at 40°C
Column	Surrounding type	Reinforced plaster board (thickness 15 mm)	0.17%	0.87	
Beam	Membrane	Reinforced plaster board (thickness 12.5 mm×2)	0.50%	0.80	7-day drying at 40°C
Beam	Surrounding type	Reinforced plaster board (thickness 15 mm)	0.20%	0.78	

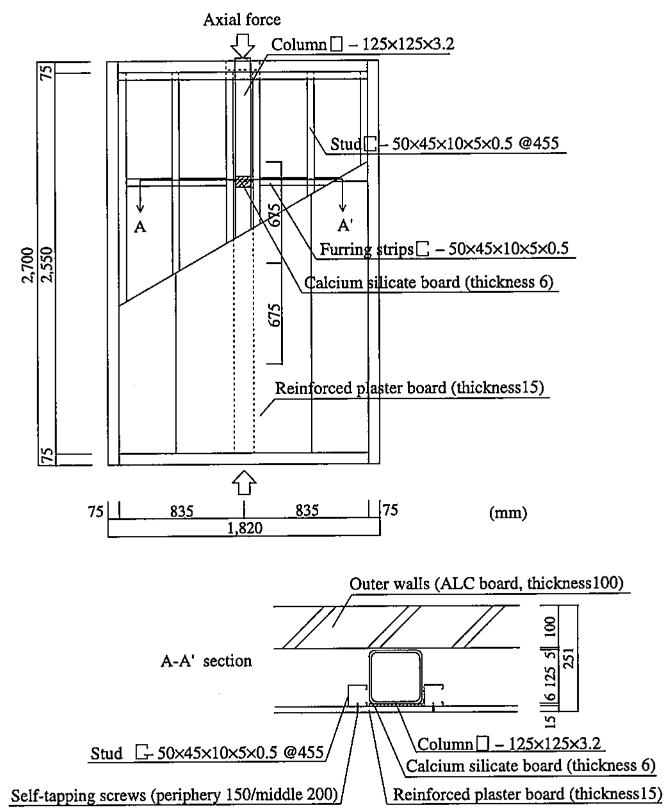

Fig. 3 Shape of the test specimen (column, membrane)

board (15 mm in thickness) is attached with self-tapping screws and to the outer walls ALC board (100 mm in thickness) is installed. The installed foundation of the plaster board is steel.

Fig. 4 shows the shapes of the surrounding type test specimen. The plaster board (15 mm in thickness) is installed to FR-steel column (□–125×125×3.2, STKR400-FR) with plaster-type adhesive. Spacers (6 mm in thickness, 600 mm) are sandwiched between plaster board and columns. In addition, corner covers (L–30×30×0.4) are installed to the corners.

4.1.2 Beams

Fig. 5 shows the shapes of the membrane test specimen. At the center of the test specimen frame, FR-steel beams (H–150×100×3.2×4.5, SM400-FR) is installed, and ALC board (100 mm in thickness) is installed thereon as the floor board. Plaster boards (12.5 mm, 2 pieces) as ceiling materials are installed with self-tapping screws to the steel foundation (furring strips) hung from the floor board.

Fig. 6 shows the shapes of the surrounding type test specimen. At the center of the test body frame, FR-steel beams (H–300×150×3.2×4.5, SM400-FR) is installed, and ALC board (100 mm in thickness) is installed thereon as the floor board. At each side of the beam, plaster board (15 mm in thickness) is installed by screws to fiber-reinforced calcium silicate board attached to the beam web. Plaster board (15 mm in thickness) is installed by self-tapping screws and plaster-type adhesive to the underside of the beam. Spacers (6mm in thickness, 600mm) are sandwiched between the beam flange and the plaster board on the beam underside. In addition, corner covers (L–30×30×0.4) are installed to the corners.

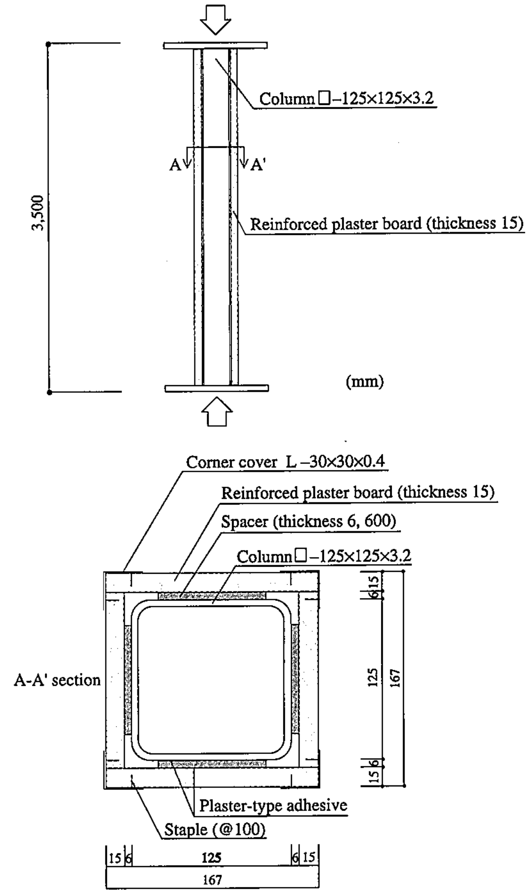

Fig. 4 Shape of the test specimen (column, surrounding type)

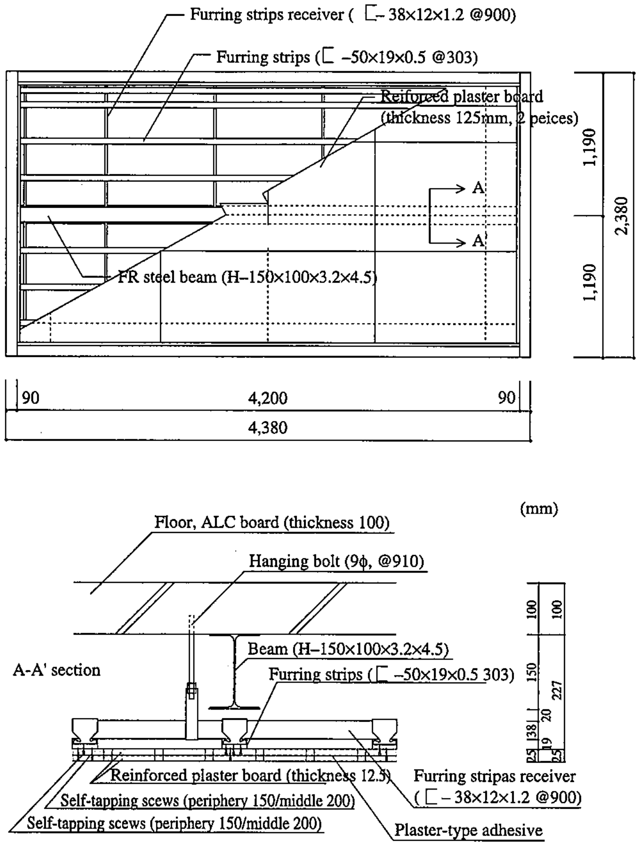

Fig.5 Shape of the test specimens (beam, membrane)

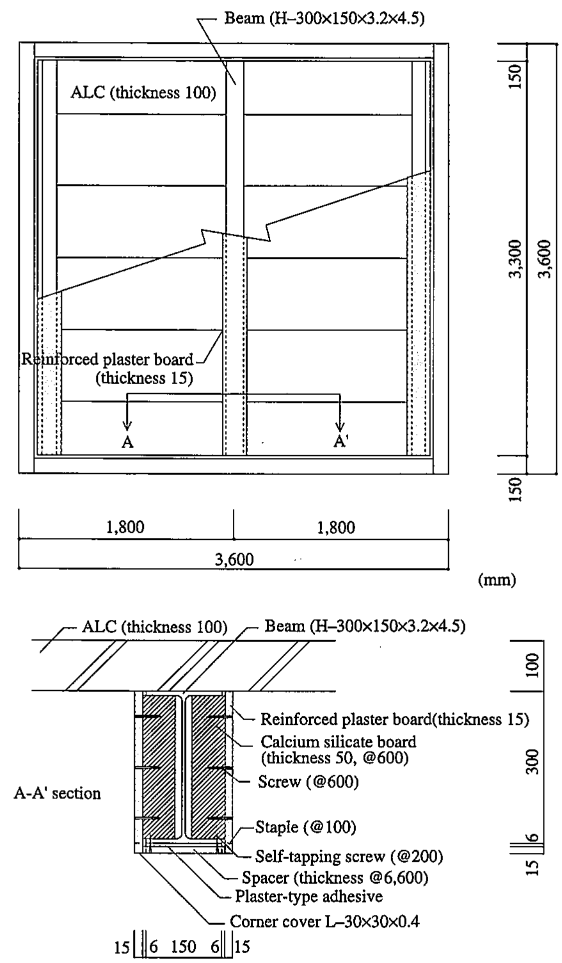

Fig. 6 Shape of the test specimens (beam, surrounding type)

4.2 Test method

The test was conducted to conform to the loaded heat tests described in Notification of the Ministry of Construction No. 2999. The followings are the criterion for the test results.

For fire heat (standard-time temperature) lasting during the required fire endurance time,

(1) The average steel temperature should not exceed 600°C, the allowable temperature of FR steel.

(2) The member deformation should not exceed the following values:

Column: Axial contraction $\leq h/100$ (mm)
Axial contraction speed $\leq 3h/1,100$ (mm/min)
Here, h: span of column (mm)

Beam: Deflection $\leq L^2/400$ d (mm)
Deflection speed $\leq L^2/9,000$ d (mm/min)
Here, L: span of beam (mm), d: height of beam (mm)

4.2.1 Column

The membrane system test specimen is tested in the furnace for walls at Japan Testing Center for Construction Materials. The span of the columns (distance between fulcrums) is 2,550 mm. Load is set to 11.03 t, a load corresponding to axial tension ratio = 0.3 based on the investigation of column axial tension (maximum axial tension ratio = 0.28) for cooperative houses. As an indoor fire was assumed, one-side (interior wall) heating was adopted. The test was completed when the columns could no longer support the load. In this report, time to collapse is defined by this time at which the load could not be supported.

The surrounding type test body is tested in the furnace for columns at General Building Research Corporation. The span of the columns (distance between fulcrums) is 3,500 mm, the effective length of heating is 3,000 mm. The test specimen was heated from all-around direction, and the test was completed at the time described above.

4.2.2 Beam

The membrane test specimen is tested in the furnace for beam at Japan Testing Center for Construction Materials. The span of the beam (distance between fulcrums) is 4,200 mm. Load equivalent to 180 kg per 1 m^2 (housing live load stipulated in the Buildings Standard Law of Japan) is applied on the floor board. In addition, either of smaller one among the load producing allowable stress for sustained loads (1,600 kgf/cm^2) in outer peripherals of the beam and the load causing the deflection of L/300 (L: span of the beam) at the beam center was applied directly. The heating was completed when the beam could not sustain the load any longer.

The surrounding type test specimen is tested in the horizontal furnace at the Japan Testing Center for Construction Materials. The span of the beam (distance between fulcrums) is 3,300 mm. The loading method and the end of the test are the same as stated above.

4.3 Test results

4.3.1 Column

In the case of the membrane test specimen, steel temperature (average temperature) is shown in **Fig. 7**, elongation and out-of-plane deformation of the column are shown **in Fig. 8**, and appearances of the test specimen before and after the test are shown in **Photo 1**. As for the steel temperature stagnation in temperature rise (approximately 100°C) due to the water evaporation of plaster board was observed (same in each of the following tests). The steel temperature in one hour is below 600°C in both cases. The collapse of column (CM1) occurs at steel temperature 694°C (time to collapse: 95 min). The out-of plane deformation of column increases from 20 to 40 min of heating, then decreases. This can be attributed to the temperature difference within the column sections. The fall-off of plaster board does not occur until the test ends.

In the case of the surrounding type test specimen, steel temperature (average temperature) is shown in **Fig. 9** and column elongation is shown in **Fig. 10**. The steel temperature in one hour is below 600°C in both cases. The collapse of column (CM1) occurs at steel temperature 790°C (time to collapse: 81 min). The fall-off of plaster board does not occur until the test ends.

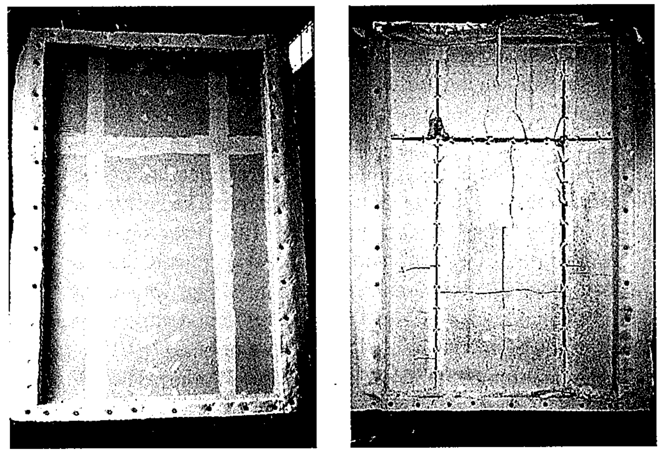

Photo 1 Test specimen before and after test (column, membrane)

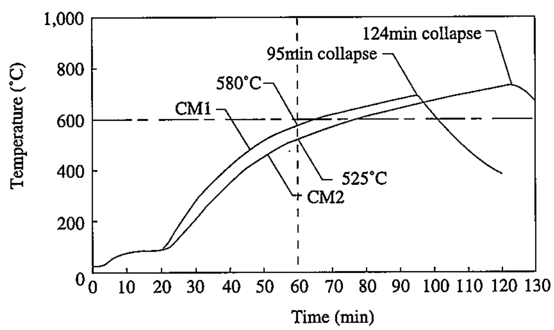

Fig. 7 Steel temperature (Column, membrane)

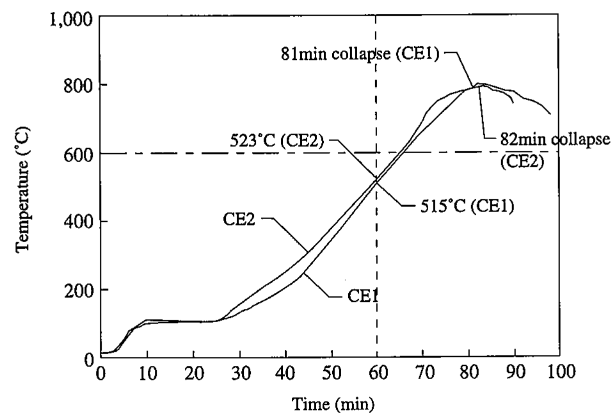

Fig. 9 Steel temperature (column, surrounding type)

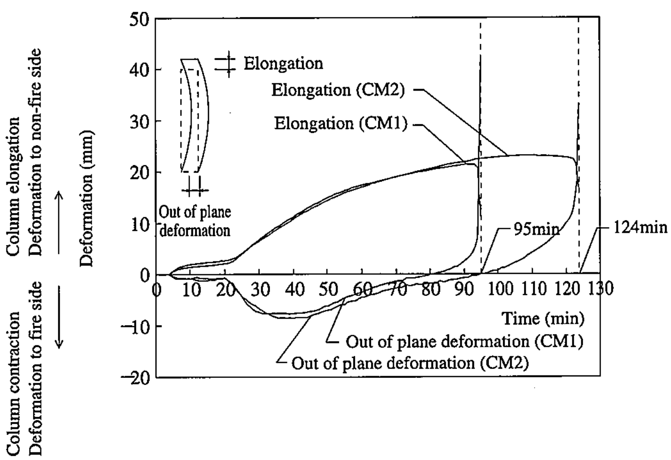

Fig. 8 Column elongation and out-of-plane deformation

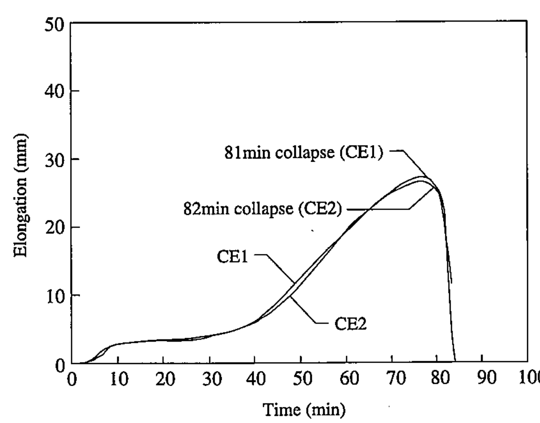

Fig. 10 Column elongation (column, surrounding type)

4.3.2 Beam

In the case of the membrane test specimen, steel temperature (average temperature) is shown in **Fig. 11**, beam deformation is shown in **Fig. 12**, and the appearances of the test specimen before and after the test are shown in **Photo 2**. The steel temperature in one hour is below 600°C in both cases. The outer lining of plaster board (BM1) falls off in 55-min heating and the inner lining in 64-min heating. The fall-off of the inner lining causes direct heating of the beam, thus abrupt rise of the steel temperature occurs. The collapse of beam (BM1) occurs at steel temperature 691°C (time to collapse: 68 min).

In the case of the surrounding type test specimen, the steel temperature (average temperature) is shown in **Fig. 13** and the beam deformation is shown in **Fig. 14**. The steel temperature in one hour is below 600°C in both cases. The collapse of beam (BE1) occurs at steel temperature 695°C (time to collapse: 70 min). The fall-off of lower plaster board occurs just before the collapse, but side plaster board does not fall off until the test ends.

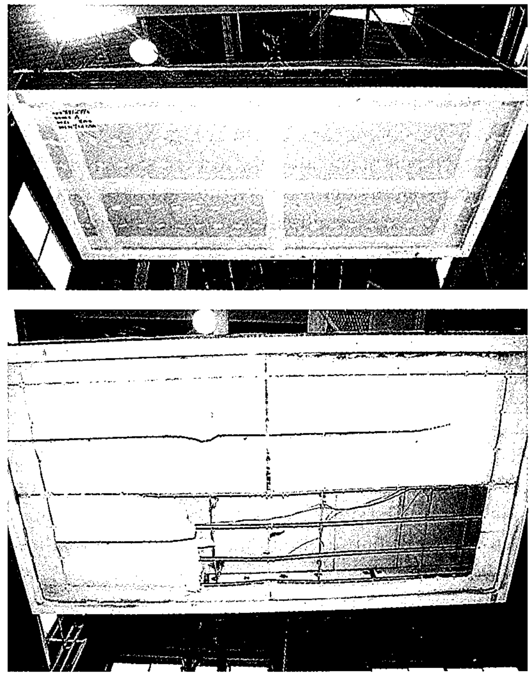

Photo 2 Test body before and after test (beam, membrane)

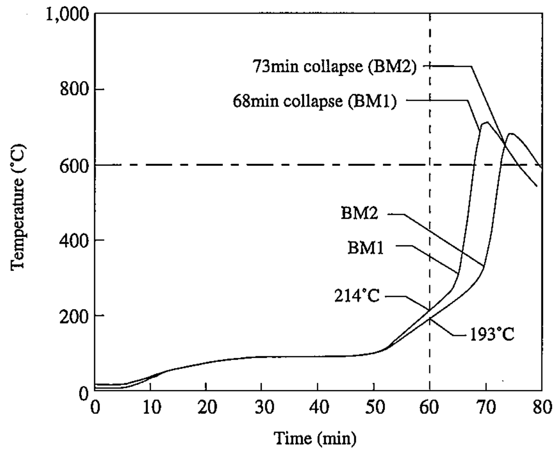

Fig. 11 Steel temperature (beam, membrane)

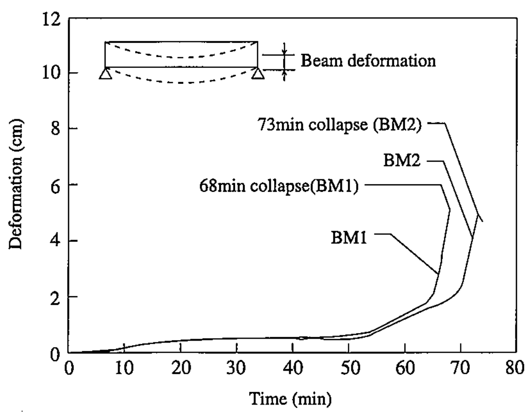

Fig. 12 Beam deformation (beam, membrane)

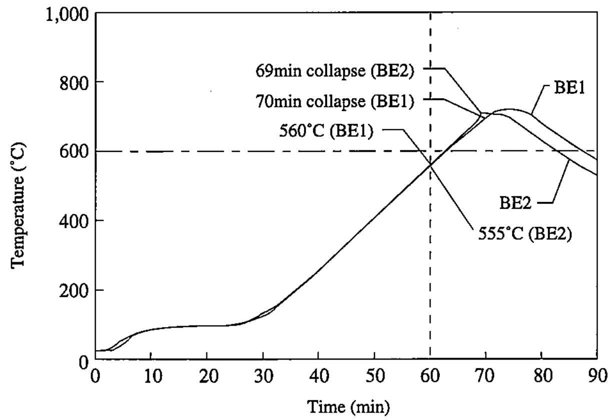

Fig. 13 Steel temperature (beam, surrounding type)

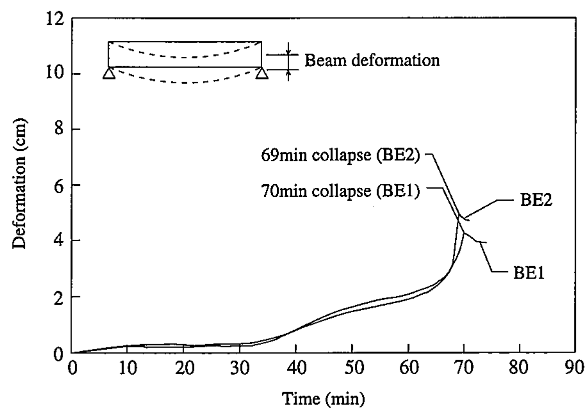

Fig. 14 Beam deformation (beam, surrounding type)

4.4 Summary

Conducting the loaded heat tests of FR steel column and beam that are thermally insulated (membrane system and surrounding type) with plaster board reveals:

(1) Column: Fire endurance equivalent one-hour fire endurance is displayed by the insulation of 15mm in thickness for both membrane system and surrounding system (condition: axial tension ratio: less than 0.3).

(2) Beam: Fire endurance equivalent of one-hour fire endurance is displayed by the insulation of 2 pieces of plaster board of 12.5 mm in thickness for membrane system and 15 mm-thick plaster board for surrounding type.

5. Structural Stability of Framework

5.1 Outline of consideration method

The structural stability of framework is verified by using elasto-plastic thermal deformation creep analysis[1]. In fire, as a result of rise in steel temperature, the mechanical properties of steel changes. This analysis calculates the rigidity and stress of each small member divided into material axial direction (each temperature) using stress-deformation curve at high temperature. This stress produces the contact force of each small member and convergence calculation is done until force balances at each contact point connecting small members in order to get deformation shapes of framework at high temperature.

An example of the analysis result is shown in **Fig. 15**. Thermal expansion of steel gives rise to deformation. In particular, low-rigidity outer column shows considerable deformation (horizontal deformation) produced by thermal expansion of the beam. The concern is lowered load bearing capacity of column as a result of the local buckling. Therefore, the load bearing capacity of the column was estimated using beam-column test at high temperature[2] described later and the allowable horizontal deformation of the column (h/30, h: story height) was set. The allowable deformation of the beam was set at $L^2/800$ d (L: span of the beam, d: height of the beam) according to the previous study[3]. In the above analysis, the heat deforma-

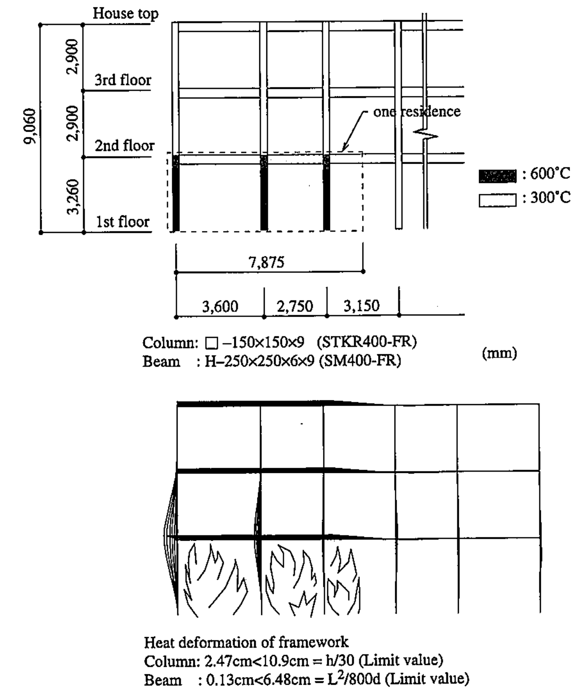

Fig. 15 Example of heat deformation analysis

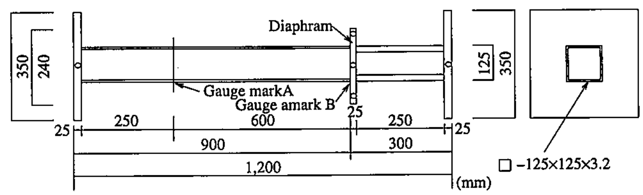

Fig. 16 Shape of test specimen

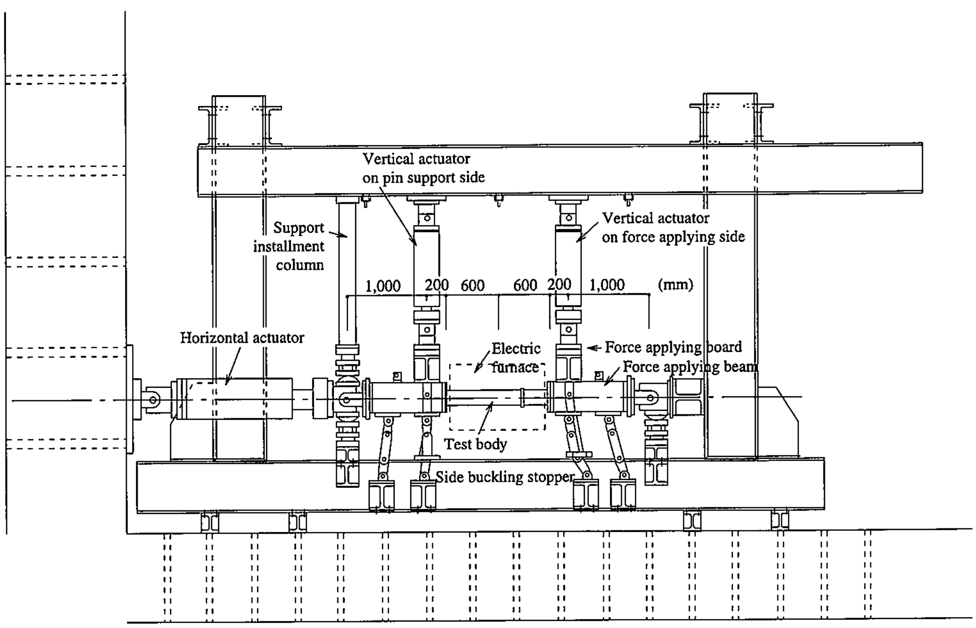

Fig. 17 Force applying equipment

tion of the framework is kept below the limit.

5.2 Beam-column test at high temperature of column

5.2.1 Test specimen

Fig. 16 shows one example of the test specimen. Column is square tube (□−125×125×3.2, STKR400-FR) produced by roll-forming of a hot-rolled FR steel plate.

Among columns used for cooperative houses lower than 4 stories, this column has the maximum width-to-thickness ratio (ratio of column width and plate thickness) of 39. The greater the width-to-thickness ratio is, the lower the local buckling resistance.

5.2.2 Test method

Force applying equipment (Chiba University) is shown in **Fig. 17**. In order to reproduce the stress situation of column during a fire, a horizontal actuator applies compressive force (column axial force) corresponding to 15 to 30% of yield axial force (σ_y = 235 N/mm^2) to column in this test. In addition, bending deformation (reproducing extension of the beam by thermal expansion) was caused by a vertical actuator on the force applying side, so that the column reaches collapse mode. Force was applied when the test specimen had been heated to given temperatures (test temperatures: room temp., 500°C, 600°C, and 650°C).

5.2.3 Test results

Fig. 18 shows an example of the test results (width-to-thickness ratio 39, axial tension ratio 0.15). The ordinate shows a dimensionless parameter of the bending moment (M_c) at B point divided by the total plastic moment (M_p) of the column at room temperature. The abscissa shows a member angle given by dividing the relative deformation (σ_B) between A and B by the gauge length (600 mm). The test results reveals that a square tube (width-to-thickness ratio 39, axial tension ratio 0.15) using FR steel possesses enough load-bearing capacity and deformation capacity even after the steel temperature reaches 650°C.

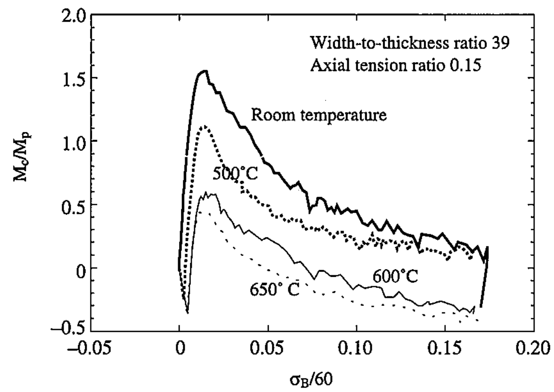

Fig. 18 Force applying test result

6. Fire Endurance Performance of Joints

The fire endurance performance is confirmed to secure the same or better high temperature endurance compared with the mother material, by using FR steel joint materials superior in high temperature performance[4].

7. Conclusion

This development establishes the fire-resistant designing of the Fire-Protective System (membrane System) using FR steel and enables applying FR steel without fire protection to cooperative houses. This development first realizes the application of FR steel without fire protection to buildings with a lot of inflammables. It is expected that this system will be expanded to other uses such as office buildings.

Acknowledgements

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