NIPPON STEEL TECHNICAL REPORT No. 66 JULY 1995

UDC691.714:699.81

Development of Fire-Resistant Steel Frame Building Structures

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Abstract:

Eliminating the fire-resistant coating of steel frame buildings would result in lower construction costs, a shorter construction period, more effective interior space utilization, better working environment, and more aesthetic building designs. As a replacemet for fire-resistant coatings, "comprehensive fire-resistant design system for building fire safety" was developed as part of a comprehensive technology development project of the Ministry of Construction. Fire-resistant (FR) steels and stainless steels were developed that feature elevated-temperature properties (fire resistance) superior to those of conventional steels. These developments have made it possible to eliminate fire-resistant coatings in some building applications. The fire-resistant steels and stainless steels for building structural use are described, and examples of fire-resistant building structures constructed from these materials are introduced.

1. Introduction

When a fire occurs in a steel frame building, its heat reduces the strength of the steel and hence that of the building. The present Building Standards Law prescribes the fire protection by fire-resistant coatings of the steel frames of buildings to be used by an unspecified number of people and of buildings in urban areas. The 3-hour fire-resistance rating specified for high-rise buildings, for example, calls for steel frames to be fireproofed with 5-cm thick wet-sprayed rock wool, so that the average steel frame temperature remains at 350℃ or less when the steel frame is heated by fire to about 1,000℃ for 3 hours. This fireproofing requirement translates into a cost increase of ￥50,000 to ￥60,000 per ton of steel when the finishing material is included. This was one factor responsible for the low-cost competitiveness of steel frame buildings. In order to shorten the construction period, make more effective use of interior space, there were extremely pressing needs for reducing the fire-resistant coating work cost as well as eliminating the fire-resistant coating. Improving the fire-resistant coating material spraying work environment is also imperative in view of the construction industry labor shortage and the need for necessary protection against dispersion of sprayed materials to the surrounding area. There also were many attempts to incorporate the steel frames themselves into the architectural design of buildings, so elimination of fire-resistant coatings was desirable in this respect as well.

In the comprehensive technology development project of the Ministry of Construction called the "Development of Comprehensive Fire-Resistant Design System for Building Fire Safety" and implemented from 1982 to 1987, techniques[1] were

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developed for comprehensively evaluating the fire safety of buildings from the fire and design conditions of buildings and the performance of building materials without referring to the specifications based on the Building Standards Law. In response to the new fire-resistance design system, there emerged two major trends concerning the elimination of fire-resistant coatings on steel frame buildings. One trend was the development by Nippon Steel in 1988 of building structural fire-resistant steels with elevated-temperature properties (fire resistance) superior to those of conventional steels for buildings. The use of fire-resistant steels reduced the need for fire-resistant coatings as compared with conventional steels, and permitted the elimination of fire-resistant coatings in some building applications. The other was the study of the fire-resistance of stainless steels based on the new fire-resistance design system as part of the comprehensive technology development project of the Ministry of the Construction "Development of New Materials and New Material Utilization Techniques in the Construction Industry" from 1988 to 1992. The results of this study led to the incorporation of the new fire-resistance design system in the "Technical Guidelines for Utilization of New Stainless Steels"[2]. This development allowed the use of uncoated stainless steel members under certain building conditions.

This article outlines the fire-resistant steels and stainless steels used as fire-resistant building structural materials, and introduces examples of fire-resistant building structures built with these materials.

2. Characteristics of Fire-Resistant Steels and Stainless Steels

Fire-resistant steels are conventional steels that are microalloyed with chromium or molybdenum to obtain dramatically improved yield strength. After rolling, they are produced by the same process as conventional steels. Steels decrease in yield strength with increasing temperature. **Fig. 1** compares the elevated-temperature yield strength (yield point) of a fire-resistant steel and a conventional steel (results not uniform). The added effects of an earthquake or storm are not considered when a building is on fire. The building must be strong enough to support its own weight or must meet allowable stress for sustained loading. Notification No. 2999 of the Ministry of Construction specifies the allowable temperatures of steels in fires at an average of 350℃ and prescribes the fire-resistant coating of steels to limit their temperature at or below 350℃ during a fire. This is because the elevated-temperature yield stress of conventional steels falls to two-thirds of their room-temperature yield stress or allowable stress for sustained loading (217 N/mm² for JIS G 3106 Grade SM490A) as shown in **Fig. 1**, and becomes lower than the yield strength required of buildings when exposed to fire. Fire-resistant steels are guaranteed so that their elevated-temperature yield stress should remain above the allowable stress for sustained loading at temperatures up to 600℃ (this guarantee is written on their mill sheets), and have much higher elevated-temperature yield strength than conventional steels. Fire-resistant steels have the following characteristics:

(1) Their elevated-temperature yield strength is extremely high compared with conventional steels (see **Fig. 1**). (It is guaranteed that the yield stress at 600℃ is equal to or higher than two-thirds of the specified room-temperature yield strength.)
(2) Their room-temperature performance meets the standards: JIS G 3106 - Rolled Steels for Welded Structures and JIS G 3136 - Rolled Steels for Building Structures. (Their design for room-temperature performance is the same as that of conventional steels.)
(3) Their weldability is the same as that of conventional steels.

Stainless steels[3] are iron-based alloys with chromium or chromium and nickel added to impart excellent corrosion resistance. The types and standards of stainless steels that can be used as building materials are shown here. These stainless steels are all austenitic and are available in the following strength levels:
(1) SUS304, SUS316, SCS13A: As strong as SS400
(2) SUS304N2: As strong as SM490

Commonly called 18-8 stainless steel, SUS304 contains about 18%Cr and 8%Ni, is the most popular stainless steel, and is as strong as the carbon steel SS400. SUS304N2 is SUS304 with added nitrogen and niobium, and is as strong as the carbon steel SM490. SUS316 contains molybdenum and other alloying elements. It features higher corrosion resistance than SUS304. Combining excellent corrosion resistance and heat resistance, stainless steels have been widely used as heat-resistant steels for pressure vessels and boiler tubes. **Fig. 2** compares the elevated-temperature strength of the stainless steel SUS304 and carbon steel SS400. At temperatures close to 200℃, the stainless steel loses the effect of heat treatment (work hardening) during manu-

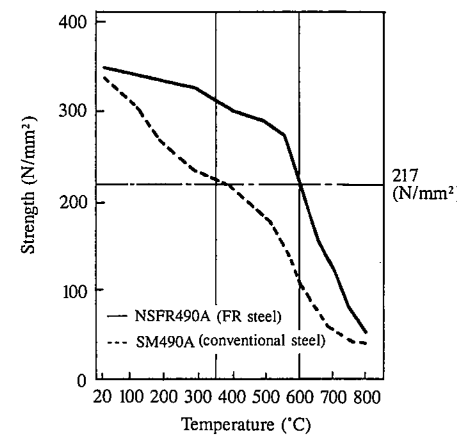


Fig. 1 Temperature dependence of yield strength of steels

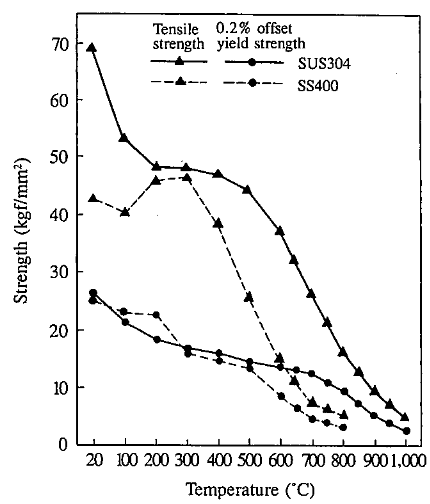


Fig. 2 Elevated-temperature strength of stainless steel

facture and its yield point declines. The rate of this yield point drop is extremely small until the temperature exceeds 700℃. Since the yield point initially decreases due to the loss of work hardening, the temperature at which the yield point falls below two-thirds of the specified room-temperature yield strength is about 500℃, which is lower than for the fire-resistant steels, but the rate of yield point decrease in the temperature region over 600℃ is smaller than that of fire-resistant steels.

3. Fire-Safe Design Guidelines for Buildings

Buildings constructed of fire-resistant or stainless steels do not meet some of the provisions of the Building Standards Law. One example is that their column and beam temperatures in fires are higher than the temperature of 350℃ specified for conventional steels. Irrespective of whether they are protected by thinner fire-resistant coatings or not protected by fire-resistant coatings, fire-resistant or stainless steel frame buildings must be individually designed to maintain fire safety, and be approved by the Minister of Construction as specified in Article 38 of the Building Standards Law. Nippon Steel commissioned the Building Center of Japan to prepare the "Fire-Resistance Design Guidelines for Buildings Constructed of Fire-Resistant Steels", and the Building Center of Japan completed the guidelines in January 1989. The fire-resistance design of each building constructed of fire-resistant or stainless steels is reviewed in the fire-resistant performance appraisal of the Building Center of Japan. The guidelines were disclosed to four companies, including other integrated steelmakers, in October 1990, and are applied by these companies to fire-resistant steels.

Fig. 3 shows the fire-resistant design flow specified in the guidelines. The fire-resistant design flow is based on the "Comprehensive Fire-Resistant Design System for Building Fire Safety". Use of fire-resistant steels has made it necessary to

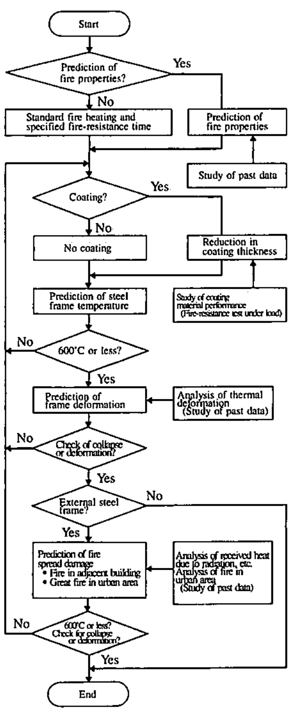


Fig. 3 Fire-resistant design flow

introduce the following criteria not covered in the Building Standards Law:

(1) In place of the conventional fire resistance test, in which the temperature of steel exposed to the standard fire is measured, a fire resistance test under load for evaluating the load carrying capacity of building members (columns and beams) at elevated temperatures to guage their fire-resistance.

(2) A technique for verifying the fire safety of steel frames by measuring the thermal deformation that rises with increasing steel temperature to 600℃.

(3) A technique for verifying the damage of steel frames in external steel frame buildings from a widespread fire in an urban area where many wooden houses are located.

The Japan Stainless Steel Association, which was founded in 1959, formed a joint government-private research agreement with the Building Research Institute, Ministry of Construction, and organized the "New Stainless Steel Utilization Technology Subcommittee". The subcommittee clarified the elevated-temperature performance of stainless steels and the fire-resistant performance of stainless steel members and frames, and established the fire-resistance design methods that reflect the excellent elevated-temperature strength (as representative of mechanical properties) of stainless steels. The fire-resistance design methods are incorporated in the "New Stainless Steel Utilization Technology Guidelines" published in 1993. The basic fire-resistance design flow of the new fire-resistance design methods is the same as described for fire-resistant steels. The exceptions are that stainless steel members with low design stress can be used unprotected at temperatures above 600℃ or the temperature at which fire-resistant steel members must be protected.

4. Application of Fire-Resistant Steels and Stainless Steels to Buildings, and their Performance Results without Fire Protection

If the above-mentioned fire-resistance design methods are followed, fire-resistant steels and stainless steels with excellent elevated-temperature strength can be used unprotected in buildings with few combustible materials or where the steel surface temperature is low when exposed to fire. Nippon Steel has developed building applications where the fire-resistant steels and stainless steels can be used unprotected. It has constructed many buildings where the fire-resistant steels and stainless steels are used without fire protection measures. **Fig. 4** shows the change in the number of buildings constructed of fire-resistant or stainless steels without fire protection and individually approved by the Minister of Construction. Among the main applications are open multistory parking lots of the self-drive type (hereinafter referred to simply as parking buildings), swimming pool and all-weather tennis court roofs, sports facilities, atria, and external steel frame structures designed to achieve aesthetic effects. Stainless steel buildings constructed by Nippon Steel and individually approved by the Minister of Construction have been increasing yearly, particularly so with parking buildings.

Buildings to be constructed of fire-resistant steels and stainless steels must be individually designed for fire resistance and approved by the Minister of Construction under Article 38 of the Building Standards Law. It is a costly and time consuming process for the users of fire-resistant steels and stainless steels to acquire individual approval from the Minister of Construction.

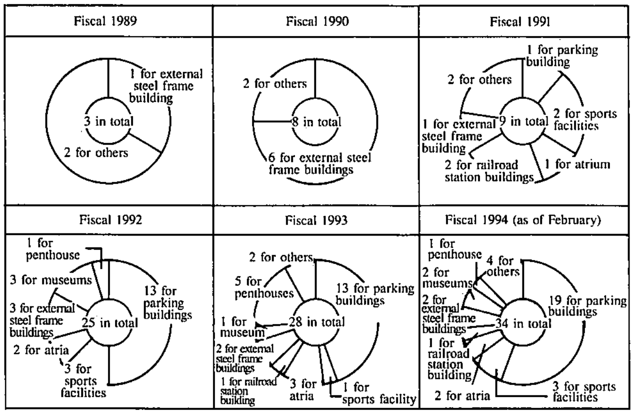


Fig. 4 Change in number of individual approvals obtained as to fire-resistant steels and stainless steels for building applications without fire protection

Table 1 General scope for approval of parking buildings

Scale of parking building	General approval pattern	Operation
1, Exclusively for parking 4 stories or less and total floor area of 20,000 m² or less 2, Combined with other application 4 upper stories or less and total floor area of 20,000 m² or less	Five integrated steelmakers individually acquire general approval under design responsibility.	Each integrated steelmaker prepares design documents, attaches them to building confirmation application form, and acquires building confirmation.

To eliminate this cumbersome procedure, those concerned are working to have the fire-resistance design methods of fire-resistant steels and stainless steels generally approved by the Minister of Construction for building applications where fire-resistant steels and stainless steels are used in large quantities. By the time this article is published, the use of fire-resistant steels and stainless steels in parking buildings will be already generally approved by the Minister of Construction with the scale limitations shown in **Table 1**.

5. Applied Examples of Fire-Resistant Steels without Fire Protection

Applied examples and fire-resistant design methods of fire-resistant steels are described below. Since the completion of the New Stainless Steel Utilization Technology Guidelines in 1993, stainless steels have not yet been used in fire-resistant applications. It is hoped that stainless steels will be approved for use in fire-resistant structural applications as soon as possible.

5.1 Parking building - Sen City Park Plaza Building

5.1.1 Building particulars

Owner: Chiba Sogo and others
Design: Urban Dynamic Institute of Takaha
Construction: Joint venture of Taisei, Kajima, Okumura, Fudo Construction, and Asahi Kensetsu
Steel frame fabrication: Hanwa
Subcontractors: Kawakami Tekko, Ohkawa Tekko, and Itoh Yousetsu Kogyo
Building area: 7,171 m²
Total floor area: 86,324 m²
Number of stories: 17 above ground and 2 below ground

Constructed in front of the JR Chiba Station in Chiba City, the Sen City Park Plaza Building is Japan's largest parking building, standing 17 stories above ground with space for 1,800 cars. Its typical floor plan, section, and general view are shown in **Fig. 5**, **Fig. 6**, and **Photo 1**, respectively. Shops ocupy the levels up to the fourth floor, and car lot spaces the other levels. Drivers enter the parking structure at the gate on the fifth floor through an external circular rampway on the east side and drive through a series of internal circular rampways to reach their desired parking space. Each parking lot is a hexagon with 39.5 m per side that surrounds a circular rampway. **Photo 2** shows a parking lot constructed with fire-resistant steel. The parking lot is framed in the span direction, braced in the longitudinal direction (periphery of the hexagon) and is constructed like a bird cage pattern by K-braces.

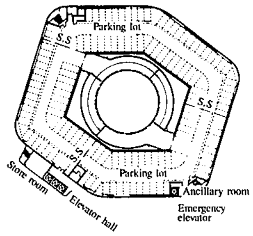


Fig. 5 Typical floor plan

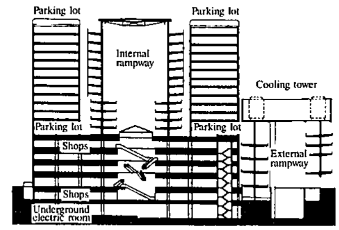


Fig. 6 Section

Photo 1 Sen City Park Plaza Building

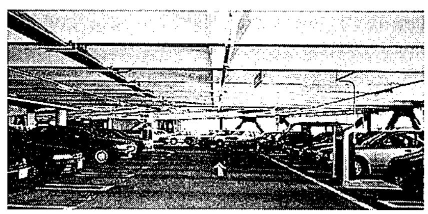


Photo 2 Internal view of parking lot in Sen City Park Plaza Building

5.1.2 Outline of fire-resistance design

Cars are mainly composed of noncombustible materials such as steel panels. Combustible materials account for about 15% of the total weight of a typical automobile as shown in **Fig. 7**. The weight of combustible materials per unit floor area in parking buildings is about 15 kgf/m², a very low value compared with approximately 50 kgf/m² for office buildings. A fire in a vehicle may spread from its tires or plastic bumpers to adjacent cars, but two or more cars will not simultaneously catch a fire from another car. Since the parking building is open to outside air, a fire will not become so violent that a flashover occurs. The temperature of fire-resistant steel columns and beams was predicted by

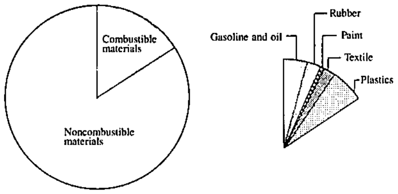
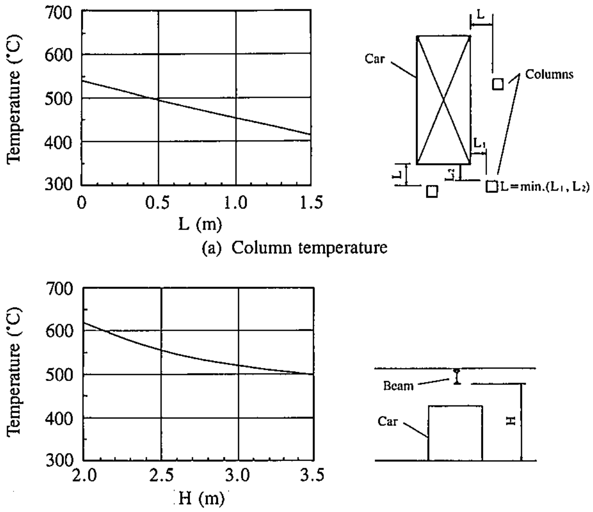


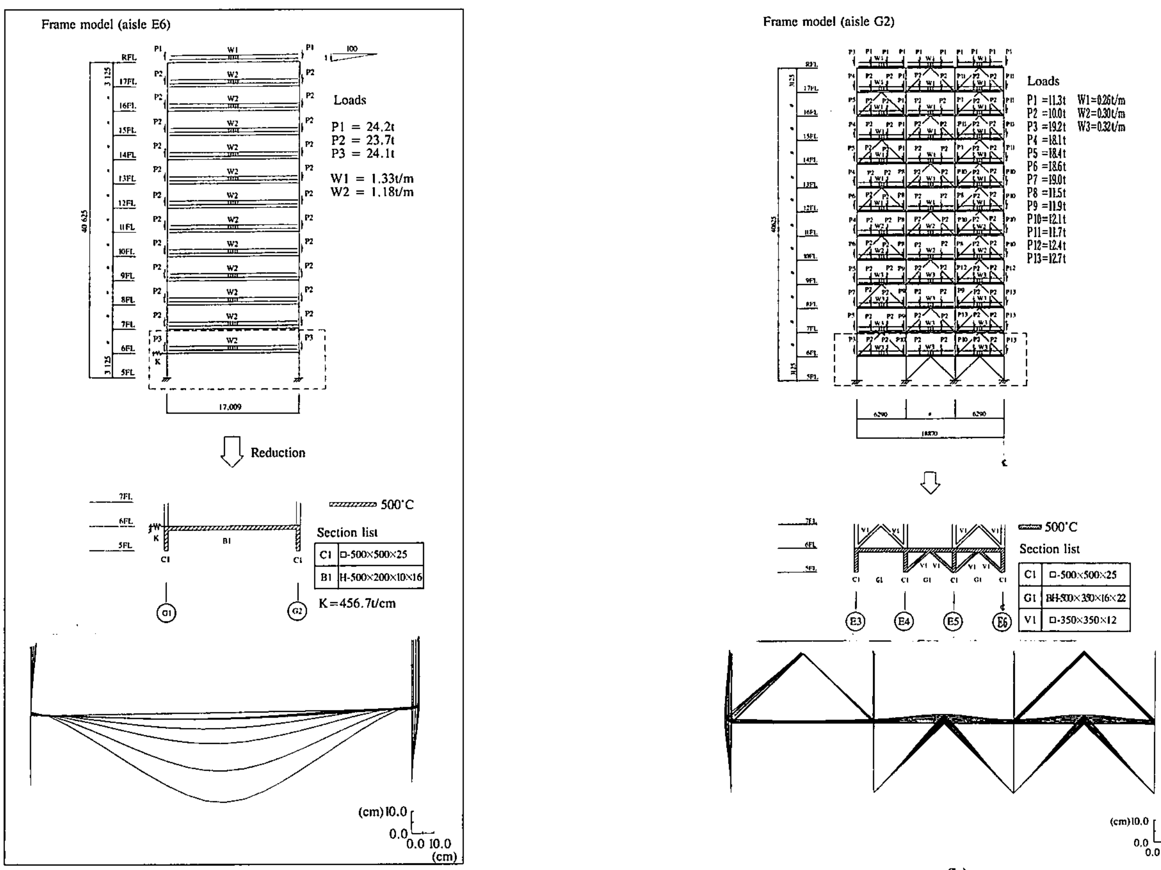
Fig. 7 Combustible materials in car



(a) Column temperature

(b) Beam temperature

Fig. 8 Temperature analysis results of columns and beams



(a) (b)

Fig. 9 Safety study results of frames

analyzing heat radiation and conduction as shown in **Fig. 8**, while referring to the results of past parking building fire experiments. This analysis demonstrated that the surface temperatures of the fire-resistant steel columns and beams remain at or below 600°C. **Fig. 9** shows the fire safety of fire-resistant steel frames. The results indicate that the frames could be erected without fire protection.

5.2 Sports facility - Tokoname Park Gymnasium

5.2.1 Building particulars

Owner: Tokoname City government
Design: Housing and Urban Development Corporation, and Environment Design Institute
Structural design: Kohzo Keikaku Engineering
Construction: Joint venture of Nishimatsu Construction, Yahagi Construction, and Hyozen Gumi
Steel frame fabrication: Nippon Steel
Building area: 5,080 m²
Total floor area: 8,661 m²
Number of stories: 4 above ground

The gymnasium was built in the Tokoname Park, Tokoname City, Aichi Prefecture. As shown in **Photo 3** and **Fig. 10**, it has such a dynamic structure that a 100.7 by 50.4 meter space truss roof is supported by four large trusses. The large trusses are constructed of fire-resistant steel treated for weathering.

5.2.2 Outline of fire-resistance design

The fire load of the main arena in the gymnasium was set at 25 kgf/m². The surface temperature analysis of a space truss exposed to a fire in the main arena is shown in **Fig. 11**. Since the fire load is low, the fire temperature is low. Because the space truss is 2.1 m apart from the window, the space truss surface temperature is 600℃ or less. **Fig. 12** shows the thermal deformation analysis of the space frame at the surface temperature. It was confirmed that the deformation of the space truss is very small and that the space truss members do not buckle locally. The fire safety of the space truss framework was thereby verified.

5.3 Atrium - La Park Misato Nagasakiya Shop

5.3.1 Building particulars

Owner: Nagasakiya Co., Ltd.
Design and construction: Fujita
Steel frame fabrication: Fujiei Industry
Building area: 7,628 m²
Total floor area: 26,410 m² (atrium: 320 m²)

The Nagasakiya Shopping Center (**Photo 4**) was built in the Misato New Town in Misato City, Saitama Prefecture. As shown in **Fig. 13**, there is an atrium in the shopping center. The atrium roof is constructed of curved lightweight steel frames and finished with aluminum panels. Given this complex design, fire-resistant steel without fire protection was planned to be used in the atrium roof as shown in **Photo 5**.

5.3.2 Outline of fire-resistance design

The building has shops on the basement, first and second floors, and parking spaces on the third floor and roof. The atrium is installed in the roof of the building. As shown in **Fig. 14**, the atrium roof framework was designed to withstand a fire from the combustion of retail merchandise on the ground floor plaza and from flames emerging through the windows from a fire in the sales area on the second floor. The study proved that the steel temperature in the atrium roof would not exceed 600℃, and confirmed the fire resistance of the atrium roof framework.

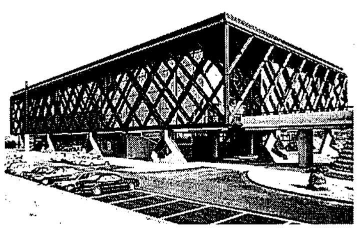


Photo 3 Tokoname Park Gymnasium

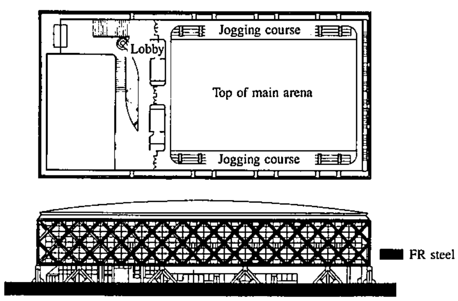


Fig. 10 Plan and section of Tokoname Park Gymnasium

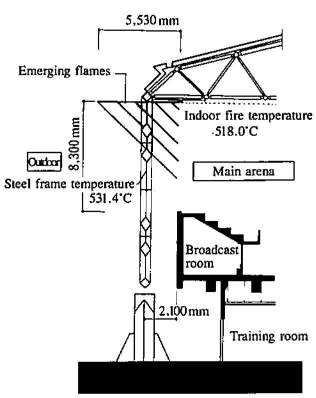


Fig. 11 Temperature analysis results for large truss

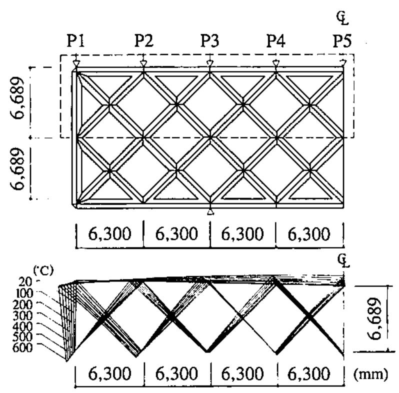


Fig. 12 Thermal deformation analysis of large truss

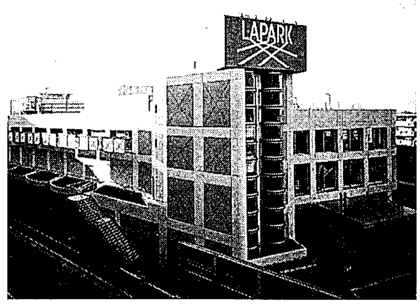


Photo 4 Nagasakiya Shopping Center

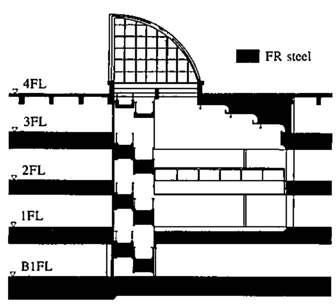


Fig. 13 Section of Nagasakiya Shopping Center

Photo 5 Atrium roof framework in Nagasakiya Shopping Center

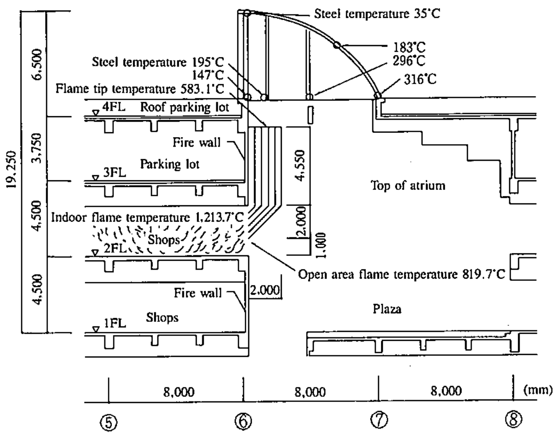


Fig. 14 Temperature analysis results for atrium root framework

5.4 External steel frame building - Hokke Club Ikenohata Hotel

5.4.1 Building particulars

Owner: Hokke Club

Architectural design: Kiyonori Kikutake Architect & Associates

Structural design: Gengo Matsui and Ohbayashi

Construction: Ohbayashi

Steel frame fabrication: Nippon Steel

Building area: 777 m^2

Total floor area: 9,798 m^2

Number of stories: 26 above ground and 3 under ground

This hotel is small in scale with 60 guest rooms, but tall to a maximum height of 110 m, as shown in **Figs. 15** and **16**. Five 4-story blocks are stacked to form an image of a tree standing in a natural setting. Since the building width is only 8 m, earthquake-resistant columns (buttresses) are erected outside. The columns and beams are made of fire-resistant steel. The general view of the hotel is shown in **Photo 6**.

5.4.2 Outline of fire-resistant design

The earthquake-resistant framework is basically of the external steel frame type, but penetrates the building (atrium) on the first to third floors. A study was conducted assuming that a fire emanated from sofas, tables or other furniture in the coffee lounge on the first floor of the atrium. This study proved that the steel temperature would not exceed 600℃ as shown in **Fig. 17**. The fire load was set at 50 kgf/m^2 for the guest rooms and at 200 kgf/m^2 for the linen rooms. The steel temperature in the earthquake-resistant framework was proved to not exceed 600℃ when exposed to flames emerging through the windows. A structural stability study also confirmed that the earthquake-resistant framework would not collapse when exposed to a fire. Since the hotel is located adjacent to a quasi-fire protection district, its safety

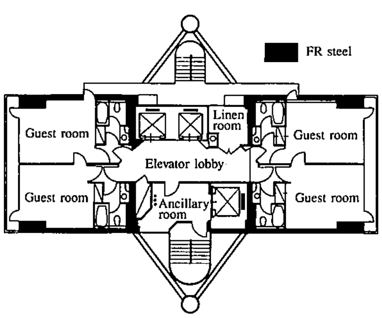


Fig. 15 Typical floor plan of Hokke Club Ikenohata Hotel

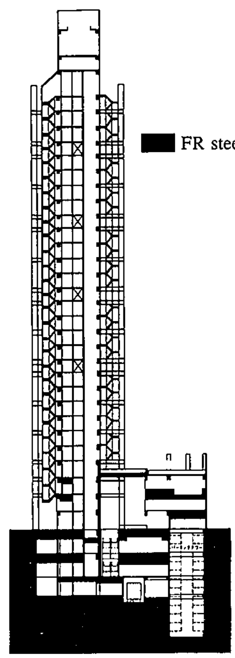


Fig. 16 Section of Hokke Club Ikenohata Hotel

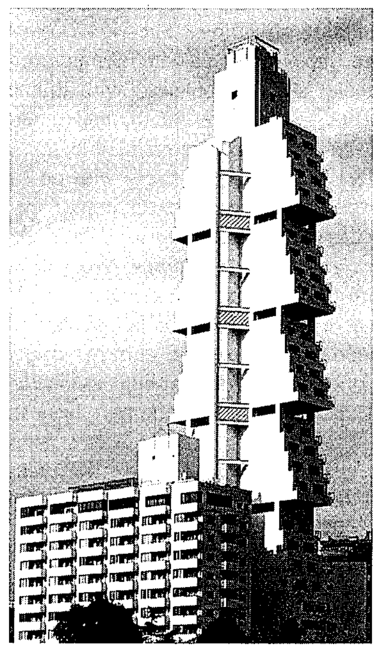


Photo. 6 General view of Hokke Club Ikenohata Hotel

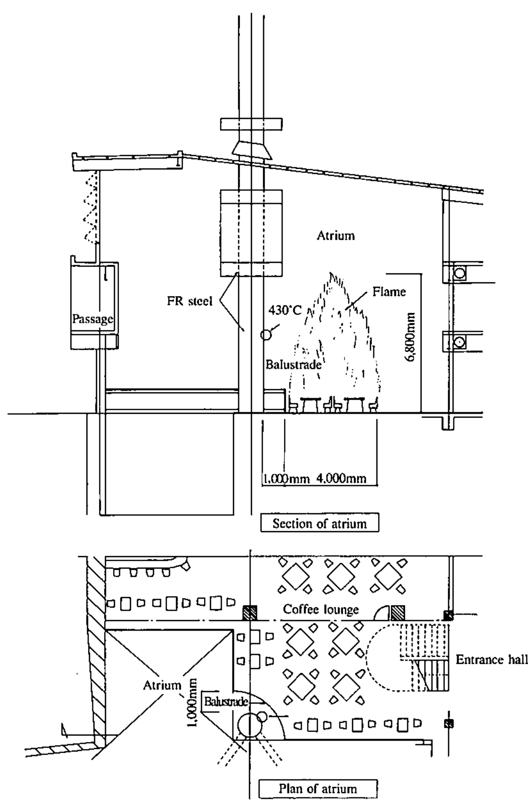


Fig. 17 Temperature analysis results for atrium

ability to withstand from damage due to a fire in the neighboring urban area is also verified.

6. Conclusions

Examples have been introduced of fire-resistant steels and stainless steels being used uncoated to form new fire-resistant building structures. The fire-resistant steels and stainless steels are superior in elevated-temperature strength to conventional steels, and can be used with thinner fire-resistant coatings in office, warehouse, retail, and other building applications with large amounts of combustible materials. Use of fire-resistant steels and stainless steels with no or reduced fire protection is expected to have a great impact on the construction cost, construction period, interior space utilization, and architectural design of these buildings. We will develop new applications for fire-resistant and stainless steels, and will create the environment where fire-resistant steels and stainless steels can be more easily used by acquiring general approval of the Minister of Construction for building applications where the fire-resistant steels and stainless steels have been successfully used.

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