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EXAMPLES AND KEY POINTS IN PERFORMANCE-BASED FIRE SAFETY DESIGN BASED ON FIRE BEHAVIOR PREDICTIONS

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0. Introduction

Safety against fires is a basic performance that buildings must be equipped with. Fire-prevention design is design that uses this performance as an index. Normally, fire prevention countermeasures for buildings do not play a part in the building's day-to-day functions, and buildings can be maintained as long as fire does not break out. Furthermore, fire prevention countermeasures account for as much as seven to ten percent of building cost. Thus, many ordinary buildings only comply with the legally mandated fire prevention countermeasures and nothing more. However, with the development of fire safety engineering in recent years, fire prevention design has entered a new phase.

Fire-prevention countermeasures based on fire safety engineering are being developed to meet the needs of new spaces. And, at the same time, possibilities in spatial design are broadening with those new fire prevention countermeasures. Today, I would like to introduce some examples of fire prevention countermeasures that give shape to the intent of architectural design within design projects. And I will go over key points in fire safety design in Japan.

Additionally, elements related to fire safety in actual design involve spatial design, structural design, equipment design, and other fields. So, fire safety design is characteristically not being built on any one model. Thus, an image of fire behavior must be formed, and elements of fire prevention countermeasures need to be converted into design conditions from the early stages of design. And those conditions must be incorporated into the individual design.

1. Process from outbreak of fire to performance-based fire safety design

A 32-story skyscraper in Madrid burnt down in February 2005 and its structure collapsed. An investigation into the fire showed a lack of sufficient compartmentalization between the floors or spandrels, allowing the fire to spread very rapidly to upper floors and also to lower floors. Also, as the window-side columns had no fireproof coating, the structure collapsed in just about two hours after the fire broke out.

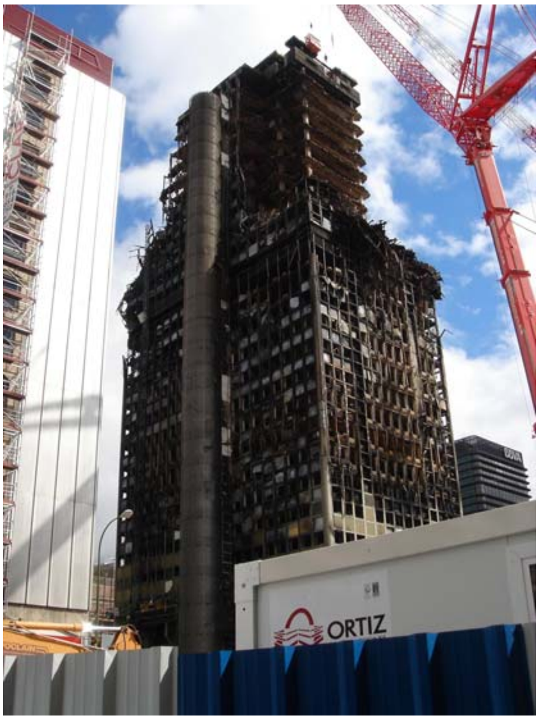

Figure 1. Collapse in the Windsor Building fire

One factor given behind this fire is that it was constructed when fire prevention rules were still being formed. However, this catastrophe could have been avoided if fire in the building was given sufficient consideration in the building's design.

Today, there are few building fires in Japan that result in major loss of life. However, fires causing huge damage have occurred in the past. The experience resulted in development of fire safety engineering, creation of fire prevention countermeasures, and establishment of fire prevention rules. Today, it has become possible to carry out evacuation safety design and fire-resistance design as performance-based design methods, based on fire behavior predictions and evaluations. In conjunction with this, we used the same architectural plane to evaluate how fire prevention performance has changed over the years, by assuming that fire prevention countermeasures set down by law in each time periods have been taken. As shown in Figure 2, safety has been greatly boosted in terms of burnout expectation value. This is the result of fire prevention countermeasures having come to be designed systematically.

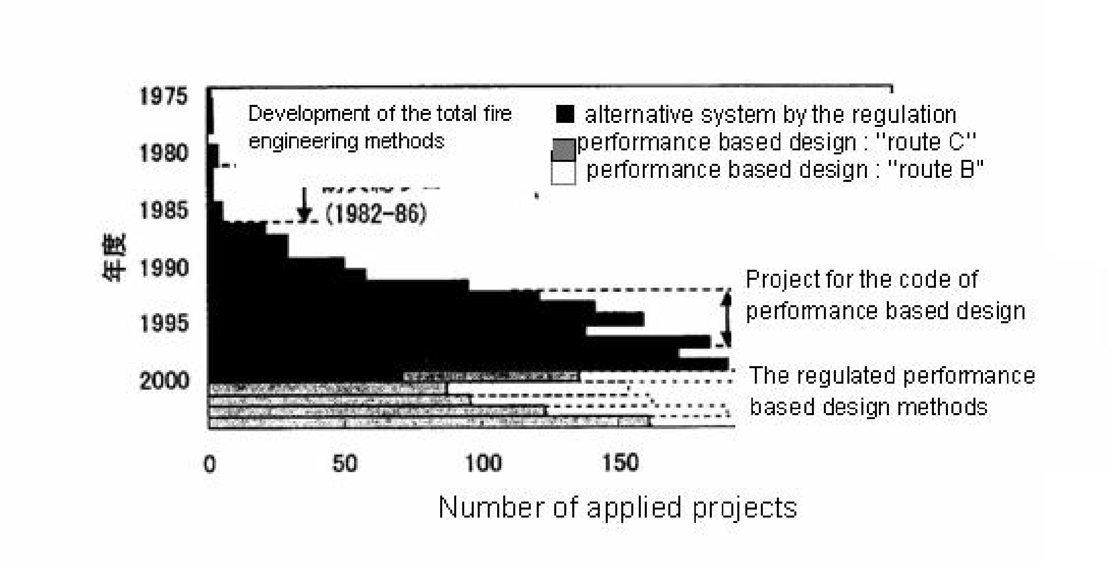

Figure 2. Example of changes in fire prevention performance by age of construction in Japan

2. Necessity of performance-based design from a designer's standpoint

More and more buildings in Japan are being designed based on fire behavior predictions and evaluations. Figure 3 shows a statistic of the number of cases where such design has been used. Figure 4 shows the main items to which such design has been applied.

As shown in Figure 4, the largest numbers of case examples are related to smoke control equipment that now constitute subsystems of evacuation safety with the stipulation of performance criteria in the Building Standards Law. Many case examples also concern exemptions of a stairwell's pit compartments, and reduction of stairway width, based on the evaluation of the entire building's evacuation safety. And in fire-resistant structures, prediction of duration of fire enables a design with reduced fire-retardant coating or wrapping, with the criteria that the structures would not collapse.

So, why do so many plans feature streamlined fire prevention countermeasures based on performance evaluations? This is because conventional specifications-like stipulations did not clarify the need for such design to suit characteristics specific to a particular building. Thus, fire prevention countermeasures became excessive. In contrast, evaluating the overall situation based on a scenario after the outbreak of fire that includes evaluation safety, structural stability, and support measures for firefighting activities, allows for a design that meets a higher level of requested performance that is equivalent to, or higher than, that of countermeasures set down by law. The result is that desired building spaces can be realistically achieved. Conversely, new forms of building design will come to be made using fire prevention countermeasure techniques. A typical example of this is atriums that exude a feeling of openness.

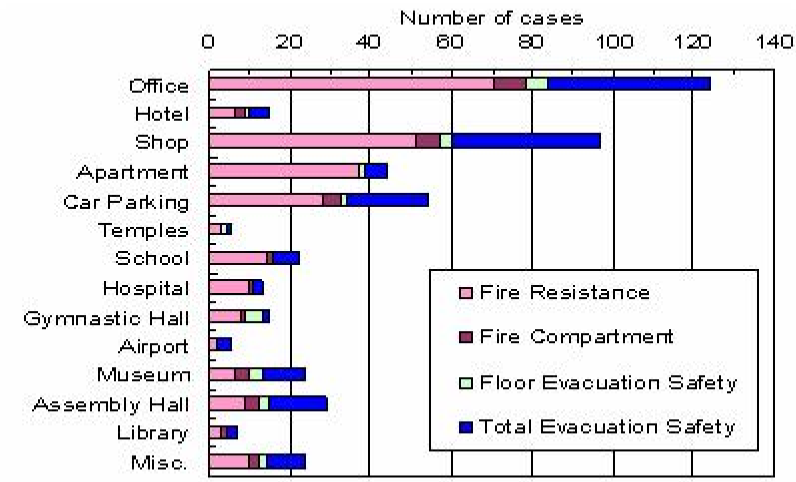

Figure 3. Application items in fire prevention design based on fire behavior predictions and evaluations.

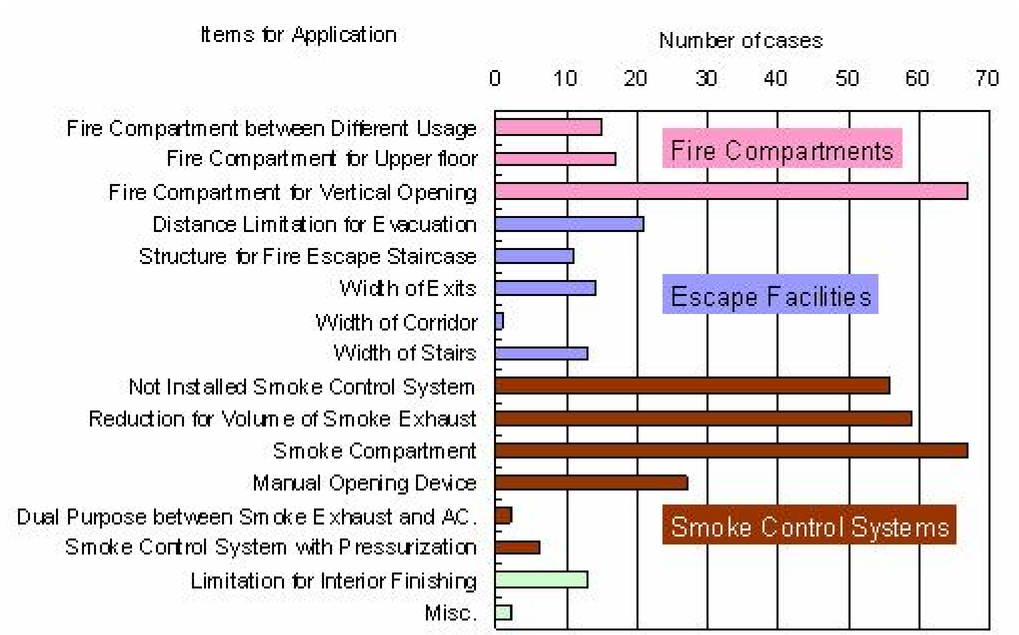

Figure 4. Pertinent application items following the stipulation of performance criteria in the Building Standards Law

3. Example of design for large-scale multiple buildings including office buildings: Sapporo Station Building

3.1 Zoning and overall structure from fire prevention perspective

This plan is for the station building in Sapporo city, Japan. It is a large-scale multiple building made up of a stationhouse, retail shops, offices, a hotel, a cinema, and a department store. For a large-scale redevelopment project to be a success, it is necessary to combine different usages in a large-scale manner. However, buildings used for large-scale multiple purposes have different spatial forms depending on the usage. User characteristics differ, as do business hours and management entities. The building would be a complex structure where diverse elements in fire safety exist together in diverse forms.

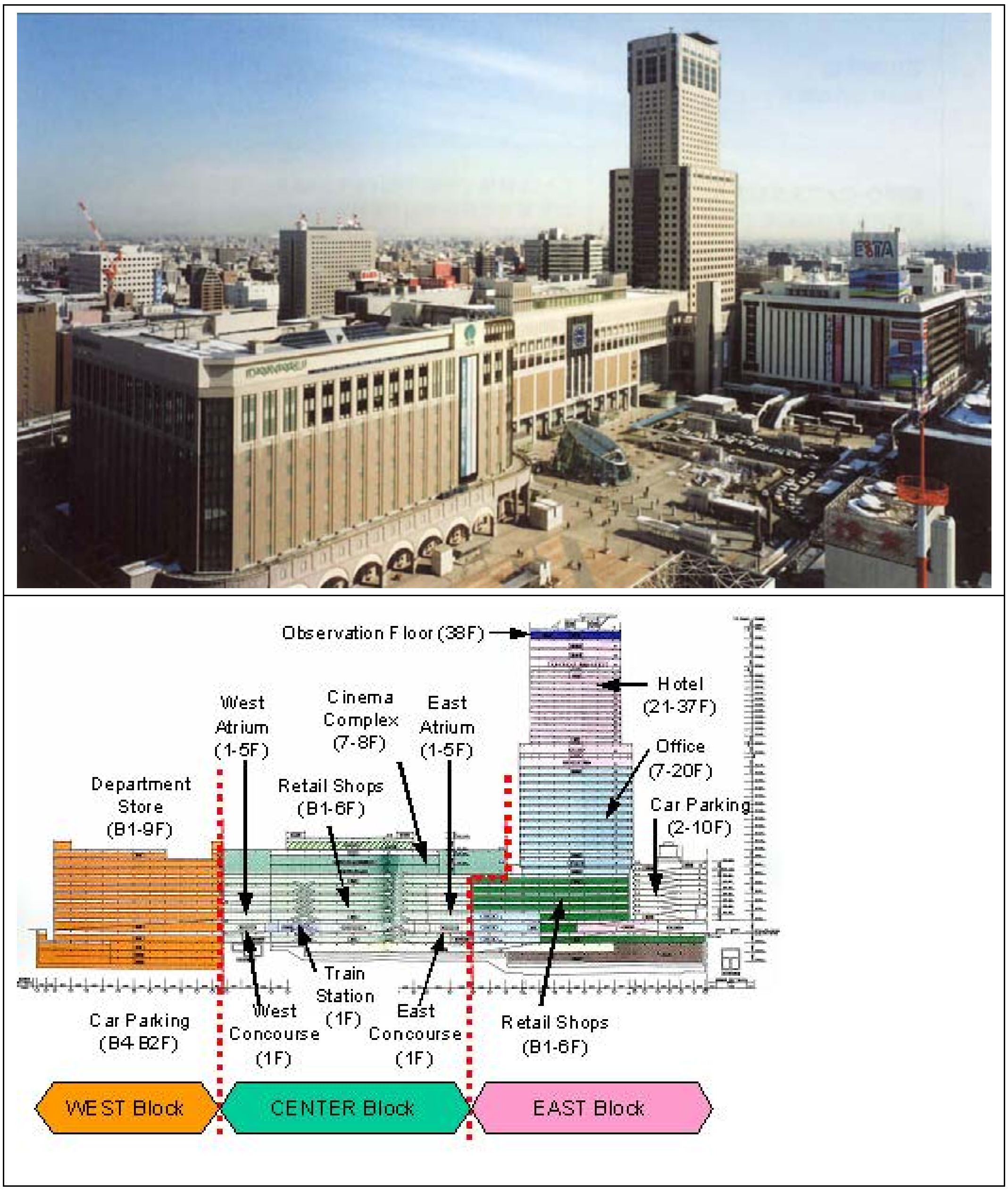

Figure 5. Exterior view and cross-sectional schematic diagram of Sapporo Station Building

If specification-like stipulations are applied to such building, not only would fire prevention countermeasures and evacuation countermeasures become excessive, as shown below; the plan would also interfere with the function of the building, and, realistically speaking, no plans could go forward under traditional fire prevention countermeasures.

- Fire prevention compartments separated by individual use
- Pit compartments for stairwell spaces
- 60cm/100m^2 stairway width in retail shops
- Need for evacuation stairways in cinema independent from that used for other purposes
- Evacuation stairways connecting to ground floor
- Rooftop evacuation plaza for the department store
- Additionally, automatic fire alarm equipment, sprinklers, connected water supplying pipes, smoke

control equipment, etc.

The intent of the design plan for this large-scale multiple building is to establish fire protection blocks to prevent the spread of fire, and to turn connecting portions into an interesting, rich space

In this case example, fire prevention compartments and connection spaces where smoke is treated are designed with the intention of providing each usage's connecting portions with functions to block the spread of fire. One of those measures is the atrium. In this method, effectiveness of evacuation in emergencies and firefighting activities are enhanced by going via parts other than blocks where fire has broken out.

As for evacuation, the lateral method was used whereby individuals evacuate horizontally to blocks other than those where fire has broken out; and stair halls equipped with anterior chambers were used as the stairs to improve anti-fire and anti-smoke performance. With this method, evacuation stairs needed for each usage can be shared with other usages, thus the number of stair halls was greatly reduced. Artificial ground outside that leads to above the ground was added, to be used as an evacuation floor.

As a result of this fire safety design, the following effects in building fire prevention countermeasures were obtained.

• Adoption of lateral evacuation method	Sharing of evacuation stairways between the cinema and retail shops Narrowing of evacuation stairways Extension of evacuation distance
• Use of artificial ground as evacuation floor	Route to ground is long. Possible even with small capacity.
• Compartmentalization of connecting spaces and smoke control	Narrowing of evacuation stairways
• Smoke control in the well	Exemption of pit compartment in the well portion

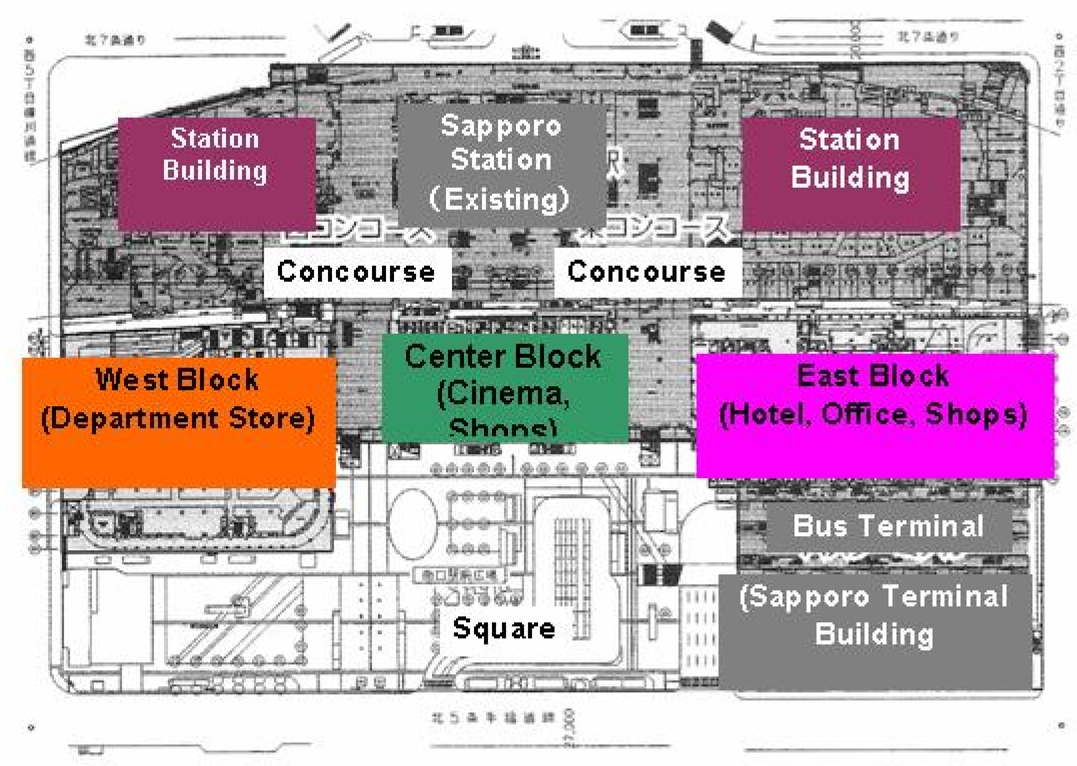

Figure 6. Zoning and connecting spaces for fire prevention

３.2 Pit compartments in atriums

Atriums have come to be frequently designed into large-scale buildings and offices as attractive spaces resembling outside air inside the building. The issue is how open the atrium should be made in relation to the interior spaces. In the past, compartmentalization by fire shutters and the like was necessary. In that case, the cost of compartmentalization became huge and the degree of effectiveness of such compartmentalization, after it was completed, was seen as a problem.

The Sapporo Station Building atrium is a space that links all the elements, connecting the stationhouse to the stores, cinema, and restaurants. As a fire prevention countermeasure, natural smoke exhaust was added that opens in conjunction with fire prevention compartments to make the space equivalent to the outside. Even though sprinklers are available, smoke propagation when some compartments are fully open was taken into consideration. As a result, safety was confirmed through smoke simulation using a two-layer zone model with the goal of the smoke not affecting the evacuees before evacuation has been completed and smoke not affecting other floors through the atrium. Furthermore, it was confirmed that even if objects in the lower part of the atrium burned or if parts facing the atrium in a certain floor caught fire, fire would not spread to the upper floors. Through studies such as these, it was decided that no fire- and smoke-prevention compartments would be established facing the stairwell.

Note: Using the results of smoke simulations, it becomes possible to design partitions and smoke control equipment that do not interfere with evacuation. Performance can be confirmed by a pressurized anti-smoke system that makes use of this technique.

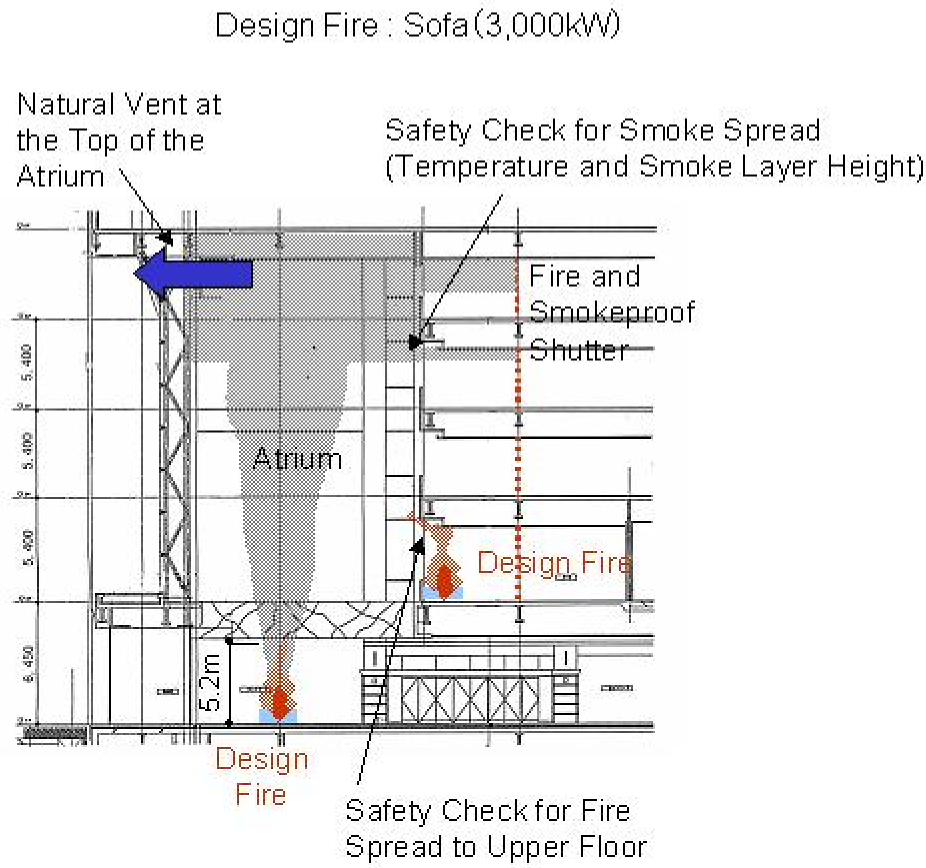

Figure 7. Concepts of an atrium’s fire prevention countermeasures

３.3 Lateral evacuation in buildings used by an unspecified number of people

The lateral evacuation method applied for the Sapporo Station Building is an important method for establishments used by an unspecified number of people, and for allowing even elderly and disabled persons to evacuate with little problem. In this method, the floor area is compartmentalized to two or more zones for fire prevention purposes. By evacuating horizontally from the fire zone to a different zone, people can take their time in evacuating. The requirements for this are that the space between various floors is thoroughly protected from fire and smoke, and that evacuation guidance is given in ways suited to the place of fire outbreak. Here, we will describe a department store which is a typical example of an establishment that adopted this lateral evacuation method.

Department stores have many flammable items; the evacuee population density may show an unspecified number and reach one person per square meter. Thus, sprinklers, fire prevention compartments, and smoke control equipment are a given. Additionally, the law stipulates stairway width to be $60cm/100m^2$, and evacuation stairways be equipped with ancillary chambers. Because of this, equipment that is not normally used ends up being provided in excess, giving rise to the question of whether or not the equipment is being properly maintained and managed.

One view is to enhance reliability by restricting fire prevention measures that must be observed so that evacuation facilities such as evacuation stairways and fire prevention compartments can be managed effectively. Furthermore, using the lateral evacuation method allows large numbers of persons to easily evacuate. And special evacuation stairways can be securely maintained even in the firefighting stage.

To turn this idea into reality, it was designed so that all the fire prevention compartments would activate with detection of fire to complete the two zones. By having people evacuate from the zone where fire broke out to another zone, they can get away to a safe area even more quickly. Air is supplied to increase pressure not only from stairway ancillary chambers but also from non-burning zones to prevent fire and smoke from diffusing in the direction people are evacuating. To maintain the pressure difference, exhaust ducts that can withstand high temperatures are installed leading from the zone where fire breaks out. This allows the elderly and other evacuees to take their time in going to the ground level from a zone other than that where fire broke out.

In the design of such a system, safety was confirmed by calculating the spread of fire and the propagation of smoke using a two-layer zone model, and conducting evacuation simulations. Also, smoke emission experiments were conducted to confirm that linkage control as well as pressure differences have been maintained.

The following benefits are produced by such a fire prevention system.

- Staircases can be made two-thirds the original width, increasing the usable area.
- Fire prevention countermeasures such as staircases and fire prevention compartments are identified, facilitating maintenance and management.
- People can be evacuated laterally, so they can take their time evacuating to ground level.
- Elderly people can also evacuate with little or no problem.
- Staircases can be kept safe for extended periods, making them useful for firefighting activities as well.

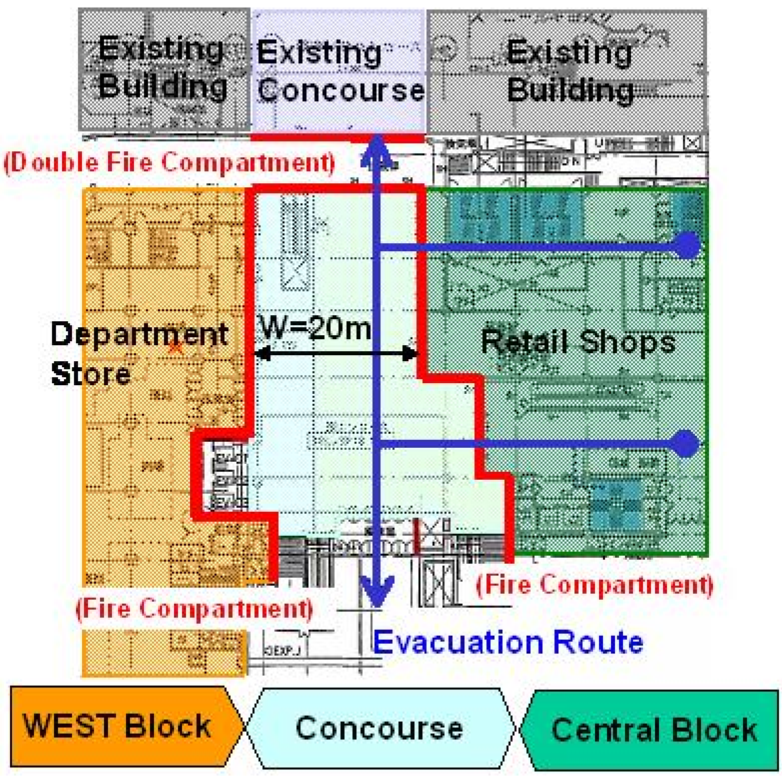

Figure 8. Fire prevention systems for department stores featuring lateral evacuation

4. Example of fire-resistant structure design

While not applied in the example previously cited, new technology in fire-resistant structures is being developed such as streamlining of the structures of a wooden construction’s large spaces as well as fire-retardant coatings. Ordinarily, large-scale wooden structures could not be built since structural materials required fireproofing coating to last two hours.

To take on that problem, duration of fire was estimated for the building in figure 9, with the assumption that fire prevention compartments are achieved, and the building was designed based on the criteria that the structure does not collapse by the added heat. The duration of continuous fire calculated from the amount of combustibles and the area of openings was 40 minutes. Based on this, a three-dimensional elastoplastic thermal response analysis was carried out for the structure/frame as a whole, instead of analysis by fire resistance for each material. In this project, it was deemed acceptable for a structure to deform, as long as it did not collapse.

As a result, although steel frames were exposed inside the building, fire-retardant coating to withstand fire for one hour was applied to primary component materials, but not for other materials. This was because the structure does not collapse even if certain components may buckle. In this way, a new structural system became possible by evaluating the fire resistance of the structure as a whole. Concepts such as this are believed to have broadened the possibility for application to CFRP and other structural materials.

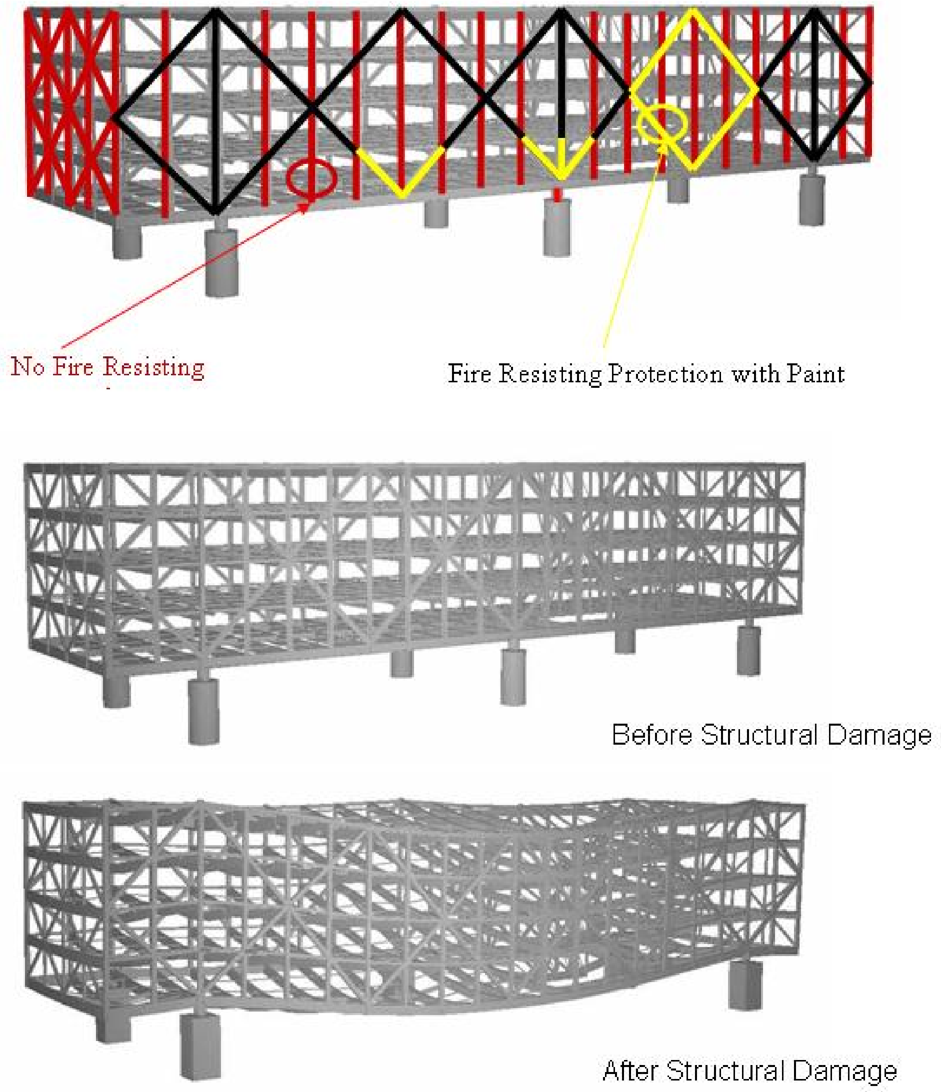

Figure 9. Example of fire-resistant structural design

5. Setting of fire phases and systemization of fire prevention countermeasures

Application of fire safety engineering has enabled the construction of buildings and spaces that are difficult to realize with fire prevention countermeasures incorporating specification-like stipulations. However, this case, too, merely grants designated performance in accordance with fire scenarios. The important thing here is whether or not the designer and building owner have set targets for fire safety and have made them clear. The reason is that no matter how extensively fire prevention countermeasures have been planned, they would not function in emergencies if they are not sufficiently maintained and managed. It would not be possible to direct people to evacuate, either.

In other words, fire prevention goals need to be made clear and fire prevention countermeasures systemized. Figure 10, made to meet such goals, shows a model of fire progression in the form of progression of fire phases. This model allows the setting of goals to determine the phase at which to stop the fire, thereby determining the fire prevention equipment that carries out linkage control. Furthermore, ways to deal with emergency situations is made clear to security staff.

Figure 11 shows a new type of automatic fire alarm equipment developed to introduce this fire phase concept. This equipment has a sensor that featuring a combination of smoke and heat detectors. It has functions to determine the stage of the fire's progression based on the room's characteristics, by monitoring the rise in heat temperature. This fire alarm equipment can automatically determine an outbreak of a fire. Thus, the entire building's fire prevention equipment can be linked and controlled, depending on the assessment of the status of the spread of fire. The building in figure 10 has made use of this technique.

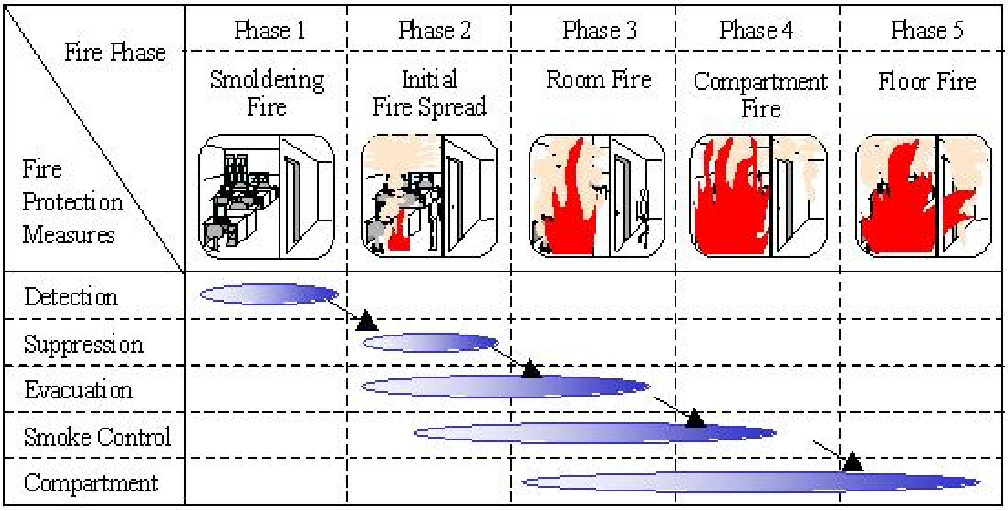

Figure 10. Concepts of fire phases

Heat and smoke detector

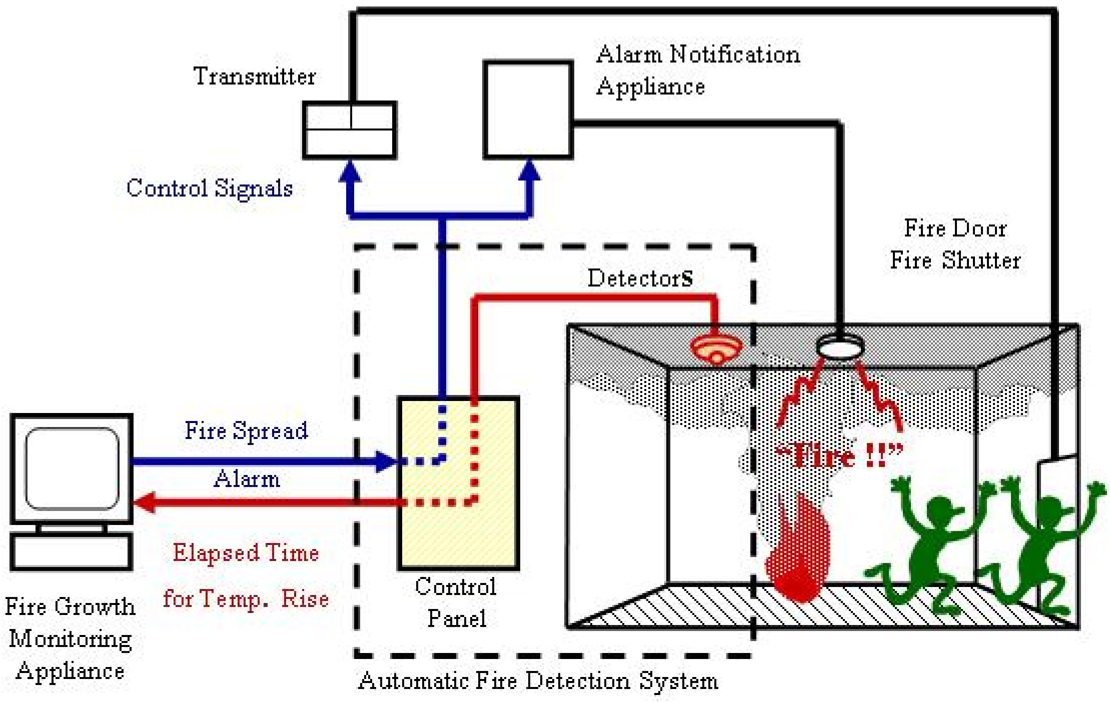

Figure 11. Automatic fire alarm equipment that incorporates the fire phase concept

6. Conclusion

Performance-based design that incorporates fire safety engineering has expanded the possibilities of building spatial design. We have become able to determine how safe a particular building is. However, such safety all depends on the fire expansion scenario and evacuation scenario.

In this age of performance-based design, accountability on the part of building owners and designers is called for, to clarify their goals in relation to fires and methods for achieving those goals. Engineer ethics are also required in this age of performance-based design. This concept is deemed effective for fire phases, so we believe that it would become an important disaster prevention planning technique in the future.

This concludes my presentation on the fire prevention design theory based on actual case examples. I believe that fire prevention design is about creating a backbone of fire safety in diverse architecture.