Improving Fire Safety in Buildings

In last month's column introducing initiatives of Japan's Building Research Institute, we looked at the Institute's efforts to unravel the mystery of wind damage to buildings. In this month's issue we look at the Institute's work to improve the fire-resistance performance of buildings as well as to develop performance regulations for fire control standards based on clarification of fire phenomena.

Despite starting on the twenty-first floor, a fire in a high-rise building in Spain in February 2005 destroyed almost the whole thirty-two-story tower with widespread collapse of the exterior walls and floors of the upper stories (**photo 1**). Had it been a wooden building, there would have been no wonder about its total destruction and collapse in a fire. However, there are hardly any examples of a high-rise building collapsing in a fire. Since the Building Research Institute had a very strong interest in the collapse of the building as a result of this fire, we organized a field trip to Spain together with Japanese fire engineers. As a result, we found that due to ongoing refurbishment of fire safety measures, no fire compartments were installed in the building where the fire broke out. Therefore, the fire was able to spread through the gaps in the exterior walls and between the floors to the upper and lower floors in a short time, and it became clear that the columns of the peripheral steel frame lost strength and broke down in the heat of the fire causing the widespread collapse.

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Photo 1: Total destruction of high-rise building in Spain with large-scale collapse of the upper floors

Constructing Fire-Resistant Buildings

In the past, many buildings and towns in Japan were constructed in wood and as a result, we have repeatedly experienced the total destruction of houses or the devastation of whole towns once a fire breaks out. Therefore, from the late nineteenth century, buildings have been constructed with non-combustible material such as brick, concrete and steel to protect buildings and cities from fire. Certainly, a building constructed with non-combustible materials will not itself burn, but many of our personal effects including clothes and furniture are combustible. Even if a building is constructed in concrete and steel, as long as there are people living in it, they will use fire and since there are a lot of combustible items inside a house, it is not possible to completely prevent the outbreak of fires. Buildings constructed with columns and beams made of steel, for example, also collapse with the impact of the heat from a fire.

What can we do to construct buildings that are fire resistant and do not collapse in a fire? First, we protect the columns, beams and other components with fire protective covering. Briefly, a fire protective covering is a heat insulating material which is made with a non-combustible material, and it prevents the heat of a fire from conducting to the components. As long as the temperature of the components is kept down, it is possible to retain the certified strength of the design.

In addition, it is important to create fire compartments to contain fires. A building or a floor is divided into several fire compartments. If a fire breaks out, it is contained inside the fire compartment where it started. Using materials that do not easily conduct heat and securing a sufficient thickness for the walls and floors of the fire compartment make it difficult for the fire to spread to surrounding areas. It is then possible to prevent the fire from spreading beyond the fire compartment and to prevent the destruction of the whole building.

Aiming to improve fire safety in buildings, the Building Research Institute is promoting research based on incidents such as the collapse of high-rise buildings caused by fires in recent years. This article introduces some recent research on improving fire-resistive performance in buildings.

Confirming Fire Resistance of Full-Size Steel Structural Components

Steel frames and steel are widely used materials in high-rise buildings and in buildings with large interior spaces. Steel, of course, does not burn but if the heat of a fire reaches high temperatures, it loses its strength and as a result, there is a risk of deformation in steel columns and beams. Therefore, the steel frame is protected with so-called fire-protective covering, which is material with high insulation properties, to prevent the heat of a fire from driving up the temperature.

The capacity of columns, beams and other components to withstand the heat of a fire and to support the weight of a building (load-bearing capacity) and the capacity of walls, floors and other components to block the heat of a fire and the flames themselves (insulation, integrity) are collectively referred to as fire-resistive performance. Components are tested for fire-resistive performance by loading them into a furnace that reproduces the heat of a fire furnace. The duration until fire-resistive performance is lost (destruction, heat penetration, holes) under exposure to the heat from the fire is called the fire resistance rating. Naturally, the longer the time, the higher the fire-resistive performance.

The Building Standards Law of Japan determines the required fire-resistive performance for components, that is, the fire resistance rating, in accordance with the purpose, number of floors and scale of buildings. There are notifications of concrete specifications. For example, where the steel frame columns (a minimum breadth end diameter of at least 25 cm) are covered with a fire-resistive covering of bricks to a thickness of at least 7 cm, the fire resistance rating is two hours.

According to the Building Standards Law of Japan, a fire resistance rating of three hours is required for columns near to the ground level in skyscrapers. It is necessary to conduct fire resistance tests of the columns to confirm they have the necessary fire resistance ratings with the applied load, but in the past these tests have not been possible with full-size columns due to the poor performance of the testing equipment. Therefore, we confirmed the fire-resistance performance with the full-size columns used in the first floor of a fifty-story building using the Building Research Institute's upgraded fire furnace for columns, which has the highest load capacity in the country.

Fire protective covering equivalent to a fire rating of 1 hour was applied to the steel frame columns that were tested. We found that the fire-resistive performance of the columns was adequate as they did not break even after more than three hours of fire testing. This was thought to be due to the impact of the large dimensions of the steel frame columns in addition to the insulating effect of the fire protective covering. It is the same reasoning whereby a small amount of heat will warm a cup of water, but a large amount of heat is necessary to warm a bathtub full of water. Since a large amount of heat is needed to heat up a steel frame column of large dimensions, it is obvious that the column as a whole is difficult to heat up. As a result, the fire rating was higher than expected.

Photo 2: Test column after fire testing where 25% of the fire resistive covering was stripped off

Next, we simulated earthquake damage to the fire protective covering and conducted a test with 25% of the covering removed. As a result of the loss of the insulating effect of the fire protective covering, the fire rating was reduced to a mere 27 minutes. Since the areas without fire protective covering conducted large quantities of heat from direct exposure to the fire, the columns were heated to a high temperature in a short time despite their large size (**photo 2**).

In the past, there has hardly been any research of fire safety measures following earthquakes. After demonstrating in this manner that damage or loss of fire protective covering has a large impact on lowering fire-resistive performance, we plan to carry on full-scale research into measures to prevent damage or loss of fire protective covering and other measures to secure fire safety in the wake of an earthquake.

Photo 3: Full-size fire testing of a wooden hybrid construction

Fire Resistance in Wooden Buildings

Since there are definite limits on the strength, fire resistance and other performance of wooden materials, efforts are underway to develop wood composites by combination with steel and other materials, or hybrid wooden structures by combination with reinforced concrete construction and other structures. For our research, we implemented the premise of a four-story building using wood composites and hybrid wooden structures.

The drawback of wood is its combustibility. It is certainly the case that small components will ignite and burn up within a short time if they are exposed to the heat of a fire but when the components are large and thick, the surface burns without the combustion reaching the interior. This is because a char layer forms when wood burns creating an insulating effect that blocks the heat from the flame.

Therefore, we combined wood and steel to develop a component with glued laminated timber (called glulam, made of several layers of dimensioned timber glued together) bonded to the circumference of a steel frame. When this component is exposed to heat, the surface of the glulam ignites but as it burns, a char layer is formed that functions as a fire protective coating, as it were, and the insulating effect can prevent the temperature in the steel frame from rising. After the heat of the fire has been removed, the glulam portion is smoldering. We refer to this material that com-

Photo 4: Fire performance after testing

bines a steel frame with wood (glulam) as a Hybrid Timber Member.

We have developed posts and beams with a fire rating of one hour using the Hybrid Timber Member and we have confirmed the performance by conducting fire resistance testing. We also designed a four-story office building using Hybrid Timber Member posts and beams, even erecting a part of the building for full-scale fire testing. As a result of a damage survey after the fire, we were able to confirm that the performance of the post and beam components was identical to the fire resistance test, allowing us to ascertain the fire-resistive performance (**photos 3, 4**).

The Building Standards Law of Japan was established to limit the height, number of floors and scale of wooden buildings without any acknowledgement of building fire resistant buildings in wood. However, the revised Building Standards Law of Japan (1998–2000) introduced performance-based provisions for the fire-resistive performance required of fireproof buildings without restrictions on the materials used for the structural components, which effectively constitutes an acknowledgement of the use of wood in fire resistant buildings. That is to say, it is now possible to construct medium-rise buildings of four to five floors using the Hybrid Timber Member that we have developed.

A succession of buildings using wood and requiring fire resistive ratings is already under construction in Japan. Wood as a building material has recently attracted worldwide attention as a sustainable material that also reduces CO_2. As a result, much is anticipated from continued research and development aiming to expand the use of wood while securing fire safety.

Prevention of Spalling in Concrete Components

Combined with rebars and steel frames, concrete is a widely used construction material for buildings, roads and tunnels. Since the concrete itself does not burn, it is thought that buildings made of concrete can withstand fire. It is certainly the case that in normal fires, there is only discoloration to the surface of the concrete and there is hardly any structural damage. However, in case of exposure to violent fires burning for a long time, spalling occurs in the surface of the components and damage is caused when portions of the concrete are stripped off. Also, as the surface of concrete was lost and the reinforcing steel became exposed, another problem arose whereby the steel became extremely hot from the heat of the fire. Since buildings are at risk of collapse in a fire if the components are damaged on this scale, it is necessary to prevent spalling of concrete (**photo 5**).

There are various theories for the spalling mechanism of concrete but the most plausible theory is that spongy pores in the concrete are destroyed with increased pressure on the moisture content when exposed to the heat of a fire. Consequently, one measure to prevent spalling might be to control the sudden rise in temperature in the surface of the concrete, but from an economical viewpoint, it is difficult to apply fire protective covering on a broad scale.

Another method might be to mix the concrete with organic fiber to create pathways to allow the moisture content under pressure to escape to the outside. Since organic fiber melts at a fairly low temperature, new pores would be generated inside the concrete when it conducts the heat from a fire and it is hoped that this would have the effect of allowing the moisture under pressure to escape. As a result, tests have confirmed that spalling would be curbed to a certain degree even when the concrete is exposed to the heat of a violent fire.

Future Research Topics

To confirm the safety performance of buildings, the Building Research Institute is working on topics such as analysis of the phenomena of fire, evaluations of the performance of fire safety measures and performance-based fire safety standards. Fire safety measures in buildings have long been required by the specifications of building regulations. Naturally, the standards in these laws

Photo 5: Spalling in concrete components

and regulations are the accumulation of the knowledge of engineers based on past experiences of fire. However, as a result of great progress in the fire science and fire safety engineering, there are now glaring inadequacies in the specification standards. With regard to the required fire-resistive performance of buildings, aside from the specification standards of the past, it is also necessary to undertake research in order to clarify the primary and fundamental performance required by the society. This is an area that the Building Research Institute plans to tackle in the future.