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MARCH 1-7, 2000

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Development of Seismic-induced Fire Risk Assessment Method for a Building

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Abstract

This study addresses the issue that fire risk would be different from usual at an earthquake, because fire protection systems could be functionally no use even when a building itself has no problem in terms of structural damage. We are developing the seismic-induced fire risk assessment method to evaluate fire risk according to the conditions such as size and type of buildings, installed fire protection systems, and the intensity of input earthquake motion. This paper describes the outline of the framework and examples of results from case study applying a tentative simplified model.

1. Introduction

As of today, while a number of studies have been conducted on fire risk assessment for usual fires, there have been very few on fire risk assessment of a building to post-earthquake fires. For one reason, the concern on fire problems at earthquakes has mainly focused on fire risks on a city area level such as number of fire ignitions and large-scale urban fires, so fire risk on a level of one building has been rarely discussed. However, at the Hanshin-Awaji earthquake, not a few fires occurred from fire-resistive buildings as well as from general wooden buildings. Also, various surveys have revealed that many fire protection systems such as sprinkler systems were damaged by earthquakes and lost its proper function because of mechanical failure and/or deformation by the earthquake motion, though otherwise they should have functioned [1,2,3].

This study focuses on the issue that fire risk would be different from usual at an earthquake, because fire protection systems could be functionally no use even when a building itself has no problem in terms of structural damage. Therefore, it is very significant to develop seismic-induced fire risk assessment method in consideration of these possible difficulties, and to enable to evaluate fire risk according to respective conditions such as size and type of buildings, installed fire protection systems as well as intensity of input earthquake motion. Furthermore, seismic-induced fire risk assessment method would be useful not only to evaluate present risks, but also to estimate how much the risk changes when fire protection systems are improved to be seismic-proof, and to find out effective countermeasures to reduce the risk. The purpose of this study is to develop the framework for seismic-induced fire risk assessment method for a building. As the study is in the middle of the development, this paper describes the outline of the framework and examples of results from a case study applying a tentative simplified model.

2. Damages to Fire Protection Systems and Fires in Past Earthquakes

Even before the 1995 Kobe earthquake, the Marine and Fire Insurance Association of Japan already recognized vulnerability of installed fire protection systems at an earthquake. And, they conducted the investigation study on the reliability of installed fire protection systems especially targeting at sprinkler systems based on the experiences in several past earthquakes including some earthquakes in the U.S. From the results of their investigations[1], it is reported that the percentages of damaged sprinkler systems among surveyed buildings were 34% in the 1993 Kushiro-oki earthquake and 41% in the 1994 Sanriku-harukaoki earthquake where the seismic intensity of both earthquakes were level 6 in JMA (Japan Meteorological Agency) scale that is about 250 cm/sec^2 to 400 cm/sec^2 in ground surface acceleration.

Also, Table 1 and Table 2 show the data on percentages of damaged fire protection systems by type in Kobe City and Osaka City respectively in the Kobe earthquake[2,3]. The seismic intensity in JMA scale was level 6 or level 7 (400 cm/sec^2 or more) in Kobe and was level 4 (25 cm/sec^2 to 80 cm/sec^2) in Osaka. The percentage of damaged sprinkler system in Kobe City is 40.8% and that of fire doors is 30.7%. And, it is more noteworthy that the percentage of damaged sprinkler system in Osaka City is 5.3%, if we consider the fact that the seismic intensity, level 4 in Osaka is much lower than level 6 or 7 in Kobe City. This means sprinkler systems are very vulnerable to seismic motion even though buildings have almost no structural damage.

Table 1 Damages to Fire Protection Systems in Kobe City.

*From the investigation report[2] on the 1995 Kobe earthquake by Kobe City Fire Department.

Type of Fire Protection Systems	Number of Damaged systems	Number of Systems Surveyed	Percentage (%) of Damaged systems
Sprinkler System	222	544	40.8
Indoor Fire Hydrant	107	451	23.7
Foam Extinguishing System	20	83	24.1
Halogenated Extinguishing System	17	162	10.5
Automatic Fire Alarm System	109	542	20.1
Emergency Generator Unit	71	444	16.0
Fire Doors	161	524	30.7

Table 2 Damages to Fire Protection Systems in Osaka City.

*From the investigation report[3] on the 1995 Kobe earthquake by Osaka City Fire Department.

Type of Fire Protection Systems	Number of Damaged systems	Number of Systems Surveyed	Percentage (%) of Damaged systems
Sprinkler System	20	380	5.26
Indoor Fire Hydrant	12	1862	0.64
Foam Extinguishing System	4	117	3.42
Halogenated Extinguishing System	2	301	0.66
Automatic Fire Alarm System	3	6528	0.05
Smoke Exhaust System	3	31	9.68
Stand Pipe	11	2144	0.51

In the 1995 Kobe earthquake, there were 261 post-earthquake structure fires, 83 (31.8%) out of which started from fire resistive buildings and 76 fires (29.1%) occurred from the buildings which height were 4 floors or more. There were four fires from the buildings installed with sprinkler system as shown in Table 3. As for three of these four fires, sprinkler system was not used. Among the above three fires, two fires that occurred at midnight spread beyond a place of fire origin, resulting in the burned area 3,600 m^2 and 35 m^2, but the other one fire was fortunately suppressed in the early stage by occupants with fire extinguisher. Therefore, if fires occur when occupants are absent and sprinkler system loses its function, fires may not be controlled and would cause large fire loss.

Table 3 Outline of Fires from the Buildings Installed with Sprinkler System in the 1995 Kobe Earthquake.

No.	Name of City	Time of Ignition	Features of Building			Usage of Sprinkler System	Burned Area (m^2)	Fire Suppression Action in the Early Stage by Occupants
			Height # of floors	Floor of Fire Origin	Occupancy			
1	Suita	17th, 06:15	11F	8F	Laboratory	Used	0	Success by Fire Extinguisher
2	Kobe	19th, 01:20	2F	1F	Warehouse	Not used	3,600	No Action and Fail
3	Kobe	18th, 02:20	11F	3F	Office	Not used	35	No Action and Fail
4	Itami	17th, 05:48	8F	7F	Office	Not used	0	Success by Fire Extinguisher

3. Framework of Seismic-induced Fire Risk Assessment Method

The damage level of active and passive fire protection systems in a building is predictable by earthquake response of a building, which is determined by frequency characteristics of earthquake motion input to a building and the vibration property of a building itself. Therefore, if the size and type of structure of a building in a particular site as well as input earthquake motion are specified as input conditions, the damage level of active and passive fire protection systems can be estimated to a certain extent. In this study, peak ground acceleration is adopted as an index of input earthquake motion level. In addition to the above, we consider the condition of response action by security staff at a fire, which is also affected by the intensity of an earthquake.

To develop a seismic-induced fire risk assessment method, we incorporated the failure probability of active and passive fire protection systems caused by an earthquake, which is main contribution of this study, into the existing fire risk assessment method[4] for usual fires. First, we introduce a simplified model to estimate earthquake response of a building, which is the base for other models or estimation to predict the damage level of active and passive fire protection systems. Then, we construct the functional failure prediction model for sprinkler systems as a representative of active fire protection systems. However, since there is very little data available for constructing prediction models for damage level of elements of compartments such as walls and fire doors, we assume reducing ratio of fire resistance time of compartments based on the data in existing literature at present. Also, we tentatively assume the failure probability of needed response actions according to the intensity of input earthquake motion. After estimation of failure probability of active and passive fire protection systems, the fire risk assessment method to predict burned area on a given fire scenario is introduced to assess the potential fire risk of a building at an earthquake. The outline of the conceptual framework for the seismic-induced fire risk assessment method is shown in Figure 1.

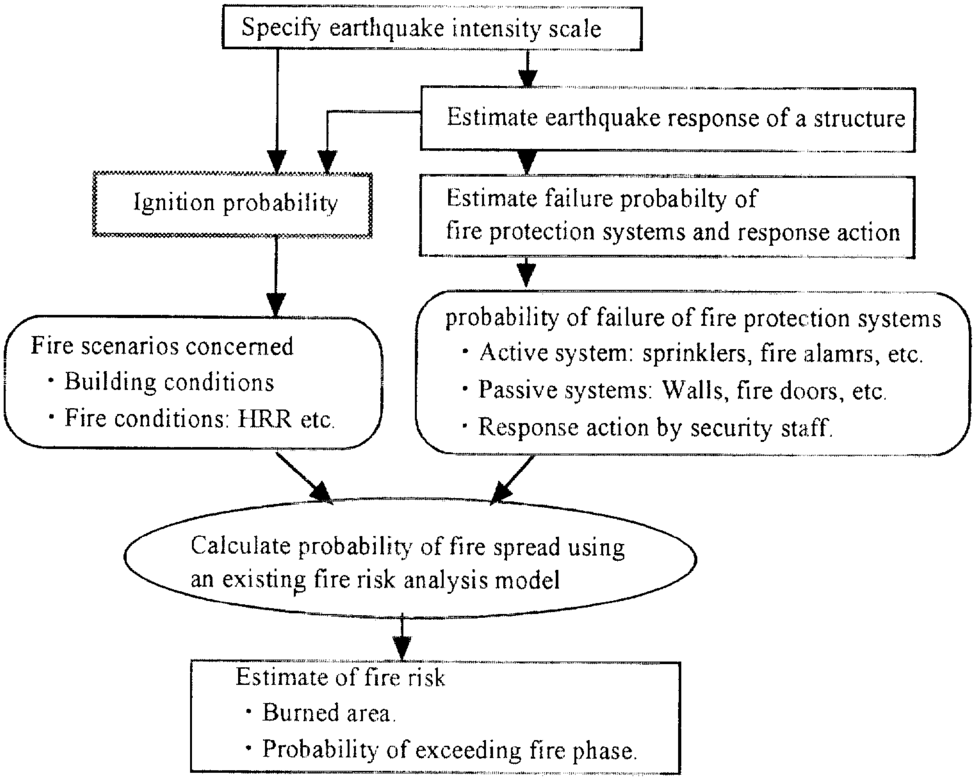

Figure 1 Conceptual Framework of Seismic-induced Fire Risk Assessment Method.

4. Prediction Model of Functional Failure Probability for Sprinkler System

As stated earlier, there could be functional failure on various fire protection systems at an earthquake, and most of those failure are likely to occur in the water suppression systems such as sprinkler system. The water suppression system does not perform its proper function as a whole system if whichever part goes wrong, because every part of these systems is linked with piping network which should keep a certain level of water pressure. In this paper, therefore, we consider the failure probability of sprinkler system as a representative case for active fire protection systems as well as the most dominant element to be addressed.

The prediction model of failure probability of sprinkler system can be constructed based on a sum-set of seismic-induced damage probability on each part of sprinkler systems such as water tank, pump, vertical piping, horizontal piping, and sprinkler heads. For each part, considering the experiences of damages caused by past earthquakes, the dominant modes of functional failure are identified. Then, the probability of damage of each part can be given as a function of intensity of input earthquake motion. Also, the probability of failure as a whole sprinkler system is estimated with a sum-set of the probability of damage of each part. Figure 2 shows the concept mentioned above for sprinkler systems for example.

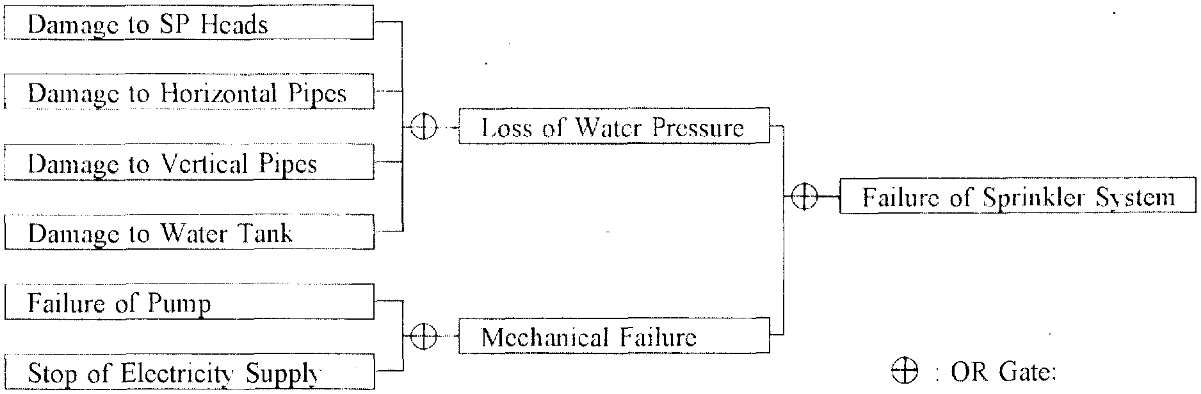

Figure 2 Fault Tree for Failure of Sprinkler System as a Whole.

By the way, even in daily time, there is certain probability of functional failure of fire protection systems caused by maintenance problems. Therefore, the probability of functional failure of sprinkler system at an earthquake is obtained by the product of the failure probability in daily time and the failure probability caused by an earthquake which is estimated as a function of earthquake response velocity. For the part i of sprinkler system, the failure probability at an earthquake is expressed as the following.

$$P_{si} = f_i(v) \cdot P_{di}$$

where,

P_{si}: Probability that part i of sprinkler system does not operate at an earthquake.
$f_i(v)$: Seismic-induced failure function for part i.
v: Earthquake response velocity. (cm/sec)
P_{di}: Failure probability in daily time.

There are two kinds of levels required for seismic-proof design of a building by the Building Codes in Japan. As to the respective levels, a standard value of response velocity as an input of earthquake motion is given for seismic-proof design in 25cm/sec for the grade 1 and 50cm/sec for the grade 2. In consideration of the relation to seismic-proof design of a building, the criteria for dividing the levels of failure probability of sprinkler system is given here using the above values and the seismic-induced failure function $f_i(v)$ for pipes and heads is defined corresponding to response velocity as shown in Table 4. The values of failure probability in this table are assumed based on the data from the investigation report[3] on the Kobe earthquake by Osaka City Fire Department.

Table 4 Failure Probability of Sprinkler System to Earthquake Response Velocity.

Response Velocity : Vr (cm/sec)	Probability of Failure (%)	
	Pipes	Heads
$0 < Vr \leqq 25$	20	20
$25 < Vr \leqq 50$	20	30
$50 < Vr$	30	40

Sprinkler system can not achieve its expected function as a whole system when any part of the system lose the function. Therefore, probability of functional failure of sprinkler system is calculated as the sum-set of failure probability of each part (P_{si}).

$$F_{sp} = 1 - \prod_{i=1}^{k}(1 - P_{si})$$

where,

F_{sp} : Probability of functional failure of sprinkler system as a whole.
k : Number of parts which consist of sprinkler system.
P_{si} : Probability that part i of sprinkler system does not operate at an earthquake.

5. Damage to Fire and Non-Fire Compartments

There are very little data from investigation available for predicting the damage of compartments caused by earthquakes. On the other hand, the assumed criteria on the damage to fire resistance time of compartments according to relative story displacement are described in the design guideline[5] of compartments issued by the Architectural Institute of Japan. Therefore, we put the reducing ratio of fire resistance time of fire and non-fire compartments depending on the relative story displacement after the above criteria as shown in Table 5.

Table 5 Reducing Ratio of Fire Resistance Time to Relative Story Displacement.

Relative Story Displacement : Dr	Reducing Ratio of Fire Resistance Time to Normal Condition	
	Fire Compartments (60min.)	Other compartments (30min.)
$0 < Dr \leqq 1/400$	1.0	1.0
$1/400 < Dr \leqq 1/300$	1.0	0.5
$1/300 < Dr$	0.5	0.0

6. Seismic Impact to Fire Protection Action by Security Staff

Fire protection action by security staff must be affected by earthquake motion, but the analytical estimate of how such response action is impacted according to the seismic intensity has not been done yet. At present, therefore, based on the existing explanatory description of human response condition corresponding to the JMA seismic intensity scale, we put the reducing ratio of execution probability of fire protection action by security staff in usual time depending on response acceleration as shown in Table 6.

Table 6 Reducing Ratio of Probability of Fire Protection Action by Security Staff.

Response Acceleration : Ar (cm/sec^2)	Reducing Ratio of Probability of Fire Protection Action to Normal Situation
$0 < Ar \leqq 100$	1.0
$100 < Ar \leqq 250$	0.5
$250 < Ar$	0.1

7. Case Study

The results of a case study applying the tentative simplified assessment method to a model building are introduced here to see how seismic-induced fire risk changes depending on the intensity of earthquake motion. The conditions and the floor plan of a model building for case study are shown in Table 7 and in Figure 3. And, the parameters on failure probability and reducing ratio of performance of fire protection systems and response action according to peak ground acceleration are shown in Table 8. As an example of results of a case study, Figure 4 shows the change of "Expected Fire Spread Area" (hereafter EFSA: in m^2) as a function of "Peak Ground Acceleration" (hereafter PGA: in cm/sec^2). The increase of EFSA at 100 of PGA is derived only from failure of sprinkler system, but the increase of EFSA from 200 to 400 of PGA is due to both failure of sprinkler system and decreasing probability of fire protection action by security staff. Then, the rapid increase of EFSA from 500 of PGA is derived from additional influence by reduced performance of compartments as well as the above two factors. To compare with EFSA from 500 of PGA, the value of EFSA at 100 of PGA is relatively small. However, if the premise, that fire brigades are expected to arrive the

Table 7 Conditions of Case Study.

Occupancy of Building	Office
Structure Type of Building	Steel Frame
Number of Floors	20 floors
Floor Height	4.0 m
Area of Floor	1,538 m^2
Floor of Fire Origin	5th Floor
Area of Room of Fire Origin	384.4 m^2
Room Height	2.7 m
Fire Growth Rate (α in $Q=\alpha t^2$)	0.05
Density of Fire Load	30 kg/m^2
Soil Type of the Ground	Soil Type -1 (Hard Soil)
Peak Ground Acceleration: Input Earthquake Motion	from 0 (Normal Condition) to 600 (cm/sec^2)

Table 8 Parameters of Failure Probability and Reducing Ratio of Performance of Fire Protection Systems and Fire Protection Action for Case Study.

Peak Ground Acceleration (cm/sec^2)	Fire Protection Systems					Reducing Ratio of Probability of Fire Protection Action
	Probability of Functional Failure of Sprinkler System			Reducing Ratio of Fire Resistance Time		
	Pipes	Heads	F_{sp}	Fire (60min.)* Compartments	Other (30min.)* Compartments	
0	0.0	0.0	0.03	1.0	1.0	1.0
100	0.2	0.2	0.36	1.0	1.0	1.0
200	0.2	0.3	0.44	1.0	1.0	0.5
300	0.2	0.3	0.44	1.0	1.0	0.5
400	0.3	0.4	0.58	1.0	1.0	0.5
500	0.3	0.4	0.58	1.0	0.5	0.1
600	0.3	0.4	0.58	0.5	0.0	0.1

* Fire resistance time here is specified for this case study.

scene normally, is changed to be more unfavorable and/or if a seismic-induced fire occurs at night when security staff are fewer, the profile of EFSA in Figure 4 would be different and the values of EFSA would be probably much larger.

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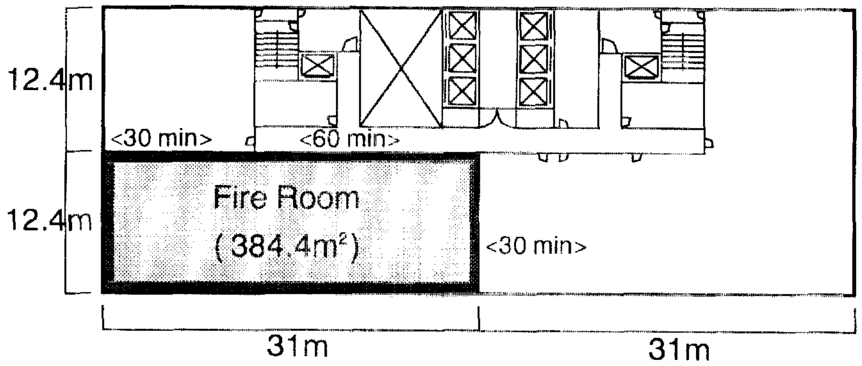

*Fire resistance time of walls and doors is indicated in < >.

Figure 3 Floor Plan of a Building for Case Study.

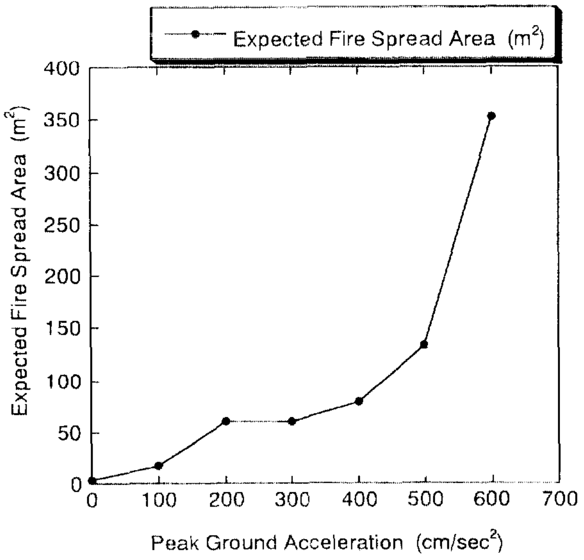

Figure 4 Expected Fire Spread Area as a Function of Peak Ground Acceleration.