Journal of Asian Architecture and Building Engineering

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tabe20

Investigation of damage to fire protection systems in buildings due to the 2016 Kumamoto earthquake: derivation of damage models for post-earthquake fire risk assessments

Tomoaki Nishino, Jun-ichi Suzuki, Nobuya Nagao & Hiroaki Notake

To cite this article: Tomoaki Nishino, Jun-ichi Suzuki, Nobuya Nagao & Hiroaki Notake (2023) Investigation of damage to fire protection systems in buildings due to the 2016 Kumamoto earthquake: derivation of damage models for post-earthquake fire risk assessments, Journal of Asian Architecture and Building Engineering, 22:4, 2123-2142, DOI: 10.1080/13467581.2022.2099401

To link to this article: https://doi.org/10.1080/13467581.2022.2099401

JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING
2023, VOL. 22, NO. 4, 2123–2142
https://doi.org/10.1080/13467581.2022.2099401

Investigation of damage to fire protection systems in buildings due to the 2016 Kumamoto earthquake: derivation of damage models for post-earthquake fire risk assessments

Tomoaki Nishino[a], Jun-ichi Suzuki[b], Nobuya Nagao[a] and Hiroaki Notake[c]

[a]Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan; [b]Department of Fire Engineering, Building Research Institute, Tachihara 1, Tsukuba, Ibaraki 305-0802, Japan; [c]Institute of Technology, Shimizu Corporation, Etchujima 3-4-17, Koto, Tokyo 135-8530, Japan

ABSTRACT

Post-earthquake fire safety is an important functional requirement of seismic-resilient buildings and depends on seismic damage to fire protection systems. Probabilistic fire risk assessments are useful in ensuring safety and consider the post-earthquake reliability of fire protection systems. This study therefore investigated damage to fire protection systems due to the 2016 Kumamoto earthquake through a questionnaire survey among hospitals to collect data available for modeling the post-earthquake reliability. Ten types of component of a fire protection system were surveyed: emergency generators, fire detectors, water tanks used for firefighting, fire pumps, sprinkler heads, indoor fire hydrant boxes, fixed glass smoke curtains, fire doors, fire shutters, and fire exit signs. The data show that there was much damage to fire detectors, sprinkler heads, fixed glass smoke curtains, and fire doors. Zero-inflated Poisson regression analysis was conducted to derive statistical damage models that describe the association of building response quantities with the number of instances of damage. Results of a case study using the models show that building shaking exceeding a peak response acceleration of 10 m/s^2 may reduce the probability of successful functioning to below 40% for a sprinkler system and to below 90% for a smoke-activated door system.

ARTICLE HISTORY
Received 12 November 2021
Accepted 29 June 2022

KEYWORDS
Seismic resilience; fire following earthquake; probabilistic risk assessment; fragility function; Kumamoto earthquake

1. Introduction

Ensuring the post-disaster functional continuity of buildings has been an important task for disaster-resilient cities. Although there are numerous definitions of resilience, a report published by the U.S. National Academies defines disaster resilience as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (National Research Council 2012). Earthquakes are a type of natural hazard that seriously affects buildings related to businesses and people's livelihoods. Even if no severe seismic damage to structural components occurs, seismic damage to nonstructural components including equipment prevents or reduces the functioning of various systems of buildings and results in significant losses to society. In particular, several studies have investigated the post-earthquake functionality of hospitals because hospitals play a critical role in treating casualties as a base for disaster medicine. Studies have investigated the physical and functional effects of past major earthquakes, such as the 2009 L'Aquila earthquake and the 2011 Christchurch earthquake, on hospitals (e.g., Nuti, Santini, and Vanzi 2004; Price, Sortis, and Schotanus 2012; Jacques et al. 2014; Achour and Miyajima 2020); experimentally investigated the seismic performances of nonstructural components including medical equipment by conducting shaking-table tests (e.g., Zaghi et al. 2012; Cosenza et al. 2015; Nikfar and Konstantinidis 2017; Sarno et al. 2019); and proposed methodologies for estimating the seismic functional losses and post-earthquake recovery process of a hospital (e.g., Miniati and Iasio 2012; Khanmohammadi, Farahmand, and Kashani 2018; Fallah-Aliabadi et al. 2020). In reducing post-earthquake societal losses, it is important to enhance the seismic resilience of individual buildings by developing effective business continuity plans.

Fire safety, in addition to structural safety and the functional continuity of systems (e.g., a heating, ventilation, and air conditioning system), is an important functional requirement of buildings even after an earthquake. In other words, a building needs to have at least the minimum required fire safety performance even after an earthquake if a building is continuously used. The post-earthquake fire safety performance of a building greatly depends on seismic damage to fire protection systems, such as a sprinkler system and a smoke-activated door system. The Kobe earthquake, which had a magnitude of 7.3 on the Japan Meteorological Agency scale, struck Kobe, Japan and the surrounding area in 1995 and destroyed more than 100,000 buildings through shaking and subsequent

CONTACT Tomoaki Nishino nishino.tomoaki.3c@kyoto-u.ac.jp Gokasho, Uji, Kyoto, 611-0011, Japan
This article has been republished with minor changes. These changes do not impact the academic content of the article.

urban fires. Additionally, this earthquake, which encouraged many studies on urban fires following earthquakes (e.g., Cousins et al. 2012; Nishino, Tanaka, and Hokugo 2012; Nishino, Tanaka, and Tsuburaya 2013; Sarreshtehdari and Khorasani 2020; Nishino 2021), was the first event in Japan in which several examples of damage to fire protection systems were reported through on-site investigations of fire-resistive buildings (Kakegawa et al. 1995). In particular, the earthquake demonstrated that damage to a component can result in the failure of a whole system designed to suppress fire and prevent the spread of fire. Japan has no legally prescribed methods for the seismic design and installation of components of fire protection systems, and components of fire protection systems have thus been individually designed and installed while referring to various related Japanese guidelines. For instance, the guidelines of the Building Center of Japan (BCJ) (The Building Center of Japan 1984) specify seismic loads and installation recommendations for components of building systems, including heating, ventilation, air conditioning, electrical, and plumbing systems. However, the guidelines mainly focus on heavy components (e.g., boilers and water tanks) and piping, and include little information on ceiling-mounted components and doors, which are commonly found among fire protection systems. Therefore, components of fire protection systems have not been designed and installed according to specific codes. Although the Fire and Disaster Management Agency (FDMA) (Fire and Disaster Management Agency 2011) provided the concept of seismic measures for fire protection systems in 2011, examples of damage to fire protection systems have been continually reported for subsequent large earthquakes (Figure 1) (Japan Association for Fire Science and Engineering 2016; National Institute for Land and Infrastructure Management, and Building Research Institute 2016). Furthermore, the vulnerability of fire

Figure 1. Examples of damage to components of fire protection systems in buildings due to the 2016 Kumamoto earthquake: (A) fire door falling off and (B) fire detector deformation. (The photographs were taken by one of the authors after the earthquake).

protection systems to an earthquake has been highlighted outside of Japan in a series of shaking-table and fire tests on a full-scale five-story building with systems (Meacham 2016). The incorporation of such a fire safety perspective into business continuity planning requires the development of a methodology for quantitatively assessing the post-earthquake fire safety performance of a building considering potential seismic damage to fire protection systems.

A probabilistic fire risk assessment, which is usually conducted for typical building fires, is useful also for understanding the post-earthquake fire safety performance of a building and improving preparedness. The concept of fire risk, as the product of the probability of fire occurrence and the expected consequence of the occurrence of fire (e.g., casualties), is widely used in the field of building fire safety engineering and uncertainties affecting the evacuation safety and fire resistance of buildings are taken into account in the fire risk assessment (e.g., Yung, Hadjisophocleous, and Proulx 1997; Beck and Zhao 2000; Tanaka 2011; Xin and Huang 2013; Ni and Gernay 2021). Fire protection systems are typically not perfectly reliable even in normal times, and various fire scenarios are thus expected for the occurrence of fire depending on the success or failure of fire protection systems. The number of possible fire scenarios can be very large and it is not possible to quantify them all, and the most important scenarios are therefore selected for analysis as shown in Figure 2. Fire risk can thus be calculated by multiplying the consequence of each scenario by its occurrence probability and summing the products, giving the expected value of consequences per day or per year. In appropriately assessing fire risk, the probability of the successful functioning of a fire protection system needs to be determined objectively, in addition to the probabilities for other uncertain factors such as the occurrence of fire (e.g., Lin 2005; Nishino and Hokugo 2020) and the fire fragility of members and structures (e.g., Gernay, Khorasani, and Garlock 2016; Chaudhary, Roy, and Matsagar 2020), while the consequence of each scenario is estimated using engineering calculation methods for fire behavior, occupant evacuation and the structural response. As for typical fires, two approaches are commonly taken in estimating the probability of successful functioning (Frank et al. 2013): a component-based approach that estimates the probability from physical survey data on system component reliability using a fault tree (e.g., Moinuddin, Innocent, and Keshavarz 2019; MacLeod, Tan, and Moinuddin 2020) and a system-based approach that estimates the probability from fire incident data (e.g., Frank, Spearpoint, and Challands 2014; Ikehata et al. 2017). In extending this typical fire risk assessment to a post-earthquake fire risk assessment, how to determine the probability of the post-earthquake successful functioning of a fire protection system needs to be discussed; that is, the question is how the seismic fragility of fire protection systems is considered.

Nonstructural component fragility functions have been developed for seismic loss estimation (e.g., Federal Emergency Management Agency (FEMA) 2018a,Federal Emergency Management Agency (FEMA) 2018b, Garcia and Soong 2003; Konstantinidis and Makris 2009; Cremen and Baker 2019; Sarno et al. 2019; Otsuki et al. 2019), where losses from damage to nonstructural components are considered to far

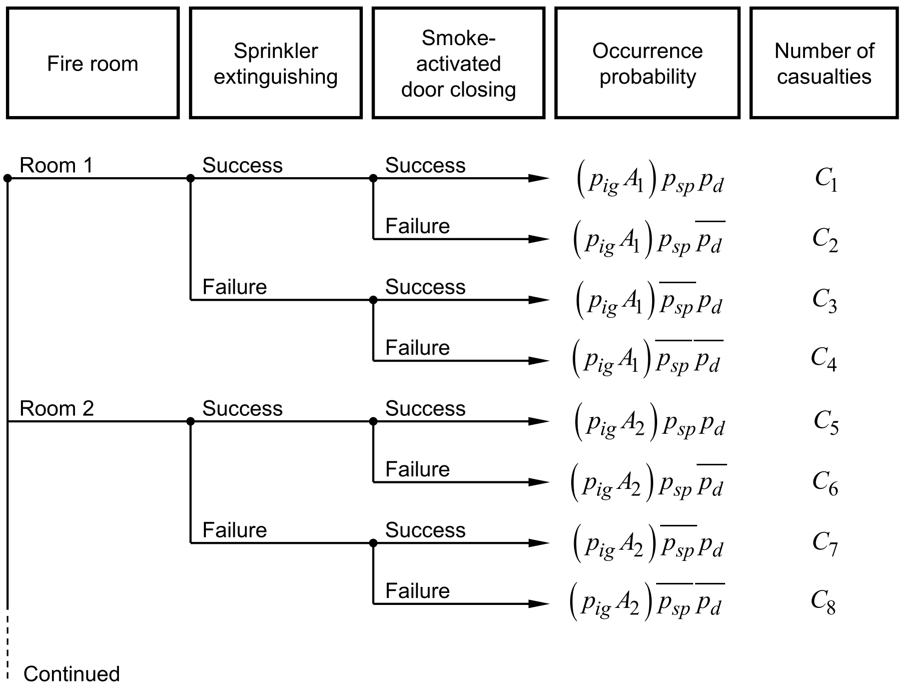

Figure 2. Example of a probabilistic building fire risk assessment approach based on selected fire scenarios considering the uncertainty of a fire room and the reliability of fire protection systems.

exceed losses from damage to structural components; e.g., Taghavi and Miranda (Taghavi and Miranda 2003) investigated the cost distribution of three typical buildings and found that nonstructural components accounted for 48% to 70% of the total cost of the buildings while structural components accounted for 8% to 18% of the total cost. As an example, the Federal Emergency Management Agency (FEMA) (Federal Emergency Management Agency (FEMA) 2018a, Federal Emergency Management Agency (FEMA) 2018b) provides a database of fragility functions of various nonstructural components for the assessment of building seismic performance. Such functions usually describe the probability of damage as a function of the strength of building shaking; e.g., as a function of the peak floor acceleration. As for fire protection systems, several studies (e.g., Tian, Filiatrault, and Mosqueda 2014; Jenkins et al. 2017) focused on fire sprinkler piping and developed its fragility functions because damage to fire sprinkler piping systems has severely limited the post-earthquake functionality of critical facilities and often resulted in widespread flooding damage in buildings. These are experimental fragility functions derived from the results of shaking-table tests for full-scale fire sprinkler piping. However, fragility functions limited to fire sprinkler piping are insufficient for the assessment of the post-earthquake fire risk of buildings because the post-earthquake fire risk of buildings depends on the fragilities of various other components as well as the sprinkler piping, such as sprinkler heads, fire pumps, fire detectors, and fire doors. There are few fragility functions of these components (i.e., other than the sprinkler piping) even in the database of nonstructural component fragility functions provided by FEMA (Federal Emergency Management Agency (FEMA) 2018a, Federal Emergency Management Agency (FEMA) 2018b). Given that the full-scale shaking-table testing of many such components is expensive, a comprehensive survey that collects data on actual damage to fire protection systems during an earthquake would be useful for understanding the seismic fragility of fire protection systems and developing damage models.

The present study therefore conducted a questi onnaire survey among hospitals affected by the Kumamoto earthquake, which had a moment magnitude of 7.1 and struck Kumamoto, Japan and the surrounding area on 16 April 2016 (1:25 a.m. local time), to gain an understanding of actual seismic damage to fire protection systems and derive statistical damage models for use in a probabilistic post-earthquake fire risk assessment. Hospitals were targeted because they alone appear to be suitable for collecting data on damage to various fire protection systems through a questionnaire survey from two perspectives. (1) Hospitals are required to install various fire protection systems under the Building Standard Law and the Fire Service Act of Japan whereas schools and offices are generally not required to install sprinkler systems and fire doors, although this depends on the building scale. (2) Reliable responses to a questionnaire survey are expected from hospitals at a higher response rate compared with other uses because facilities of hospitals are generally tightly controlled. Statistical modeling was conducted to investigate the association of the strength of building shaking with the number of instances of damage to a given type of component of a fire protection system. A zero-inflated Poisson distribution was adopted as a statistical model for data analysis to separately estimate the effects of the explanatory variable on the probability of damage occurring somewhere in a building and on the rate of damage upon the occurrence of damage (e.g., the number of instances of damage per 1000 m^2 of floor area). A peak response acceleration or a maximum displacement ratio estimated by reducing each building surveyed to an equivalent single degree of freedom (SDOF) system was considered as a representative measure of the strength of building shaking and was adopted as the explanatory variable. Model parameters were estimated using the Bayesian inference to cope with the limited amount of data. A hypothetical case study was conducted to demonstrate how to calculate the probability of the post-earthquake successful functioning of a fire protection system using the derived damage models.

2. Questionnaire survey

This section describes the method used to collect data on damage to components of fire protection systems resulting from the Kumamoto earthquake and presents an overview of the collected data.

2.1. Method

Self-administered questionnaires were mailed to 309 hospitals on 26 August 2016. Hospitals subjected to peak ground acceleration (PGA) of 1 m/s^2 or more during the Kumamoto earthquake were targeted as shown in Figure 3. A distribution of the PGA was estimated using a quick estimation system for an earthquake map triggered by observation records (QuiQuake) (National Institute of Advanced Industrial Science and Technology (AIST) 2019) and used to determine which hospitals to target. Ninety-four completed questionnaires were collected before 15 October 2016. The response rate was thus approximately 30%. The response rates for different PGA ranges were 25% for a range of 1.0 to 4.0 m/s^2, 39% for a range of 4.0 to 8.0 m/s^2, and 29% for a range of 8.0 m/s^2 or more. The response rates do not appear to vary greatly among the different PGA ranges.

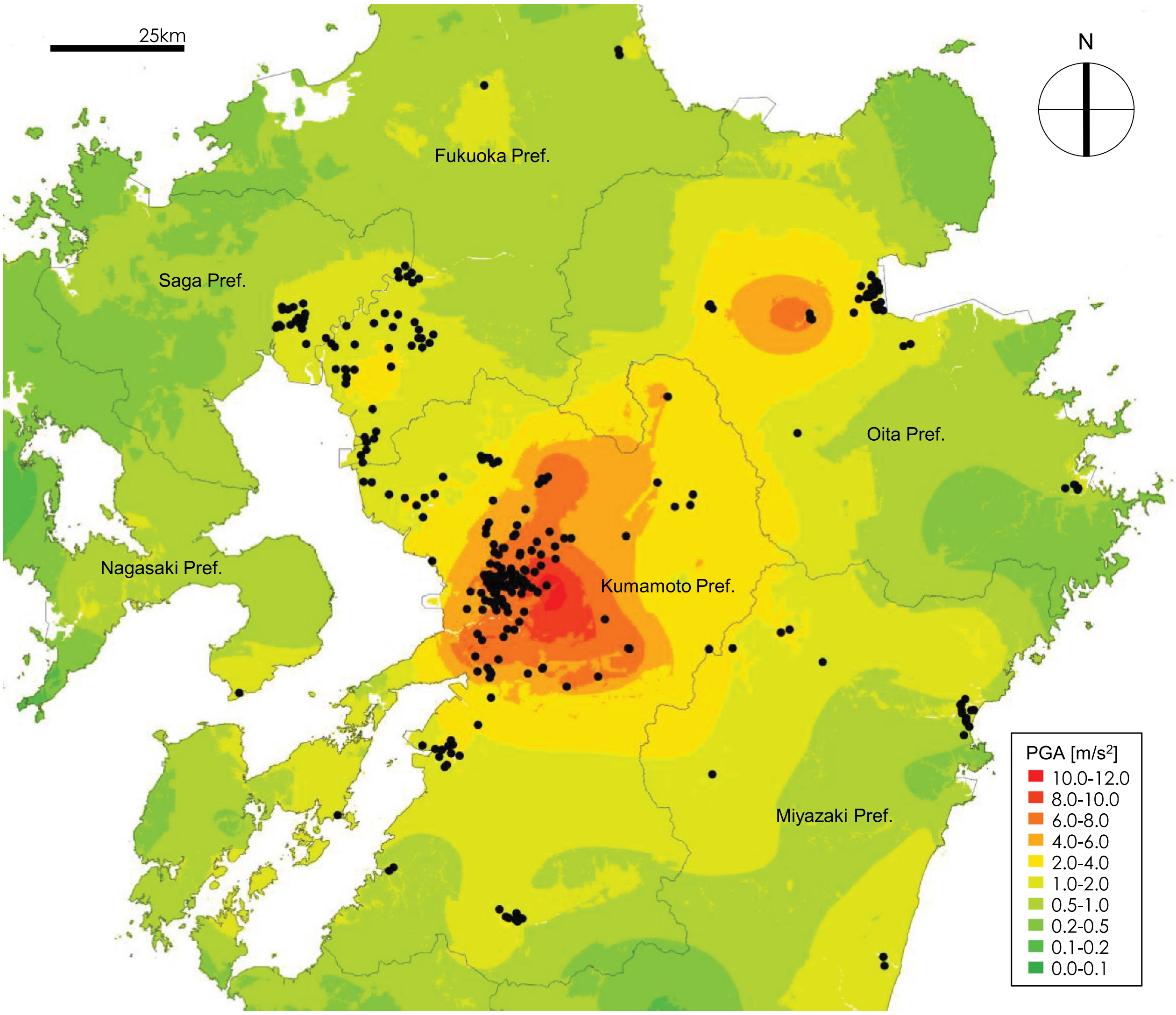

Figure 3. Distribution of the PGA for the Kumamoto earthquake of moment magnitude 7.1 that struck on 16 April 2016 (1:25 a.m. local time) estimated using QuiQuake (National institute of advanced industrial science and technology (AIST) 2019) and locations of 309 hospitals to which questionnaires were mailed.

Damage to 10 types of component were surveyed; these components were (1) emergency generators, (2) fire detectors, (3) water tanks used for firefighting, (4) fire pumps, (5) sprinkler heads, (6) indoor fire hydrant boxes, (7) fixed glass smoke curtains, (8) fire doors, (9) fire shutters, and (10) fire exit signs. To determine which components to survey, the causal relationship of the functional failure of six types of system, which are expected to be activated or effective in fires in terms of protecting life, was modeled using a fault tree diagram as shown in Figure 4. This fault tree model assumes that components are damaged independently of each other. As an example, a sprinkler system was assumed to comprise a commercial power supply backed up by emergency generators, water tanks, pumps, piping, and heads and to lose its function if at least one of these components were to be damaged. However, sprinkler piping was omitted from the types of component surveyed because (1) it is difficult for respondents, who are not experts in damage diagnosis, to visually confirm damage to piping, which is typically hidden behind walls and ceilings, and give accurate responses and (2) fragility functions of piping in Japanese buildings have been previously reported in the literature (Suwa and Kanda 2008). As another example, a smoke-activated door system was assumed to comprise detectors and doors neglecting potential damage to electrical wiring and receivers and to lose its function if at least one of these components were to be damaged. Smoke-activated door and shutter systems and an exit guidance system were assumed to be independent of the commercial power supply and emergency generators because they are required to have a built-in rechargeable battery for a loss of power under the Fire Service Act of Japan. For simplicity, the fault tree model neglected ceiling vibration and damage, which correlate with damage to ceiling-mounted components such as sprinkler heads and fire detectors. Instead, the questionnaires asked about the damage states of ceiling-mounted components so that respondents could distinguish between the presence and absence

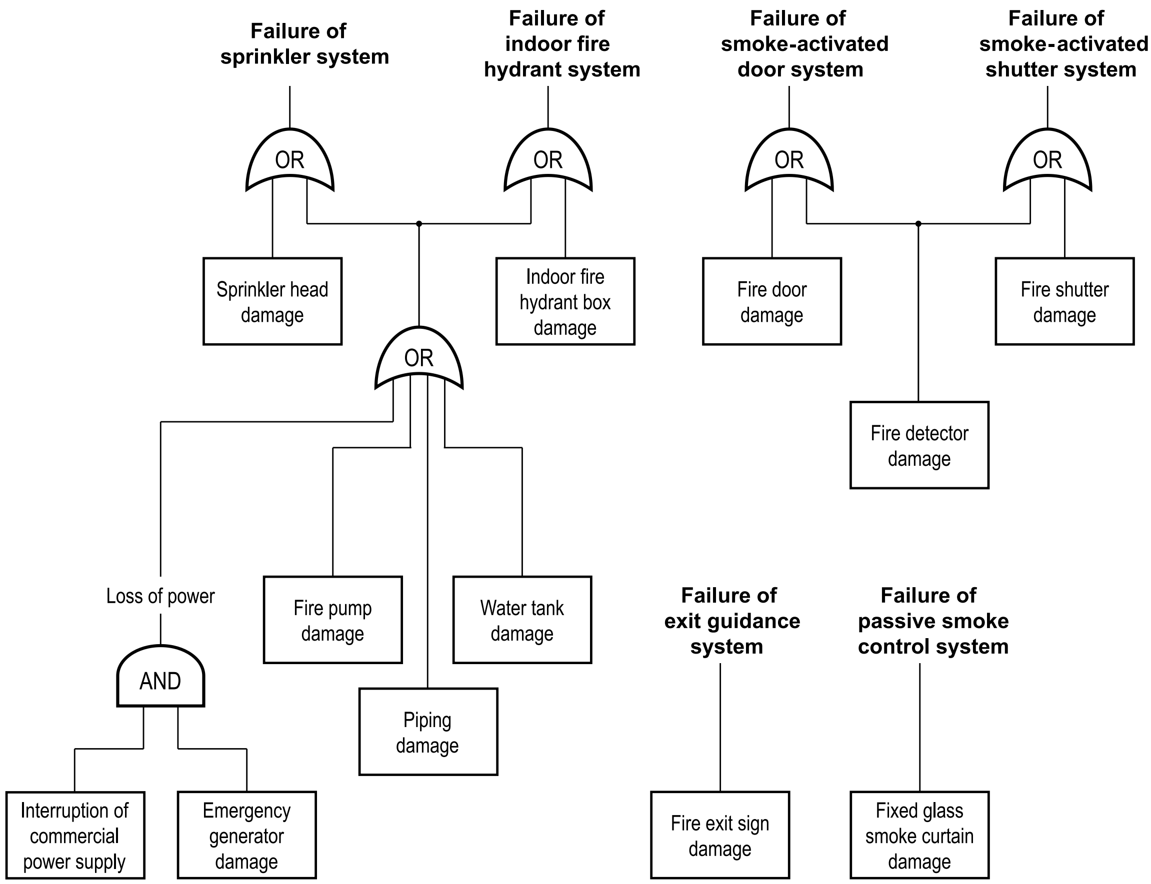

Figure 4. Simplified fault tree diagram considered for the functional failure of fire protection systems due to an earthquake used in determining which components to survey.

of ceiling collapse, such as the falling of sprinkler heads with ceiling collapse and the deformation of sprinkler heads without ceiling collapse, as described below. Photographs of the components except water tanks used for firefighting were included in the questionnaires as shown in Figure 5 to allow respondents to clearly recognize the types of component surveyed and avoid misunderstandings.

Four questions were asked for each type of component surveyed: (1) whether the given type of component was installed, (2) which damage states were observed (multiple answers allowed), (3) how many instances of damage were observed for each damage state, and (4) on which floors the damage was observed (multiple answers allowed). However, the number of installations was omitted from the questions because (1) counting the number of installations imposes an enormous burden on respondents and may reduce the response rate and (2) the number of installations can be roughly estimated for some types of component surveyed because their installation intervals are prescribed by the Building Standard Law and the Fire Service Act of Japan. Only the number of staircase fire doors was obtained from responses by specifying six types of staircase plan that differ in terms of the number of doors in the questionnaires and allowing respondents to report the number of each type of staircase plan. Damage states of each type of component surveyed were defined in advance and specified in the questionnaires as shown in Figure 6 to allow respondents to objectively evaluate damage. As an example, specified damage states of sprinkler heads were that (1) sprinkler heads had fallen with ceiling collapse, (2) sprinkler heads had dangled with ceiling collapse, (3) sprinkler heads had deformed without ceiling collapse, and (4) water had been sprayed by false activation. Check boxes were added beside damage state descriptions for the respondents to check to easily aggregate data. Note that responses to the question of on which floor the damage was observed were treated as damage occurring on the corresponding floor ground for floor-mounted components and on the corresponding floor ceiling for ceiling-mounted components. Additionally, surveyed building attributes were (1) the construction type, (2) the construction year, (3) the total floor area, (4) the horizontal projected area, (5) the number of floors, (6) the floor-to-floor height, (7) the presence or absence of seismic retrofitting, and (8) the presence or absence of a base-isolation system. The respondents were specified to be people knowledgeable of damage to buildings and components due to the earthquake, such as a person in charge of facility management or disaster management. In the case that a hospital comprised

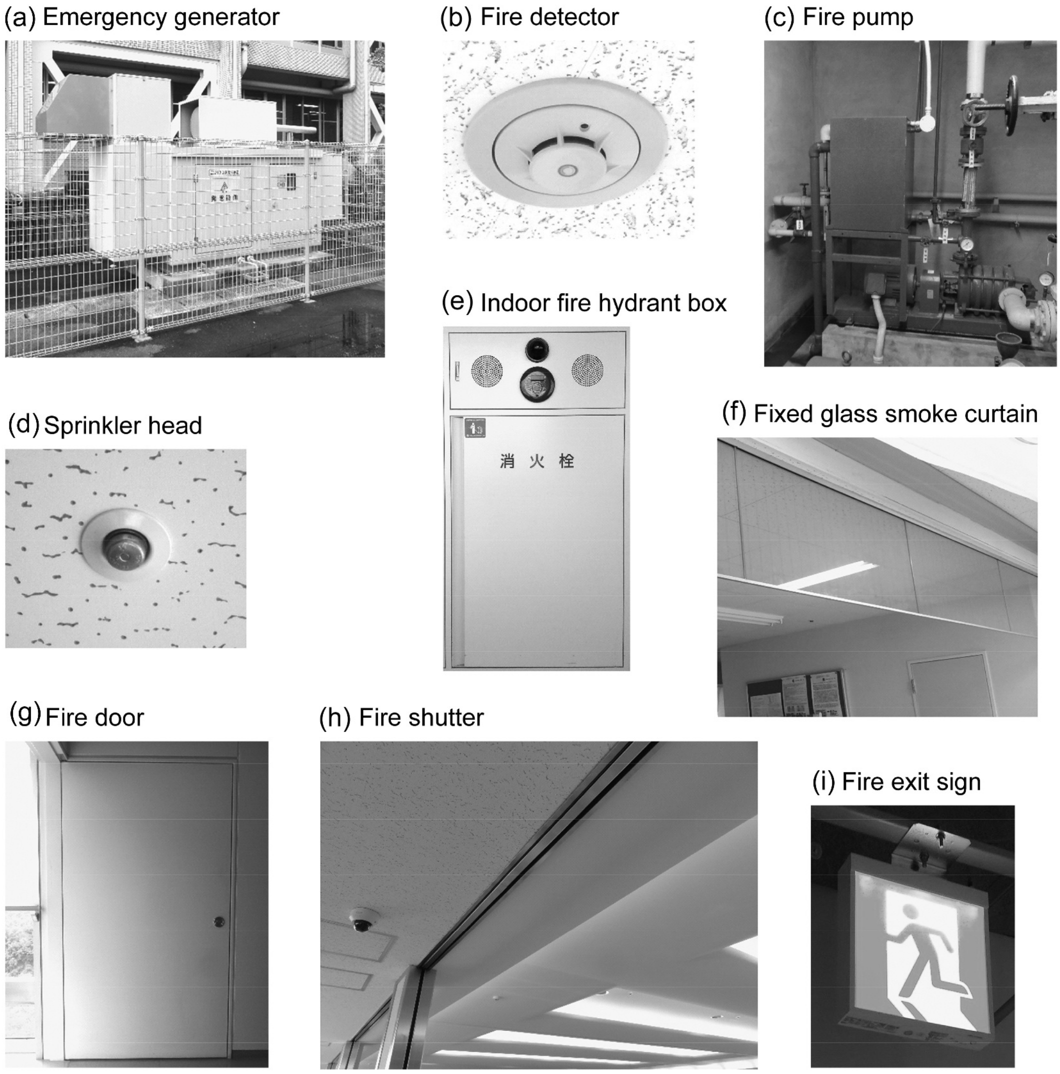

Figure 5. Photographs of components included in the questionnaires to allow respondents to clearly recognize the types of component surveyed and avoid misunderstandings.

multiple buildings, answers were obtained for one representative building or the most seriously damaged building.

2.2. Overview of collected data

Results of the survey are summarized for 69 buildings without base-isolation systems.

Figure 7 shows the construction types and the numbers of floors for the 69 buildings surveyed. Construction was classified as steel (S) construction, reinforced concrete (RC) construction, steel-framed reinforced concrete (SRC) construction, and hybrid construction (i.e., the combination of different structural materials, such as a building having upper steel and lower RC structures). Approximately 65% of the buildings are RC buildings. Almost all the buildings are mid-rise buildings with 3 to 10 floors.

Figure 8 shows the construction types and ages for the 69 buildings surveyed. The construction age was classified as (1) construction in or before 1984, when no seismic measures appear to have been implemented for building systems because no practical guidelines had been published, (2) construction between 1985 and 2011, when seismic measures appear to have been implemented for environmental system components of buildings, such as boilers, water tanks, and piping, according to the recommendations of the BCJ (The Building Center of Japan 1984), and (3) construction in or after 2012, when seismic measures may have been implemented also for the components of fire protection systems on the basis of a report of the FDMA (Fire and Disaster Management Agency 2011). Approximately 93% of the buildings were constructed in or before 2011. The survey data therefore appear to represent damage to components of fire protection systems for which seismic measures were hardly implemented.

Figure 9 shows the PGA and peak ground velocity (PGV) at each site of the 69 buildings surveyed as estimated by QuiQuake (National Institute of Advanced Industrial Science and Technology (AIST) 2019). The estimated PGAs range from 1 to 10 m/s^2

Q6. Damage to sprinkler heads

- Did your building install sprinkler heads?

  ☐ Yes ☐ No

- Which damage states were observed? How many instances of damage were observed for each damage state?
  - Sprinkler heads fell with ceiling collapse.

    ☐ Yes (_____ instances) ☐ No ☐ Unknown
  - Sprinkler heads dangled with ceiling collapse.

    ☐ Yes (_____ instances) ☐ No ☐ Unknown
  - Sprinkler heads deformed without ceiling collapse.

    ☐ Yes (_____ instances) ☐ No ☐ Unknown
  - Water was sprayed by false activation.

    ☐ Yes (_____ instances) ☐ No ☐ Unknown

- On which floors was the above damage observed? (multiple answers allowed)

  ☐ 1st floor ☐ 2nd floor ☐ 3rd floor
  ☐ 4th floor ☐ 5th floor ☐ 6th floor
  ☐ 7th floor ☐ 8th floor ☐ 9th floor
  ☐ 10th floor or above ☐ Basement floor

Figure 6. Example of the questions on damage to the types of component surveyed included in the questionnaires.

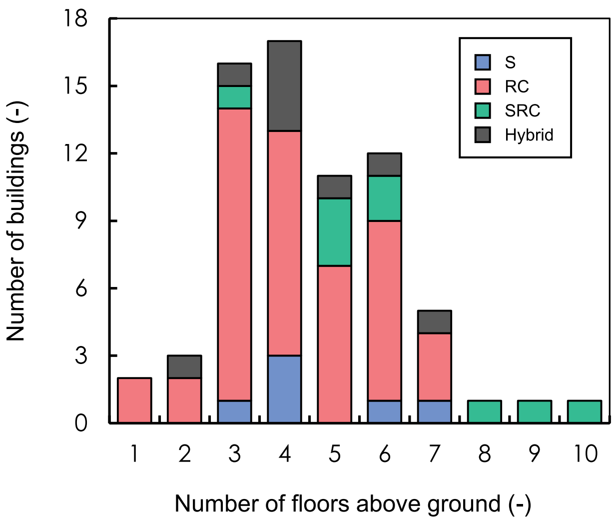

Figure 7. Construction types and numbers of floors for the 69 buildings surveyed.

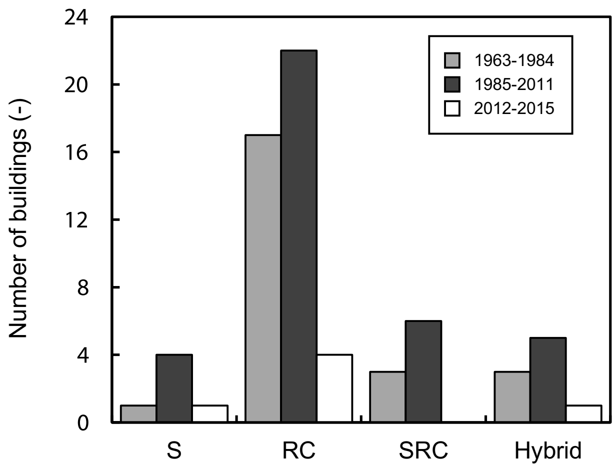

Figure 8. Construction types and ages for the 69 buildings surveyed.

while the estimated PGVs range from 0.1 to 1.0 m/s. The collected data include buildings subjected to a wide range of ground motions from strong to weak.

Figure 10 shows the observed damage states by construction age for the nine types of component surveyed. Damage to fire pumps was not observed. Damage to fire detectors, sprinkler heads, fire doors, and fire exit signs was observed in many buildings. Examples of observed damage to sprinkler heads were (1) the heads dangling with ceiling collapse, (2) deformation of the heads without ceiling collapse, and (3) false activation (i.e., water was sprayed unnecessarily). Examples of observed damage to fire doors were (1) the doors falling off, (2) failure of the doors to close because of deformation, and (3) failure of the doors to open/close because of obstacles. There is no characteristic difference in the observed damage between buildings constructed in or before 1984 and buildings constructed between 1985 and 2011, which have relatively large sample sizes. This result is expected because seismic measures of ceiling-mounted components and doors, which are commonly found among fire protection system components, are not included in the recommendations of the BCJ (The Building Center of Japan 1984), which are mainly for heavy components and piping. In contrast, there being few observations of damage to emergency generators and water tanks used for firefighting suggests an effect of the recommendations of the BCJ. Damage to ceiling-mounted components and doors was observed in buildings constructed in or after 2012, even though

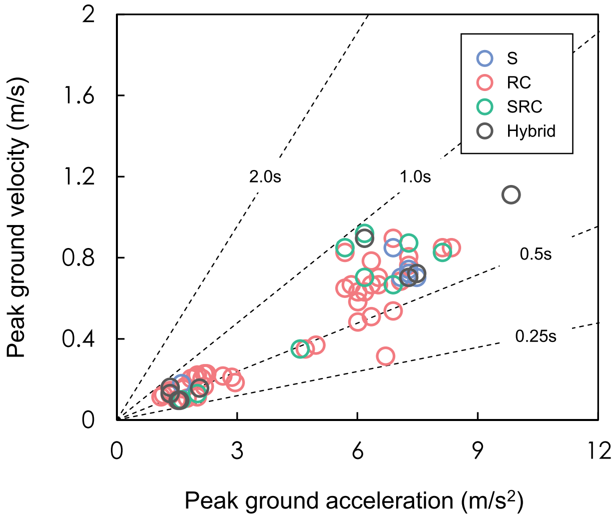

Figure 9. PGA and PGV at each site of the 69 surveyed buildings obtained using QuiQuake (National Institute of Advanced Industrial Science and Technology (AIST) 2019). The dotted lines represent the equivalent predominant periods of ground motions calculated as 2π times the PGV/PGA ratio.

the FDMA (Fire and Disaster Management Agency 2011) provided the concept of seismic measures of the components of fire protection systems in 2011.

3. Statistical modeling

This section describes the statistical modeling conducted to investigate the association of the strength of building shaking with the number of instances of damage to a given type of component of a fire protection system. The four types of component for which much damage was observed were subject to the modeling: (1) fire detectors, (2) sprinkler heads, (3) fixed glass smoke curtains, and (4) fire doors. However, the models generalized the fragility of each type of component as a whole without distinguishing damage states because the amount of data was not sufficient to derive the models for different damage states. A zero-inflated Poisson distribution was adopted as a statistical model to separately estimate the effects of the explanatory variable on the probability of damage occurring somewhere in a building and on the rate of damage upon the occurrence of damage (e.g., the number of instances of damage per 1000 m^2 of floor area). A peak response acceleration or a maximum displacement ratio of an equivalent SDOF system was adopted as the explanatory variable considering that it is representative of the strength of building shaking. The peak response acceleration and the maximum displacement ratio were newly estimated using an acceleration response spectrum of ground motion for each of 40 buildings surveyed, excluding buildings with hybrid structures and buildings constructed before 1982 without seismic retrofitting. Model parameters were estimated using the Bayesian inference to cope with the limited amount of data; that is, each of the model parameters was treated as a random variable for which a probability distribution describes degrees of belief in values, and the prior distribution was updated using the data on the basis of Bayes' theorem. A program for the Bayesian inference was developed using Stan software (Stan Development Team 2016), which is a state-of-the-art platform for statistical modeling and high-performance statistical computation. Note that damage models derived from the data do not reflect the effect of seismic measures of fire protection systems because the data hardly include buildings constructed after the FDMA (Fire and Disaster Management Agency 2011) reported the concept of seismic measures of fire protection systems.

3.1. Model formulation

The data used in this study include data for quite a few buildings in which no damage to components of fire protection systems occurred (i.e., the data include excessive zeros), and Poisson regression, which is typically used in modeling count data, is thus likely to underestimate the inherent fragility of the components. To overcome this difficulty, zero-inflated Poisson regression is applied; that is, it is assumed that (1) the event that damage occurs to the j-th type of component somewhere in the i-th building follows a Bernoulli distribution with a probability of ω_{ij} and (2) the number of instances of damage to the j-th type of component in the i-th building y_{ij} follows a Poisson distribution with a mean of λ_{ij}. In other words, we toss a hypothetical coin that lands heads up with a probability of ω_{ij}. If the coin lands heads down, the number of instances of damage y_{ij} is zero. If the coin lands heads up, the number of instances of damage y_{ij} is generated from a Poisson distribution with a mean of λ_{ij}. A mixture of a Poisson distribution and a Bernoulli distribution is called a zero-inflated Poisson distribution and is usually used to model count data with excessive zeros (Lambert 1992). The cumulative distribution function of a log-normal distribution, which is typically used in modeling seismic fragility, is applied to the relationship between the probability ω_{ij} and the explanatory variable while the log-link function, which is typically used in Poisson regressions, is applied to the relationship between the mean λ_{ij} and the explanatory variable.

The probability distribution of the number of instances of damage to the j-th type of component in the i-th building y_{ij} is given by the zero-inflated Poisson distribution

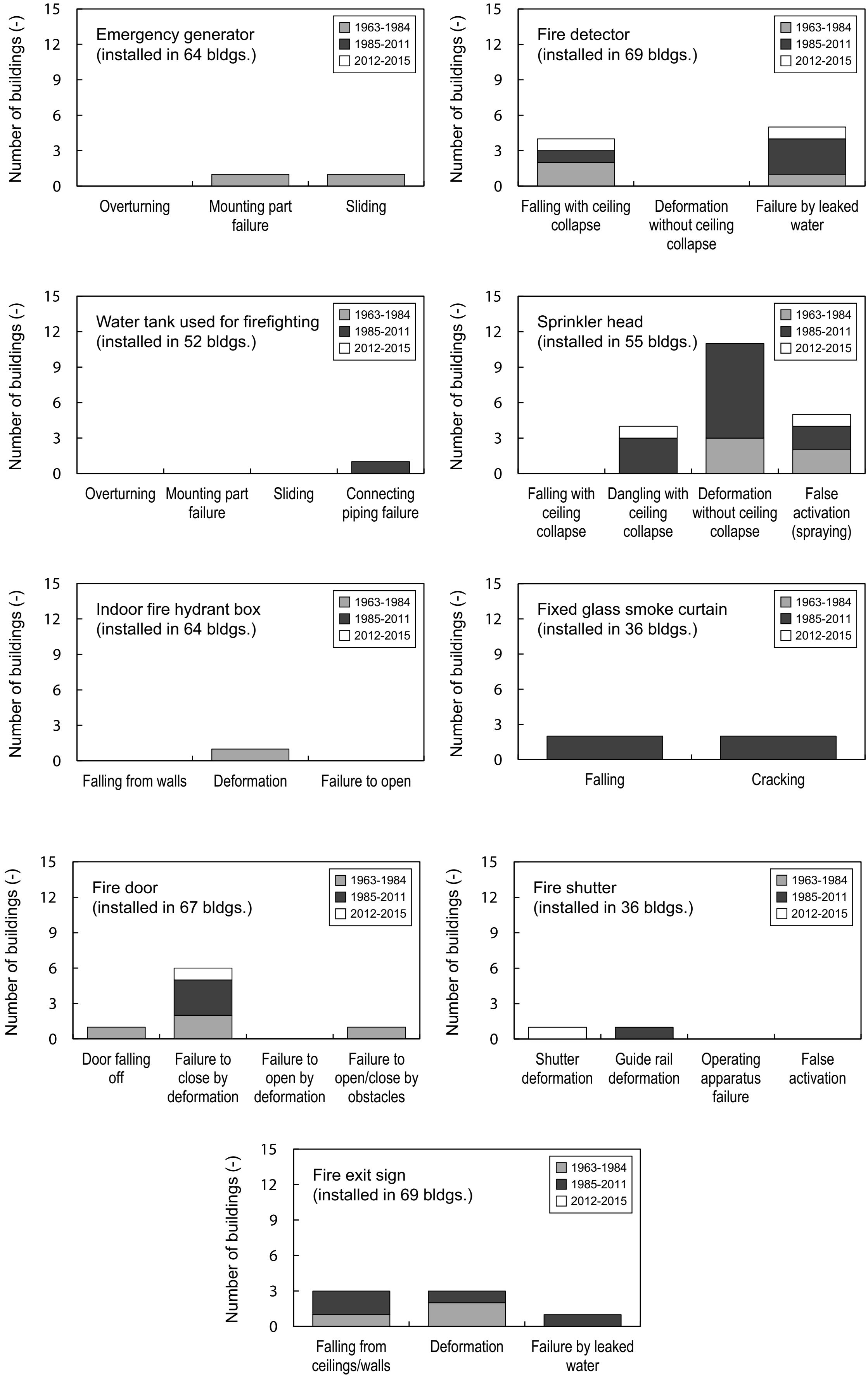

Figure 10. Observed damage states by construction age for the nine surveyed types of component of a fire protection system. Damage to fire pumps was not observed.

$$p(y_{ij}|\lambda_{ij},\omega_{ij}) = \begin{cases} (1-\omega_{ij})+\omega_{ij}e^{-\lambda_{ij}} & (y_{ij}=0) \\ \omega_{ij}\lambda_{ij}^{y_{ij}}e^{-\lambda_{ij}}/y_{ij}! & (y_{ij}\geq 1) \end{cases} \quad (1)$$
$$i = 1,\cdots,N_j \quad j=1,\cdots,K,$$

where N_j is the number of buildings with the j-th type of component and K is the number of types of component.

The probability ω_{ij}, which is the probability of damage occurring to a given type of component somewhere in a building, depends on the size of the building as well as the strength of building shaking because the number of installations of the component depends on the size of the building. Therefore, a building with a total floor area of 1000 m^2 is considered as the reference building and the probability for the reference building is modeled as the cumulative distribution function of a log-normal distribution. The probability ω_{ij} for a building with a given total floor area $A_{F,i}$ is given by

$$\omega_{ij} = 1-\left[1-\Phi\left(\frac{\ln(x_i/\theta_j)}{\beta_j}\right)\right]^{A_{F,i}/1000} \quad (2)$$
$$i=1,\cdots,N_j \quad j=1,\cdots,K,$$

where Φ is the cumulative distribution function of a standard normal distribution, x_i is the explanatory variable, θ_j is the median (i.e., the value of the explanatory variable when the probability for the reference building is 50%), and β_j is the logarithmic standard deviation. Note that the logarithmic standard deviation β_j is considered to be common to all types of component, and its value is fixed at 0.4 by reference to the FEMA P-58 fragility function fitting procedure (Federal Emergency Management Agency (FEMA) 2018a, Federal Emergency Management Agency (FEMA) 2018b).

Let Q_{ij} be the number of installations of the j-th type of component in the i-th building; however, for some types of component of which the number of installations is not obtained from the survey, let Q_{ij} be the total floor area of the i-th building. Let r_{ij} be the rate of damage to the j-th type of component in the i-th building upon the occurrence of damage; that is, for types of component of which the number of installations is obtained from the survey, the rate of damage is treated as the ratio of the number of instances of damage to the number of installations. In contrast, for types of component of which the number of installations is not obtained from the survey, the rate of damage is treated as the number of instances of damage per 1000 m^2 of floor area. The mean λ_{ij}, which is expressed as the product of Q_{ij} and r_{ij}, is modeled using a log-link function:

$$\ln\ \lambda_{ij} = \ln(Q_{ij}r_{ij}) = \ln[Q_{ij}\exp(a+b_jx_i)] = a+b_jx_i+\ln Q_{ij}$$
$$i = 1,\cdots,N_j \quad j=1,\cdots,K, \quad (3)$$

where a is the intercept, and b_j is the slope. The above equation treats $\ln Q_{ij}$ as an offset term. Note that the intercept a is considered to be common to all types of component.

3.2. Bayesian inference framework

The probability of the data D being obtained is given as the product of zero-inflated Poisson distributions for all buildings and all types of component:

$$p(D|a,b_1,\cdots,b_K,\theta_1,\cdots,\theta_K) = \prod_{j=1}^{K}\prod_{i=1}^{N_j} p(y_{ij}|\lambda_{ij},\omega_{ij}) \ . \quad (4)$$

The posterior distribution is expressed by

$$\mathit{Posterior\ distribution} \propto p(D|a,b_1,\cdots,b_K,\theta_1,\cdots,\theta_K) \times \mathit{Prior\ distribution} \quad (5)$$

based on Bayes' theorem, and the prior distribution thus needs to be specified.

A non-informative prior distribution is specified for each of the intercept a and the slope b_j, which can take any positive or negative value. A normal distribution with a mean of zero and a standard deviation of 100 is adopted. This distribution is typically used as a sufficiently flat probability distribution in Bayesian statistics.

$$a \sim \mathit{Normal}(0,100) \quad (6)$$

$$b_j \sim \mathit{Normal}(0,100) \qquad j=1,\cdots,K \quad (7)$$

A non-informative prior distribution is specified also for the median θ_j, which can take any positive value. A uniform distribution that ranges from 0 to 1000 is adopted. This distribution is also typically used as a sufficiently flat probability distribution in Bayesian statistics.

$$\theta_j \sim \mathit{Uniform}(0,1000) \qquad j=1,\cdots,K \quad (8)$$

Therefore, the posterior distribution can be expressed by

$$p(a,b_1,\cdots,b_K,\theta_1,\cdots,\theta_K|D) \propto p(D|a,b_1,\cdots,b_K,\theta_1,\cdots,\theta_K)p(a)\prod_{j=1}^{K}p(b_j)\prod_{j=1}^{K}p(\theta_j) \quad (9)$$

The Markov chain Monte Carlo method (Metropolis et al. 1953) is used to obtain the posterior distribution. The method generates samples from the distribution of the product of the likelihood and the prior distribution and adopts samples that are diagnosed as having converged to the equilibrium distribution as a substitute for the posterior distribution. Four Markov chains are initiated with different combinations of initial conditions to ensure that they converge to similar posterior distributions. The Markov chains are built using Hamiltonian Monte Carlo sampling (Neal 2011) in Stan software. Each chain generates 4000 samples. The first 2000 samples, which appear to depend on an initial value, are removed (i.e., these are the burn-in sequence of the chain). The remaining 2000 samples are used to obtain the posterior distribution (i.e., a total of 8000 samples are used). The $\hat{R}$ statistic (Gelman and Rubin 1992) is used for convergence diagnosis. The statistic is a measure of the ratio of the average variance of samples within each chain to the variance of the pooled samples across chains. It is considered that there is convergence to the posterior distribution for all values for $\hat{R}$ below 1.1 according to the recommendation of Gelman and Rubin (Gelman and Rubin 1992).

3.3. Explanatory variables

Engineering demand parameters that quantify the structural response at each floor level, such as the peak floor acceleration and maximum inter-story drift ratio, are typically used to estimate damage to nonstructural components (Applied Technology Council (ATC), 2004). However, it is not possible to know such detailed structural response quantities for the buildings surveyed because little information is available on structural response simulations. Therefore, the response quantities of an equivalent SDOF system were adopted as the explanatory variable by assuming that they are representative of the above engineering demand parameters and thus are also correlated with damage to nonstructural components. Specific response quantities used were determined for each type of component subject to modeling by taking into account the response sensitivity of nonstructural components; that is, acceleration-sensitive and/or deformation-sensitive components. For fire detectors, sprinkler heads, and fixed glass smoke curtains, which are mounted on the ceiling, a peak response acceleration of an equivalent SDOF system was adopted because suspended ceiling systems typically consist of acceleration-sensitive nonstructural elements (Qi et al. 2020). For fire doors, of which frames are fixed to the wall, a maximum displacement ratio of an equivalent SDOF system was adopted because walls are typically considered to be deformation-sensitive components. These response quantities were estimated using an acceleration response spectrum of ground motion for each building analyzed. The estimation procedure is as follows. (1) A building with multiple floors is reduced to an equivalent SDOF system, and its equivalent natural period and damping ratio are calculated using an existing empirical equation (Kambara and Hayashi 2001) that was derived from numerical results of a time-history response analysis of a multiple-degree-of-freedom system that models typical Japanese buildings designed after 1981. (2) A hypothetical acceleration response spectrum of ground motion is calculated from the PGA and PGV considering the equivalent damping ratio for each building site based on the recommendations on seismic loads of the Architectural Institute of Japan (Architectural Institute of Japan 2015). (3) The value of a peak response acceleration is read from the spectrum for the corresponding period, and a maximum displacement ratio is calculated from the peak response acceleration considering the equivalent height and natural period.

The height of an equivalent SDOF system H_e is obtained by assuming that the first mode shape follows an inverted-triangle distribution:

$$H_e = \frac{2N+1}{3N} H \,, \tag{10}$$

where N is the number of floors and H is the building height.

The natural period T_e and damping ratio h_e of an equivalent SDOF system are given for each construction type by empirical equations (Kambara and Hayashi 2001) that consider that the natural period and damping ratio increase when a structure plastically deforms over the elastic limit:

$$T_e = \begin{cases} T_0 & (\mu < 1) \\ \sqrt{\mu} T_0 & (\mu \geq 1) \end{cases} \quad (\mathrm{S}) \,, \tag{11}$$

$$T_e = \begin{cases} \{(\sqrt{3}-1)\mu + 1\} T_0 & (\mu < 1) \\ \sqrt{3\mu} T_0 & (\mu \geq 1) \end{cases} \quad (\mathrm{RC/SRC}) \,, \tag{12}$$

$$h_e = \begin{cases} 0.02 & (\mu < 1) \\ 0.12\left(1 - \frac{1}{\mu}\right) + 0.02 & (\mu \geq 1) \end{cases} \quad (\mathrm{S}) \,, \tag{13}$$

$$h_e = \begin{cases} 0.07\mu + 0.03 & (\mu < 1) \\ 0.15\left(1 - \frac{1}{\sqrt{\mu}}\right) + 0.1 & (\mu \geq 1) \end{cases} \quad (\mathrm{RC/SRC}) \,, \tag{14}$$

$$\mu = \frac{\left(\frac{T_0}{2\pi}\right)^2 S_a(T_0, h_0)/H_e}{R_y} \,, \tag{15}$$

where T_0 is the elastic natural period, h_0 is the initial damping ratio (i.e., 0.02 for S construction and 0.03 for RC/SRC construction), and $R_y(= 1/150)$ is the yield displacement ratio. The elastic natural period T_0 is obtained using equations adopted for design in Japan:

$$T_0 = 0.03H \quad (\mathrm{S}) \,, \tag{16}$$

$$T_0 = 0.02H \quad (\mathrm{RC/SRC}) \,. \tag{17}$$

The hypothetical acceleration response spectrum of ground motion $S_a(T, h)$, which is a function of the natural period T and damping ratio h, is given for each building site (Architectural Institute of Japan 2015) as

$$S_a(T,h) = \begin{cases} (1+3T/T_c)F_h a_g & (T < 0.5T_c) \\ 2.5F_h a_g & (0.5T_c \le T < T_c) \\ 2.5(T_c/T)F_h a_g & (T_c \le T) \end{cases}, \quad (18)$$

$$F_h = 1.5/(1+10h) \ , \quad (19)$$

$$T_c = 1.6\pi v_g/a_g \ , \quad (20)$$

where a_g is the PGA and v_g is the PGV. Note that the values of the PGA and PGV are obtained using QuiQuake (National Institute of Advanced Industrial Science and Technology (AIST) 2019). Figure 11 compares the hypothetical spectrum with observed spectra for the Kumamoto earthquake (National Research Institute for Earth Science and Disaster Resilience, NIED K-NET, KiK-net 2019), which are derived from 68 waveforms recorded at 34 seismic stations (two horizontal components for each station) with PGAs ranging from 0.9 to 11.6 m/s^2. Note that, only in this comparison, the damping ratio was uniformly set at 0.05 for simplicity. The hypothetical spectrum roughly approximates the average of the observed spectra, and the peak response acceleration is thus estimated roughly for each building analyzed because there is no ground motion observation record and it is not possible to accurately assess the acceleration response spectrum.

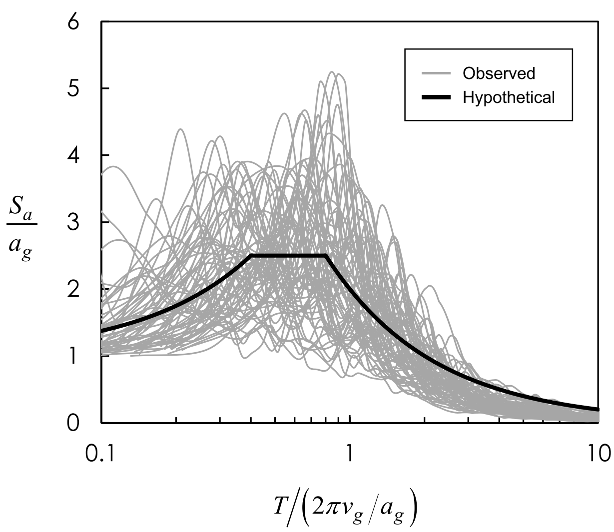

Figure 11. Comparison of the normalized hypothetical acceleration response spectrum of ground motion (Architectural Institute of Japan 2015) with spectra observed during the 2016 Kumamoto earthquake (National Research Institute for Earth Science and Disaster Resilience, NIED K-NET, KiK-net 2019). Note that, only in this comparison, the damping ratio was uniformly set at 0.05.

The maximum displacement ratio of an equivalent SDOF system R_e is given by

$$R_e = \frac{\delta_e}{H_e} = \frac{S_a(T_e, h_e)(T_e/2\pi)^2}{H_e} \ , \quad (21)$$

where δ_e is the maximum displacement of an equivalent SDOF system.

3.4. Results and discussion

Figure 12 shows the damage models derived from the data and their comparison with the data. The statistics of each model parameter are summarized in Table 1. All values for $\hat{R}$ are below 1.1 and it is considered that there is convergence to the posterior distribution (Gelman and Rubin 1992). The damage models shown adopt the median as the value of each parameter. Note that the models for the probability of damage occurring somewhere in a building, which are shown for the reference building with a total floor area of 1000 m^2, cannot be compared with the data because the data include buildings with various total floor areas. As for the models for the rate of damage upon the occurrence of damage, the data for fire doors are plotted by dividing the number of instances of damage by the number of installations while the data for the other types of component, of which the number of installations was not obtained from the survey, are plotted by dividing the number of instances of damage by the total floor area. The damage models demonstrate the effectiveness of the zero-inflated Poisson regression adopted in this study; that is, the regression is reasonably successful in deriving the models for the rate of damage upon the occurrence of damage without being excessively pulled to the zero data because of the separation of the effects of the explanatory variable on the probability of damage occurring somewhere in a building and on the rate of damage upon the occurrence of damage. As expected, the probability of damage occurring somewhere in a building and the rate of damage upon the occurrence of damage increase with the building response quantities regardless of the type of component. As for the three types of ceiling-mounted component excluding the fire doors, the models for the rate of damage upon the occurrence of damage appear to fit well to the non-zero data. Note that the difference in models for the rate of damage upon the occurrence of damage does not mean the difference in the component's inherent fragility because the number of installations per floor area is different depending on the type of ceiling-mounted component. This component's fragility difference will be discussed in the following paragraph. The models for the probability of damage occurring somewhere in a building shows that the probability rapidly increases when the peak response acceleration exceeds approximately 6 m/s^2 for fixed

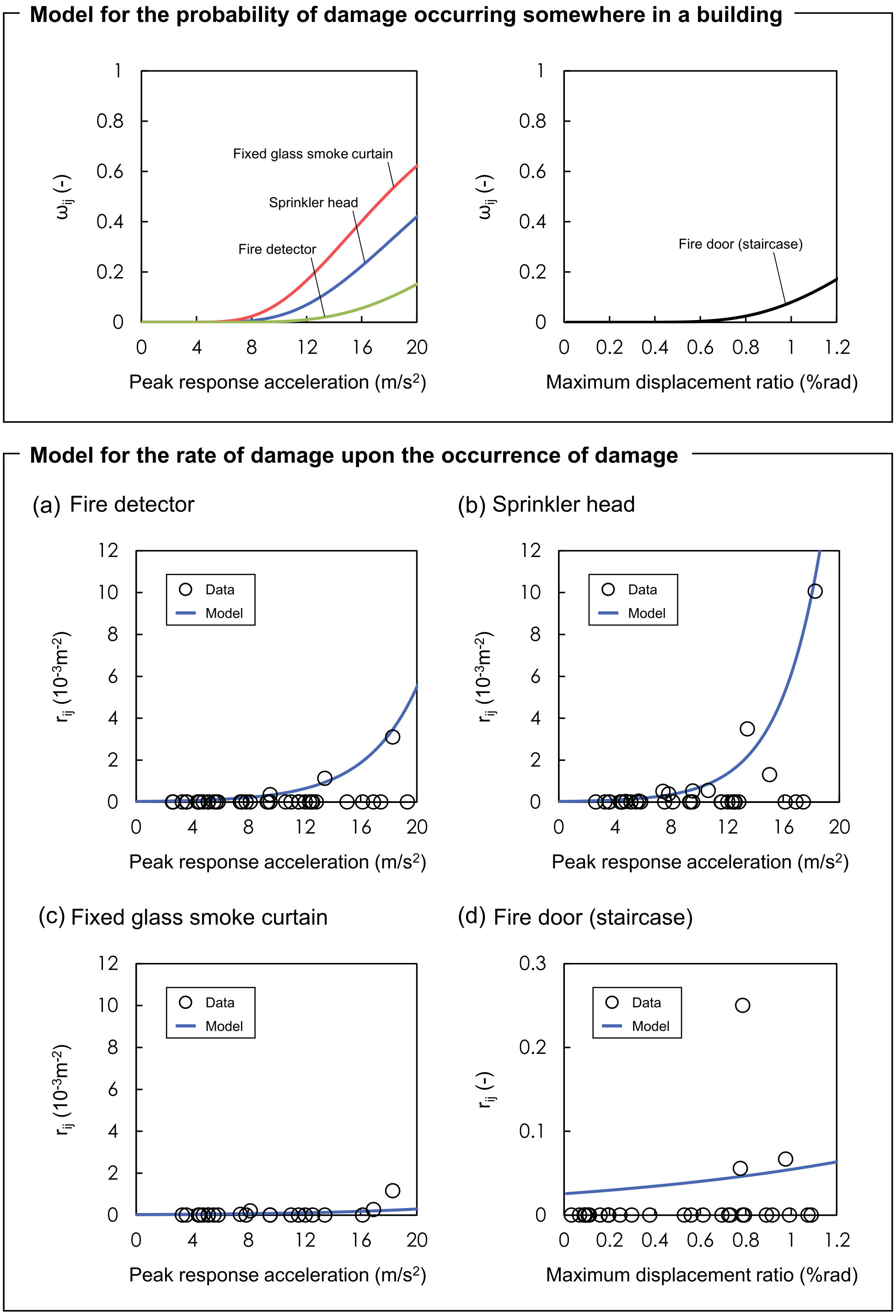

Figure 12. Damage models for the four types of component of a fire protection system derived from the data and their comparison with the data.

glass smoke curtains, 8 m/s^2 for sprinkler heads, and 9 m/s^2 for fire detectors. This suggests objective criteria of structural performance used for design to fully maintain the functionality of these ceiling-mounted components. For instance, the Japan Structural Consultants Association (Kitamura, Miyauchi, and Uramoto 2006) proposed the criteria of structural performance to evaluate the level of post-earthquake building functionality with respect to several structural response quantities, such as inter-story drift and floor acceleration, and adopted 2.5 or 5.0 m/s^2 as the criterion for floor acceleration. The derived models for the probability of damage occurring somewhere in a building can reinforce these existing recommendations in the aspect of post-earthquake fire safety. Meanwhile, with respect to fire doors, there is a data point far from the model prediction of the rate of damage upon the occurrence of damage, although damage to partition walls and doors is known for having a high correlation with the maximum story drift ratio, which is a response quantity similar to the maximum displacement ratio. The damaged fire doors in

Table 1. Statistics of model parameters obtained adopting Bayesian inference.

Parameter		Mean	SD	Median	$\hat{R}$
a		−3.6797	0.2936	−3.6700	1.0023
b_j	Fire detector	0.2684	0.0236	0.2686	1.0015
	Sprinkler head	0.3308	0.0212	0.3306	1.0017
	Fixed glass smoke curtain	0.1214	0.0378	0.1218	1.0006
	Fire door (staircase)	0.7010	0.8123	0.7605	1.0006
θ_j	Fire detector	30.5409	3.2855	30.2037	0.9999
	Sprinkler head	21.7405	1.4246	21.6808	0.9997
	Fixed glass smoke curtain	17.9829	4.7142	17.6677	1.0009
	Fire door (staircase)	1.7477	0.2970	1.7565	1.0007

the building for this data point may have been in an unusual state before the earthquake. However, the model for the probability of damage occurring somewhere in a building shows that the probability rapidly increases when the maximum displacement ratio exceeds approximately 0.6% rad. This tendency is roughly consistent with the results of full-scale tests on the seismic performance of partition walls and doors (Kato et al. 2006), which showed that a door with a drift ratio of 0.5% rad first failed to open or close but recovered after unloading whereas a door with a drift ratio of 1.5% rad failed to open or close and did not recover after unloading. The damage models, especially with respect to fire doors, require further validation through the collection of more data for different earthquakes.

Figure 13 shows rough estimates of the component-based rate of damage upon the occurrence of damage for the three types of ceiling-mounted component. Their installation intervals are prescribed by the Building Standard Law and the Fire Service Act of Japan, and the model predictions of the floor-area-based rate of damage upon the occurrence of damage (i.e., the number of instances of damage per 1000 m^2 of floor area) were thus converted into the component-based rate of damage upon the occurrence of

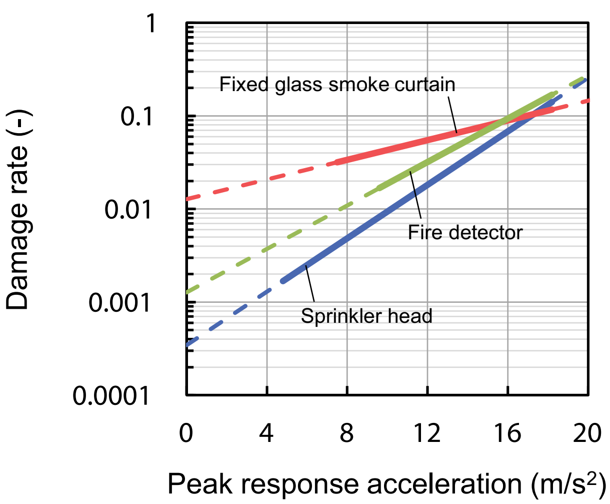

Figure 13. Rough estimates of the component-based rate of damage upon the occurrence of damage for the three types of component of a fire protection system.

damage (i.e., the ratio of the number of instances of damage to the number of installations) by assuming the number of installations per unit floor area on the basis of the regulations. The assumptions are one fire detector per 50 m^2 of floor area, one sprinkler head per 13.5 m^2 of floor area, and one fixed glass smoke curtain per 500 m^2 of floor area. Note that the estimates are illustrated as a solid line within the range between the minimum and maximum accelerations when damage to components was observed and are illustrated as a dotted line outside the damage-observed range. Within the damage-observed range, fire detectors and sprinkler heads appear to have similar fragilities while fixed glass smoke curtains appear to be more vulnerable. This could be related to the feature of component specifications; that is, the sizes, shapes, and mounting arrangements of fire detectors and sprinkler heads are similar but much different from those of fixed glass smoke curtains.

4. Case study on post-earthquake system reliability

This section presents a hypothetical case study to demonstrate how to calculate the probability of the post-earthquake successful functioning of a fire protection system using the derived damage models. The case study focuses on a sprinkler system and a smoke-activated door system.

The probability of the successful functioning of a fire protection system for normal fires is typically expressed as the product of the probability of activation upon the occurrence of fire p_1 and the probability of successful functioning under activation p_2. In this case study, the event of a fire being extinguished is considered as the successful functioning under the activation of a sprinkler system while the event of a fire door closing without being obstructed by uncontrolled goods is considered as the successful functioning under the activation of a smoke-activated door system. These probabilities are typically estimated from fire incident data and system inspection data; e.g., Ikehata et al. (Ikehata et al. 2017) analyzed Japanese fire incident data to quantify the reliability of a sprinkler system and estimated p_1 and p_2 to be 0.90 and 0.65 respectively whereas Kakegawa (Kakegawa 1997) analyzed Japanese system inspection data to quantify the reliability of a smoke-activated door system and estimated p_1 and p_2 to be 0.93 and 0.97 respectively.

The probability of the post-earthquake successful functioning p_S is therefore obtained by adding the probability of the functional failure of a fire protection system resulting from seismic damage to components p_F:

$$p_S = (1 - p_F)p_1p_2 \ . \quad (22)$$

Considering the causal relationship between the functional failure of a system and damage to components as shown in Figure 4, and assuming that components are damaged independently of each other, the probability of the functional failure p_F is given as

$$p_F = 1 - \left(1 - p_{interruption} p_{generator}\right)\left(1 - p_{pump}\right)\left(1 - p_{piping}\right)\left(1 - p_{tank}\right)\left(1 - p_{head}\right) \quad (23)$$

for a sprinkler system and

$$p_F = 1 - \left(1 - p_{detector}\right)\left(1 - p_{door}\right) \quad (24)$$

for a smoke-activated door system, where $p_{interruption}$ is the probability of the interruption of the commercial power supply while $p_{generator}$, p_{pump}, p_{piping}, p_{tank}, p_{head}, $p_{detector}$, and p_{door} are respectively the probabilities of damage to the emergency generator, fire pump, sprinkler piping, water tank used for firefighting, sprinkler head, fire detector, and fire door. The probability of the interruption of the commercial power supply can be calculated from seismic intensity measures using an empirical equation derived from Japanese post-earthquake power outage rate data (Nojima and Kato 2014). The probabilities of damage to the emergency generator and sprinkler piping can be calculated using existing empirical fragility functions derived from Japanese earthquake damage data (Suwa and Kanda 2008; Deguchi, Kohno, and Tsujimoto 2001). The probabilities of damage to the sprinkler head, fire detector, and fire door can be calculated using the derived damage models as the product of the probability of damage occurring somewhere in the building ω_{ij} and the component-based rate of damage upon the occurrence of damage r_{ij}. The probabilities of damage to the fire pump and water tank used for firefighting are approximated as zero for simplicity because such damage was hardly observed in the buildings surveyed.

Figure 14 shows an example of calculating the probability of the post-earthquake successful functioning of fire protection systems for buildings with a total floor area of 1000 m^2 subjected to varying peak response accelerations. The Japan Meteorological Agency seismic intensity, which is required for calculating the probability of the interruption of the commercial power supply, was assumed to be 6.2 considering a very severe but infrequent ground motion. The PGV, which is required for calculating the probability of damage to the emergency generator, was assumed to be 0.8 m/s again considering a very severe but infrequent ground motion. The maximum displacement ratio was calculated from the peak response acceleration by assuming the natural period and the equivalent height for simplicity. The calculation example suggests that the post-earthquake reliability of fire protection systems generally decreases from the normal reliability and the decrement greatly depends on the strength of building shaking; that is, the probability of

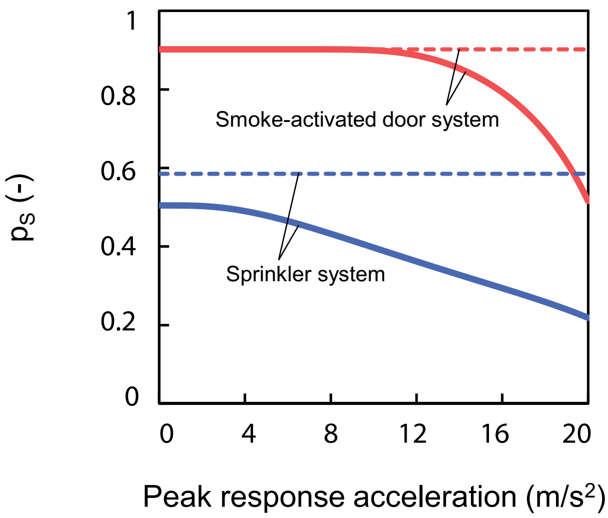

Figure 14. Calculation example of the probability of the post-earthquake successful functioning of fire protection systems (solid lines) for buildings with a total floor area of 1000 m^2 subjected to varying peak response accelerations and its comparison with the probability of the successful functioning in normal times (dotted lines).

the post-earthquake successful functioning (shown by solid lines) is lower than the probability of the successful functioning in normal times (shown by dotted lines), and the decrement becomes large with an increase in the peak response acceleration. Conversely, the example suggests that seismic measures implemented to reduce the building response, as well as seismic measures of components of fire protection systems, are effective in maintaining the reliability of fire protection systems and ensuring the post-earthquake fire safety of a building. In particular, the sprinkler system appears to be more vulnerable than the smoke-activated door system to building shaking. The probability of the interruption of the commercial power supply and the probability of damage to sprinkler piping appears to be strongly reflected in the probability of the post-earthquake successful functioning of the sprinkler system.

5. Conclusions

Damage to fire protection systems due to the 2016 Kumamoto earthquake was investigated through a questionnaire survey among hospitals to gain an understanding of actual seismic damage and derive statistical damage models for use in a probabilistic post-earthquake fire risk assessment. Ten types of component of a fire protection system were surveyed: emergency generators, fire detectors, water tanks used for firefighting, fire pumps, sprinkler heads, indoor fire hydrant boxes, fixed glass smoke curtains, fire doors, fire shutters, and fire exit signs. The collected data show that much damage occurred to fire detectors, sprinkler heads, fixed glass smoke curtains, and fire doors whereas few observations were made of damage to emergency generators, water tanks used for firefighting, and fire pumps. The zero-inflated Poisson regression adopted in this study was reasonably successful in separately deriving the models for the probability of damage occurring somewhere in a building and for the rate of damage upon the occurrence of damage for the four types of component. The models were formulated as a function of a peak response acceleration or a maximum displacement ratio of an equivalent SDOF system, and their parameters were estimated adopting Bayesian inference to cope with the limited amount of data. Note that a considerable portion of the data was collected for buildings constructed when there were no concepts of seismic measures of fire protection systems, and it is thus considered that the derived models do not reflect the effect of seismic measures. The case study results show that the post-earthquake reliability of a sprinkler system and a smoke-activated door system can be calculated using the derived models in combination with existing seismic fragility functions, and the probability of successful functioning may be reduced from 58% (in normal times) to 21%–39% for a sprinkler system and from 90% (in normal times) to 51%–89% for a smoke-activated door system when a peak response acceleration of a building ranges from 10 to 20 m/s^2. These results highlight an important aspect of the safety of seismic-resilient buildings; that is, fire safety should be considered as an important functional requirement of buildings even after an earthquake. The results of this study are expected to be useful in verifying whether a building will have the minimum required fire safety performance after an earthquake through a probabilistic fire risk assessment. However, the derived models generalized the fragility as a whole without distinguishing damage states because the amount of data was not sufficient to derive models for different damage states. This aspect may be improved in future work by collecting more data on the actual damage from various earthquake events. This further data collection will also enable a quantification of inter-event variability and model updating. This will make an important contribution to appropriate probabilistic post-earthquake fire risk assessments.

List of Abbreviations

BCJ	Building Center of Japan
FDMA	Fire and Disaster Management Agency
FEMA	Federal Emergency Management Agency
PGA	peak ground acceleration
PGV	peak ground velocity
QuiQuake	quick estimation system for earthquake maps triggered by observation records
SDOF	single degree of freedom

Acknowledgments

The questionnaire development and survey implementation were supported by the Building Research Institute. The authors are grateful to the 94 respondents who completed the questionnaire. This work was partially supported by the Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (KAKENHI) under grant number JP18H01678 and by the Core-to-Core Collaborative Research Program of the Earthquake Research Institute at the University of Tokyo and the Disaster Prevention Research Institute at Kyoto University. The authors also thank Dr. M. Kurata, Associate Professor, Kyoto University, for providing helpful comments and Glenn Pennycook, MSc, from Edanz for editing a draft of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Japan Society for the Promotion of Science (JSPS Grant-in-Aid for Scientific Research JP18H01678) [grant number 18H01678]; and the Core-to-Core Collaborative Research Program of the Earthquake Research Institute at the University of Tokyo and the Disaster Prevention Research Institute at Kyoto University.

Notes on contributors

Dr. Tomoaki Nishino is an associate professor at the Disaster Prevention Research Institute (DPRI), Kyoto University, Japan. He completed a doctoral degree in engineering at Kyoto University in 2011. His research interests include building fire modeling, natural hazard triggered large outdoor fire modeling (e.g., earthquake fire and tsunami fire), multi-hazard risk assessment, and resilience quantification.

Dr. Jun-ichi Suzuki is a senior researcher at the Department of Fire Engineering, Building Research Institute (BRI), Japan. He completed a doctoral degree in engineering at Tokyo university of science in 2007. His research interests include development of fire resistance evaluation methods for various type of buildings and testing methods for building elements.

Mr. Nobuya Nagao graduated from the Department of Architecture and Architectural Engineering, Kyoto University, Japan, in 2020 and obtained a Master's degree in engineering.

Dr. Hiroaki Notake is a leader at the Fire Safety Engineering Group, Center for Construction Engineering, Institute of Technology, Shimizu Corporation, Japan. He completed a doctoral degree in engineering at Tsukuba University in 2011. His research interests include system development

for building fire protection measures, building evacuation safety engineering, and building fire risk engineering.

References

Achour, N., and M. Miyajima. 2020. "Post-earthquake Hospital Functionality Evaluation: The Case of Kumamoto Earthquake 2016." *Earthquake Spectra* 36 (4): 1670–1694. doi:10.1177/8755293020926180.

Applied Technology Council (ATC). 2004. "Engineering Demand Parameters for Nonstructural Components, ATC-58, Project Task Report, Phase 2, Task 2.3." Redwood City, CA.

Architectural Institute of Japan. 2015. Seismic Loads . *Recommendations for Loads on Buildings* (Tokyo, Japan). Chapter 7. pp. 409–482. Chapter 7.

Beck, V. R., and L. Zhao. 2000. "CESARE-RISK: An Aid for performance-based Fire design-some Preliminary Results." *Fire Safety Science* 6: 159–170. doi:10.3801/IAFSS.FSS.6-159.

The Building Center of Japan. 1984. "Recommendations for Seismic Design of Building Systems, Supervised by the Building Guidance Division of the Housing Bureau." *Ministry of Construction* (in Japanese).Tokyo, Japan.

Chaudhary, R. K., T. Roy, and V. Matsagar. 2020. "Member and Structural Fragility of Reinforced Concrete Structure under Fire." *Journal of Structural Fire Engineering* 11 (4): 409–435. doi:10.1108/JSFE-02-2019-0015.

Cosenza, E., L. Di Sarno, G. Maddaloni, G. Magliulo, C. Petrone, and A. Prota. 2015. "Shake Table Tests for the Seismic Fragility Evaluation of Hospital Rooms." *Earthquake Engineering & Structural Dynamics* 44 (1): 23–40. doi:10.1002/eqe.2456.

Cousins, J., G. Thomas, D. Heron, and W. Smith. 2012. "Probabilistic Modeling of post-earthquake Fire in Wellington, New Zealand." *Earthquake Spectra* 28 (2): 553–571. doi:10.1193/1.4000002.

Cremen, G., and J. W. Baker. 2019. "Improving FEMA P-58 non-structural Component Fragility Functions and Loss Predictions." *Bulletin of Earthquake Engineering* 17 (4): 1941–1960. doi:10.1007/s10518-018-00535-7.

Deguchi, Y., M. Kohno, and M. Tsujimoto. 2001. "Damage Function of Building Equipment." *Journal of Structural Engineering (Architectural Institute of Japan)* 47B: 647–652. (in Japanese).

Fallah-Aliabadi, S., A. Ostadtaghizadeh, A. Ardalan, M. Eskandari, F. Fatemi, M. R. Mirjalili, and B. Khazai. 2020. "Risk Analysis of Hospitals Using GIS and HAZUS: A Case Study of Yazd County, Iran." *International Journal of Disaster Risk Reduction* 47: 101552. doi:10.1016/j.ijdrr.2020.101552.

Federal Emergency Management Agency (FEMA). 2018a. *Seismic Performance Assessment of Buildings Volume 1 - Methodology, FEMA P-58-2*. Washington: Federal Emergency Management Agency.

Federal Emergency Management Agency (FEMA). 2018b. *Seismic Performance Assessment of Buildings Volume 2 – Implementation Guide, FEMA P-58-2*. Washington: Federal Emergency Management Agency.

Fire and Disaster Management Agency 2011 . "Report on the Concept of Fire Protection Systems Responding to large-scale Earthquakes." Accessed 13 March 2020. https://www.fdma.go.jp/singi_kento/kento/items/01_houkokusyo2.pdf

Frank, K., N. Gravestock, M. Spearpoint, and C. Fleischmann. 2013. "A Review of Sprinkler System Effectiveness Studies." *Fire Science Reviews* 2 (1): 6. doi:10.1186/2193-0414-2-6.

Frank, K., M. Spearpoint, and N. Challands. 2014. "Uncertainty in Estimating the Fire Control Effectiveness of Sprinklers from New Zealand Fire Incident Reports." *Fire Technology* 50 (3): 611–632. doi:10.1007/s10694-012-0297-2.

Garcia, D. L., and T. T. Soong. 2003. "Sliding Fragility of block-type non-structural Components. Part 1: Unrestrained Components." *Earthquake Engineering & Structural Dynamics* 32 (1): 111–129. doi:10.1002/eqe.217.

Gelman, A., and D. B. Rubin. 1992. "Inference from Iterative Simulation Using Multiple Sequences." *Statistical Science* 7 (4): 457–472. doi:10.1214/ss/1177011136.

Gernay, T., N. E. Khorasani, and M. Garlock. 2016. "Fire Fragility Curves for Steel Buildings in A Community Context: A Methodology." *Engineering Structures* 113: 259–276. doi:10.1016/j.engstruct.2016.01.043.

Ikehata, Y., J. Yamaguchi, Y. Deguchi, and T. Tanaka. 2017. "Statistical Analysis on the Reliability of Sprinkler Systems: Study on a risk-based Evacuation Safety Design Method." In K. Harada, K. Matsuyama, K. Himoto, Y. Nakamura, K. Wakatsuki (Eds.)*Fire Science and Technology 2015*, 331–339. Singapore: Springer.

Jacques, C. C., J. McIntosh, S. Giovinazzi, T. D. Kirsch, T. Wilson, and J. Mitrani-Reiser. 2014. "Resilience of the Canterbury Hospital System to the 2011 Christchurch Earthquake." *Earthquake Spectra* 30 (1): 533–554. doi:10.1193/032013EQS074M.

Japan Association for Fire Science and Engineering. 2016. "Seismic Damage of Fire Protection Systems and Impacts on Fire Safety. Report on Fires following the 2011 Great East Japan Earthquake." *Chapter* 8: 1–38. (in Japanese).

Jenkins, C., S. Soroushian, E. Rahmanishamsi, and E. M. Maragakis. 2017. "Experimental Fragility Analysis of Pressurized Fire Sprinkler Piping Systems." *Journal of Earthquake Engineering* 21 (1): 62–86. doi:10.1080/13632469.2016.1157528.

Kakegawa, S., A. Murata, Y. Yashiro, and M. Hirota. 1995. "Seismic Damage to Fire Safety Measures and Fire Risk in a Building." Technical Research Report of Shimizu Construction Co., Ltd. 62. 135–150. (in Japanese).

Kakegawa, S. 1997. A study on an evacuation safety evaluation method based on fire scenarios [Doctoral Thesis]. Japan: Nagoya University. (in Japanese).

Kambara, H., and Y. Hayashi. 2001. "Study on Seismic Force Intensity Indices to Evaluate Building Responses and Damage: Investigation by Using a Simple Formula to Predict Building Response." *Journal of Structural and Construction Engineering (Transactions of AIJ)* 66 (543): 69–76. (in Japanese). 10.3130/aijs.66.69_1.

Kato, M., T. Matsumiya, K. Suita, Y. Matsuoka, and M. Nakashima. 2006. "Test on Seismic Performance Evaluation of Interior Partition Walls: Result of Experiment (E-Defense Experimental Projects for Steel buildings-part 7)." Summaries of technical papers of Annual Meeting Architectural Institute of Japan, C-1, Structures III Kanagawa University, Japan, 709–710. (in Japanese).

Khanmohammadi, S., H. Farahmand, and H. Kashani. 2018. "A System Dynamics Approach to the Seismic Resilience Enhancement of Hospitals." *International Journal of Disaster Risk Reduction* 31: 220–233. doi:10.1016/j.ijdrr.2018.05.006.

Kitamura, H., Y. Miyauchi, and H. Uramoto. 2006. "Study on Standards for Judging Structural Performances in Seismic Performance Based Design: Evaluation of the Safety Limit Value and Margin I and II Levels in JSCA Seismic Performance Menu." *Journal of Structural and Construction Engineering (Transactions of AIJ)* 71 (604): 183–191. (in Japanese). 10.3130/aijs.71.183_1.

Konstantinidis, D., and N. Makris. 2009. "Experimental and Analytical Studies on the Response of Freestanding Laboratory Equipment to Earthquake Shaking." *Earthquake Engineering & Structural Dynamics* 38 (6): 827–848. doi:10.1002/eqe.871.

Lambert, D. 1992. "Zero-inflated Poisson Regression, with an Application to Defects in Manufacturing." *Technometrics* 34 (1): 1–14. doi:10.2307/1269547.

Lin, Y. 2005. "Estimations of the Probability of Fire Occurrences in Buildings." *Fire Safety Journal* 40 (8): 728–735. doi:10.1016/j.firesaf.2005.07.005.

MacLeod, J., S. Tan, and K. Moinuddin. 2020. "Reliability of Fire (Point) Detection System in Office Buildings in Australia – A Fault Tree Analysis." *Fire Safety Journal* 115: 103150. doi:10.1016/j.firesaf.2020.103150.

Meacham, B. J. 2016. "Post-earthquake Fire Performance of Buildings: Summary of a large-scale Experiment and Conceptual Framework for Integrated performance-based Seismic and Fire Design." *Fire Technology* 52 (4): 1133–1157. doi:10.1007/s10694-015-0523-9.

Metropolis, N., A. Rosenbluth, M. Rosenbluth, M. Teller, and E. Teller. 1953. "Equations of State Calculations by Fast Computing Machines." *Journal of Chemical Physics* 21 (6): 1087–1092. doi:10.1063/1.1699114.

Miniati, R., and C. Iasio. 2012. "Methodology for Rapid Seismic Risk Assessment of Health Structures: Case Study of the Hospital System in Florence, Italy." *International Journal of Disaster Risk Reduction* 2: 16–24. doi:10.1016/j.ijdrr.2012.07.001.

Moinuddin, K. A. M., J. Innocent, and K. Keshavarz. 2019. "Reliability of Sprinkler System in Australian Shopping Centres – A Fault Tree Analysis." *Fire Safety Journal* 105: 204–215. doi:10.1016/j.firesaf.2019.03.006.

National Institute for Land and Infrastructure Management, and Building Research Institute. 2016. "Quick Report of the Field Survey on the Building Damage by the 2016 Kumamoto Earthquake." Accessed 13 March 2020. https://www.kenken.go.jp/japanese/contents/publications/data/173/index.html

National Institute of Advanced Industrial Science and Technology (AIST). "QuiQuake: Quick Estimation System for Earthquake Map Triggered by Observed Records." Accessed 17 January 2019. https://gbank.gsj.jp/QuiQuake/index.en.html

National Research Council. 2012. *Disaster Resilience: A National Imperative*. Washington, D.C: National Academies Press.

National Research Institute for Earth Science and Disaster Resilience, NIED K-NET, KiK-net. 2019. *National Research Institute for Earth Science and Disaster Resilience*. doi:10.17598/NIED.0004.

Neal, R. 2011. *MCMC Using Hamiltonian Dynamics, Chapter 5 of the Handbook of Markov Chain Monte Carlo*. Edited by, S. Brooks, A. Gelman, G. Jones, and X. Meng, Boca Raton, US: Chapman & Hall/CRC Press. 116–162

Ni, S., and T. Gernay. 2021. "A Framework for Probabilistic Fire Loss Estimation in Concrete Building Structures." *Structural Safety* 88: 102029. doi:10.1016/j.strusafe.2020.102029.

Nikfar, F., and D. Konstantinidis. 2017. "Shake Table Investigation on the Seismic Performance of Hospital Equipment Supported on wheels/casters." *Earthquake Engineering & Structural Dynamics* 46 (2): 243–266. doi:10.1002/eqe.2789.

Nishino, T., T. Tanaka, and A. Hokugo. 2012. "An Evaluation Method for the Urban post-earthquake Fire Risk considering Multiple Scenarios of Fire Spread and Evacuation." *Fire Safety Journal* 54: 167–180. doi:10.1016/j.firesaf.2012.06.002.

Nishino, T., T. Tanaka, and S. Tsuburaya. 2013. "Development and Validation of a potential-based Model for City Evacuation in post-earthquake Fires." *Earthquake Spectra* 29 (3): 911–936. doi:10.1193/1.4000155.

Nishino, T., and A. Hokugo. 2020. "A Stochastic Model for Time Series Prediction of the Number of post-earthquake Fire Ignitions in Buildings Based on the Ignition Record for the 2011 Tohoku Earthquake." *Earthquake Spectra* 36: 232–249.

Nishino, T. 2021. "Probabilistic Analysis of the Vulnerability of Fire Departments to Ignitions following Megathrust Earthquakes in the Nankai Trough Subduction Zone, Japan." *Fire Safety Journal* 120: 103038. doi:10.1016/j.firesaf.2020.103038.

Nojima, N., and H. Kato. 2014. "Modification and Validation of an Assessment Model of post-earthquake Lifeline Serviceability Based on the Great East Japan Earthquake Disaster." *Journal of Disaster Research* 9 (2): 108–120. doi:10.20965/jdr.2014.p0108.

Nuti, C., S. Santini, and I. Vanzi. 2004. "Damage, Vulnerability and Retrofitting Strategies for the Molise Hospital System following the 2002 Molise, Italy, Earthquake." *Earthquake Spectra* 20 (1_suppl): 285–299. doi:10.1193/1.1768541.

Otsuki, Y., M. Kurata, K. A. Skalomenos, Y. Ikeda, and M. Akazawa. 2019. "Fragility Function Development and Seismic Loss Assessment of Expansion Joints." *Earthquake Engineering & Structural Dynamics* 48 (9): 1007–1029. doi:10.1002/eqe.3171.

Price, H. J., A. D. Sortis, and M. Schotanus. 2012. "Performance of the San Salvatore Regional Hospital in the 2009 L'Aquila Earthquake." *Earthquake Spectra* 28 (1): 239–256. doi:10.1193/1.3673595.

Qi, L., K. Kunitomo, M. Kurata, and Y. Ikeda. 2020. "Investigating the Vibration Properties of Integrated Ceiling Systems considering Interactions with Surrounding Equipment." *Earthquake Engineering & Structural Dynamics* 49 (8): 772–793. doi:10.1002/eqe.3264.

Sarno, L. D., G. Magliulo, D. D'Angela, and E. Cosenza. 2019. "Experimental Assessment of the Seismic Performance of Hospital Cabinets Using Shake Table Testing." *Earthquake Engineering & Structural Dynamics* 48 (1): 103–123. doi:10.1002/eqe.3127.

Sarreshtehdari, A., and N. E. Khorasani. 2020. "Post-earthquake Emergency Response Time to Locations of Fire Ignition." *Journal of Earthquake Engineering*. doi:10.1080/13632469.2020.1802369.

Stan Development Team. 2016. "Stan Modeling Language: User's Guide and Reference Manual, Version 2.14.0." https://mc-stan.org

Suwa, H., and J. Kanda. 2008. "Damage Ratio Curves of Building Equipments by Using the Damage Database Due to 1995 Hyogoken Nanbu Earthquake." *Journal of Structural and Construction Engineering (Transactions of AIJ)* 73 (633): 1935–1941. (in Japanese). doi:10.3130/aijs.73.1935.

Taghavi, S., and E. Miranda. 2003. "Response Assessment of Nonstructural Building Elements." *PEER Report 2003/05*. Berkeley, CA: Pacific Earthquake Engineering Research Center.

Tanaka, T. 2011. "Integration of Fire Risk Concept into performance-based Evacuation Safety Design of Buildings." *Fire Safety Science* 10: 3–21. doi:10.3801/IAFSS.FSS.10-3.

Tian, Y., A. Filiatrault, and G. Mosqueda. 2014. "Experimental Seismic Fragility of Pressurized Fire Suppression Sprinkler Piping Joints." *Earthquake Spectra* 30 (4): 1733–1748. doi:10.1193/111011EQS278M.

Xin, J., and C. Huang. 2013. "Fire Risk Analysis of Residential Buildings Based on Scenario Clusters and Its Application in Fire Risk Management." *Fire Safety Journal* 62: 72–78. doi:10.1016/j.firesaf.2013.09.022.

Yung, D., G. V. Hadjisophocleous, and G. Proulx. 1997. "Modelling Concepts for the risk-cost Assessment Model Firecam and Its Application to a Canadian Government Office Building." *Fire Safety Science* 5: 619–630. doi:10.3801/IAFSS.FSS.5-619.

Zaghi, A. E., E. M. Maragakis, A. Itani, and E. Goodwin. 2012. "Experimental and Analytical Studies of Hospital Piping Assemblies Subjected to Seismic Loading." *Earthquake Spectra* 28 (1): 367–384. doi:10.1193/1.3672911.