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FRAGILITY EVALUATION OF PLUMBING SYSTEM SUBJECTED TO SEISMIC LOADING BASED ON FLOOR ACCELERATION RECORDS

K. Fujita[(1)], L. Xie[(2)]

[(1)] *Associate Professor, Department of architecture and architectural engineering, Kyoto University, fm.fujita@archi.kyoto-u.ac.jp*
[(2)] *Graduate student, Department of architecture and architectural engineering, Kyoto University, fm-xie@archi.kyoto-u.ac.jp*
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Abstract

A business continuity plan (BCP) is strongly desired toward disaster-prevented resilient buildings in Japan. Structural health monitoring technology is expected to be useful for rapid decision making after an earthquake disaster to judge whether it is needed to evacuate from the building or not, and the building can be used uninterruptedly or not. Many researches have focused on detecting damage to structural components such as columns and beams, but it has been reported that damages to non-structural components are a direct cause of abandoning the continued building use in recent disasters. A damage possibility evaluation based on the fragility analysis of non-structural components may be helpful information for making the BCP for resilient buildings.

This paper presents the fragility analysis method of plumbing system behind ceiling based on the estimated or recorded floor seismic accelerations. Seismic loadings to the plumbing system are evaluated from the view point of the structural health monitoring for structural components. The fragility curves are known to be derived from the reliability theory, where the maximum responses and strength of the objective structures are given by the probability distribution, each other. To evaluate the fragility curves of the plumbing systems from the theoretical approach, it is necessary to consider the stochastic procedures in dynamic properties and damage states of the objective non-structural components. For this purpose, it is proposed in this paper that the plumbing systems are treated as a single degree of freedom (SDOF) model considering the boundary conditions, mass and length of plumbing pipe. Assuming the seismic resistance supporting member is regarded as rigid boundary or flexible boundary respectively, the upper and lower bounds of the natural frequencies of the plumbing system can be derived. Furthermore, the strength of the plumbing system used for the criterion of damage states can be converted to the dimension of acceleration based on the proposed SDOF model.

The validity of the proposed fragility evaluation method of the plumbing system is verified by numerical simulations that perform the time-history analysis of detailed finite element models of the plumbing system considering actual placements of various supporting members for seismic resistance and dead weight. Since it is also necessary to evaluate the structural safety of the plumbing system of existing buildings, fragility curves of the plumbing system are compared with different seismic standards: current design standard and old standard that are no longer used in Japan.

Keywords: Fragility analysis; Piping system; Structural health monitoring;

1. Introduction

In disaster facilities and other important facilities, it is necessary to prepare a business continuity plan (Business Continuity Plan: BCP) to formulate a recovery plan in advance in normal times. BCP requires that damage to buildings after an earthquake be estimated based on the amplitude of the ground motion, and building managers need to immediately determine whether it is possible to continue using the building after the disaster. There are various types of disasters, and in recent years, not only earthquakes but also such as flood damages have been considered. As for the earthquake disaster, it is useful to accurately assess damage to structural and non-structural members of the building when executing a recovery plan. One of solutions to these issues, a monitoring system that estimates the maximum response or time-history response of the building, such as interstory drifts and floor accelerations during the earthquake and identify the damage based on various sensors placed in the building would be beneficial. However, monitoring for non-structural members such as ceilings and partition walls, which made business continuity difficult in recent earthquake damages such as Kumamoto earthquake, has not been established yet.

This paper proposes a new damage assessment method for non-structural members as part of the development of a comprehensive building monitoring system including both structural members and non-structural members. In the proposed method, the fragility evaluation of the plumbing system is investigated. Since the plumbing system in the building is typically behind the ceiling supported by an upper slab, the absolute acceleration of the upper slab can be regarded as the input to of the objective building. Therefore, the floor accelerations of the building is needed for fragility evaluation of the plumbing system. When the accelerometer is not installed at the target story in the building, we need to estimate the time-history response of the floor acceleration by applying structural health monitoring technique. As for the structural health monitoring system, there are various methods to be studied. A common purpose of the structural health monitoring systems is to estimate the experienced maximum interstory drift caused by the seismic loading. On the other hand, authors have established several system identification methods to identify the physical model of buildings from observed floor accelerations. When we cannot measure all floor accelerations due to restriction of the initial and maintenance costs of monitoring system, floor accelerations where no sensors are placed can be estimated by calculating the time history analysis of the identified model. In this paper, we assume the floor acceleration of objective story can be given by those other system identifications. For a given floor acceleration input, the probability distributions of response and capacity of the plumbing system are derived by simplified single degree of freedom models, finally the fragility evaluation of the plumbing system is investigated.

There are many related studies on fragility evaluation based on reliability theory [1-4]. Shinozuka et al. evaluated the damage probability of concrete columns on expressway viaducts by classifying the degree of damage [2]. The specific ground motion is chosen as the input excitation, and the PGA distribution at the survey point is estimated by considering the distance from the epicenter and near observation spot. Since the objective concrete columns are widely spread, PGA distribution of the specific ground motion can be used as the probability distribution of response. Nakamura (2008) evaluates the earthquake risk of a group of buildings where buildings are located at different sites. In the theory shown in Nakamura (2008), the damage correlation for a specific earthquake based on the relative distance of the building [3]. As for the fragility analysis for the plumbing system of high-rise building, Endo et al. (2008) proposed the theory of fragility evaluation considering correlation of damage state of the plumbing system [4]. The responses of interstory drift and floor acceleration at each story are used as input motion.

Formulations on fragility evaluation for the plumbing system shown in this paper is similar to these related references based on reliability theory, but this paper presents how to obtain probability distributions necessary for fragility evaluation by introducing the simplified single degree of freedom model for plumbing system. The validation of proposed method is verified by numerical simulations of the plumbing system using the software “AutoPIPE” specialized in analysis of plumbing systems.

2. Design of plumbing system

The plumbing system investigated in this paper is assumed to be in important facilities after the disaster, such as disaster base hospitals. Depending on the construction age of the building, it is assumed that there are various types of construction methods of plumbing systems. In order to compare the differences between standard design guideline of plumbing systems, two different standard design guidelines in Japan, i.e. Building Equipment Seismic Design and Construction Guidelines published from the Building Center of Japan in 1982 and 2014, are used for plumbing system design. Table 1 shows specifications of standard span lengths of the deadload supporting member of water supplying pipe in the current design guideline of 2014. While, those in old design guideline of 1982 is shown in Table 2. As for the water supplying pipe in the plumbing system, the main differences between the two design guidelines are the pitch spacing of the deadload support members and the grade of the seismic support members. The seismic supporting member is used to prevent the piping from shaking. Although there are many types of seismic supporting members in the actual design, the seismic supporting member can typically suppress the vibration of the piping in the direction perpendicular to the axis. In the design guideline in 2014, new support members called S_A-grade as seismic supporting member have been added, while traditional seismic supporting member is referred as A-grade. Considering these differences in each design guideline, three types of plumbing system with different boundary conditions and degree of fixation are examined in this paper according to each design guideline.

We assume the seismic supporting member is fixed at the upper floor slab as shown in Fig.1. The steel material used for seismic supporting member is SS400 equilateral angle iron. The dimensions of the all supporting members are same with $l = 1{,}000$ [mm] and $h = 500$ [mm]. Considering the design criteria of seismic supporting member as S_A-grade and A-grade, in this study, the cross-section of the S_A-grade supporting member is designed as L-65×65×6, and that of A-grade supporting member is designed as L-50×50×6, respectively.

In this paper, the layouts of water supplying pipe designed in accordance with the 1982 and 2014 standard design guidelines are investigated for fragility evaluation as shown in Figs.2 [6,7]. In Figs.(2), a fixed point means a point where the translation and rotation of the node are all constrained. In the actual plumbing system, such fixed points may be in the location of vertical piping. The main pipe diameter of the designed plumbing system is set as 150 [mm], and the branch pipe diameter is set as 50 [mm]. The schedule of both pipes is 40, which is the most commonly used. Piping schedule is known to classify the thickness of a pipe. In the schedule 40, a ratio of the inside diameter to thickness of pipe is between from 29 to 39. The layouts shown in Fig.2(a), (c) and (e) are designed by design guideline 1982, while Fig.2(b), (d) and (f) correspond to design guideline 2014.

Table 1 Current design guideline of plumbing system in 2014 standard span length of deadload support & suspension bolt (water supplying pipe)

Diameter (A)	15	20	25	32	40	50	65	80	100	150	200	250	300
Standard span length of deadload support [m]	2.0					3.0							
Suspension bolt	M10									M12			M16

Table 2 Old design guideline of plumbing system in 1982 standard span length of deadload support & suspension bolt (water supplying pipe)

Diameter (A)	15	20	25	32	40	50	65	80	100	125	150	200-
Standard span length of deadload support[m]	1.8		2.0			3.0			4.0			5.0

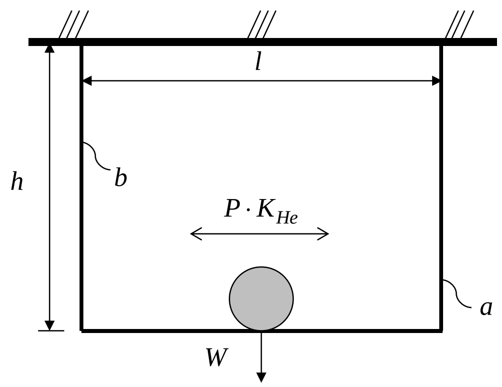
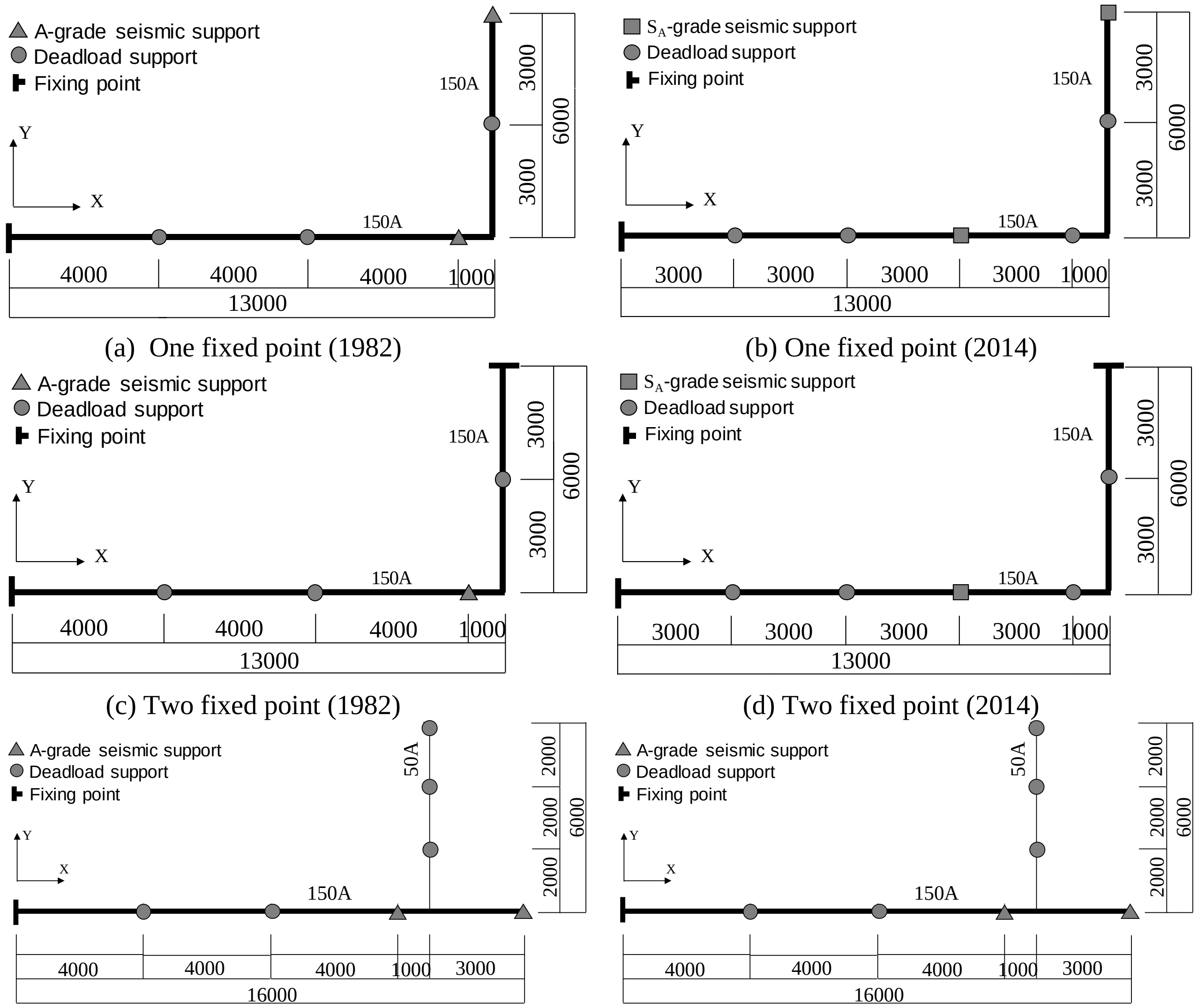


Fig.1 Design of seismic support



(a) One fixed point (1982)
(b) One fixed point (2014)
(c) Two fixed point (1982)
(d) Two fixed point (2014)
(e) One fixed point with brunch pipe (1982)
(f) One fixed point with brunch pipe (2014)

Fig.2 Layouts of plumbing system for different design code in 1982 and 2014

3. Simplified single degree of freedom model of plumbing system

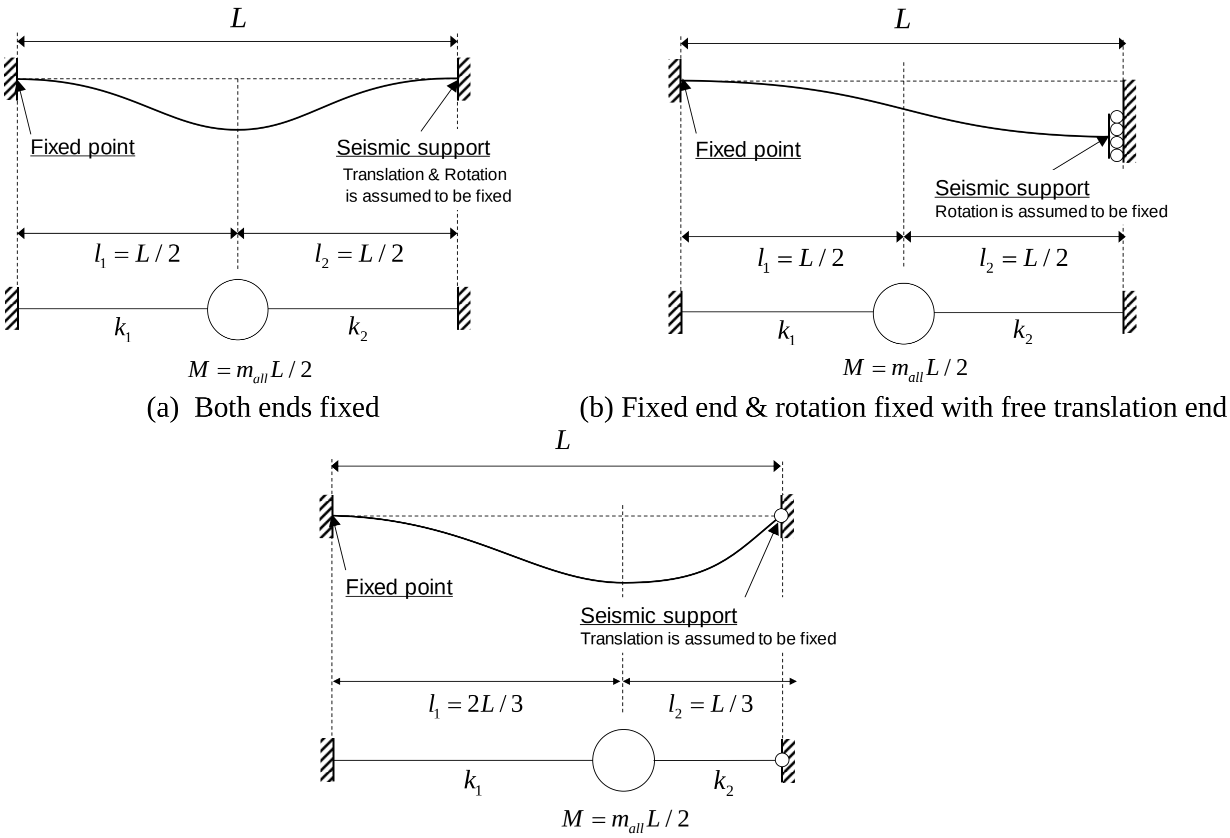
In this section, simplified analytical models of the plumbing system for fragility evaluation are implemented by focusing on the difference in the boundary conditions in each case. In the literature on fragility evaluation, probability distributions of the response and the capacity of the objective structure are required in the formulation. In this study, the fragility curve of the plumbing system is evaluated according to the similar formulation as in previous studies, but the evaluation method of probability distributions necessary for formulations of fragility evaluation presented in the next section is proposed by using simplified model of plumbing system in this section.

The issue to be investigated in this paper is to assess the probability of damage to the plumbing system on the specific story at the particular earthquake. Although the plumbing system is supported by multiple deadload supporting members and can be regarded as the multi-point supported structure, the input excitation is given as identical floor acceleration derived from rigid in horizontal floor response assumption. In studies on structural health monitoring, the main purpose is to estimate the time history or the maximum floor response at the particular floor where no sensor located, but in this study identification of floor acceleration is out of scope. Therefore, seismic loadings to the plumbing system are treated deterministically, not as probability statistics.

3.1 Probability distribution of seismic response of plumbing system

In order to evaluate the probability distribution f_R of the seismic response of plumbing system subjected to the deterministically given floor acceleration, a simplified analytical model as a single degree of freedom (SDOF) model is investigated in this paper. Since it is difficult to estimate the natural frequencies and mode shapes that mainly affect the response of the plumbing system without observation of themselves, let us consider the upper and lower bounds of natural frequency of the plumbing system. This is equivalent to dealing with epistemic uncertainties where inevitable modelling errors of analytical model from actual objects are taken into account. For the piping layout shown in Figs.2 (a) and (b), i.e. plumbing system with one fixed point, the translation in y-direction at the position of seismic supporting member is not completely fixed. This is because the pipe along the y-axis of the L-shaped plumbing system is not fixed at the end of the pipe.

Let us consider modeling the section from the fixed point to the seismic support in y-direction. In this case, upper and lower bounds of the natural frequency are assumed to be given by Figs.3(a) and (b), respectively. While, for the piping layout shown in Figs.2 (c) and (d), y-direction translation at the seismic support is small, but we cannot neglect rotational response of the pipe at the seismic support position. Therefore, upper and lower bounds of the natural frequency are assumed to be given by Figs.3 (a) and (c), respectively. In Figs.3, L is the length from the fixed point to the position of seismic support. m_{all} is the mass per unit length taking into account both the mass of the pipe and fluid in the pipe. Since the concentrated mass as the SDOF model can be regarded to be supported by springs on both sides, the stiffness of this model is given by sum of these spring stiffnesses. Stiffnesses k_1 and k_2 can be derived according to Bernoulli-Euler beam theory.



(c) Fixed end & translation fixed with free rotation end

Fig.3 Single degree of freedom model for evaluation of plumbing system

The probability distribution of the fundamental natural frequency of the plumbing system is assumed to be given by lognormal distribution, where the logarithmic average value is determined by the mean of upper and lower bounds of the fundamental natural frequency calculated by mass and stiffness of the simplified model shown in Figs.3, and the standard deviation is set so that the probability of falling below the lower limit and exceeding the upper limit is 1% or less. Monte Carlo simulation are well known as a method of obtaining probability distributions by numerical simulation with random variation of parameters. In this paper, the probability distribution of the seismic response of plumbing system is provided by Monte Carlo simulations based on the time history response analysis of the SDOF model following the probability distribution of fundamental natural frequency. After we obtain the distribution of the seismic response of plumbing system, maximum likelihood estimation method is applied to estimate probabilistic parameters of the distribution. In the maximum likelihood estimation, we assume that the probability distribution of the seismic response of plumbing system is set as a lognormal distribution. The lognormal distribution is well used in the fragility evaluation based on the reliability theory.

3.2 Probability distribution of capacity of plumbing system

Evaluation of analytical fragility curves based on the reliability theory requires a probability distribution f_C of the capacity of the objective structures. As for the evaluation of capacity, it is known that the yield stress varies widely depending on material properties or manufacturing variations. This variation is known as aleatoric uncertainty. In this paper, to deal with this aleatoric uncertainty on the evaluation of capacity of plumbing system, the lower bound of the single degree of freedom model shown in Section 3.1 is used to determine the mean of the probability distribution. Focusing on the bending moment of the Bernoulli-Euler beam shown in Fig.3 and assuming that the damage of the pipe occurs at the fixed point, the equivalent acceleration at the concentrated mass position can be derived where the stress of the pipe at the fixed point becomes the allowable bending stress. Equivalent acceleration capacities a_{y1}, a_{y2} of Fig.3 (b) and Fig.3 (c) are described as

$$a_{y1} = \frac{8\sigma_y A}{3M\,L},\quad a_{y2} = \frac{39\sigma_y A}{14M\,L} \tag{1a,b}$$

In addition, the damage mode of plumbing system is defined as the value obtained by multiplying the equivalent acceleration capacity in Eqs.(1) to a damage coefficient, e.g. a damage coefficient is 1.1 for a minor damage. This value is used as the average value of the probability distribution of the capacity of plumbing system. The standard deviation of the probability distribution of the capacity of plumbing system is determined so that the lower end of distribution does not exceed the equivalent acceleration capacity. The probability distribution of the plumbing system capacity is given as a lognormal distribution.

4. Fragility evaluation based on reliability theory

In the evaluation of fragility of structures based on the reliability theory [5], the performance function H representing the damage state is defined as the ratio of the probability distribution f_C of capacities of the structure to the probability distribution f_R of responses of the structure. As same with other studies, assuming that f_C and f_R follow the lognormal distribution, respectively, the probability function $f_H(h)$ of damages of plumbing system is defined as

$$f_H(h) = \frac{1}{h\zeta_H\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\ln H - \lambda_H}{\zeta_H}\right)^2\right] \tag{2}$$

where λ_H and ζ_H are the logarithmic mean and the standard deviation of $f_H(h)$, those are given as

$$\lambda_H = \lambda_C - \lambda_R,\ \zeta_H = \sqrt{\zeta_C^{\,2} + \zeta_R^{\,2}} \tag{3a,b}$$

where $\lambda_C, \zeta_C, \lambda_R, \zeta_R$ are the logarithmic mean and the starndard deviation of the capacity of plumbing system, and those of the seismic response of plumbing system. These statistical parameters are given from simplified analytical model of plumbing system as shown in Section 3. When the performance function H falls down below 1, damages in the objective structures possibly occurs. Therefore, the fragility as the probability of damage can be calculated by integration over range $0 < H < 1$ described as

$$p_f = P[H \le 1] = \int_0^1 \frac{1}{h\zeta_H \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln H - \lambda_H}{\zeta_H} \right)^2 \right] dh \tag{4}$$

From Eq.(4), fragility curves can be derived by varying the amplitude of response according to input ground motions or changing the definition of degree of damage state, e.g. minor / moderate / major damage.

5. Numerical examples

In this section, numerical examples to evaluate the fragility of damages of plumbing systems subjected to seisimic loading are investigated based on the proposed method. We assume that designed plumbing systems shown in Fig.2 locate at the top floor in the 5 story building model. Fig.4 shows the elevation of the 5 story planar frame model, and cross sections of beams and columns are sammrized in Table 3. The input ground motion is Mashikimachi EW (2016), recoreded at KMMH16 (K-net) in Kumamoto earthquake (2016). The input ground motion and the observed top floor response of the 5 story frame model are shown in Figs.5.

In order to verify the fragility curve obtained by the proposed method, detailed analytical models of the plumbing system are investigated, and the fragility evaluation of the plumbing system is compared with results of the proposed method. The detailed analytical models of the plumbing system shown in Fig.2 are created using the commercial software AutoPIPE, which can provide the static and the dynamic analysis of piping systems. Figs.6 shows examples of the mode shape of the target plumbing system. As shonw in Figs.6, assuming that the maximum bending moment of pipe occurs at the fixed point, we focus on the mode frequency where the y-direction amplitude of the pipe in the section targeted by the simplified model. Comparison of natural frequencies derived by detailed models with upper and lower bounds of the fundamental natural frequency of proposed SDOF model are shown in Table 4. Natural frequency of the detailed model is derived

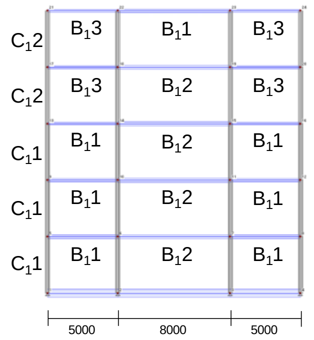


Fig.4 5 story frame model

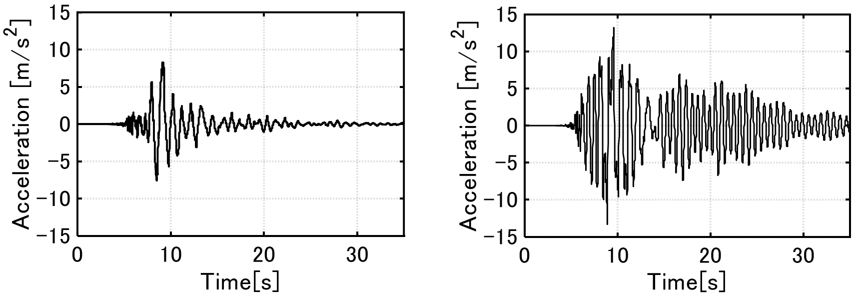
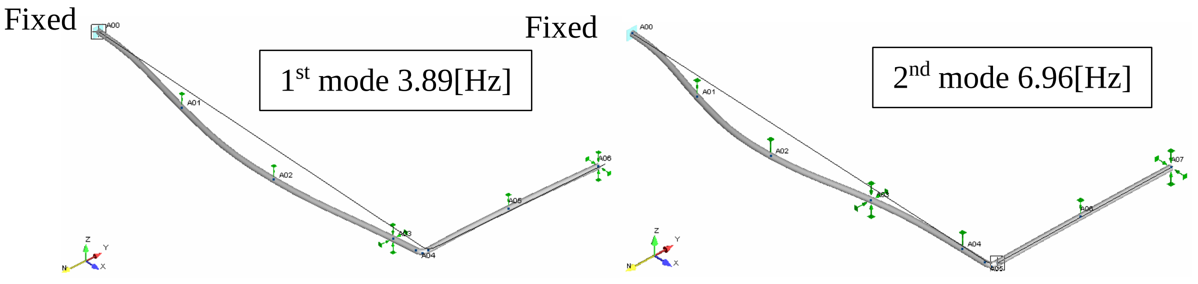


Fig.5 Input and top floor response (Mashikimachi EW (2016))



(a) One fixed point (Design guideline 1982)　　(b) One fixed point (Design guideline 2014)

Fig.6 Mode shape of plumbing system by eigenvalue analysis

Table 3 Section list

ID	Section
$B_1$1	H-600×300×12×28
$B_1$2	H-650×300×12×28
$B_1$3	H-600×300×9×19
$B_1$4	H-550×150×6×12
$C_1$1	□-600×600×16
$C_1$2	□-700×700×16
$C_1$3	□-700×700×19

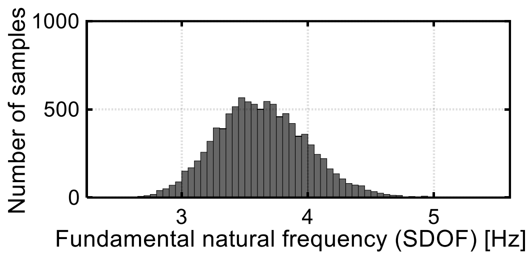
Table 4 Comparison of natural frequency

Plumbing layouts	Design guideline	SDOF [Hz]		Detailed Model [Hz]
		Upper boud	Lower bound	
One fixed without brunch	1982	4.83	2.41	3.89
	2014	8.58	4.29	6.69
Two fixed without brunch	1982	4.83	3.84	3.99
	2014	8.58	6.82	6.94
One fixed with brunch	1982	4.83	2.41	3.90
	2014	8.58	4.29	6.99

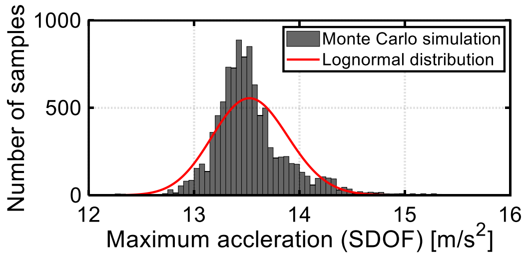
by referring the specific eigenmode where the amplitude of the pipe in the section targeted for the simplified model is predominant as shown in Fig.6. Therefore, the natural frequency of the detailed model shown in Table 4 is not necessarily corresponding to the fundamental natural frequency. From Table 4, it can be confirmed that the natural frequency of detailed model of plumbing system is included between lower and upper bounds of fundamental natural frequencies derived by the simplified model considering different boundary conditions. For two fixed plumbing system, the fundamental natural frequency derived from the detailed model is close to the lower bound of the simplified model. This is because the actual deformation of the pipe of the target mode shape is similar to the boundary conditions in the lower bound.

5.1 Fragility evaluation of plumbing system derived by simplified SDOF model

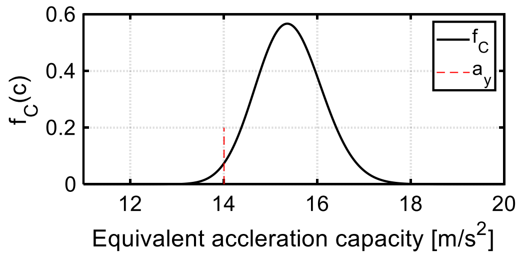
For fragility analysis based on the reliability theory, probability distributions f_R and f_C are needed. In Fig.7, as the example of the one fixed plumbing system without brunch pipe designed according to guideline in 1982 (See Fig.2(a)), these probability distributions and the finally obtained fragility curve derived by the proposed simplified model of plumbing system are shown, respectively.



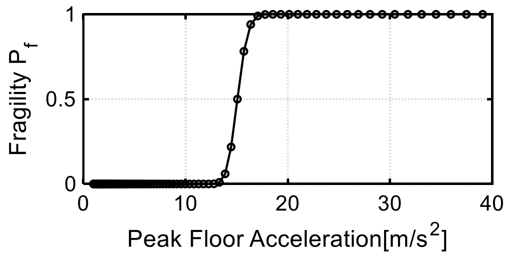
(a) histogram of fundamental natural frequency



(b) histogram and probability distribution of maximum acceleration



(c) probability distribution of capacity

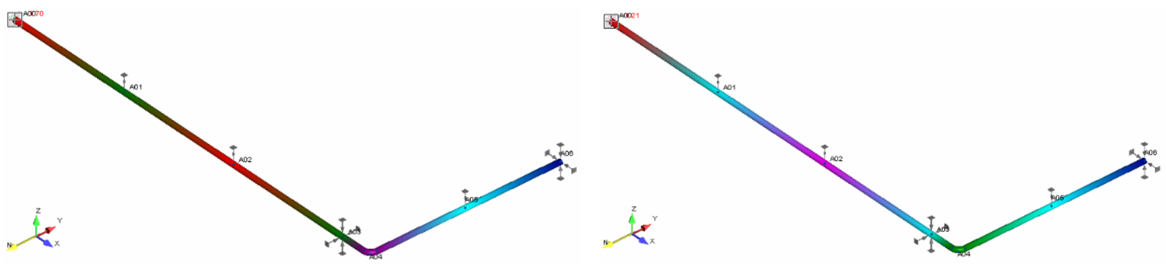


(d) Fragility curve

Fig.7 Fragility analysis of one fixed plumbing system designed by guideline 1982 derived from proposed simplified model

5.2 Damage evaluation of plumbing system derived by detailed analytical model

In order to compare the fragility evaluation derived by the proposed method, the maximum stress contour of objective plumbing system is investigated for specified input floor accelerations. Fig.8 shows the examples of the stress contour of plumbing system of one fixed without brunch designed according to the guideline in 1982 (See Fig.2(a)). From these figures derived in detailed model of plumbing system, it is possible to investigate where damages occur in the plumbing system. Assuming that the plumbing system is damaged when the maximum stress exceeds the temporary allowable yield stress with multiplying damage state coefficient, the input magnification factor to the floor acceleration response can be determined so that the plumbing system may be damaged. The experimental fragility curve can be derived by assuming that when the maximum stress is less than this criterion, the damage function is set to be 0, and when the maximum stress is over the criterion, the damage function is set to be 1. These fragility evaluation results are compared as following section.



(a) Input magnification : 1.0 (b) Input magnification : 0.7

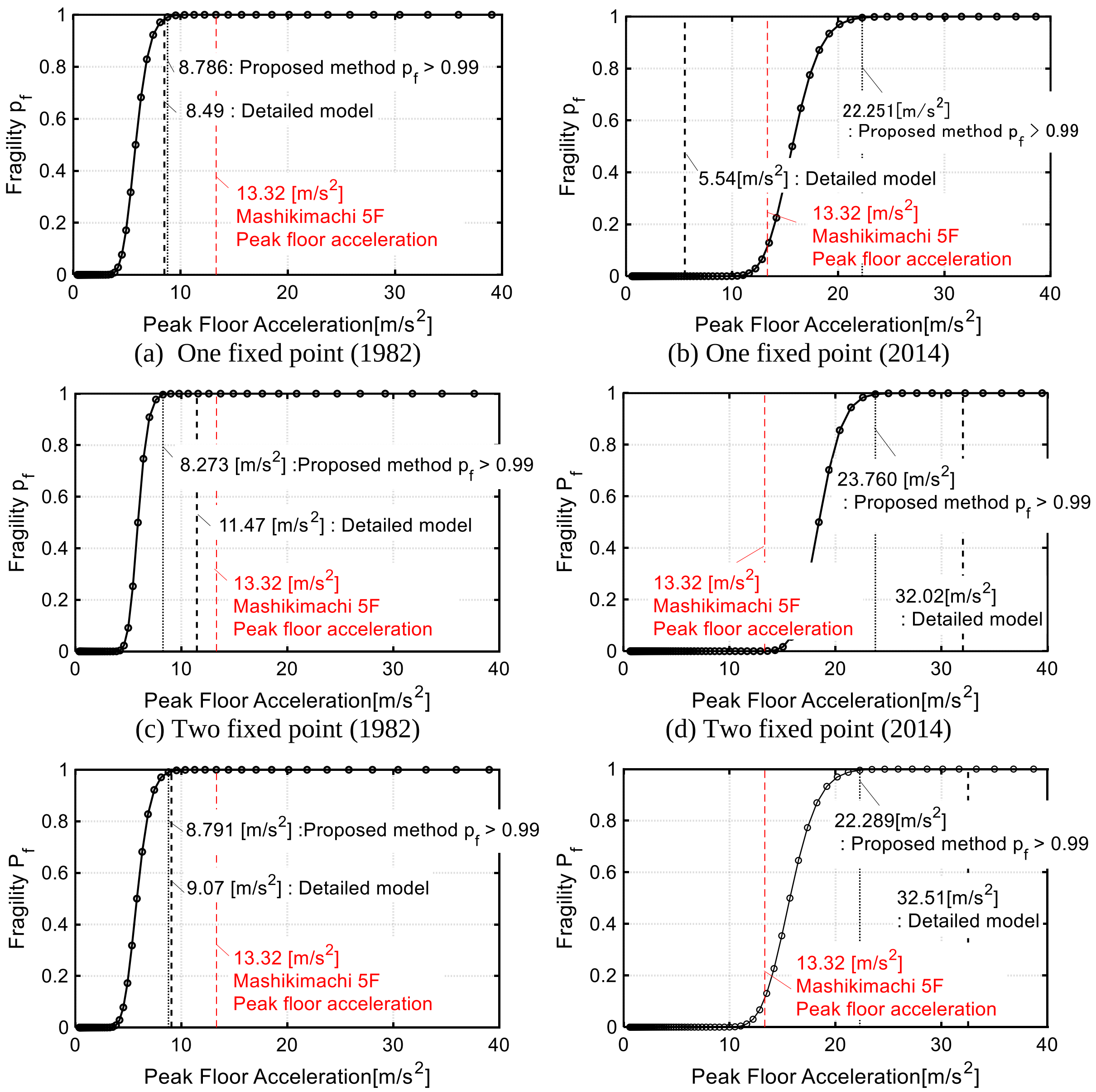
Fig.8 Stress contour of one fixed plumbing system designed by guideline 1982
subjected to top floor acceleration of 5 story frame model

5.3 Comparison of fragility evaluations

Fig.9 shows the comparison of the fragility evaluation derived by the proposed method, where the simplified SDOF model is provided only from the layout of target plumbing system, and is compared with that of detailed model. In Figs.9, the amplitude of input floor acceleration where the maximum stress of plumbing system in detailed model is corresponding to the damage state stress is shown as black thick dash line, while the peak floor acceleration where the fragility probability derived by the proposed simplified model reaches more than 0.99 is shown as black thin line, respectively.

Let us see the results of plumbing system designed by guideline in 1982. From Figs.9, it can be confirmed that the fragility evaluations by the proposed method has been obtained with high accuracy in the case of the pipe with one fixed point and one fixed point with branch pipes (Figs.9 (a) and (e)). These cases are numerical examples showing the usefulness of the proposed method. While, as for the two fixed point pipe shown in Fig.9 (c), the amplitude of peak floor acceleration derived by detailed model is a little large compared with the fragility obtained in this study. This may be the probability distribution of response of pipe system is different from the actual response. The influence of the degree of fixation of the L-shaped pipe in the x-direction on the response in the y-direction needs to be further considered in the simplified model.

Next, let us investigate the comparison of fragility evaluation by simplified model in the pipe designed in accordance with design guideline in 2014. From Figs.9 (b), (d) and (f), there can be seen some differences in the fragility evaluation results of plumbing system. We need to investigate possible factors for more accurate fragility evaluation and modify the boundary conditions of SDOF model. The amplitude of floor acceleration derived by the detailed model of one fixed point plumbing system is significantly small compared with others. From the investigation of detailed model, it has been confirmed that the critical floor acceleration is determined where the location of damage has been confirmed at the corner of the *L*-shape plumbing system, and this result is out of consideration in this study. Furthermore, since the maximum stress of pipe can be seen at the fixed point in y-direction for all other cases, it should be noted that the stress of pipe may be concentrated at the corner of the *L*-shaped pipe depending on the layout of plumbing system, and the position of S_A-grade seismic support. For other cases of plumbing system designed by the guideline in 2014, the amplitude of floor acceleration derived by the detailed model is more than 30 m/s^2. These results are slightly larger than that of the proposed method. A possible reason of this difference is that the stiffness of seismic support is not considered in the simplified SDOF model. There is a large gap for evaluation of the capacity of the plumbing system with such seismic supports. Furthermore, since the lower bound SDOF model is used for evaluation of capacity, it is reasonable that the fragility evaluation using proposed simplified model are on the safe side.



(a) One fixed point (1982) (b) One fixed point (2014)

(c) Two fixed point (1982) (d) Two fixed point (2014)

(e) One fixed point with brunch pipe (1982) (f) One fixed point with brunch pipe (2014)

Fig.9 Comparison of fragility evaluation for various plumbing systems

6. Conclusions

Fragility analysis method for the plumbing system in the building subjected to seismic loadings has been presented for deterministically given floor acceleration. In the proposed method, simplified single degree of freedom models for estimating the lower and upper bounds of the fundamental natural frequency and evaluating the capacity of plumbing system. Following conclusions are summarized.

1. The simplified single degree of freedom model of the plumbing system can be derived by focusing the section from the fixed point of the piping to the position of the seismic support. By changing the combination of boundary conditions, the upper and lower bounds of natural frequency can be estimated in this simplified model. It has been confirmed that the actual natural frequency derived by detailed analytical model for the target section of piping is included in the range obtained by the proposed method. The probability distribution of the seismic response of the plumbing system was evaluated through the Monte Carlo simulations taking into account the epistemic uncertainty of the modeling.
2. The objective plumbing systems investigated in this paper were designed by comparing the differences between the design standard guidelines of the plumbing system published from Japan Building center in 1982 and in 2014. Main difference of plumbing system design is summarized as span length of vertical supporting members and the seismic supporting member design. In the proposed simplified modeling of the plumbing system, we considered a difference of span length of vertical supporting members and proposed the method to deal with the concentrated mass of piping.
3. From the comparison of fragility evaluation derived by detailed analytical model with proposed method, it has been confirmed that the bending moment of plumbing system subjected to seismic loadings is maximized at the fix point in most cases of plumbing system investigated in this study. This corresponds to the assumption of proposed simplified model of the plumbing system. From the comparison of fragility evaluation of the plumbing system designed in guideline 1982, the fragility evaluation derived by proposed method can be corresponding to the results of detailed model. While, there may be a slight difference in the critical floor acceleration where the probability of damage increases in the plumbing system designed in accordance with guideline in 2014. This may be because the influence of higher mode of the plumbing system or the vibration characteristics of floor accelerations. Further study is needed in the simplified models considering the differences in the stiffness of seismic supporting members.

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