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Seismic Damage Estimation for Buildings by Bayesian Inference using Real Time Monitoring Data

T. Yamada(1),N. Nojima(2), H. Egashira(3) , H. Uchibori(4), C. Chaimongkhol (5)

(1) *Sumitomo Mitsui Construction Co., LTD., Japan, TetsuyaYamada@smcon.co.jp*
(2) *Professor, Department of Civil Engineering, Gifu University, Gifu, Japan, nojima@gifu-u.ac.jp*
(3) *Sumitomo Mitsui Construction Co., LTD., Japan, egasirah@smcon.co.jp*
(4) *Sumitomo Mitsui Construction Co., LTD., Japan, huchibori@smcon.co.jp*
(5) *Sumitomo Mitsui Construction Co., LTD., Japan, C-CHANANUN@smcon.co.jp*

Abstract

After an earthquake, early damage estimation of damaged buildings is important for Business Continuity Plan (BCP). In this paper, Bayesian inference for damage probabilities using real time monitoring data is proposed. The authors developed the structural monitoring system for evaluating structural failure levels by measuring relative story displacement. This system can obtain failure data of monitored buildings just after an earthquake. Damage of non-monitored buildings and exposed area against earthquake can be estimated by analyses of the monitored data.

Bayesian inference which can estimate uncertain phenomenon (posterior distribution) from prior distribution and likelihood function is applied to the damage estimation of structures. In this paper, posterior distribution is included in a posterior fragility curve of a structure due to new earthquake, prior distribution is included in a prior fragility curve obtained by damage investigations due to historical earthquakes and a likelihood function is generated by the damage probability based on real time monitoring data.

Parametric studies were conducted to understand the characteristics of Bayesian inference model for the estimation. The characteristics of the prior fragility curve are a distribution form which is determined by mean and standard deviation of normal distribution, and a distribution of probabilities which is assumed by Beta distribution. The variation can be evaluated by pre-investigation hypothetical sample which expresses the uncertainty of probability based on Beta distribution.

The parameters for likelihood functions are the number of targeted total buildings and the ratio of the monitored data to the total buildings. The likelihood functions are generated by monitored damage data in an actual earthquake and by Monte Carlo method considering the variation (uncertainties) of probability in a simulation at every seismic intensity.

The parametric studies clarify that the number of monitored buildings largely influence the posterior fragility curve. The more the number increases, the higher the certainty increases and the smaller the region of 95%HDR (Highest Density Region) of Beta distribution.

Application example is conducted using damage data due to historical earthquakes [1]. The paper showed the numbers of damaged buildings for every damage level and at every measured seismic intensity. Referring these data, it was investigated how the ratio of the monitored buildings to the total buildings influence to the estimation of the posterior fragility curve. Lack and differences of the number of monitored data at every seismic intensity influence to the certainty of maximum likelihood damage level distribution.

Through these studies, the applicability and consideration for uncertainty of damage probability of the proposed method are shown.

Keywords: Seismic Damage Monitoring; Damage Estimation; Bayesian Inference; Fragility Curve

[1] Midorikawa S, Itou Y, Miura H (2011): Vulnerability Functions of Buildings based on Damage Survey Data of Earthquakes after the 1995 Kobe Earthquake. Journal of JAEE, Vol.11, No.4, 34-47.

1. Introduction

After an earthquake, early damage estimation of damaged buildings is important for Business Continuity Plan (BCP). In this paper, Bayesian inference for damage probabilities using real time monitoring data is proposed. We developed the structural monitoring system for evaluating structural failure levels by measuring relative story displacement. This system can obtain failure data of monitored buildings just after an earthquake. In Bayesian inference, posterior distribution of damage probability can be calculated from prior distribution of damage probability and likelihood function based on actual damage information. Initially assumed fragility curve is updated using this theory. Damage of an exposed area against earthquake and non-monitoring buildings can be estimated by the analyses of the monitoring data.

Parametric studies of this estimation models are conducted and the characteristics of the model are clarified. First, uniformly distributed cases of monitoring structures are investigated. Second, in conscious of the situation during an actual earthquake, non-uniform cases are investigated. Maximum likelihood damage level distribution is proposed for easily understanding damage estimations of non-monitoring buildings.

2. Damage Monitoring of Structures at an earthquake

2.1 Monitoring system

The system that immediately evaluates the damage of a building consists of a device for measuring the relative story displacement [1], a personal computer, an Internet network, a mail server, and a cloud server (Fig. 1). The displacement orbit data of the building measured during an earthquake is delivered from the mail server to the registered mail address. In addition, the data of multiple buildings is aggregated on the cloud server, and the damage status of each can be confirmed on the web.

The system judges the relationship between the maximum value of the displacement and the threshold value of the damage level of the building determined in advance, and distribute the information on safety of the building.

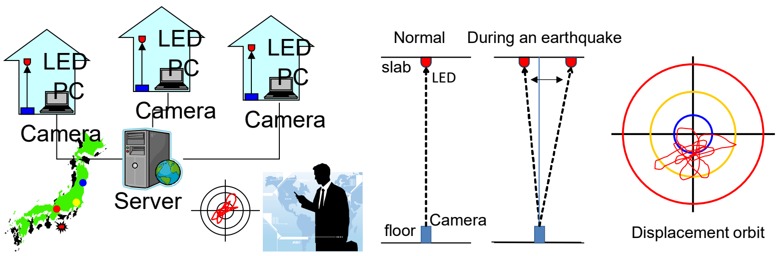


Fig.1- Monitoring System

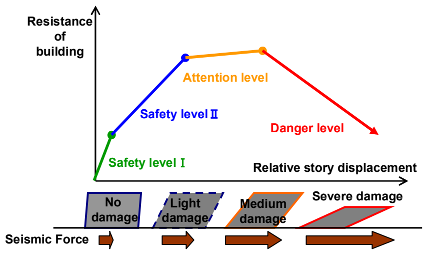


Fig.2-Damage estimation diagram

2.2 Damage estimation

The judgment of the degree of damage is based on the relationship between relative story displacement and resistance of the building shown in Fig. 2; ①Safety level Ⅰ (No damage, continuous use is possible) ②Safety level Ⅱ (Light damage, continuous use is possible). ③Attention level (aftershock caution, limited continuous use possible) ④ Danger level (continuous use impossible) is determined by three threshold displacements. In terms of the structural characteristics, safety level Ⅰ corresponds to elastic range, safety level Ⅱ corresponds to pre-yielding, attention level to post-yielding, and danger level to post peak resistance.

3. The flow of Bayesian damage inference

Damage levels of buildings are sent to a server in real time through monitoring devices. More reliable fragility curve is obtained by updating existing fragility curves. Bayesian update process is based on the algorithm shown in [2].

Utilizing this algorithm, local governments and business entities can determine the overall damage levels of targeted groups of buildings (M_T^i i: measured seismic intensity (SI)) using damage data of monitored buildings (M_0^i). The flow of damage estimation is shown below.

3.1 Data collection at an earthquake

Data on relative story displacement are immediately sent just after an earthquake, and building damage of no, light, medium, or severe is determined by pre-set damage level threshold. The measured seismic intensities (SI) of the monitored locations were obtained from real-time earthquake information provided by "National Research Institute for Earth Science and Disaster Resilience [3]" and "Real-time Earthquake and Disaster Information Consortium (REIC) [4]". By combining these, the numbers of damaged buildings at each damage level for each measured SI is tabulated.

3.2 Prior distribution of the damage probability

In this Bayesian damage inference, prior distribution includes the uncertainty of the existing fragility curve. Immediately after the earthquake, rough estimates are initially made using the existing fragility curves. If the existing fragility curve matches a true fragility curve, the damage estimation will be correct.

Fragility curves between measured SI and damage probability dealt with in this study assume the probability distribution by normal distribution (mean λ and standard deviation ξ) from the previous research result [5]. This fragility curve includes the variation among the damage statistics. This variation is treated as a random variable expressed by β distribution β (p, q) in this Bayesian inference [6]. The parameters p and q of the β distribution obtained from the average value μ and the standard deviation σ of the damage probability at each SI are calculated by the following Eq.(1) [6].

$$f(x)=\frac{x^{p-1}(1-x)^{q-1}}{\int_0^1 u^{p-1}(1-u)^{q-1}\,du},\quad p=\mu\left\{\frac{\mu(1-\mu)}{\sigma^2}-1\right\}\quad,\ q=\frac{1-\mu}{\mu}p \tag{1}$$

Prior fragility curve is modeled using a pre-investigation hypothetical sample M_0' which takes the form of "the numbers of damage are estimated as n'_{0_k} out of the total number M_0' k: level of damage" as an index indicating the uncertainty of the prior distribution related to the β distribution. M_0' is represented by μ and σ, or p and q as follows [6].

$$M_0' = \frac{\mu(1-\mu)}{\sigma^2} - 4 = (p+q) - 3 \tag{2}$$

For mathematical simplification, the prior distribution of the damage probability p_k may be modeled by Dirichlet distribution Eq. (3) (also called a multivariate β distribution) which forms conjugate pairs with multinomial distribution in applying the Bayesian damage inferences. Here, k = 1 (no damage), 2 (light damage), 3 (medium damage), 4 (severe damage), therefor K=4 in this study.

$$f_p(\mathbf{p}|M_0',\mathbf{n}_0')=\Gamma(M_0'+K)\prod_{k=1}^{K}\frac{p_k^{n'_{0k}}}{\Gamma(n'_{0k}+1)}) \tag{3}$$

3.3 Likelihood function based on actual damage information

The likelihood function is represented by the number of buildings ${n_0}^i_k$ for each damage level k (no damage, light damage, medium damage, and severe damage) caused by the actual earthquake. This monitoring data is used to calculate the likelihood function as the likely observation data obtained by the earthquake. The number of data obtained by monitoring M_0^i is the sum of the number of buildings at each damage level, ${n_0}^i_k$ as follows.

$$M_0^i = \sum_{k=1}^{4} {n_0}^i_k \tag{4}$$

k =1(No Damage), 2(Light Damage), 3(Medium Damage), 4(Severe Damage)
i : Measured SI(0.0~7.0 every0.1)

3.4 Posterior distribution of the damage probability

Suppose that as a result of damage investigation, the number of damage was confirmed to be n_{0k} from the partial samples M_0 out of the total number of structures M_T. Fig.3 schematically shows the situation under consideration. Taking advantage of the nature of conjugate pairs, the posterior distribution of p_k when n_{0k} damage have been confirmed is obtained as the Dirichlet distribution below.

$$f_p'(\mathbf{p}|M_0\ , M_0', \mathbf{n}_0\ , \mathbf{n}_0') = \Gamma(M_0 + M_0' + K) \prod_{k=1}^{K} \frac{p_k^{n_{0k}+n_{0k}'}}{\Gamma(n_{0k}+n_{0k}'+1)}) \tag{5}$$

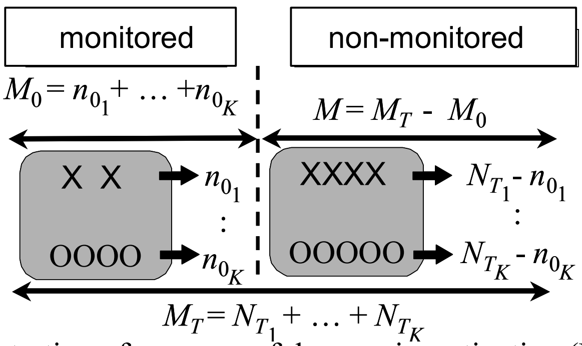


Fig.3 -Schematical illustration of progress of damage investigation (Modified from [2])

The process of integrating the initial damage estimation based on the prior fragility curve and the actual damage information based on the damage monitoring is performed only by simple parameter conversion. In this probability density function (multivariate β distribution), the average value μ_{p_k}' and the standard deviation σ_{p_k}' of the variable p_k are given by the following equations.

$$\mu_{p_k}' = \frac{n_{0k}+n_{0k}'+1}{M_0+M_0'+K} \tag{6}$$

$$\sigma_{p_k}' = \sqrt{\frac{(M_0+M_0'-n_{0k}-n_{0k}'+K-1)(n_{0k}+n_{0k}'+1)}{(M_0+M_0'+K)^2(M_0+M_0'+K+1)}} \tag{7}$$

Percent Highest Density Region (HDR) of the β distribution β(p,q) is used as an indicator of the reliability of the posterior distribution [7]. The parameters p and q of the β distribution obtained from the average value μ and the standard deviation σ of the damage probability at each SI are calculated by the Eq. (1).

3.5 Predictive distribution of the damage probability

Based on the posterior distribution of the damage probability, the predictive distribution of the number of damaged buildings is shown [2].

The number of damaged buildings in a building group with the total number of buildings M_T is n_{Tk}, is called "predictive distribution [8]". The average value $\mu'_{N_{Tk}}$ and the standard deviation $\sigma'_{N_{Tk}}$ of the total number of damaged buildings n_{Tk} are given by the following equations.

$$\mu'_{N_{Tk}} = n_{0k} + \mu'_{p_k}(M_T - M_0) \tag{8}$$

$$\sigma'_{N_{Tk}} = \sigma'_{pk}\sqrt{(M_T - M_0)(M_T + M'_0 + K)} \tag{9}$$

3.6 Damage estimation

The goal of this study is to estimate the damage level of non-monitoring buildings (M_T -M_0) in Fig.3, here M_T: the total number of buildings and M_0 ($<M_T$) : the number of monitoring buildings. Based on Bayesian damage inference, it is possible to obtain the posterior distribution of the damage probability and the predictive distribution of the number of damaged buildings. From these results, the fragilities at each damage level (no damage, light damage, medium damage, and severe damage) for each SI are compared to determine the maximum likelihood damage level. The maximum likelihood damage level is determined by the fragility curve obtained from the numbers of damaged buildings based on the predictive distribution. The method is described below.

The state of the presence or absence of damage for each measured SI is treated as binary data, and the distribution is fitted to a logistic distribution and regressed by a logit function.

Using the numbers of buildings with no, light, medium, and severe damage estimated by the predictive distribution, binary data are created by dividing into ①severe damage and no severe damage, ②medium, severe damage and except them, ③light, medium, severe damage and except them. The fragility curves for severe damage, medium fragility curve, and light damage fragility curve, no damage, are obtained from ①, ① and ②, ② and ③, ③ respectively.

The regression method using the logit model is shown below [9]. The logit model assumes a linear model of the measured seismic intensity SI as shown below with the damage probability p.

$$\ln\left(\frac{p}{1-p}\right) = b_0 + b_1 \times SI \qquad SI\text{ : Measured seismic intensity} \tag{10}$$

Thus, the damage probability p is expressed by the following equation.

$$p = \frac{\exp(b_0+b_1\times I)}{1+\exp(b_0+b_1\times I)} \tag{11}$$

The parameters b_0 and b_1 are obtained by satisfying the following conditions. δ is a binary variable indicating whether there is damage (δ = 1) or not (δ = 0).

$$\mathrm{L} = \ln\prod_{i=1}^{n} p^{\delta_i}(1-p)^{(1-\delta_i)} = \sum_{i=1}^{n}\{\delta_i lnp + (1-\delta_i)\ln(1-p)\} \rightarrow max \tag{12}$$

Fig. 4 shows an example of fragility curves based on the logit model obtained as a result of the analysis.

Fig. 5 shows the maximum likelihood damage level obtained for each measured SI from Fig. 4. In the case of real earthquake, there is only one information of damage datum, so the damage level distribution is represented by a single graph as in a). In this study, Monte Carlo simulation is performed using random numbers to evaluate non-uniformity and uncertainty of data as describing in Chapter 5. In this case, the fragility curve varies due to various uncertain factors, and several damage level distribution lines are obtained. The size of a bubble as shown in Fig. 5 b) can expresses the frequency of occurrence of the maximum likelihood damage level for each measured SI by accumulating the results of all simulations. When a bubble is drawn for medium and severe damage at the same measured SI, it indicates that both damage levels have posibilities, and we can recognize the magnitude of the possibility from the size of the bubble.

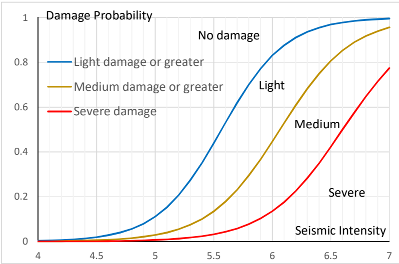
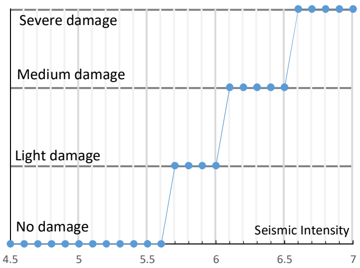
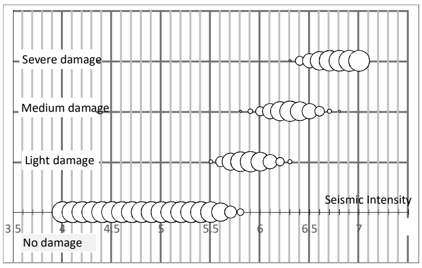


Fig.4 – Sample of fragility curve based on logit model





a) Real earthquake b) Monte Carlo simulation

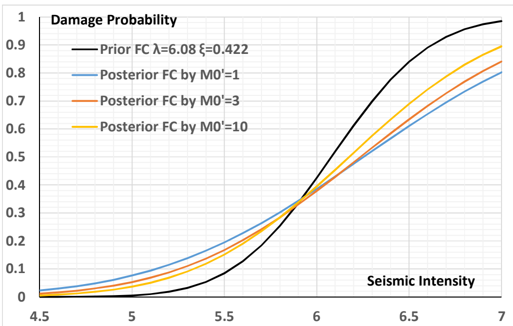
Fig. 5 – Damage level distribution map(Logit Model oriented)

4. Parametric studies of Bayesian damage inference simulation

4.1 Parameters of Prior Fragility Curve

(1) Pre-investigation hypothetical samples

A pre-investigation hypothetical sample is the indicator of the uncertainty in the prior fragility curve assumed at the beginning of Bayesian estimation, as shown in Eq. (2). Fig. 6 shows the effect on the posterior fragility curve in the cases of M_0' of 1, 3, and 10. Posterior fragility curve approaches to the prior fragility curve as M_0' increases.



(medium damage or greater)

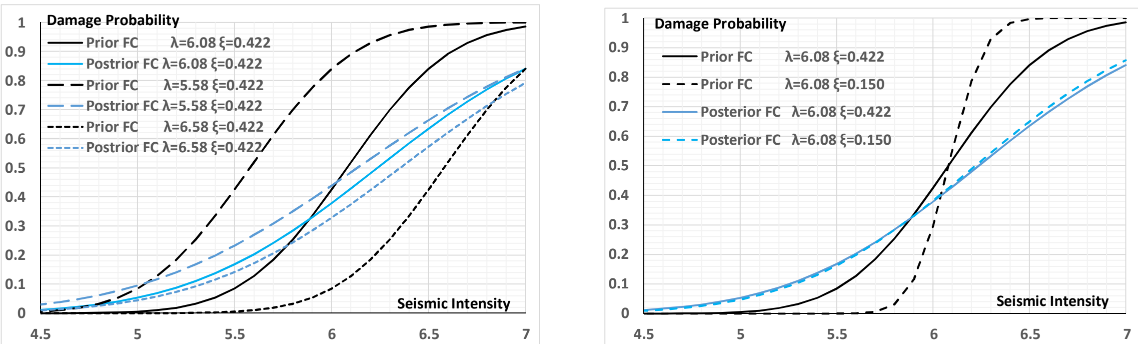
Fig. 6 – Influence of pre-investigation hypothetical samples M_0'

(2) Forms of prior fragility curve

In this Bayesian estimation, the prior fragility curve of a building is assumed by a normal distribution model. Fig. 7 shows the results of examining the effects of the normal distribution parameters (mean λ, standard deviation ξ) on the posterior fragility curve.

In Fig. 7 a), the effect of mean λ is shown. Black lines and blue lines indicate the prior and the posterior fragility curves respectively. The solid lines are the case of λof 6.08 (medium damage or greater), refer to fragility curve of the wood structures (1972-1981) [5]. λ of the dash and dot lines are 5.58 and 6.58, which are almost correspond to the upper and lower limits of 95%HDR of β distribution of the solid black line when M_o'= 3. In each case, standard deviation ξ = 0.422, M_o'= 3, the total number of buildings and the pseudo monitoring data assumed to be 100 and 10 buildings, the reference fragility curve for the pseudo-monitoring data is assumed by solid black line of which variation is equivalent to M_o'= 3. The posterior fragility curves are shown in blue. The ratio of variation of λ of the posterior fragility curves to the prior fragility curves is about 20% under the above assumptions.

Next, the result of the influence of the standard deviation ξ is shown in Fig. 7 b). In contrast to the black solid line ξ = 0.422, the black dash line ξ = 0.150 based on reference [10], and the blue solid line and broken line are the corresponding posterior fragility curves. The total number of buildings is 100, and the pseudo monitoring data is 10 buildings. The standard deviation ξ refer to the difference between the fragility curves of the wood structures (1972-1981)[5] and (-1981)[10]. Although the shapes of the prior fragility curves are different, there is no effect on the posterior fragility curve.



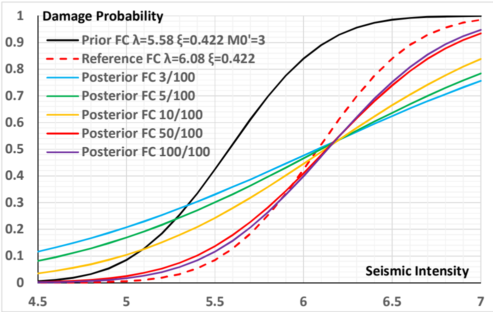
a) Influence of average λ b) Influence of standard deviation ξ

Fig. 7 – Parametric studies of Prior Fragility Curve (medium damage or greater)

4.2 Parameters of monitoring data

In this section, the effect of the number of the monitoring data is investigated. For simplicity, the number of monitoring data for each measured SI is assumed to be uniform. The prior fragility curves are assumed as light damage or greater (λ=5.08, ξ=0.422), medium damage or greater (λ =5.58, ξ =0.422), severe damage (λ =6.08, ξ =0.422), and the pre-investigation hypothetical sample M_o'= 3 [2]. The reference fragility curve for pseudo-monitoring data refer to the wood structures (1972-1981) in Reference [5].

The ratio of the number of monitoring data to the total number of buildings is used as a parameter. The effect on the posterior fragility curve in the cases of 3, 5, 10, 50, and 100 monitoring buildings per the total 100 buildings are examined. Fig. 8 shows the posterior fragility curves for medium damage or greater of each cases. In the figure, the solid black line shows the prior fragility curve, and the red broken line shows the reference fragility curve of the pseudo-monitoring data. The posterior fragility curve approaches the reference as the ratio increase. The case of 50 is almost the same as the case of 100.

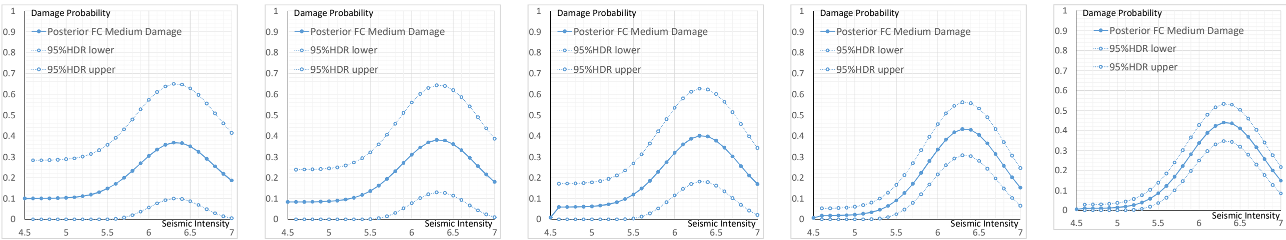


(medium damage or greater)

Fig. 8–Comparison of Posterior Fragility Curves in terms of monitoring ratio

Fig. 9 shows the posterior fragility curves for medium damage and the lower and upper limits of 95% HDR when the monitoring data is 3, 5, 10, 50 and 100%. Although the range of 95%HDR varies depending on the measured SI, the maximum values are 52%, 50%, 43%, 25%, and 19% respectively.

In Figs. 8 and 9, the greater the monitoring ratio, the closer the posterior damage curve approaches to the true value, and at the same time, the higher the reliability. Therefore, when the ratio of monitoring is small, the reliability of the posterior fragility curve is necessary to be considered.



a)3% b)5% c)10% d)50% e)100%

Fig. 9 – Comparison of Posterior Fragility Curve and 95%HDR range (Medium damage)

5. Simulation of non-uniform monitoring data at each seismic intensity

5.1 Concept of non- uniformity

The assumption in Chap. 4 is that the total number of buildings and monitoring data for each measured seismic intensity (SI) are the same (uniform). However, when an earthquake actually occurs, various situations for the number of damaged buildings for each measured SI are assumed in according to the location of the epicenter and the density of the buildings. This non-uniformity at each SI area is discussed in Chap. 5.

In the simulation, the non-uniformity from 0 to M_T building ($\underline{M_T}$) is generated using uniform random. In addition, the ratio of the monitored buildings in M_T is set to R_M% as maximum of which range is varied from 0 to R_M % ($\underline{R_M}$) using uniform random. Therefore, the total number in a certain SI area is $\underline{M_T}$, and the number of monitoring buildings becomes $\underline{R_M}\times\underline{M_T}$ which is equal to M_0 in Fig.3.

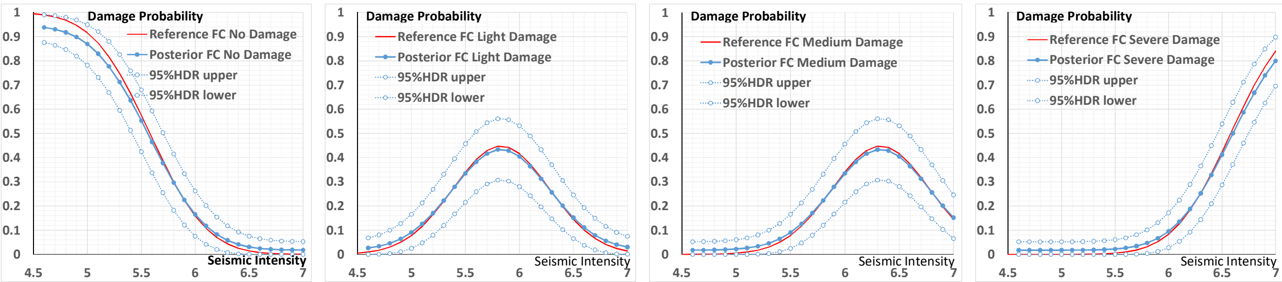
5.2 Non-uniformities of the total number of buildings and the percentage of monitoring buildings

The maximum total number of target buildings $\underline{M_T}$ is assumed to be 100 for every measured SI range 0.1. The maximum monitoring ratio R_M is assumed to be 50%. Other assumptions are as follows, the prior fragility curve and the reference fragility curve for generating pseudo-monitoring data are based on the wood structures (1971-1981)[5], and the pre-investigation hypothetical sample M_0' of the prior distribution is 3.

Fig. 10 shows the posterior fragility curve and 95% HDR for each damage level. The average of the discrete posterior distribution for each SI is shown by a solid line (blue ●), and the corresponding upper and lower limits of 95% HDR are shown by dash lines (blue ◯). The red solid line indicates the reference fragility curve for generating pseudo-monitoring data. Fig. 10 a) is the uniform case, and b) is the non-uniform case. The zigzag line in b) of the posterior fragility curve is due to the variations in the total number of buildings and the number of monitoring buildings by uniform random. The reliabilities of the posterior fragility curves of b) become non-uniform and low.

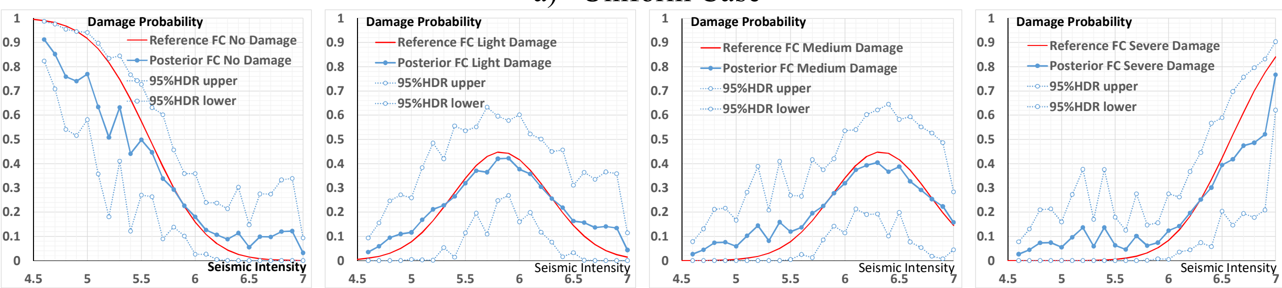
Fig. 11 shows the damage level distribution map based on the method described in 3.6 Damage Estimation. This figure shows the maximum likelihood damage level for each measured SI based on the fragility curve obtained by the logit model from the results of 100 Monte Carlo Simulations (MCS) using uniform random.

In the uniform case, the maximum likelihood damage level is uniquely determined for any measured SI. In the non-uniform case, the damage level may not be uniquely determined in SI of 5.7, 6.1, 6.4, 6.5. The size of the circle represents the frequency and the probability. The damage level distribution can indicate the variation in the occurrence frequency of the maximum likelihood damage level considering non-uniformities.



No damage　Light damage　Medium damage　Severe damage

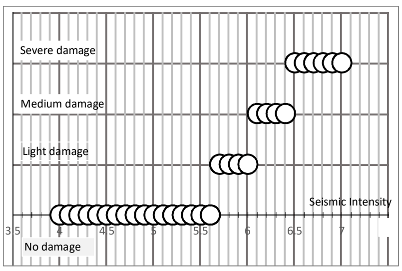
a) Uniform Case



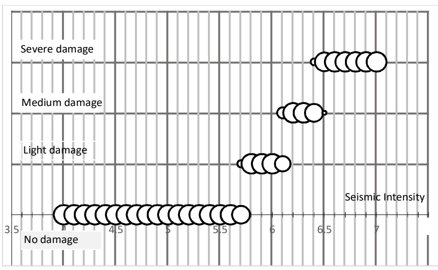
No damage　Light damage　Medium damage　Severe damage

b) Non-uniform Case

Fig. 10 –Posterior Fragility Curve and 95%HDR range



a) Uniform Case



b) Non-uniform Case

Fig. 11 –Maximum likelihood damage level distribution

6. Damage estimation method using historical earthquake damage data

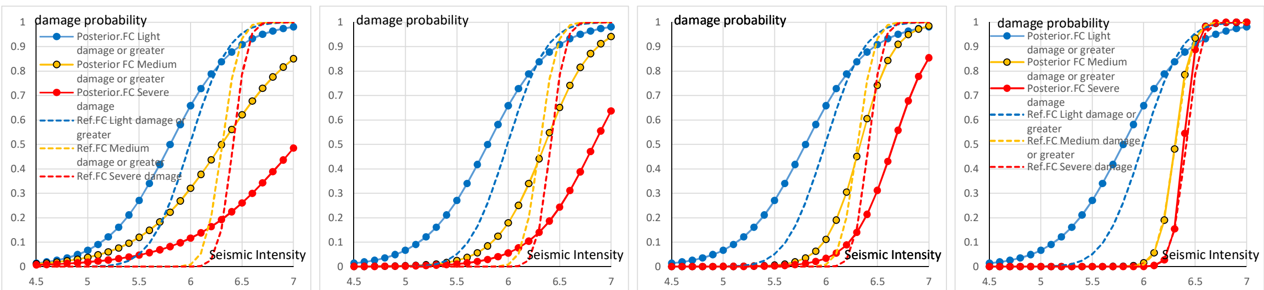
An application of this Bayesian inference for an actual earthquake is described. The number of damaged buildings data from Niigata-ken Chuetsu-oki earthquake (M6.8) is applied. According to the damage researches of this earthquake, the measured SI is in the range of 5.0 to 6.3, and the number of damaged buildings for every measured SI 0.1 belonging to wood structures is shown in Table1. The simulations were performed assuming that the actual numbers of monitoring buildings are 10%, 50%, 80% and 100% of the total. Other assumptions are as follows, the prior fragility curve refer to the case of wood structures (1972-1981) [5], the pre-investigation hypothetical sample $M_0' = 3$, and the reference fragility curve for the monitoring data is the regression curve based on the investigation data of Table 1.

Table 1 –Damage numbers of wood structures (-1981) (the Niigata-ken Chuetsu-oki earthquake)[10]

Seismic Intensity	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3
No damage	345	63	128	234	50	0	64	0	51	0	0	0	24	2
Light damage	1	1	0	11	0	0	29	0	38	0	0	0	7	80
Medium damage	0	0	0	0	0	0	1	0	0	0	0	0	5	50
Severe damage	0	0	0	0	0	0	0	0	1	0	0	0	1	24
Sub Total	346	64	128	245	50	0	94	0	90	0	0	0	37	156

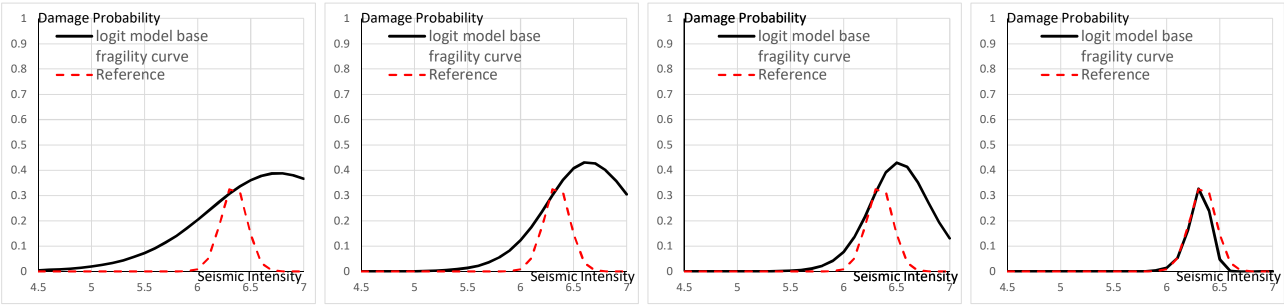
Fig.12 shows the results of cumulative fragility curve obtained from the logit model of predictive distribution. The ratio of monitoring data increases, gradually the fragility curves seem to approach to the reference fragility curve (dash line). The estimation of the posterior fragility curve for the lighter damage becomes better than that for the severer damage in the each ratio. This may because inadequate data at more than SI of 6.3. Solid black line in Fig.13 shows the fragility density curve of medium damage obtained from the gap between yellow (medium damage or greater) and red (severe damage) lines in Fig.12. Red dash line means the regression curve based on the investigation data of Table 1. The ratio of monitoring data increases, gradually the fragility density curves seem to approach to the reference curve (red dash line).

From the differences between these cumulative fragility curves, the fragilities of light, medium, and severe damage are obtained. The size of circles expresses the probabilities for each damage level at every SI as shown in Fig.14. The spredness of the distribution of damage levels decreases as the ratio of monitoring data increses. The maximum likelihood damage level for each measured SI is obtained from Fig.14. The results are shown in Fig.15. Differences in judgment of damage level are seen in the range of more than 6.4. In the range below 6.3, there is no difference by the ratio. In this examples, the estimation results are acceptable within the range of monitored SI area, even if the ratio is relatively low. But in the range more than 6.4 of no SI data area, the variation of damage levels is observed depending on the ratio.



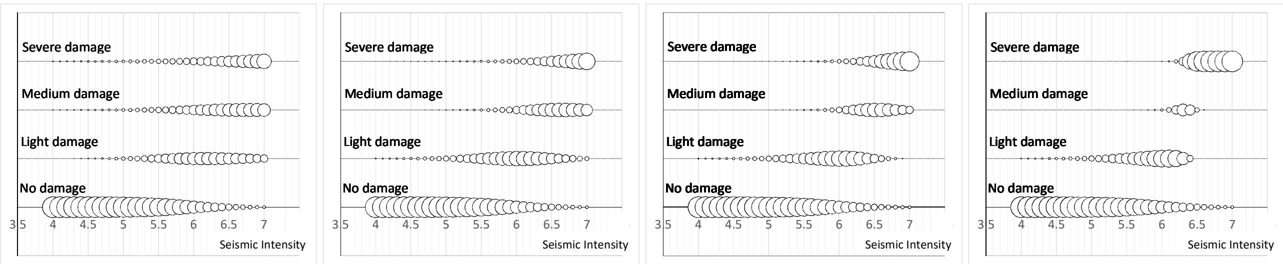
a) 10%(121 bldgs.) b) 50%(606 bldgs.) c) 80%(968 bldgs.) d) 100%(1215 bldgs.)

Fig. 12 –Posterior and Reference cumlative fragility curves based on logit model(Niigata-ken Chuetsu-oki earthquake)



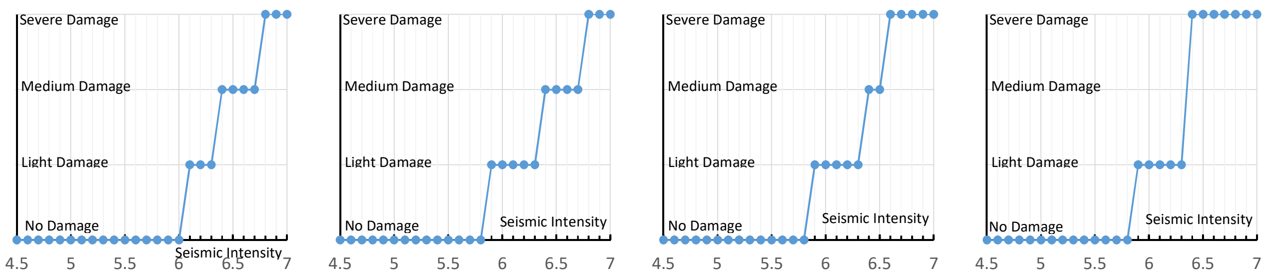
a) 10%(121 bldgs.) b) 50%(606 bldgs.) c) 80%(968 bldgs.) d) 100%(1215 bldgs.)

Fig. 13 –Posterior and reference fragility curve based on logit model (Medium damage)



a) 10%(121 bldgs.) b) 50%(606 bldgs.) c) 80%(968 bldgs.) d) 100%(1215 bldgs.)

Fig. 14 – Damage probability distribution(Niigata-ken Chuetsu-oki earthquake)



a) 10%(121 bldgs.) b) 50%(606 bldgs.) c) 80%(968 bldgs.) d) 100%(1215 bldgs.)

Fig. 15 –Maximum likelihood damage level map(Niigata-ken Chuetsu-oki earthquake)

7. Conclusion

The method using Bayesian inference to easily understand the damage status of buildings in exposed area including non-monitored buildings using damage monitoring data during an earthquake is proposed.

In the damage probability model, the prior fragility curve and the likelihood function based on the monitoring data are the main variable factors, and the characteristics of each parameter were examined by the simulations, and the following findings were obtained. .

(1) Pre-investigation hypothetical sample, M_0' is a parameter indicating the reliability of the prior fragility curve, and as the value of M_0' is increased, the posterior fragility curve tends to approach the prior fragility curve.

(2) The prior fragility curve assumes normal distribution. When the average λ is changed, the posterior fragility curve moves in the shift direction of the prior fragility curve. The influence for the variation range of λ is about 20%. Also, the influence of varying the standard deviation ξ tends to be less than the case of the average λ.

(3) If the total number of the targeted buildings and the monitoring ratio increase, the posterior fragility curve seems asymptotically to approach to the actual fragility curve, and its reliability increases in simulations. Appropriate prediction can be obtained except 100% monitoring, however the adequate ratio varies depending on the numbers and distribution of monitoring data.

(4) Assuming actual earthquake damage, if the total number of the targeted buildings and the monitoring ratio for each seismic intensity area are non-uniform, the reliability of the discrete posterior fragility curves also become non-uniform. If a logit model is applied to the result of the predictive distribution of the number of damaged buildings to cope with this non-uniformity, the regressive continuous fragility curve can be obtained stably. From this result, the maximum likelihood damage level can be presented.

(5) Damage estimation study using actual historical earthquake data indicated that validity of the estimation depends on the distribution of seismic intensity area of the monitored data. This Bayesian inference in the area of the monitored seismic intensity can estimate maximum likelihood damage level regardless of the monitoring ratio, but in the area of non-monitored data, the uncertainty of the predictive distribution should be considered.

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