Seismic Assessment Method for Indoor Injury Risk and Its Application

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SUMMARY:
There seems to be no end to casualties caused by the furniture overturned during earthquake shaking in Japan. In order to contribute to accelerate the indoor safety promotion in earthquakes, we propose a new diagnostic method for injury risk potential of targeted household caused by indoor furniture overturned based on the injury risk probability of indoor space formulated from the binominal distribution model. Using the diagnostics we can treat 4 types of situations which respond to how to treat the aleatory uncertainty such as seismic severity of forthcoming event and the epistemology uncertainty such as probability of furniture overturned.

Keywords: Seismic casualty, Diagnostics of indoor risk, Furniture overturned

1. INTRODUCTION

A really heavy casualties caused by furniture overturned have still occurred during swaying buildings by earthquakes in Japan. While various countermeasures against a homely lethal weapon including decreasing the number of indoor furniture, fixing furniture on the wall and arranging furniture to safe geometry are supposed to be considered as efficient measures, but the proposed indoor countermeasures are neither widely applied nor actually relevant by the reason why technical supports encouraging the implementation of these countermeasures have been limited as mentioned by the fact that the basic technology of diagnosis of indoor injury risk is not developed, which is necessary to percept the injury risk surrounding our daily lives and to evaluate the effectiveness of countermeasures done. In the previous WCEE Nachi and Okada (2008) formulated the arithmetic model concerning the occurrence of injured at home based on the probability theory. In this paper we propose the diagnosis of indoor injury risk following the above model in order to contribute to accelerate the seismic indoor safety promotion.

2. INDOOR CASUALTY MODEL

A main subject in this chapter is to define the probabilistic scale of indoor risk regarding casualties caused by furniture overturned on the basis of the view of the stochastic model that is approximated by binominal distribution. Although the wooden frame structure of building that is commonly used as Japanese dwelling house is targeted in this research, the proposed method is applicable for any houses independent of type of structure.

Let consider the effective floor space (*Se* [m^2]) which means the room space allows inhabitants to stay and give its definition by subtracting the installation area (*Sf* [m^2]) of the *m* pieces of furniture from the total floor area (*S* [m^2]) of the closed room space as follows:

$$Se = S - \sum_{i=1}^{m} Sf_i \tag{2.1}$$

The ratio of the area occupied by overturning or falling of furniture (*Str* [m^2]) against the effective floor space (Se [m^2]), which is hereinafter shortened to “Overturning Ratio”, is as follows:

$$Rtr = \frac{\sum_{i=1}^{t} Str_i}{Se} \tag{2.2}$$

When the effective floor area (Se [m^2]) is divided into N parts of planes by making into a unit area which one resident occupies, the number of division of the area occupied by overturning or falling of furniture can be expressed as the product of N by Rtr. When it is assumed that one resident is distributed at random within the effective floor area, the probability (p) that the injured will be reported is denoted by the following formulas equally to the probability of choosing one piece of plane from (N x Rtr) pieces of the area occupied furniture overturned as against the effective floor area divided into N pieces planes.

$$p = {}_{N\times Rtr}C_1 \big/ {}_{N}C_1 = Rtr \tag{2.3}$$

where,

$${}_{n}C_{k} = \frac{n!}{k!(n-k)!} \tag{2.4}$$

As showing in the above equations the injury probability for one person staying in a closed room space is equal to Rtr. In case of plural number of inhabitants staying there the probability can be formulated as an approximate model by using a binominal distribution with a main parameter of the area ratio Rtr described above; and it can be expressed as a following formula, where n is the population there, and k is the number of the injured person.

$$P[X = k] = {}_{n}C_{k} Rtr^{k} (1-Rtr)^{n-k} \qquad k = 0,1,2,\cdots,n \tag{2.5}$$

3. DIAGNOSIS OF INDOOR RISK

For quantitating safe from seismic danger at each of the rooms, we propose an estimation method for the occurrence probability by the number of injured at each room as being an estimation unit. This method has advantages of easy operation for estimating how effective the countermeasures such as furniture fixation and arrangement are.

Generally, diagnosis cannot be implemented without ambiguity involving two kinds of uncertainty defined by A. H-S Ang and W. H. Tang (2007). One is called aleatory uncertainty which is associated with the randomness of the underlying phenomenon. The other is called epistemic uncertainty which is associated with imperfect models of the real world. We propose the following four types of diagnosis characterized by combining the above uncertainties.

3.1. Diagnosis 1: Diagnosis of the maximum potential injury risk in each room

3.1.1. Method for Diagnosis 1

In case of making the seismic severity of ground motion fixed without considering aleatory uncertainty, this diagnosis method can be applied for houses under the strong ground motions greater than 50 cm/sec, what you call seismic movement level 2. The results of this risk assessment give the decision making based on the assumption of the worst disastrous situation from pessimistic side. It is a diagnostic method which calculates the probability for the injured assuming that all the furniture possible to topple, which means both unstable with a large ratio of height against depth and unfixed to the wall etc., turns over. The probability distribution (*P[X=k]*) for various numbers (k) of the injured can be calculated by substituting the Overturning Ratio (*Rtr*) in this condition for Eqn. 2.5. Since the probability means a possibility on the number of the injured in the worst dangerous case, this is called the maximum potential injury risk for inhabitants in each room.

3.1.2. Example of Diagnosis 1

Based on the Diagnosis 1, a detached house with wooden-frame structure is examined as an example. Fig.3.1. shows the second floor plan which we put into damage investigation in the 2003 Tokachi-oki Earthquake, Japan. This figure indicates the fall situation of furniture and the position of two children who stayed in the room when the earthquake attacked. Fortunately, nobody was injured in this house. We carried out the questionnaire survey on seismic intensity at the time of the damage investigation in the area of about 2 km around, and we obtained the average JMA intensity 5.4 there, which is equal to 8 in the MSK intensity scale.

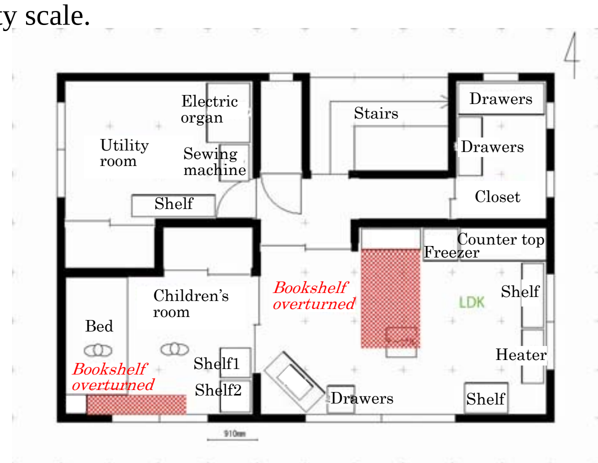


Figure3.1. The second floor plan of the house damaged in the Tokachi-oki Earthquake

We try to diagnosis the children's room which locates at the south-eastern corner of the floor plan in Fig.3.1. Table 3.1 shows the list of the furniture arranged in the children's room, the installation area of the furniture (*Sf*) and the area occupied by overturning of the furniture (*Str*). Diagnosis 1 is the method in assuming that all the furniture toppled, and the damage situation of this children's room is simulated as shown in Fig.3.2. As shown in the following the Overturning Ratio (*Rtr*) is simply calculated in Eqn.2.2 under the condition that some pieces of furniture overturned do not overlap each other:

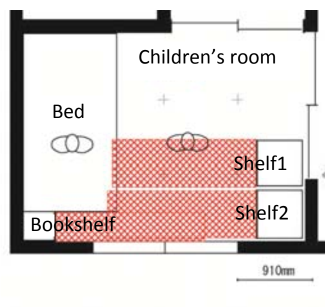
$$Rtr = \frac{\sum_{i=1}^{t} Str_i}{Se} = \frac{(0.63 + 0.96 + 1.08)}{\{9.9 - (0.14 + 0.30 + 0.33)\}} = 0.29 \tag{3.1}$$

Table 3.1. The Dimensions of Furniture, and Installation Area and Area Occupied by Overturning of Furniture

Room	Floor area *S* [m^2]	Furniture	Width *W* [mm]	Depth *D* [mm]	Height *H* [mm]	Installation area *Sf* [m^2]	Area occupied *Str* [m^2]
Children's room	9.9	Bookshelf	350	400	1800	0.14	0.63
		Bed	1150	2200	600	0.00	0.00
		Shelf1	550	550	1750	0.30	0.96
		Shelf2	600	550	1800	0.33	1.08

That is, in the case of the children's room of this house, it turns out that about 30% of floor area can serve as dangerous space. In addition, since a bed serves as an evacuation space for residents during earthquake swaying, it is not included in the installation area of furniture.

There were two residents in this room, so calculating the probability distribution (*P[x=k]*) from Eqn.2.5 about the case of *k*=0, 1, and 2, we obtain Fig.3.3. The case of *k*=0 with no injured (*P[x=0]*) gives the highest probability of 50.2%. However, it is almost equal to 50% that is the threshold value of whether there occurs injured or no injured. Therefore, this room should be considered as a space inhering very high risk potential under the earthquake motion of level 2. The probability for one injured person (*P[x=1]*) is 41.3%. As known in Fig.3.2 the spatial relationship of the resident and the area occupied by the furniture overturned actually shows that one person overlapped with an area possible of overturning of Shelf 1.



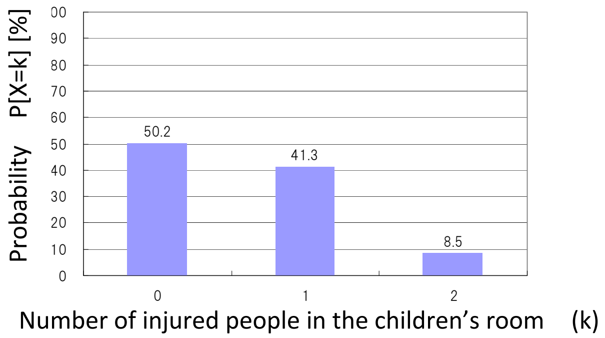


Figure 3.2. Damage situation under Diagnosis 1 **Figure3.3.** Probability distribution estimated by Diagnosis 1

3.2. Diagnosis 2: Diagnosis for earthquake motion of level 1

3.2.1. Method for Diagnosis 2

This is a simple diagnostic way in which the probability of overturning of furniture can be obtained from only the proportion concerning the form of furniture without consideration about earthquake ground motion which means aleatory uncertainty. The relation between the proportion (*H/D*) which is called the aspect ratio of the height (*H*) against the depth (*D*) of furniture and the overturning probability of furniture (*R*) is given on the basis of our data in which the number of investigated furniture is 3,581 as shown in Fig.3.4. The plots in this figure indicate the relation between the overturning probability and the average value of an aspect ratio in the value range by the integer number of ± 0.5, and the numerical number in this figure shows the number of furniture included in each class. As the linear relation is accepted among both of variables, the following Eqn. 3.2 can be derived by the least square method weighted with relative frequency of furniture in each class.

$$R = 0.052\frac{H}{D} + 0.01 \quad (3.2)$$

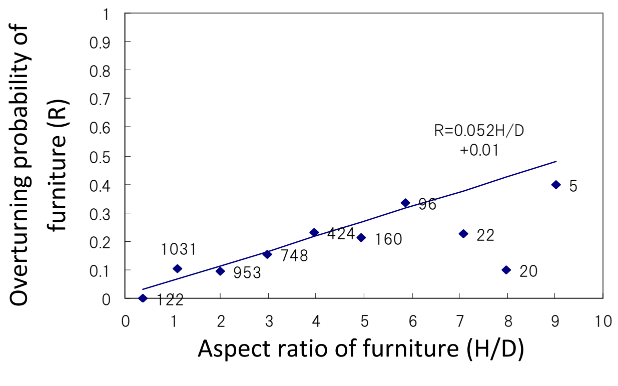


Figure 3.4. Relation between aspect ratio and probability of overturning of furniture

The seismic intensity investigation conducted simultaneously with our damage survey suggests that the conditions of toppling of furniture by Eqn. 3.2 can be applied when the seismic intensity on floor response is equivalent to 3.8 to 6.9 in the JMA intensity scale. While the earthquake ground motion data effective of Eqn. 3.2 covered the overall ranges of seismic hazards, the examples of our investigation included more damage cases in relatively smaller seismic intensity ranges than larger intensity ranges, and almost all the damage level of the investigated houses was not estimated exceeding heavy damage. That is the reason why we regard this second type of diagnosis using the relation equations given by our investigation as a method applicable to be used in case of seismic movement level 1, of which maximum ground velocity is between 25 and 50cm/sec.

In Diagnosis 2 we can estimate the Overturning Ratio (*Rtr*) defined by Eqn. 2.2 through a probable value (*R*) given by Eqn. 3.2. In this case, it is necessary to calculate the probability (*P(Rtr)*) bringing into the conditions of the Overturning Ratio (*Rtr*).

$$P(Rtr_j) = \prod_{i,i'=1}^{m} R_{j,i} \cdot (1 - R_{j,i'}) \qquad (i, i' = 1 \sim m, \quad i \neq i', \quad j = 1 \sim 2^m) \tag{3.3}$$

where, *Rtr* is calculated in the combination of all the states of the furniture arranged, that is toppled or no toppled. When *m* pieces of furniture are arranged in the room the state (*j*) of combining in 2^m ways should be considered. The injured probability distribution (*P[X=k]*) with the number (*k*) of injured person can be derived from Eqn. 2.5 by the stochastic product of the occurrence probability (*P(Rtr)*) and the binominal distribution as follows:

$$P[X = k] = \sum_{j=1}^{2^m} \left\{ P(Rtr_j)\, {}_nC_k\, Rtr_j^{\,k} (1 - Rtr_j)^{n-k} \right\} \qquad (k = 0, 1, 2, \cdots, n) \tag{3.4}$$

3.2.2. Example of Diagnosis 2

We try to diagnosis by the method of Diagnosis 2 using the same example as the Diagnosis 1. In Diagnosis 2 we cannot decide as unique as we treat through Diagnosis 1 on the situation of toppled or no toppled for all the furniture. First, we calculate the overturning ratio (*Rtr*) in Eqn. 3.2 using the H/D of each furniture, then we obtain the occurrence probability (*P(Rtr)*) by Eqn. 3.3. In this case there are three pieces of furniture, that is, Bookshelf, Shelf 1, and Shelf 2, we must consider all the situation of furniture of the cases of 1 to 8. Table 3.2 shows the probability in each case and Fig. 3.5 indicates the relation between the Overturning ration (*Rtr*) and the occurrence probability (*P(Rtr)*) in each case. In Table 3.2 we can see that Bookshelf with the overturning probability (*R*) of 24.4% is more easily prone to be overturned than other Shelves which keep the overturning probability of about 18%.

Table 3.2. Overturning Probability of Furniture and Its Occurrence Probability in Children's Room

	H [mm]	D [mm]	*Rtr*	*R*	1-*R*	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Bookshelf	1800	400	0.069	0.244	0.756	×	○	×	×	○	×	○	○
Shelf1	1750	550	0.105	0.175	0.825	×	×	○	×	○	○	×	○
Shelf2	1800	550	0.118	0.180	0.820	×	×	×	○	×	○	○	○
Occurrence Probability *P(Rtr)*						0.511	0.165	0.109	0.112	0.035	0.024	0.036	0.008
Overturning Ratio *Rtr*						0.000	0.069	0.105	0.118	0.174	0.223	0.187	0.292

○: Overturned, ×: Non overturned
Rtr: Overturning Ratio, *R*: Overturning probability of furniture,
1-*R*: Non-overturning probability of furniture

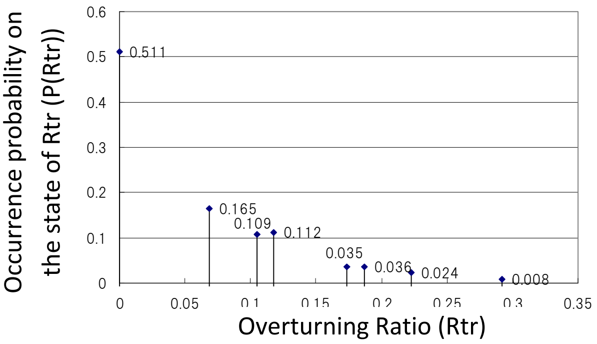


Figure 3.5. Relation between the Overturning Ratio and its occurrence probability

However, it is understandable that the most probable situation is Case 1 in which all the furniture is not overturned under the seismic movement level 1. Its occurrence probability (*P(Rtr)*) is 51.1%. Otherwise, the Cases keeping the occurrence probability (*P(Rtr)*) over 10% are equivalent to Cases 2 to 4 in which only a piece of furniture is fallen down. The Overturning Ratio (*Rtr*) in these cases distributes from 6.9 to 11.8% which means narrow area occupied by furniture overturned and a relatively low risk of injured. The most probable situation of them is Case 2, where the probability of *P(Rtr)* is 16.5% but the Overturning Ratio of *Rtr* is only 6.9%, shown in Fig. 3.6. By using the distribution of *P(Rtr)* in Fig. 3.5 and by substituting into Eqn. 3.4 we obtain the injured probability distribution (*P[X=k]*) in Fig. 3.7. This figure shows that the probability occurs no injured is as high as 89.5%, and so it turns out that this room is comparatively safe against the seismic movement level 1.

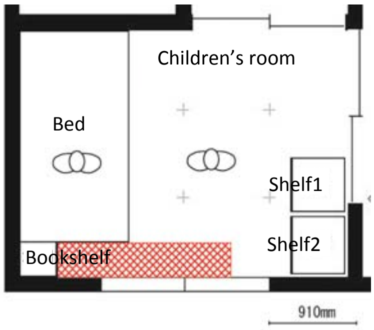


Figure 3.6. Damage situation at the occurrence probability (P(Rtr)) of 16.5% under Diagnosis 2

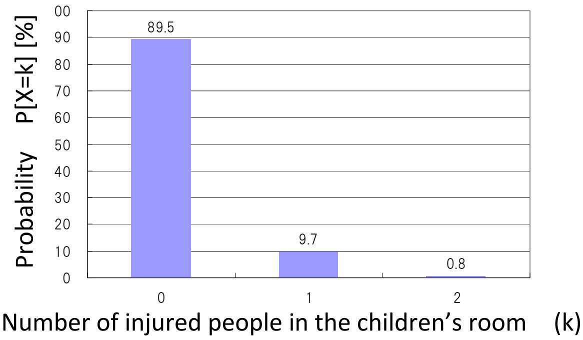


Figure3.7. Probability distribution estimated by Diagnosis 2

3.3. Diagnosis 3:

3.3.1. Method for Diagnosis 3

When we can obtain or specify the input information to the target area we may apply the third type of risk assessment which treats definitely how the state of furniture changes to the specific input motions. This method is so simple without considering epistemic uncertainty. In this method the parameters considered as earthquake motions are the maximum acceleration (A_{max} [cm/sec^2]) and the maximum velocity (V_{max} [cm/sec]) of floor response. We can decide whether furniture turn over or keep standing by comparing these two kinds of parameters of swaying with the critical acceleration (A_{cr} [cm/sec^2]) and the critical velocity (V_{cr} [cm/sec]) which mean the minimum values having furniture overturned given by the following equations [Ishiyama(1982)]:

$$A_{cr} = \frac{D}{H} g \tag{3.5}$$

$$V_{cr} = 0.4\sqrt{\frac{8gr}{3} \cdot \frac{1-\cos\alpha}{\cos^2\alpha}} \tag{3.6}$$

where, D and H are the depth [cm] and the height [cm] of furniture, and g expresses acceleration due to gravity [cm/sec^2], respectively. r is the length from the center of gravity to the corner of furniture and α is its angle in a section of furniture. The probability distribution (*P[X=k]*) for various numbers (k) of the injured can be calculated by substituting the Overturning Ratio (*Rtr*) in the state of furniture for Eqn. 2.5.

3.3.2. Example of Diagnosis 3

We try to diagnosis by the method of Diagnosis 3 using the same example as the former. Since it is necessary to set up an earthquake motion concretely in the diagnostic method 3, the 2003 Tokachi-oki earthquake is assumed. As mentioned in the above, the seismic intensity around this household was 5.4 in the JMA intensity scale. With considering the amplified floor response effect because the children's room shown in this example is on the second floor, we decide the floor response of this room as 5.87 in the JMA intensity scale. Then we can judge the state of whether each of furniture falls down or not by comparing Eqns. 3.5 and 3.6 with the A_{max} and V_{max} transferred from the above floor response. Consequently, the method has estimated all the furniture in this room overturn (*Rtr*=0.29) and the injured probability distribution (*P[X=k]*) shown in Fig. 3.8 is the same results as the maximum potential injury risk by Diagnosis 1. Ishiyama came up with the discriminant given by Eqns. 3.5 and

3.6 without considering friction between furniture and floor. That may be why the number of furniture overturned in this method is more than the real state of furniture in Fig.3.1.

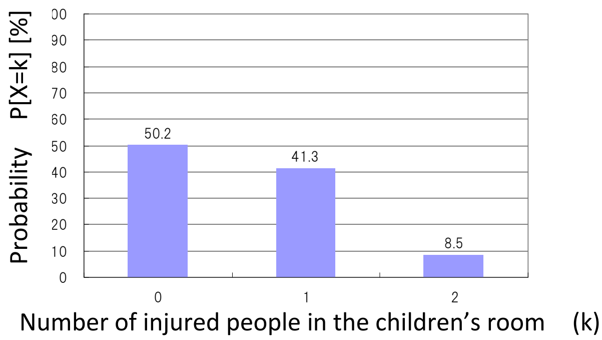


Figure3.8. Probability distribution estimated by Diagnosis 3 assuming that the floor response is 5.87

3.4. Diagnosis 4: Diagnosis for an assumed earthquake motion

3.4.1. Method of Diagnosis 4

Considering both kinds of uncertainty indicated by Ang and Tang, we propose the fourth type of diagnosis which is the most faithful but complicated method for indoor risk assessment. The difference from Diagnosis 3 is that Diagnosis 4 treats the state of furniture as probability distribution of overturning furniture estimated by the following equation [Kaneko and Hayashi(2004)]:

$$R = \Phi\left(\frac{(\ln A_{\max} - \lambda)}{\zeta}\right) \tag{3.7}$$

$$e^{\lambda} = \begin{cases} \dfrac{D}{H} g\left(1+\dfrac{D}{H}\right) & , F_e \le F_b' \\ 10\dfrac{D}{\sqrt{H}}\left(1+\dfrac{D}{H}\right)^{2.5} \cdot 2\pi F_e & , F_e > F_b' \end{cases} \tag{3.8}$$

$$F_b' = F_b\left(1+\frac{D}{H}\right)^{-1.5} = \frac{15.6}{\sqrt{H}}\left(1+\frac{D}{H}\right)^{-1.5} \tag{3.9}$$

$$F_b = 15.6H^{-0.5} \tag{3.10}$$

$$\zeta = 0.1(1+F_e)^{0.5} \tag{3.11}$$

$$F_e = \frac{A_{\max}}{2\pi V_{\max}} \tag{3.12}$$

where, the probability of overturning of rigid body (R) is given by the logarithmic normal distribution function (Φ) of the peak floor acceleration (A_{max} [cm/sec^2]). e^{λ} is the median of the log-normal distribution, F_e [Hz] is an equivalent frequency to floor response, F_b' and F_b mean the border frequency whether furniture overturns or not in the case that furniture shaking is dominated in response acceleration or response velocity, respectively. ζ is log-standard deviation of the distribution. V_{max} is the peak floor velocity. When A_{max} and V_{max} of floor response are given, the overturning probability of furniture (R) can be estimated by the above equations. As the same operation of Diagnosis 2 the probability (*P(Rtr)*) and the injured probability distribution (*P[X=k]*) can be calculated using Eqns. 3.3 and 3.4, respectively.

3.4.2. Example of Diagnosis 4

We illustrate the result of Diagnosis 4 with the same example as Diagnosis 3. Using Eqns. 3.7 to 3.12 over floor response 5.87 in the Japanese seismic intensity scale we obtain the probability of overturning of each furniture; that is, 98% for Bookshelf, 10% for Shelf 1, and 14% for Shelf 2. Fig. 3.9 shows the probability distributions (*P(Rtr)*) to each the Overturning Ratio (*Rtr*). The most presumable state where only the Bookshelf overturns with the Overturning Ratio (*Rtr*) of 0.07 in Fig.3.10 indicates the occurrence probability of about 76%. This result is substituted for Eqn. 3.4 and then the injury probability distributions *P [X=k]* are obtained as shown in Fig. 3.11. Probability with no injured is the highest at 82.2%.

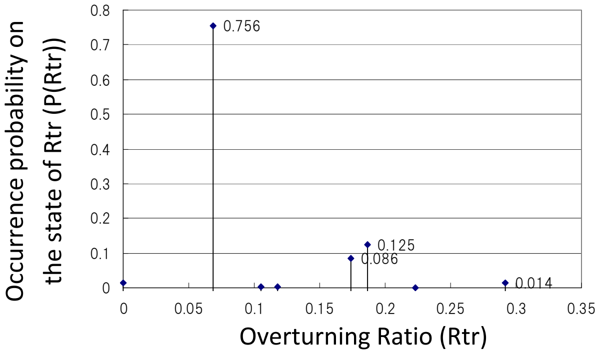
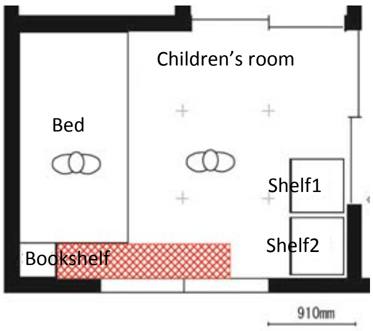


Figure 3.9. Relation between the Overturning Ratio and its occurrence probability



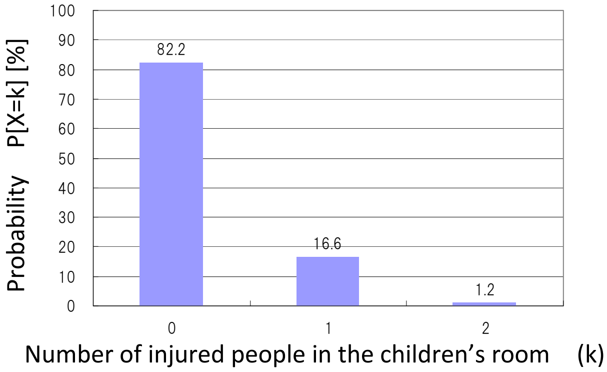


Figure 3.10. Damage situation at the occurrence probability (*P(Rtr)*) of 75.6% under Diagnosis 4

Figure3.11. Probability distribution estimated by Diagnosis 4

4. CONCLUSIONS

We proposed 4 types of diagnosis for seismic indoor injury risk in this paper. Applying these types of diagnosis, we can disclose the inherent features at indoor risk characterized by regional differences in Japan, so that we can finally indicate the measures for living safety life.

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