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# SEISMIC SAFETY EVALUATION METHOD FOR BUILDING CONTENTS

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**ABSTRACT :**

A simple and convenient methodology to evaluate indoor safety for buildings subjected to earthquake shakings has been developed. The methodology consists of three main estimation components: (1) an approximate evaluation of the maximum responses of a building due to earthquake shaking, (2) estimation of risks of overturning and sliding of furniture, and (3) estimation of damage of nonstructural elements of a building. The developed response evaluation formulas can estimate the maximum acceleration, velocity, and story displacement of each story of a building by using only the story number and the classification of structure (RC/Steel) of the building and the *PGA* and *PGV* of the earthquake. Based upon the estimated maximum responses, the risks of overturning and sliding of specified pieces of furniture and the damage of specified nonstructural elements can be estimated and classified into four levels. The methodology has been verified by comparing with the actual observed earthquake damage in the 2005 West Off Fukuoka Earthquake and the 2004 Mid Niigata Prefecture Earthquake.

**KEYWORDS:** indoor damage, overturning of furniture, sliding of furniture, nonstructural elements, response estimation

## 1. INTRODUCTION

Overturning or sliding of furniture and other building contents and damage of nonstructural elements due to earthquake shaking may injure building occupants even when the building structural frame does not suffer severe damage. Overturned furniture and damaged nonstructural elements may also interfere with evacuation of building occupants after earthquakes. Therefore, it is very important to evaluate seismic indoor damage of a building and take preventive measures against earthquakes. In this study, an indoor safety evaluation method for a building subjected to earthquake shaking has been developed that takes into account the above-mentioned risks. The flow of the indoor safety evaluation is shown in Figure 1.

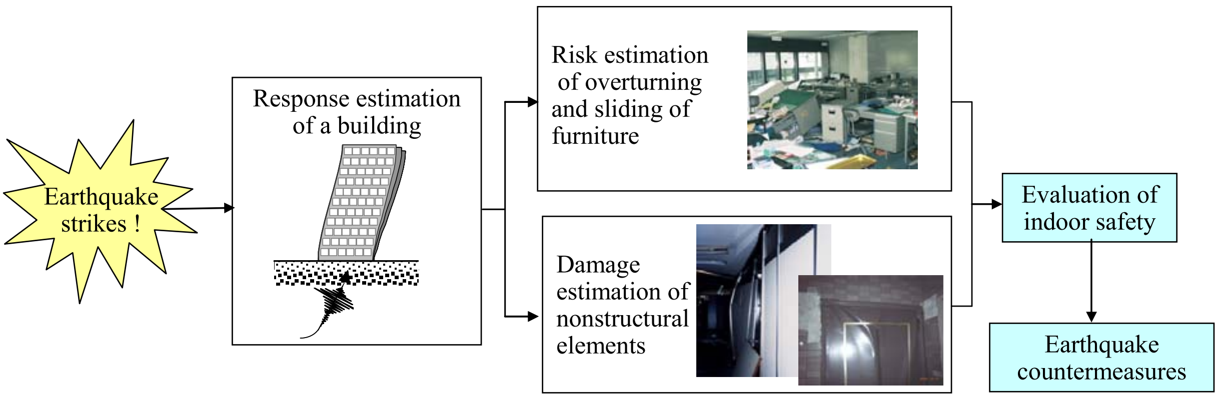



Figure 1 The flow of the indoor safety evaluation

The developed evaluation methodology consists of three main estimation components: (1) an approximate evaluation of the maximum responses of a building due to earthquake shaking, (2) estimation of risks of overturning and sliding of furniture, and (3) estimation of damage of nonstructural elements of a building. The paper introduces each of the three estimation methods.

## 2. RESPONSE ESTIMATION OF A BUILDING

Simple equations to estimate seismic responses of buildings have been developed by using only the story number and the classification of structure (RC/Steel) of the building and the *PGA* and *PGV* of the earthquake. Since a conventional response analysis requires an analytical model of a building and the time history record or the response spectrum of the earthquake, it is hard for non-engineers to obtain these data and carry out the proper simulation analyses. The developed equations can be used without expertise, and provide approximate maximum responses with reasonable accuracy for the estimation of the risks of overturning and sliding of furniture and the estimation of damage of nonstructural elements.

A large number of time-history response analyses have been carried out on standard buildings using multi-mass shear models whose parameters are shown in Table 1. 1,027 collected earthquake records were used for the analyses, the *PGA* of which are normalized to 100 cm/sec$^2$.

Table 1 Parameters of standard building models

| | RC building | Steel building |
|---|---|---|
| Story number : $N$ | $N$ = 5, 10, 15, 20, 25, 30, 40, 50 | |
| Natural period of 1st mode : $T$ | $T$ = 0.07$N$ | $T$ = 0.1$N$ |
| Floor mass | uniform distribution | |
| Story stiffness | trapezoidal distribution<br>stiffness ratio of 1st/top story=3.0 | |
| Damping factor of 1st mode : $h$ | $h$ = 0.03 | $h$ = 0.02 |
| Damping factors for higher modes | frequency proportional | |

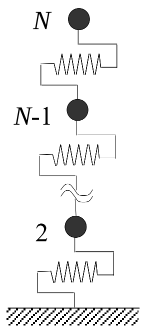



Figure 2 shows the average maximum responses, $R$ (maximum floor acceleration [*Acc*], velocity [*Vel*], or story displacement [*Dis*]) of a 20-story RC building for the same range of earthquake *PGA*/*PGV* values. The figure indicates that $R$ (=*Acc*, *Vel*, *Dis*) varies considerably with *PGA*/*PGV* even for the same *PGA* (=100cm/sec$^2$).

The story-wise distribution of $R$ (=*Acc*, *Vel*, *Dis*) can be simplified to a piecewise-linear shape represented by two straight lines as shown in Figure 3. $R^{H,M,L}$ , $R$ at the top [H], middle [M], and 1st floor [L], can be expressed by the following formula:

$$R^{H,M,L} = \frac{d}{a(PGA/PGV)^2 + b(PGA/PGV) + c} \cdot f(N) \cdot PGA \tag{2.1}$$

$$f(N) = \frac{g}{eN + f} \tag{2.2}$$

where $f(N)$ is a correction function for the story number $N$, and $a$, $b$, $c$, $d$, $e$, $f$ and $g$ are coefficients to be determined based on the results of response analyses such as that shown in Figure 4 which shows the relationships between *PGA*/*PGV* and $R^{H,M,}$ for a RC building with $N$=10, 30, 50 stories. Table 2 shows the coefficients for $R$ (=*Acc*, *Vel*, *Dis*) of RC and steel buildings.

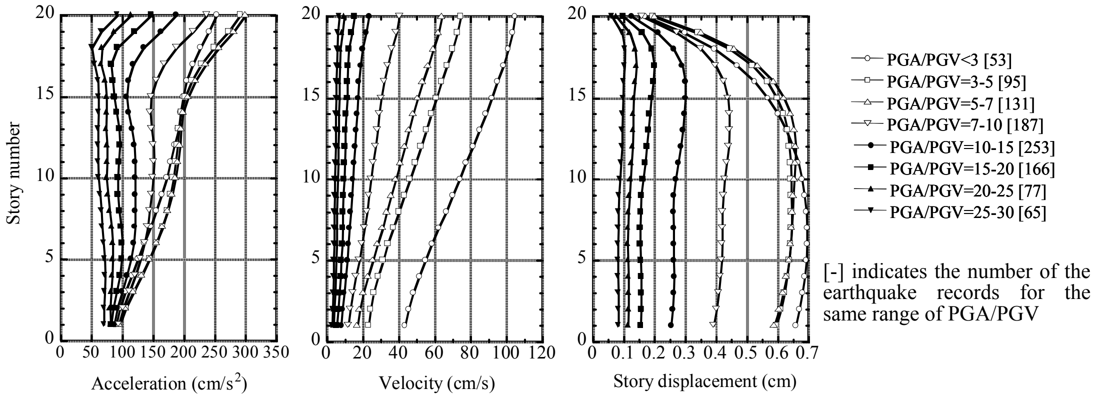



Figure 2 Average maximum responses of the 20-story RC building

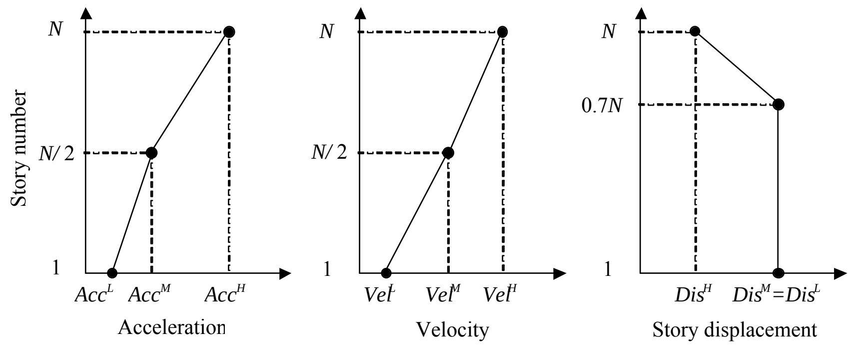



Figure 3 Simplified story-wise distributions of maximum responses

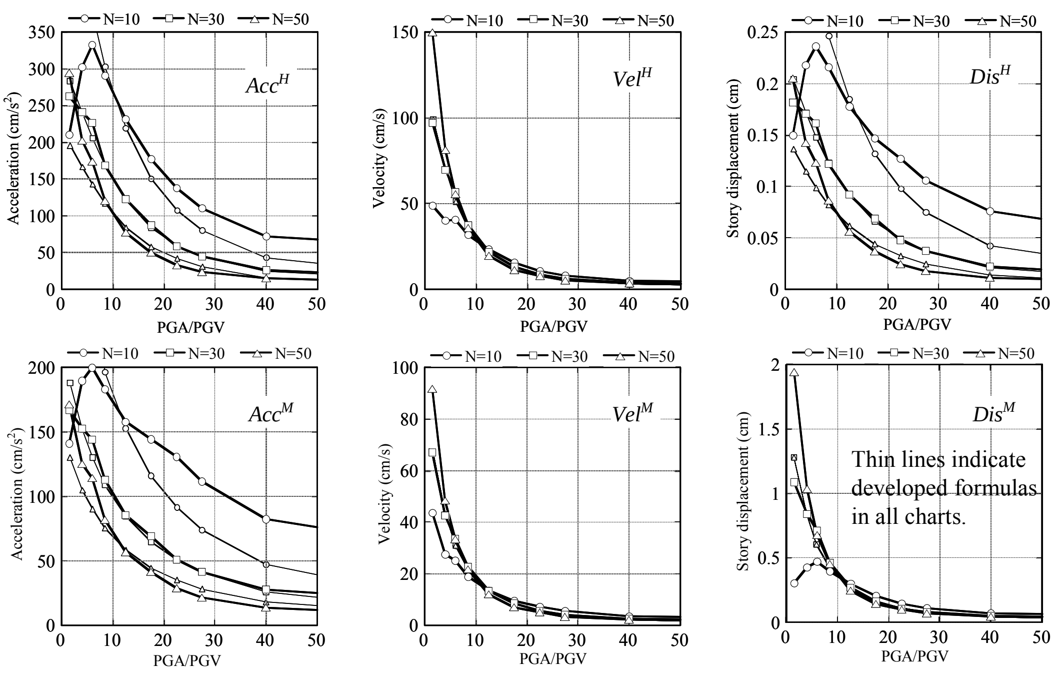



Figure 4 The relationships between $PGA/PGV$ and $R^{H,M}$ for a RC building with $N$=10, 30, 50

Table 2 Coefficients in Eqns.2.1 and 2.2 for RC and steel buildings

| | RC building | | | | | | | Steel building | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *a* | *b* | c | *d* | *e* | *f* | *g* | *a* | *b* | c | *d* | *e* | *f* | *g* |
| $Acc^H$ | 1 | 7 | 161 | 493 | 1 | 15 | 45 | 1 | 14 | 125 | 526 | 1 | 5 | 35 |
| $Acc^M$ | 1 | 47 | 478 | 1037 | 1 | 15 | 45 | 1 | 54 | 262 | 820 | 1 | 5 | 35 |
| $Acc^L$ | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| $Vel^H$ | 1 | 4 | 47 | 55 | 0 | 1 | 1 | 1 | 3 | 29 | 52 | 1 | 105 | 135 |
| $Vel^M$ | 1 | 9 | 48 | 43 | 0 | 1 | 1 | 1 | 2 | 30 | 32 | 1 | 105 | 135 |
| $Vel^L$ | 1 | 62 | 65 | 74 | 0 | 1 | 1 | 1 | 34 | 60 | 49 | 0 | 1 | 1 |
| $Dis^H$ | 1 | 13 | 223 | 0.5 | 1 | 10 | 40 | 1 | 14 | 124 | 0.7 | 1 | 5 | 35 |
| $Dis^M$ | 1 | 8 | 49 | 0.8 | 0 | 1 | 1 | 1 | 10 | 22 | 1.3 | 0 | 1 | 1 |
| $Dis^L$ | 1 | 8 | 49 | 0.8 | 0 | 1 | 1 | 1 | 10 | 22 | 1.3 | 0 | 1 | 1 |

## 3. RISK ESTIMATION OF OVERTURNING AND SLIDING OF FURNITURE

The risks of the overturning of furniture can be estimated by overturning ratio *R* based on (Kaneko, 2003) and Kaneko et al., 2004) as follows.

$$R = \begin{cases} \alpha \cdot \Phi((\ln Acc_f - \lambda_A)/\zeta_A) & ,F_f \le F_b \\ \alpha \cdot \Phi((\ln Vel_f - \lambda_V)/\zeta_V) & ,F_f > F_b \end{cases} \tag{3.1}$$

$$\lambda_A = \ln(\,(B/H)g \cdot (1+B/H)\,) \tag{3.2}$$

$$\lambda_V = \ln(\,10B/\sqrt{H} \cdot (1+B/H)^{2.5}\,) \tag{3.3}$$

where $Acc_f$ [cm/sec$^2$] is the maximum acceleration and $Vel_f$ [cm/sec] is the maximum velocity of floor response, $\Phi$ is the normal distribution function with mean value $\lambda_A$ or $\lambda_V$ and standard deviation $\zeta_A$ or $\zeta_V$ which is assumed to be 0.2 or 0.3 for an individual piece of furniture. $H$ [cm] and $B$ [cm] are the height and the depth of furniture, g is the acceleration of gravity, $F_f$ [Hz] is the equivalent frequency of floor, $F_b$ [Hz] is the boundary frequency of the furniture given by

$$F_f = Acc_f\,/\,(2\pi Vel_f) \tag{3.4}$$

$$F_b = 15.6/\sqrt{H} \cdot (1+B/H)^{-1.5} \tag{3.5}$$

In Eqn.3.1, $\alpha$ is the slide-resistant coefficient which ranges from 0 to 1 and is determined by considering the ratio $B/H$ and the friction coefficient between the floor and furniture. If the friction coefficient ranges from $\mu_1$ to $\mu_2$, $\alpha$ can be given as follows.

$$\alpha = \begin{cases} 0 & , \quad \mu_2 \le B/H \\ (\mu_2 - B/H)/(\mu_2 - \mu_1), & \mu_1 \le B/H < \mu_2 \\ 1 & , \quad B/H < \mu_1 \end{cases} \tag{3.6}$$

The risks of the sliding of furniture can be estimated by expected sliding distance $\Delta$ [cm] which is given by the product of the coefficient $(1-\alpha)$ and the sliding distance $\delta$ [cm] estimated by the following formula (Kaneko et al., 1999).

$$\Delta = (1-\alpha) \cdot \delta \tag{3.7}$$

$$\delta = \begin{cases} 0.02 \cdot \mu_1^{-0.3} \cdot F_f^{-0.5} \cdot (Vel_f - \mu_1 g/(2\pi F_f))^{1.56} & ,Vel_f > \mu_1 g/(2\pi F_f) \\ 0 & ,Vel_f \le \mu_1 g/(2\pi F_f) \end{cases} \tag{3.8}$$

Figure 5 shows the examples of the relationships between floor responses and overturning ratio $R$ or expected sliding distance $\Delta$ of the furniture shown in Table 3. The risks of overturning and sliding of furniture are classified into four levels as shown in Table 4.

Table 3 Parameters of furniture

| Furniture | $H$ [cm] | $B$ [cm] | $B/H$ | $\lambda_A$ | $\lambda_V$ | $\zeta_A$ | $\zeta_V$ | Floor condition | $\mu_1$ | $\mu_2$ | α |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bookshelf-1 | 180 | 45 | 0.25 | 5.99 | 4.30 | 0.2 | 0.3 | slippery | 0.15 | 0.4 | 0.6 |
| Bookshelf-2 | | | | | | | | moderate | 0.2 | 0.7 | 0.9 |
| Bookshelf-3 | | | | | | | | rough | 0.6 | 1.0 | 1.0 |
| Roller cabinet | 100 | 50 | 0.50 | 6.60 | 4.93 | 0.2 | 0.3 | — | 0.05 | 0.2 | 0.0 |

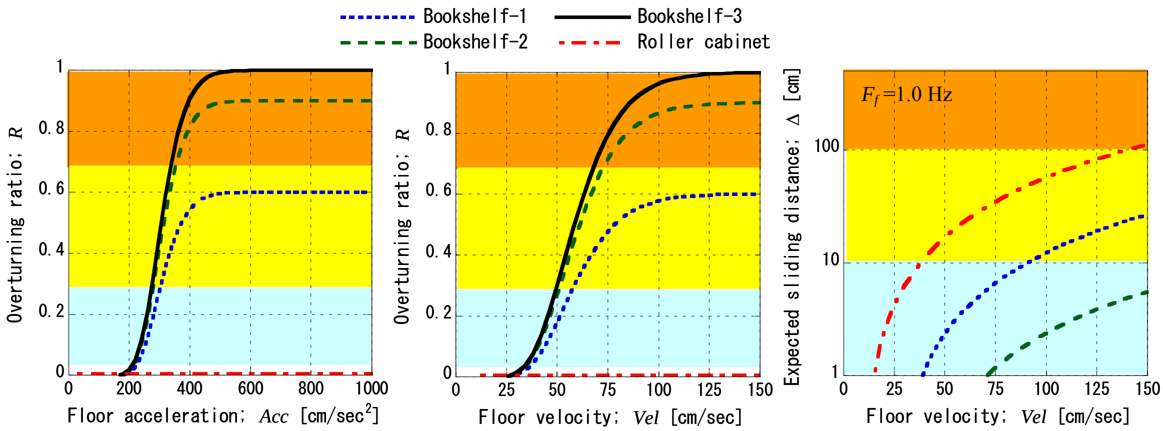



Figure 5 The relationships between floor responses and overturning ratios or sliding distance of furniture

Table 4 Risk levels of overturning and sliding of furniture

| Risk level | 0 (Low) | 1 (Medium) | 2 (High) | 3 (Very High) |
|---|---|---|---|---|
| Overturning risk | $R < 0.03$ | $0.03 \leqq R < 0.3$ | $0.3 \leqq R < 0.7$ | $0.7 \leqq R$ |
| Sliding risk | $\Delta < 1$cm | 1cm$\leqq \Delta <$ 10cm | 10cm$\leqq \Delta <$ 100cm | 100cm$\leqq \Delta$ |

N.B. $R$ : Overturing ratio, $\Delta$: Expected sliding distance

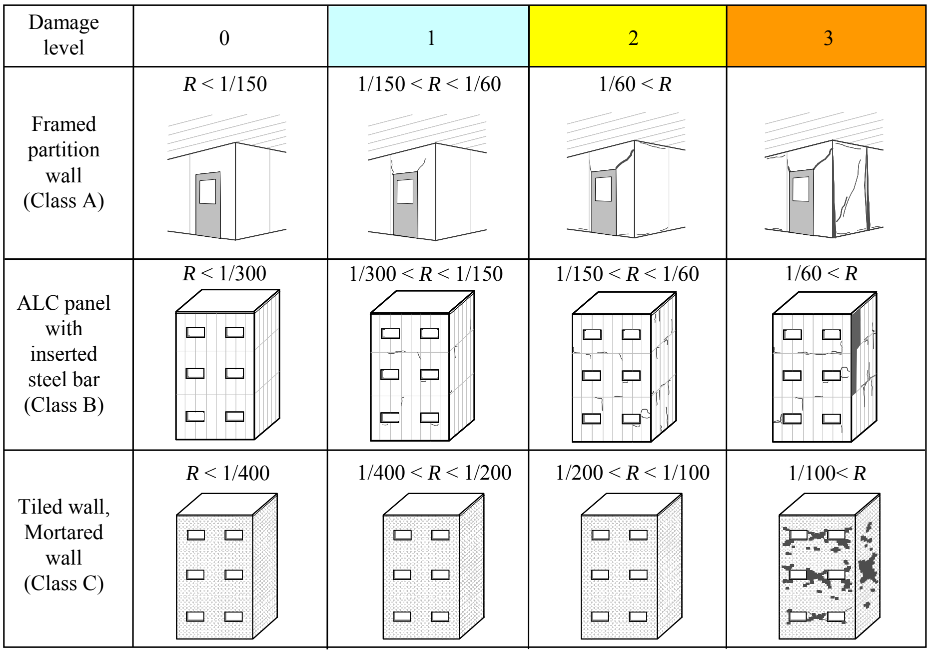
## 4. DAMAGE ESTIMATION OF NONSTRUCTURAL ELEMENTS

Earthquake-resistant capabilities of nonstructural elements are categorized into four classes based on the various published documents of earthquake simulator tests as shown in Table 5. In Table 5, damage of nonstructural elements such as outer and inner walls in classes *A*, *B* and *C* is assumed to be caused by the story drift angle, while damage of ceiling elements in class *D* is assumed to be caused by the story drift angle and response acceleration. Figure 6 shows examples of relationships between the response and damage level of nonstructural elements in classes *A*, *B* and *C* where damage levels are classified into four levels (Kaneko et al., 2005).

Table 5 Classification of earthquake-resistant capabilities for nonstructural elements

| Class | Seismic resistant capability | Examples of nonstructural elements | Damage is caused by |
|---|---|---|---|
| A | High | ALC panel of rocking type, curtain wall, framed partition wall, window glass in general | story drift angle |
| B | Medium | ALC panel with inserted steel bar, direct-adhered partition wall | |
| C | Low | tiled wall on RC surface, mortared wall | |
| D | – | ceiling | story drift angle and response acc. |

N.B. ALC=*Autoclaved Lightweight aerated Concrete*




N.B. *R* : story drift angle

Figure 6 Relationships between story drift angle and damage level of nonstructural elements

## 5. VERIFICATION OF PROPOSED EVALUATION METHODOLOGY

Proposed evaluation methodologies are verified by comparing the estimated results with the actual damage for earthquakes. Figure 7 shows the estimated overturning ratios of furniture in a 15-story RC building in comparison with the actual overturning ratios surveyed by questionnaires after the 2005 West off Fukuoka earthquake (March 20, 2005). Maximum floor responses, *Acc* and *Vel* of every story are estimated by the developed response estimation formulas with the observed *PGA* and *PGV* at the nearest observation point. The overturning ratios of furniture are estimated for a group of average tall furniture in a residence. The estimated overturning ratios agree well with the results of questionnaire survey, and both results show that almost no furniture turn in the lower floors, but half of the furniture or a part of the furniture turns in the upper floors.

Figure 8 shows the estimated damage levels of three nonstructural elements in three chosen cities along with the results of field surveys after the 2004 Mid Niigata prefecture earthquake (October 26, 2004). The damage levels are evaluated based on the estimated maximum story drift angles of a three-story steel building using the observed *PGA* and *PGV* in each of the chosen cities in Niigata prefecture and the fragility characteristics of the elements specified in Figure 6. Figure 8 shows the estimated damage level agree well with the actual observed damage.

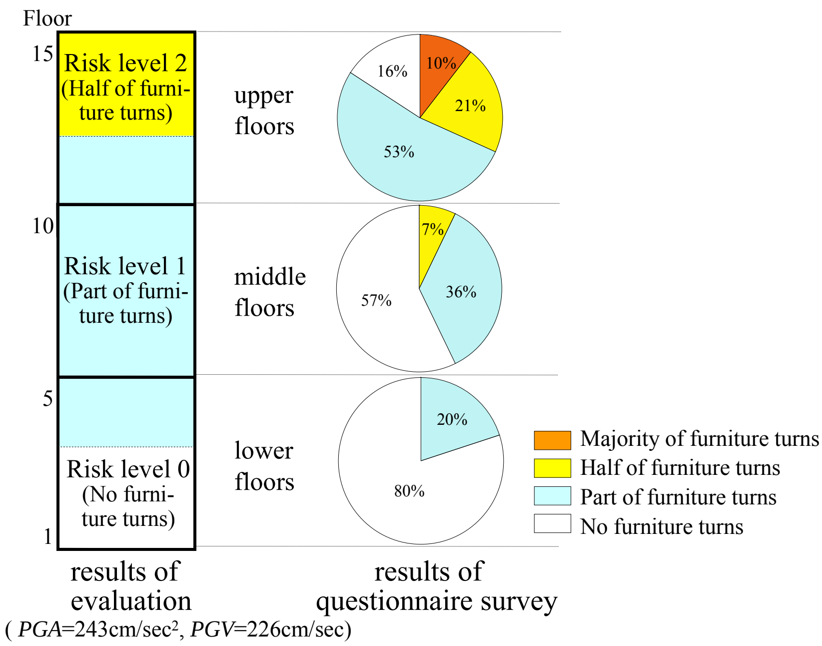



Figure 7 Estimated overturning ratios of furniture in a 15-story RC building in comparison with the actual overturning ratios surveyed by questionnaires after the 2005 West off Fukuoka earthquake (March 20, 2005)

| | Nagaoka City (PGA=418cm/s$^2$, PGV=32cm/s) | | Tokamachi City (PGA=1283cm/s$^2$, PGV=52cm/s) | | Ojiya City (PGA=838cm/s$^2$, PGV=77cm/s) | |
|---|---|---|---|---|---|---|
| | Estimated damage level | Results of field survey | Estimated damage level | Results of field survey | Estimated damage level | Results of field survey |
| Window glass (Class A) | 0 | Nil or minimal damage | 1 | | 1 | Dmage in about 40% of buildings |
| ALC panel (Class B) | 1 | No damage or minor damage  | 2 | Mostly minor damage | 2 | Major damage or fallen off  |
| Tiled wall, Mortared wall (Class C) | 2 | No damage or minor damage  | 2 | Major cracks or partially fallen off | 3 | Major cracks or fallen off  |

Figure 8 Estimated damage levels of three nonstructural elements in three chosen cities along with the results of field surveys after the 2004 Mid Niigata prefecture earthquake (October 26, 2004)

## 6. CONCLUSIONS

A simple and convenient methodology to evaluate indoor safety for buildings subjected to earthquake shakings has been developed. The methodology consists of three main estimation components: (1) an approximate evaluation of the maximum responses of a building due to earthquake shaking, (2) estimation of risks of overturning and sliding of furniture, and (3) estimation of damage of nonstructural elements of a building.

The developed response evaluation formulas can estimate the maximum acceleration, velocity, and displacement of each story of a building by using only the story number and the classification of structure (RC/Steel) of the building and the *PGA* and *PGV* of the earthquake. Based upon the estimated maximum responses, the risks of overturning and sliding of specified pieces of furniture and the damage of specified nonstructural elements can be estimated and classified into four levels. The methodology has been verified by comparing the estimated results with the actual observed earthquake damage in the 2005 West Off Fukuoka Earthquake and the 2004 Mid Niigata Prefecture Earthquake.

The developed methodology can make it possible for non-experts to evaluate seismic indoor damage easily and to determine the order of priority for earthquake countermeasures of buildings.

## ACKNOWLEDGEMENTS

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