EARTHQUAKE INSURANCE RATES FOR RC HIGH-RISE COMMERCIAL BUILDINGS IN TAIWAN

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SUMMARY

Many insurance companies in California, U.S.A., paid tremendous monetary compensation after the Northridge earthquake. The purpose of this paper is to propose the rational proper earthquake insurance rates for RC high-rise commercial buildings in Taiwan.

Theoretical simulation and statistics are mostly used in estimate the expected earthquake loss and earthquake insurance. Because the lack of the field earthquake loss records in Taiwan, a method by using dynamic nonlinear incremental spectrum analysis [Liu, 1998] which combines seismic damage assessment and earthquake loss evaluation is discussed in this paper. Dynamic nonlinear incremental spectrum method is used to calculate the structural responses when ground acceleration shakes from zero and increases gradually up to crack, yield and total collapse of the building. During each loading step, member stiffness, damping ratio, P-Δ effect and plastic hinges are changed. At the meantime, according to the damage mode, total crack length is estimated for each damaged member. Before ultimate state, repair costs for epoxy injection are calculated according to the crack length of each member. After ultimate state, repair costs for steel or carbon fiber jacketing are determined to recover the plastic zone of each member.

Total repair cost for each building is taken as a reasonable quantitative index of the earthquake loss for that category of buildings. The earthquake insurance fee is calculated by the integration over the earthquake loss and the annual exceedance probabilities. Seismic damage assessment of RC building is proposed as reference for earthquake insurance rate for similar category of buildings. In this paper, the earthquake loss and earthquake insurance of a RC high-rise commercial building in Taiwan is proposed. A complusory earthquake insurance for public buildings and an optional earthquake insurance for private buildings are also suggested in this paper.

INTRODUCTION

Before ultimate state, cracking is important for damage assessment and stiffness degradation of RC members during loading stages. The most popular repaired method of cracked RC members is epoxy injection. The repair cost is counted by the cracking length. So the repair cost is calculated by the cracking number and the cracking length of each member. After ultimate state, plastic hinges by flexure and diagonal shear cracks are repaired by steel or carbon fiber jacketing. The unit cost is based on the market price in Taiwan.

Estimating formulas of flexural and shear crack number are introduced as follows:

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Crack number and crack length by flexure:

The cracking number by flexure of each member is proposed by the formula of Oh and Kang [Oh and Kang, 1987]

$$\frac{\mathbf{s}}{\mathbf{D_b}} = \mathbf{c}_0 + \frac{0.236\times10^{-6}}{\boldsymbol{\varepsilon}_{sa}{}^2} \qquad , \qquad \mathbf{c}_0 = 25.7\left(\frac{\mathbf{t_b}}{\mathbf{c}_1}\right)^{4.5} + 1.66\left(\frac{\mathbf{A}_1}{\mathbf{A}_{s1}}\right)^{1/3}$$
(1)

where $\mathbf{s}$ is the average cracking space of one member, $\mathbf{D_b}$ is the diameter of the reinforcing bar, $\boldsymbol{\varepsilon}_{sa}$ [Sheu, 1976] is the average strain of the longitudinal steel, $\mathbf{c}_0$ indicates the minimum value of cracking spacing, $\mathbf{t_b}$ is the bottom cover measured from the center of lowest bar, $\mathbf{c}_1$ is the distance from the extreme tension fiber to the neutral axis, $\mathbf{A}_1$ is the average effective area of concrete around each reinforcing bars and $\mathbf{A}_{s1}$ is the area of each reinforcing bar. Equation (1) indicates the flexure crack spacing is diminished as the strain grows. See Figure 1.

Crack number by flexure under monotonic load

Figure 2 indicates the relationship of moment and flexure crack spacing at one constant axial forcing. When the moment increases gradually, the crack spacing decreases quickly. And the moment increases continuously, the crack spacing comes to a constant gradually. Theoretically, the average crack number is the length of member over average crack spacing, but the moment is not constant at the member like Figure 3. For solving this problem, the member was separated by plus moment and minus moment into two sections $\mathbf{L}_1$ and $\mathbf{L}_2$. For example, as Figure 3, the length of the cracking range on length $\mathbf{L}_1$ of the member is $\mathbf{L}_1(\mathbf{M}_1 - \mathbf{M}_{cr})/\mathbf{M}_1$, $\mathbf{M}_1$ means the maximum moment at length $\mathbf{L}_1$ and $\mathbf{M}_{cr}$ means the cracking moment. $\mathbf{s}_1$ represented the average crack spacing on length $\mathbf{L}_1$ of the member and $\mathbf{s}_2$ represented the average crack spacing on length $\mathbf{L}_2$ of the same member. Therefore, $\mathbf{s}_1$ will be calculated as $(\mathbf{Area})_{s1}/(\mathbf{M}_1 - \mathbf{M}_{cr})$ and the average crack number $\mathbf{n}_1$ at length $\mathbf{L}_1$ is $\frac{\mathbf{L}_1}{\mathbf{s}_1}\cdot\frac{\mathbf{M}_1 - \mathbf{M}_{cr}}{\mathbf{M}_1}$. The average crack number $\mathbf{n}_2$ on length $\mathbf{L}_2$ is calculated by the same method. The total crack number of this member is $\mathbf{n} = \mathbf{n}_1 + \mathbf{n}_2$.

Crack number by flexure under cyclic load

The stress under cyclic load could be several conditions as Figure 4. Each member was separated as the method described previously. If the moment on the separated section of the member was both plus or minor, as Figure 4(a), the crack number is calculated based on the envelope of the moment. If the moment on the separated section of the member is out of phase, as Figure 4(b), the crack number is the sum calculated respectively from the plus moment and minor moment.

Crack number by flexure under biaxial load

It is proposed the location of cracking may be overlapped for 50% probability under biaxial load. It is calculated the crack number $\mathbf{n}_x$ of axial x and the crack number $\mathbf{n}_y$ of axial y independently. The final crack number $\mathbf{N}_{xy}$ is as

$$\mathbf{N}_{xy} = \frac{(\mathbf{n}_x + \mathbf{n}_y)_{max} + (\mathbf{n}_x + \mathbf{n}_y)}{2} \qquad (2)$$

$\mathbf{l}_c$ represented a crack length by flexure which combines the width $\mathbf{b}$ of the section of the member and two times of the distance from the extreme tension fiber to the neutral axis, as Figure 5.

Crack number and crack length by shear:

According to Bazant [Bazant and Oh, 1983], it indicated that the location of the crack of the member is happened at the intersection of the bars (see Figure 6). The crack spacing $\mathbf{s}$ should be the times of the distance of the joint of bars, as $\mathbf{s} = \mathbf{ma}/\sqrt{2}$, $\mathbf{m} = 1,2,3...$. So the minimum crack spacing $\mathbf{s}_{min}$ of the member will be $\mathbf{a}/\sqrt{2}$. In this paper, the average crack spacing $\mathbf{s}$ at the ultimate state was 1.5 times of $\mathbf{s}_{min}$, as

$$\mathbf{s} = 1.5 \cdot \mathbf{a}/\sqrt{2} \approx 1.06\mathbf{a} \tag{3}$$

Crack number and crack length by shear for RC walls

According to the test data of Hwang [Hwang, 1989] and Yang [Yang, 1991], the crack number $\mathbf{N_s}$ at shear $\mathbf{V}(\mathbf{V} > \mathbf{V_c})$ can be found from the following equation (see Figure 7)

$$\mathbf{N_s} = \mathbf{N_{su}}\left[-0.7\left(\frac{\mathbf{V}}{\mathbf{V_u}}\right)^2 + 2\left(\frac{\mathbf{V}}{\mathbf{V_u}}\right) - 0.262\right] \tag{4}$$

$\mathbf{N_{su}}$ is the predicted shear crack number at ultimate state, $\mathbf{V_c}$ is the crack shear and $\mathbf{V_u}$ is the ultimate shear.

This paper assumed every crack length is equal to the average crack length $\mathbf{l_w}$ of 45 degree. The $\mathbf{l_w}$ is as:

$$\mathbf{l_w} = \sqrt{2} \cdot \mathbf{h} \cdot \mathbf{w}/(\mathbf{h} + \mathbf{w}) \tag{5}$$

$\mathbf{h}$ is the height of the wall and $\mathbf{w}$ is the width of the wall.

Crack number and crack length by shear for columns and beams

Using the same method like walls to calculate the shear crack number and length, according to the test data of Sheu [Sheu, 1992] and Suen [Suen, 1993], the crack number $\mathbf{N_{sc}}$ at shear $\mathbf{V}(\mathbf{V} > \mathbf{V_c})$ can be found from the following equation (see Figure 8)

$$\mathbf{N_{sc}} = \mathbf{N_{su}}\left[-0.5\left(\frac{\mathbf{V}}{\mathbf{V_u}} \cdot \frac{\mathbf{M}}{\mathbf{M_u}}\right)^2 + 1.6\left(\frac{\mathbf{V}}{\mathbf{V_u}} \cdot \frac{\mathbf{M}}{\mathbf{M_u}}\right) - 0.176\right]$$

(6)

The factors that effected the crack number on columns and beams are $(\frac{\mathbf{V}}{\mathbf{V_u}}) \cdot (\frac{\mathbf{M}}{\mathbf{M_u}})$

This paper assumed the crack range at crack just happened ($\mathbf{V} = \mathbf{V_c}$) is 1/4 times of the depth $\mathbf{h}$ of the section. It means the crack length at $\mathbf{V} = \mathbf{V_c}$ is $\sqrt{2}\mathbf{h}/4$ because of the crack angle is 45 degree. At the ultimate state ($\mathbf{V} = \mathbf{V_u}$), the crack range was included all the depth of the section. It means the crack length at $\mathbf{V} = \mathbf{V_u}$ is $\sqrt{2} \cdot \mathbf{h}$. If shear $\mathbf{V}$ was between $\mathbf{V_c}$ and $\mathbf{V_u}$, the crack length would be proportional to the shear loading.

EVALUATION OF REPAIR COST

From the previous section, the seismic damage situation could be found. The type of damage could be subdividen into flexure damage, shear damage and axial force damage. Therefore, the different type of seismic damage could be apply its correspondent repaired method. Before ultimate state, the repair cost only depended on the cracks. After ultimate state, if plastic hinges were happened at columns or beams because of the flexure damage, repair cost must be evaluated by choosing the steel or carbon fiber covered on the plastic hinge zone. If the damage was caused by shear happened at columns or beams, the retrofitted method is the same as the one on flexure damage. If the damage was happened on walls, a better method is to dismantle the wall and rebuild a new one. Table 1 is the relationship between repair cost and repaired method in Taiwan.

EVALUATION OF EARTHQUAKE INSURANCE RATE

Repair cost is taken as a reasonable quantitative index of the earthquake loss. The expected annual loss (AEL) is calculated by the integration over the earthquake loss and its correspondent annual exceedance probabilities, as Figure 9. In insurance, the concept of AEL is based on the spirit of the pure premium, as

pure premium = (the value of loss × the probability of loss) ×(the value of the property)
(7)

In this paper, the value of loss was equal to the repair cost of a building structure, the loss of probability was equal to the annual exceedance probabilities, and the value of the property was equal to the dismantled and rebuilt cost that would be the recompense for insuring. Therefore, AEL is the pure premium in insurance, the expected annual loss rate (**AELR**) is the pure premium rate.

According to the Department of the Treasury in Taiwan [Insurance Development Center, 1996], the additional premium rate is 35.5% highest of the premium rate in earthquake insurance, so the pure premium rate is 64.5% least of the premium rate . The premium rate is including the additional premium rate and the pure premium rate. Therefore, the premium rate is 1.55 times highest of the pure premium rate, as

Premium rate = 1.55 ×pure premium rate
(8)

ANALYSIS OF HIGH-RISE COMMERCIAL BUILDING

A 20-story RC commercial building is built on seismic zone 1A, 2 , 3 based on the Building Code of in Taiwan [The Ministry of Interior, 1996], its plans, the elevation and the perspective are shown in Figure 10. The repair cost at every peak ground acceleration (**PGA**) could be evaluated by using the previous damage assessment method under medium soil spectra [The The Ministry of Interior, 1996] (see Figure 11). Figure 12,13,14 was shown the relationship between the roof displacement, the base sear, the PGA and the repair cost of different damage type. The repair cost caused by the flexure damage on columns and beams was 75%, caused by RC walls was 20% and caused by shear on columns and beams was only 5% of total repair cost was found in the three seismic assessment figures.

The cost of the building dismantled and rebuilt (**RPC**) was evaluated by the value provided from the construction in Taiwan. $\mathbf{RC}_i$ represents the repair cost at PGA = i. The earthquake loss rate at PGA = i could be evaluated as $\mathbf{LR}_i(\mathbf{RC}_i/\mathbf{RPC})$, shown in Figure 15. The repair cost was zero at PGA equal to zero because the cracking width was very small under vertical loads (dead load and live load) which could be ignored. The repair cost was equal to the RPC when the building collapses. It is shown in Figure 15 that the repair cost was almost proportional to the PGA before the building collapses. Under the same PGA, the repair costs are higher in low-risk regions. This figure is very important information for evaluating the earthquake insurance rate.

According to the repair cost in different PGA combined with the annual exceedance probabilities of the building region, the pure premium will be evaluated as shown in Figure 16. Under the same PGA, the earthquake insurance rate are higher in high-risk regions due to earthquake frequency. Finally, the premium can be defined as times of the pure premium.

CONCLUSIONS

1. Repair cost of RC elements: before ultimate state, repair costs are calculated according to the crack length. Flexural and shear cracks are calculated respectively from semi-empirical formula. After ultimate, repair costs are based on damage modes.
2. Before collapse of high rise buildings, the earthquake loss is almost proportional to PGA and near 75% of the earthquake loss is due to the flexural damage of beams and columns.
3. Under the same PGA, repair costs are higher in low-risk zones, but the earthquake insurance rates are higher in high-risk zones due to the earthquake frequency and magnitude.

4. The earthquake insurance rates are proposed for many levels based on the annual exceedance probabilities of 10%, 5%, 2%, 1%, 0.2% for insurants to choose. And the earthquake insurance rates are between 0.2% and 1% of the annual exceedance probabilities.
5. A complusory earthquake insurance rate for public buildings was based on the annual exceedance probabilities of 0.2%. The optional earthquake insurance rates for private buildings for different annual exceedance probabilities are also suggested by this paper.

REFERENCES

1. Bazant, Z. P. and Oh, B. H. (1983), “Spacing of Cracks in Reinforced Concrete”, *Journal of Structural Engineering, ASCE*, Sept., 2066-2085pp.
2. Hwang, G. S. (1989), “The Chang of Stiffness and Damage Assessment for Two-Story Reinforced Concrete Shearwalls Subject to Reversed Cyclic Horizontal Loadings”, Master Thesis, Dept. of Architecture, Univ. of Cheng Kung, June, Tainan, Taiwan, R.O.C.
3. Insurance Development Center (1996), “Commentary of Insurance Law”, Taiwan, R.O.C., 577-578pp.
4. Liu, Pai-Mei (1998), “Earthquake Insurance Rates for Medium and High-Rise RC Commercial Building Structures before and after Fire Damages”, Ph. D. Dissertation Dept. of Architecture, Univ. of Cheng Kung, July, Tainan, Taiwan, R.O.C., 8-23pp.
5. Oh, B. H. and Kang Y. J. (1987), “New Formulas for Maximum Crack Width and Crack Spacing in Reinforced Concrete Flexural Members”, *ACI Structure Journal*,Mar./Apr., 103-112pp.
6. Sheu, Maw-Shyong (1976), “A Grid Model for Prediction of the Monotonic and Hysteretic Behavior of Reinforced Concrete Slab-Column Connections Transferring Moments”, Ph. D. Dissertation Civil Engrg. Dept. Univ. of Wish., Seattle, Wash., U.S.A., 15-22pp.
7. Sheu, R. N. (1992), “Experimental Study of Improving Reinforced Concrete Short Columns”, Master Thesis, Dept. of Architecture, Univ. of Cheng Kung, June, Tainan, Taiwan, R.O.C.
8. Suen, Y. J. (1993), “Improvement of Reinforced Concrete Short Columns”, Master Thesis, Dept. of Architecture, Univ. of Cheng Kung, June, Tainan, Taiwan, R.O.C.
9. The Ministry of Interior (1996), “Building Design Code”, Taiwan, R.O.C.
10. Yang, C. F. (1991), “Aseismic Behaviours of Reinforced Concrete Shear Walls With Openings and Boundary Columns”, Master Thesis, Dept. of Architecture, Univ. of Cheng Kung, June, Tainan, Taiwan, R.O.C.

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Table 1: Unit cost for repairing in Taiwan

	Item	**Unit**	**Unit Cost(NT$)**
REPAIRING	Epoxy injection	m	1000
	Steel jacketing and painting	m^2	9000
	Carbon fiber jacketing and painting	m^2	4500
Recasting	Dismantle of concrete	m^3	1400~1700
	Dismantle of brick	m^3	700~850
	Steel	t	14000~15000
	Template	m^2	400~500
	Concrete	m^3	1850~2000
	Brick	piece	4
	1/2B Brick laying	m^2	750
	1B Brick laying	m^2	1500
	1:3 Mortor Brushing	m^2	300
	Painting	m^2	110
Others	Prestressing	strut	5000
	Scaffold	m^2	180
	Transportation	m^3	500

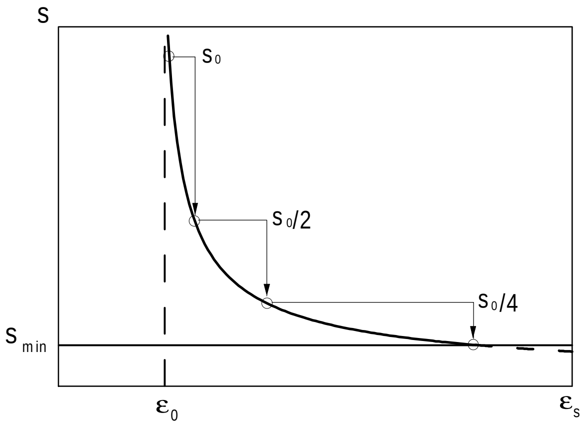

Figure 1 Relationship between crack spacing and strain of rebars

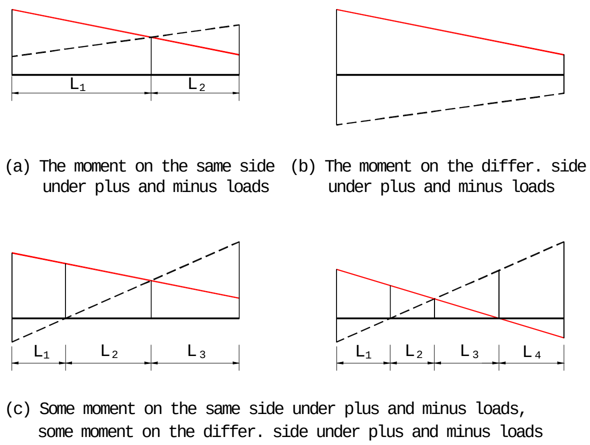

Figure 4 Moment combination under plus and minus loads

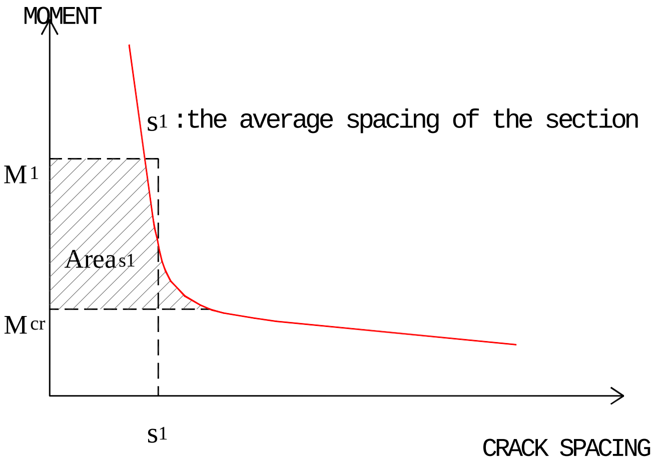

Figure 2 Relationship between Moment and crack spacing

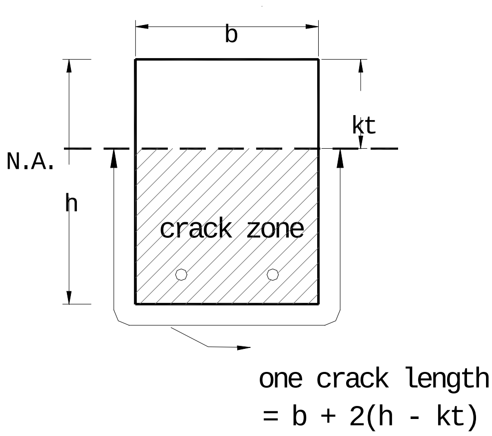

Figure 5 Flexural crack spacing

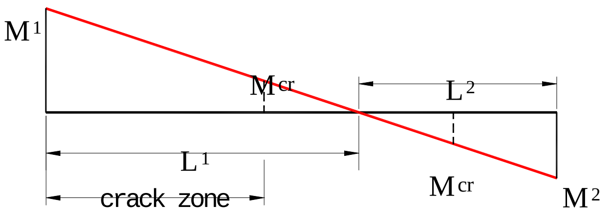

Figure 3 The moment variation of the member

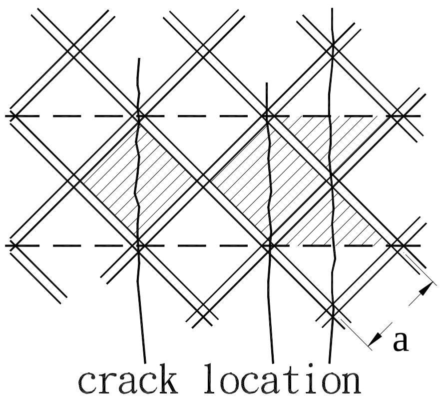

Figure 6 Parallel cracks skew to bars

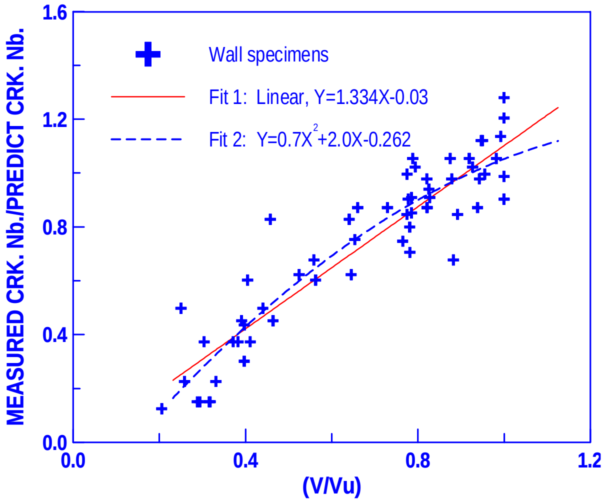

Figure 7 Relationship between crack of walls and loads

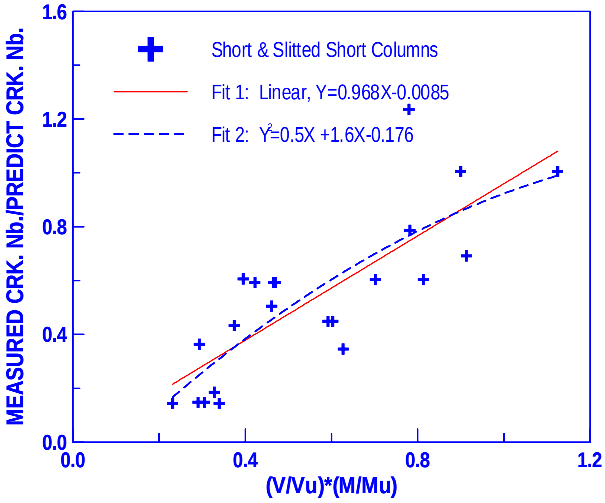

Figure 8 Relationship between crack of columns and loads

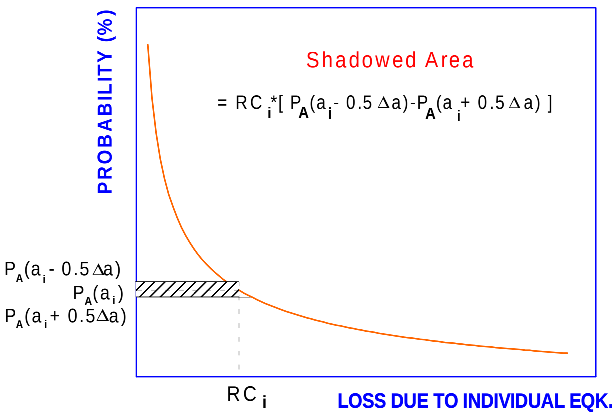

Figure 9 Relationship between probability and earthquake loss

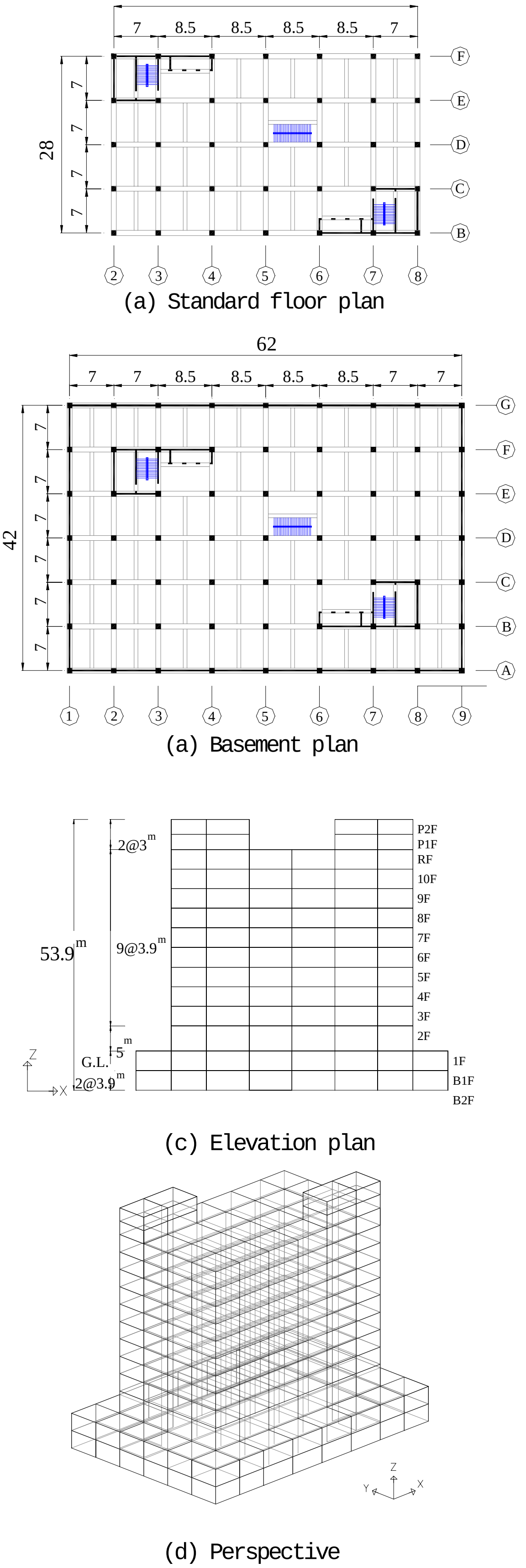

Figure 10 High-rise Commercial Building Structure

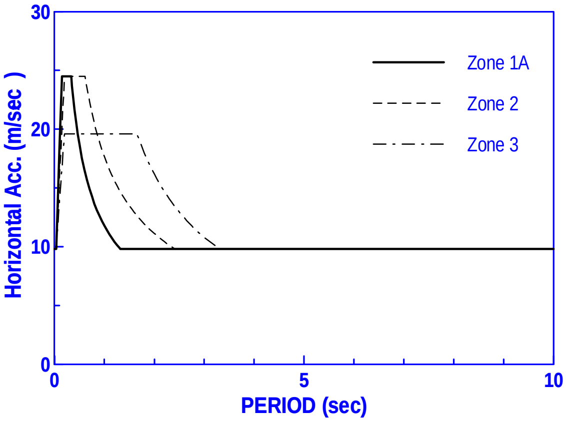

Figure 11 Horizontal sprctrum in Taiwan

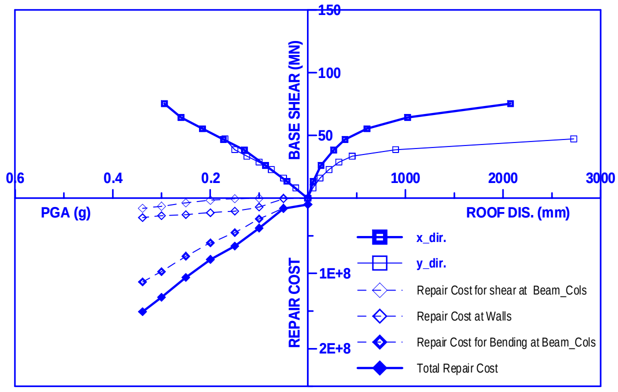

Figure 13 Vulnerability assessment and repair cost diagram at Zone 3

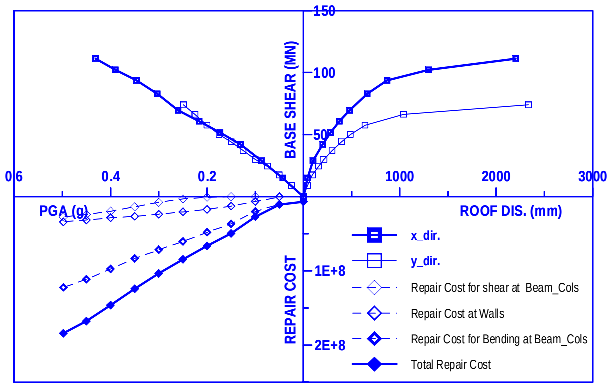

Figure 12 Vulnerability assessment and repair cost diagram at Zone 1A

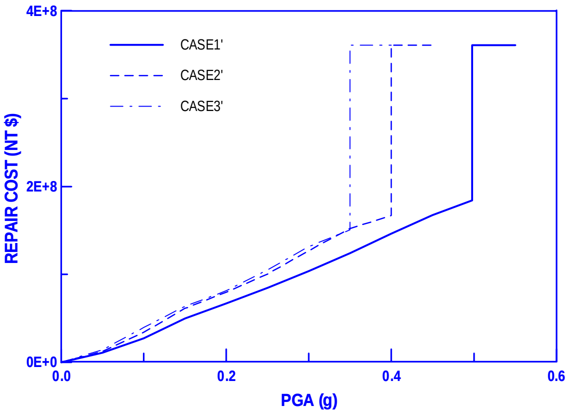

Figure 15 Repair cpst of commercial building structure

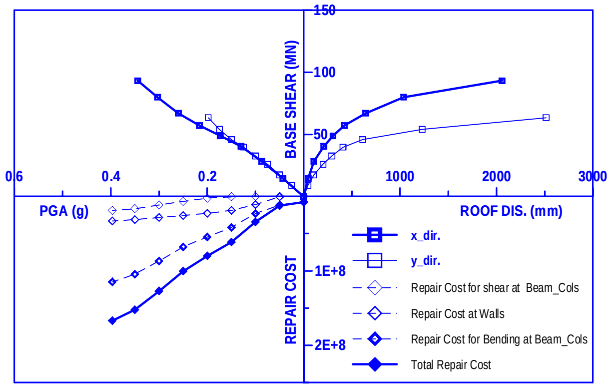

Figure 13 Vulnerability assessment and repair cost diagram at Zone 2

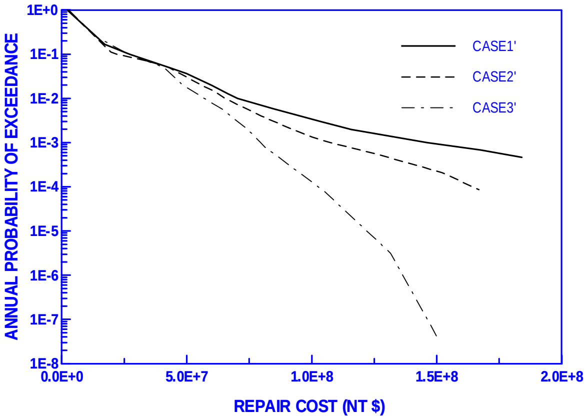

Figure 16 Relationship between repair cost and probability