A STUDY ON SEISMIC REPAIR COST OF R/C BUILDING STRUCTURES USING A GEOMETRICAL DAMAGE ESTIMATION MODEL OF R/C MEMBERS

NORIYUKI TAKAHASHI
Institute of Industrial Science, The University of Tokyo, Japan
ntaka@iis.u-tokyo.ac.jp
YOSHIAKI NAKANO
Institute of Industrial Science, The University of Tokyo, Japan
iisnak@iis.u-tokyo.ac.jp

ABSTRACT

To evaluate visible damage of reinforced concrete (R/C) members such as crack width and length, cyclic load tests of one third scaled R/C members were carried out. Based on the tests, a geometrical damage estimation model is proposed to quantify each crack width and corresponding length. The model consists primarily of a geometrical condition for the relationship between the sum of crack widths and drift ratio and a probabilistic model between crack widths and lengths.

Applying the proposed model to seismic response analyses of R/C building structures modeled as fish-bone shaped frames, the damage and repairing process, as well as life cycle economic loss were simulated. Life cycle economic loss was defined here as the repairing cost for maintenance of the functionality of a building through its life length. As a result, it is implied that the case of main damages on beams will suffer more life cycle economic losses than the case of main damages on columns because of the extent of damaged area and the construction cost of falsework.

1. INTORODUCTION

Loss estimation of a building due to earthquake events in its life length is important to facilitate the decision making of the building owner to choose the reasonable seismic performance. In this paper, life cycle economic loss defined as the repairing cost of a building structure through its life length was simulated using a new damage estimation model which is partially based on cyclic load tests of one third scaled R/C members.

2. EXPERIMENTAL PROGRAM

2.1 Test specimens, setup and instrumentation

Two R/C beam specimens proportioned to approximately 1/3 of full scale were tested under cyclic loading. The design parameters and corresponding values are given in Table 1. The dimension for the test specimens and test setup are shown in Figure 1. To obtain the propagation of crack width and length corresponding to attained and present drift ratio, the cyclic displacement pattern shown in Figure 2 was operated. Crack widths were measured at the points shown in Figure 3 by crack gauges. Crack lengths were measured by image processing of sketched and scanned cracking pattern.

Table 1: Description of Test Specimens

Specimen	Concrete Strength (N/mm^2)	Rebar - Tensile reinforcement ratio to the section	Yield strength of rebar (N/mm^2)	Lateral reinforcement - Lateral reinforcement ratio to the section	Yield strength of lateral reinforcement (N/mm^2)	Failure mode
F-1	30	8-D13 - 0.0121	295	D4@60 - 0.0022	295	Flexure
S-1	18		785		295	Shear

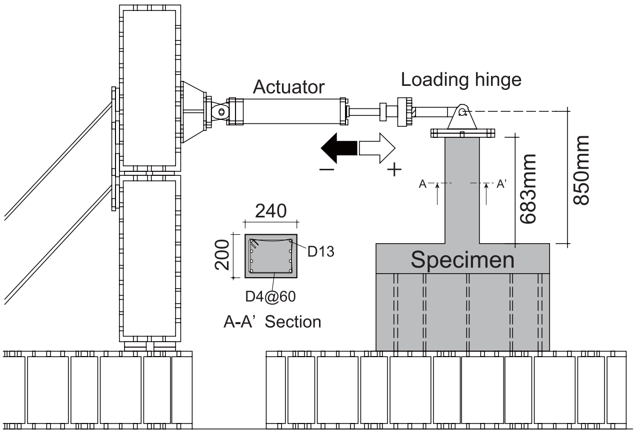


Figure 1: Dimension of Beam Specimen and Test Setup

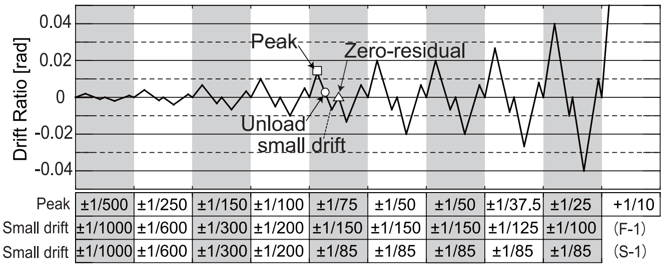


Figure 2. Cyclic Displacement Pattern

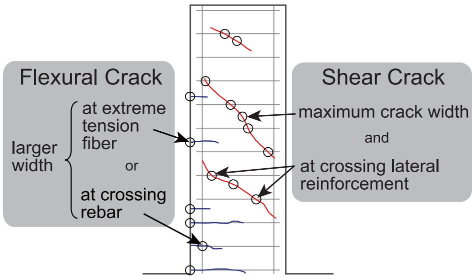
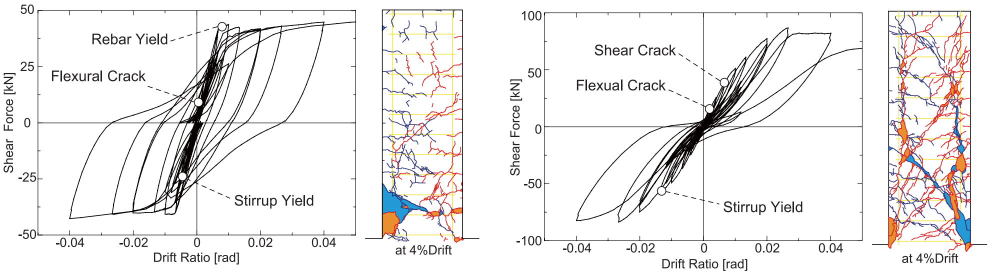


Figure 3: Crack Measurement Point

2.2 Test results

Figure 4 shows the shear force versus drift response for each specimen and the cracking pattern at 4.0% drift. Measured maximum and average crack widths are shown in Figure 5. Measured crack lengths are shown in Figure 6. Crack width and length of specimen S-1 increased rather than specimen F-1 in large drift.



(a) Specimen F-1 (b) Specimen S-1

Figure 4: Shear Force versus Drift Ratio Response, and Cracking Pattern

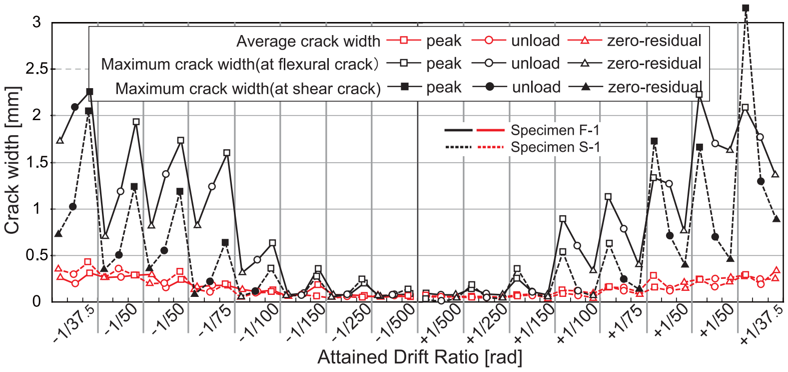


Figure 5: Crack Width for Attained Drift Ratio

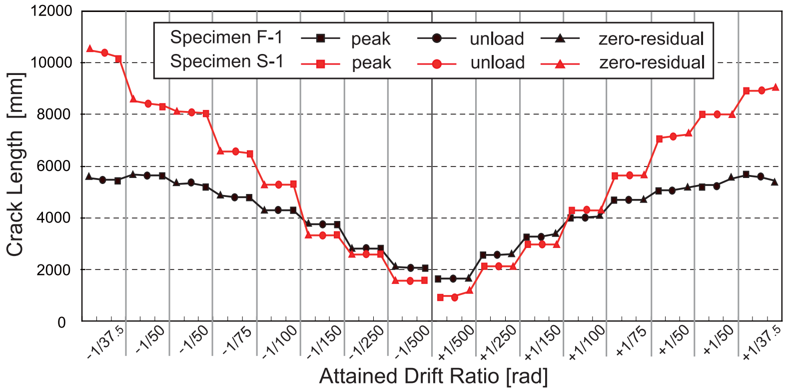


Figure 6: Crack Length for Attained Drift Ratio

3. GEOMETRICAL DAMAGE ESTIMATION

3.1 Geometrical damage estimation model

Architectural Institute of Japan (AIJ, 2004) proposed geometrical macro model of relation between crack width and drift ratio shown in Figure 7. In this paper, this relation is expressed as

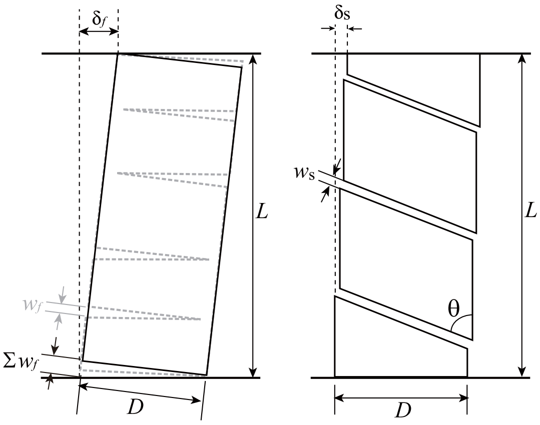
$$R = R_f + R_s = \frac{\sum w_f}{D - x_n} + \frac{2\sum w_s \cdot \cos\theta}{L} \tag{1}$$

where, R_f: flexural drift ratio, R_s: Shear drift ratio, w_f: flexural crack width, w_s: shear crack width, D: depth, x_n: distance from extreme compression fiber to neutral axis, and L: clear span, respectively. CEB-FIP (1978) proposed crack spacing shown in Figure 8. Crack length at stabilized crack pattern due to Figure 8 is expressed as

$$l_{av,f} = \frac{\zeta \cdot L \cdot (D - x_n)}{S_{av}} \tag{2a}$$

$$l_{av,s} = \frac{D}{\sin\theta}\left(\frac{D\cos\theta + L\sin\theta}{S_{av}} - 2q\right) + \frac{q \cdot (q+1) \cdot S_{av}}{\sin\theta\cos\theta} \tag{2b}$$

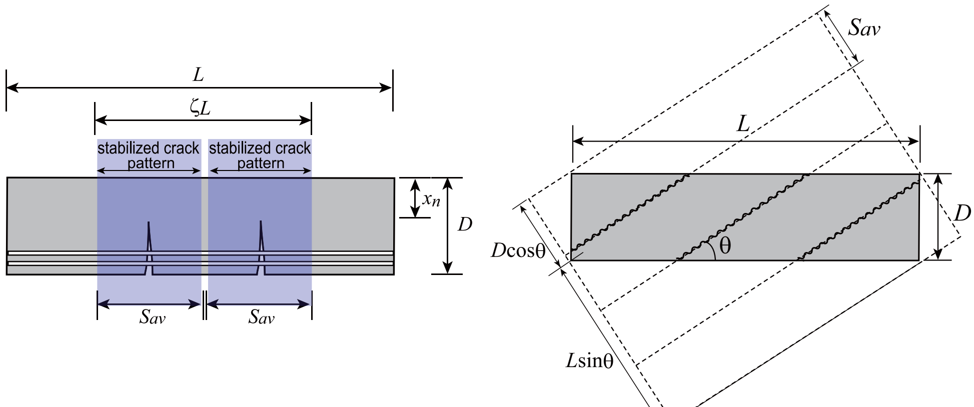
where, $l_{av,f}$: stabilized flexural crack length, $l_{av,s}$: stabilized shear crack length, S_{av}: crack spacing, θ: crack angle, and q: quotient of $D\cos\theta$ / S_{av}, respectively.



(a) Geometrical model of relation between Flexual crack width - Drift

(b) Geometrical model of relation between Shear crack width - Drift

Figure 7: Geometrical Model between Crack Width and Drift



(a) Flexural crack spacing

(b) Shear crack spacing

Figure 8: Crack Spacing

Estimation results of crack width of specimen F-1 and S-1 due to this geometrical model are shown in Figure 9 and 10, respectively. The estimated crack width of specimen F-1 can approximately simulate the experimental result. On the contrary, that of specimen S-1 can approximately simulate the experimental result only at the unloaded drift, and it overestimates at the peak drift and underestimates at the zero-residual drift. It implies that the geometrical model shown in Figure 7 matches up with the unloaded drift condition. In the after-mentioned study on life cycle economic loss estimation, the residual drift after excitation is supposed to be similar to the unloaded drift, and it is assumed that the crack width can be calculated from the residual drift after excitation with the geometrical model.

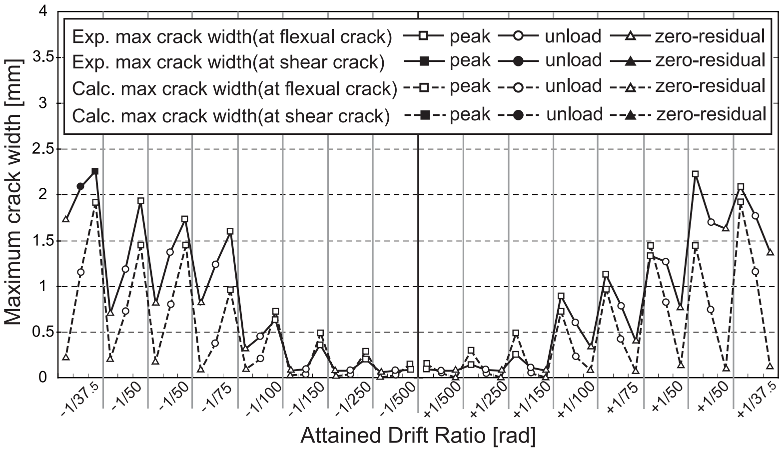


Figure 9: Crack Width Estimation of Specimen F-1

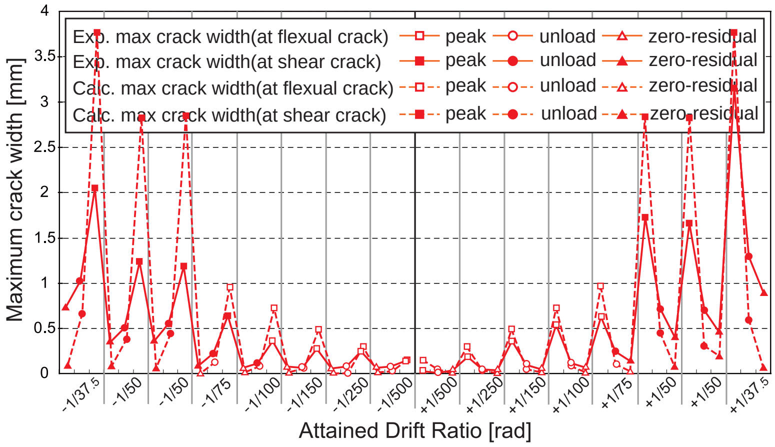


Figure 10: Crack Width Estimation of Specimen S-1

Estimation results of crack length of specimen F-1 and S-1 due to the geometrical model are shown in Figure 11. The estimated crack length represents essentially the length at stabilized crack pattern, thus the propagation of crack length can not be expressed. Based on Figure 11, a new crack length propagation model is proposed in Figure 12. In Figure 12, β means the ratio of flexural drift to total drift. In the after-mentioned study on life cycle economic loss estimation, it is assumed that the clack length can be calculated from the attained maximum drift with the geometrical model.

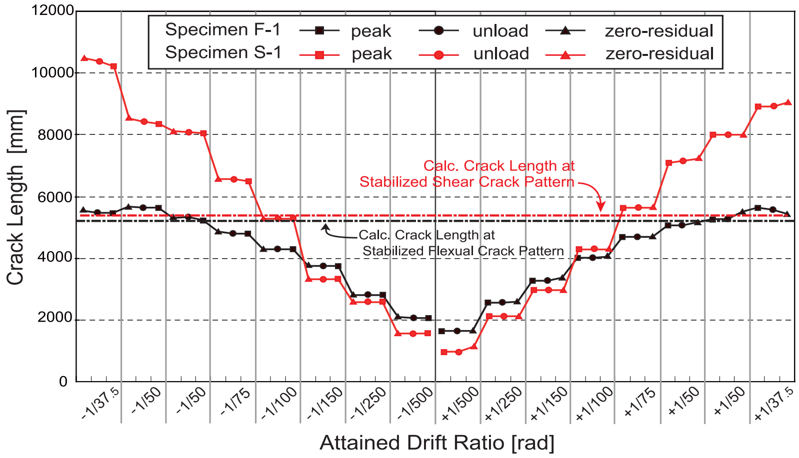


Figure 11: Crack Length Estimation

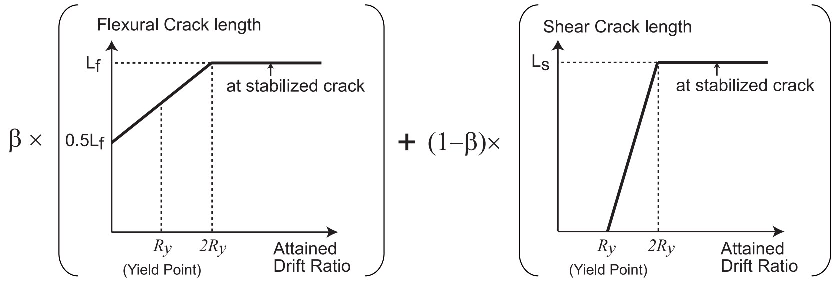


Figure 12: Crack Length Propagation Model

Additionally, the spalling propagation model based on previous research (Takahashi, 2005) shown in Figure 13 is proposed, though it depends not on the geometrical model but on the empirical model. It is formulated as

$$SR = \alpha_{sp} \times (IDR_{max} - R_0) \qquad (3)$$

where, SR: spalling ratio [m^2/m^2], α_{sp}: constant value (= 3.67), R_0: initial spalling drift ratio (= 0.01), and IDR_{max}: attained maximum drift ratio.

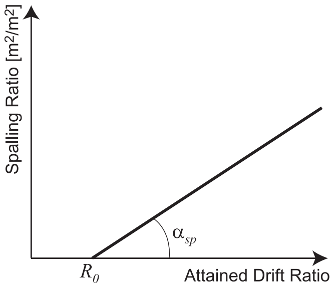


Figure 13: Spalling Propagation Model

3.2 Probabilistic model between crack width and length

A new probabilistic model between crack widths and lengths is also introduced. Crack length distribution to crack width is represented as log-normal distribution in this proposed model. Figure 14 shows the crack length distribution histogram at the drift of +0.01 rad. Comparing the calculated results with experimental results, the crack length distribution of both specimen can be simulated by log-normal distribution with standard deviation σ = 3.0. As concern with the standard deviation, the different values, σ = 0.22~1.49, were proposed by other researchers (Takimoto et al., 2004 and Igarashi et al., 2009). It means that the standard deviation of crack length distribution is unstable. In the after-mentioned study on life cycle economic loss estimation, the standard deviation is assumed to be 1.1.

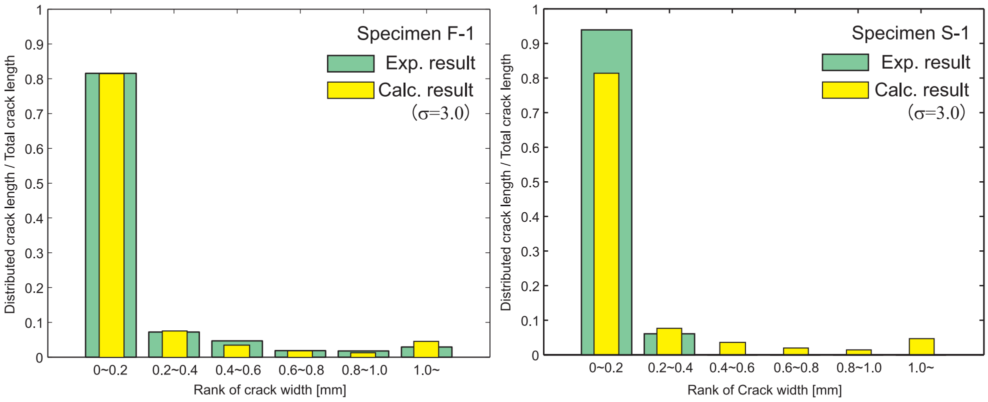


Figure 14: Crack Length Distribution to Crack Width (at +0.01 rad.)

4. LIFE CYCLE COST ESTIMATION

4.1 Input ground motion

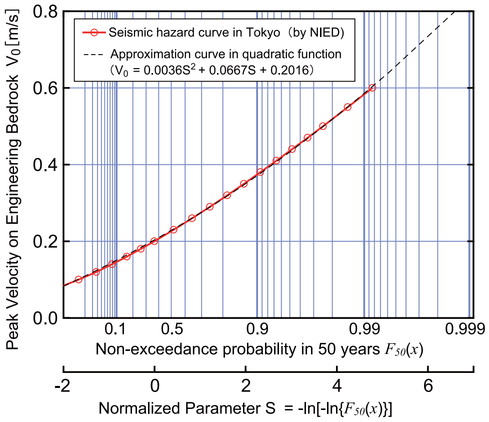
To estimate the lifecycle economic loss, the scenario of earthquake events through lifecycle is necessary, then peak velocities of ground motion on engineering bedrock are firstly calculated based on the seismic hazard curve proposed by National research Institute for Earth science and Disaster prevention (NIED, 2005). Secondly, a series of peak velocities on the medium soil through lifecycle is created such that they fit the probabilistic distribution using the plotting position equation. Plotting position equation is represented by

$$F(x) = \frac{i-\alpha}{N+1-2\alpha} \tag{4}$$

where, N: total number of years in record, i: rank in descending order (i.e. from highest to lowest), x: value of i_{th} data, $F(x)$: exceedance probability and α: constant value. α is calculated as Equation 5 to define the probability of exceedance for the largest earthquake as $P(i)$% in lifecycle years,

$$\alpha = \frac{(N+1)\ln(1-P(i))+iT}{2\ln(1-P(i))+T} \tag{5}$$

where, $P(i)$: i_{th} data's probability of exceedance in T years. The sequence of earthquake is rearranged in a random order. This series of peak velocity is used as a target to modify an input base accelerogram. Figure 15 shows the seismic hazard curve in Tokyo proposed by NIED (NIED, 2005). Figure 16 shows the example of lifecycle peak ground velocities on the medium soil in Tokyo in the case of 50 years life length and 10% in 50 years as the probability of exceedance for the largest earthquake.



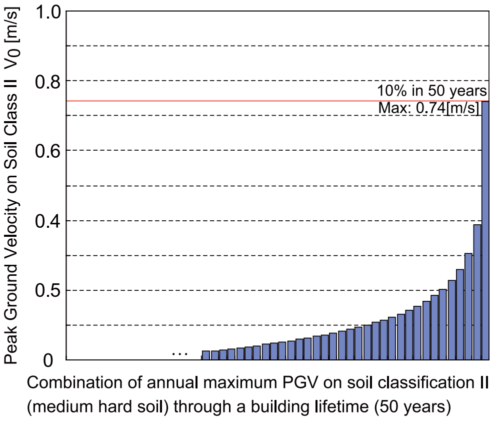
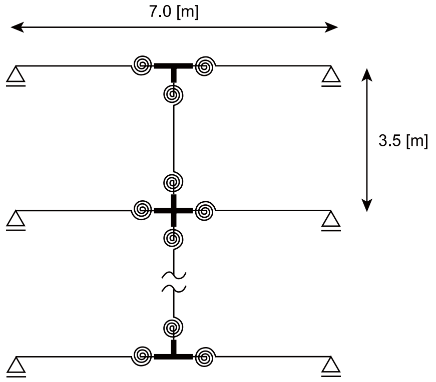


Figure 15: Hazard Curve in Tokyo   *Figure 16: Example of Life Cycle PGV*

4.2 Structural model

Two fishbone-shaped frames shown in Figure 17 are studied for estimating the life cycle repair cost. One is strong-column and weak-beam frame with beam rebar strength σ_s=390kN. Another is weak-column and strong-beam frame with beam rebar strength σ_s=490kN. Takeda hysteresis model (Takeda et al. 1970) is used for each member modeled as one-component model. Viscous damping factors proportional to instantaneous stiffness are assumed to be 3%. The cracking strength is assumed to be one third of yielding strength, the secant stiffness at yielding point is assumed to be 30% of the linearly elastic stiffness, and the third stiffness after yielding is assumed to be 1% of the linearly elastic stiffness for each member.



Common Variable:
Mass : 1.2 tonf/m^2
Column : 700×700 (Fc32, 8-D32/ σ_s=390kN)
Beam : 400×800 (Fc24, 8-D25/ σ_s=*)
Footing : 600×1800 (Fc32, 12-D32 / σ_s=390kN)

*Analytical Parameter:
(a) Strong-column and weak-beam type
Beam rebar strength: σ_s=390kN
(b) Weak-column and strong-beam type
Beam rebar strength: σ_s=490kN

Figure 17: Structural Model

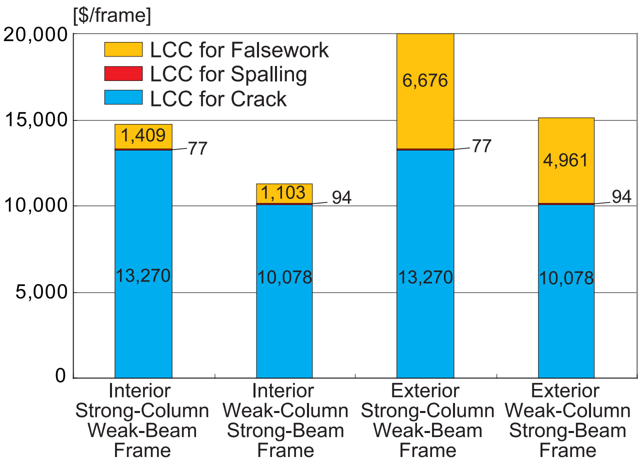
4.3 Calculation results of life cycle economic loss

Providing the maximum drift ratio is larger than yielding drift (assumed to be 1/120 rad. in this study), structures are repaired according to the scenario described in Table 2. If the maximum displacement is smaller than yielding drift, structures are left unrepaired with damage such as a stiffness degradation. Estimated life cycle economic losses of two structures defined as the repairing cost of structures through their life length are shown in Figure 18. Life cycle economic loss due to repairing the cracks are higher in the strong-column and weak-beam structure than the weak-column and strong beam strucutre, but life cycle economic loss due to repairing the spalling are higher in the weak-column and strong beam strucutre than the strong-column and weak-beam structure.

Repairing cost of spalling depends on the maximun interstory drift ratio through the life length. As shown in Figure 19, the maximum interstory drift ratio, which come out at the 2nd floor, is larger in the the weak-column and strong beam strucutre than the strong-column and weak-beam structure. On the contrary, repairing cost of cracking depends not on the maximun drift ratio but on the extent of cracking area. The strong-column and weak-beam structure shows the smaller maximum drift ratio at the 2nd floor, but its drift ratio at the other floor is larger than that of the weak-column and strong beam strucutre. This extent of cracking area affects the repairing cost of cracking. Life cycle economic loss due to falsework is larger in the case of the exterior frame or the strong-column and weak-beam structure because of the extent of damaged area.

Table 2: Repairing Scenario

Condition	Repair method		Unit price
Crack width < 0.2mm	Sealing		$9.1 /m
Crack width < 1.0mm	Epoxy injection		$66.0 /m
Crack width ≥ 1.0mm	U-cut sealing / Cement grout		$125.4 /m
Spalling ratio < 0.05	Patching resin mortar		$\$270.0\ /\text{m}^2$
Spalling ratio ≥ 0.05	Jacketing / Replacement		$\$542.3\ /\text{m}^2$
at Interior Column	No falsework		$\$20.0\ /\text{m}^2$
at Interior Beam	False-work hight	Half floor hight	
at Exterior Column		Damaged floor level	
at Exterior Beam		Damaged floor level + half floor hight	



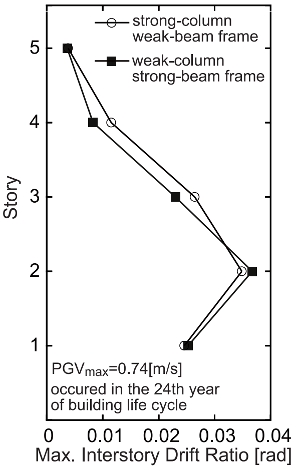


Figure 18: Calculated Life Cycle Economic Loss *Figure 19: Maximum IDR*

5. CONCLUDING REMARKS

Life cycle economic loss defined as the repairing cost of a building structure through its life length was simulated using a new damage estimation model which is partially based on cyclic load tests of one third scaled R/C members. It is concluded that strong-column and weak-beam system will suffer more life cycle economic loss than weak-column and strong-beam system because of the extent of cracking area and the construction cost of falsework.

REFERENCES

AIJ, 2004. *Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings (Draft)*. (in Japanese)
CEB-FIP, 1978. *Model Code for Concrete Structures*
Igarashi, S., 2009. Development of Analytical Model for Reparability Evaluation of RC Columns Based on Damage (Part 1 – Part 3), Summaries of Technical Papers of Annual Meeting of Architectural Institute of Japan, Vol.C-2, 513-518. (in Japanese)
NIED, 2005. Japan Seismic Hazard Information Station (J-SHIS), http://www.j-shis.bosai.go.jp/j-shis/
Takahashi, N. et al., 2005. Repair Cost Function in Seismic Reparability Assessment for R/C Structures, Proc. of Japan Concrete Institute, Vol.27, No.2, 1543-1548. (in Japanese)
Takahashi, N. et al., 2006. Life Cycle Input Ground Motion Intensities for the Seismic Loss Estimation of the Building through its Lifetime, Proc. of 12th Japan Earthquake Engineering Symposium, 422-425. (in Japanese)
Takimoto, K. et al., 2004. Study on Evaluation of Damage of RC Beams using Crack Data, Journal of the Japan Society of Civil Engineers, No.760/V-63, 135-145. (in Japanese)
Takeda, T. et al., 1970. Reinforced concrete response to simulated earthquakes, Journal of Structural Division, ASCE, 96:ST12, 2557-2573