Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 237

EXPERIMENTAL STUDY ON DAMAGE QUANTIFICATION OF R/C MEMBERS UNDER EARTHQUAKES

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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 are carried out. Based on the tests, a damage estimation model is proposed to quantify each crack width and corresponding length. The model consists of a geometrical relationship between the sum of crack widths and drift ratio and a probabilistic model between crack widths and lengths. The proposed model shows that estimated flexure crack widths successfully approximate the measured crack widths in Specimen F-1 designed to fail in flexure. But in Specimen S-1 designed to fail in shear, estimated shear crack widths overestimate the measured crack widths at peak load stages and underestimate them at zero-residual drift stages. And the probabilistic model between crack widths and lengths are discussed.

Introduction

Loss estimation of a building due to earthquake events is important to facilitate the decision making of the building owner to choose the reasonable seismic performance. Generally it is assumed that the visible damage of reinforced concrete (R/C) members such as crack width and length are subjected to one of principal components for seismic loss (e.g. structural repair cost) estimation. In this paper, the visible damage is modeled as a geometrical relationship between the sum of crack widths and drift ratio and a probabilistic model between crack widths and lengths.

Experimental Program

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 Fig. 1. To obtain the propagation of

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crack width and length corresponding to attained and present drift ratio, the cyclic displacement pattern shown in Fig. 2 was operated. Crack widths were measured at the points shown in Fig. 3 by crack gauges and by image processing. 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

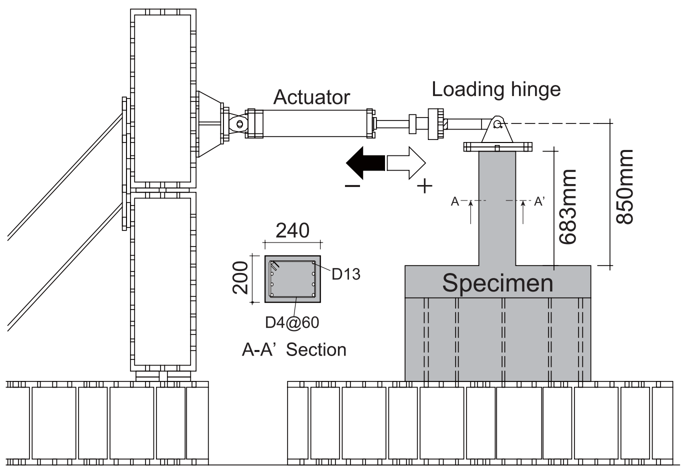
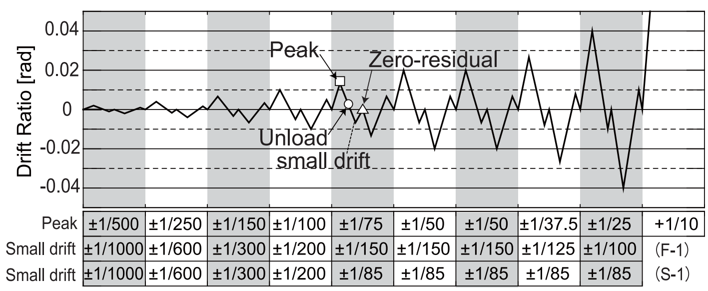


Figure 1. Dimension of Beam Specimen and Test Setup.



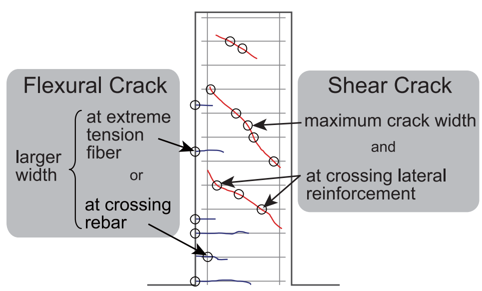


Figure 2. Cyclic Displacement Pattern. Figure 3. Crack Measurement Point.

Test Results

Fig. 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 Fig. 5.

Measured crack lengths are shown in Fig. 6. Specimen F-1 designed to fail in flexure opened existing cracks due to increase in drift ratio instead of generating new cracks after yielding. Therefore total crack length did not increase significantly. On the other hand, Specimen S-1 designed to fail in shear generated new cracks due to the increase in drift ratio after yielding. Crack length as well as crack width increased. Crack width and length of specimen S-1 increased rather than specimen F-1 in large drift.

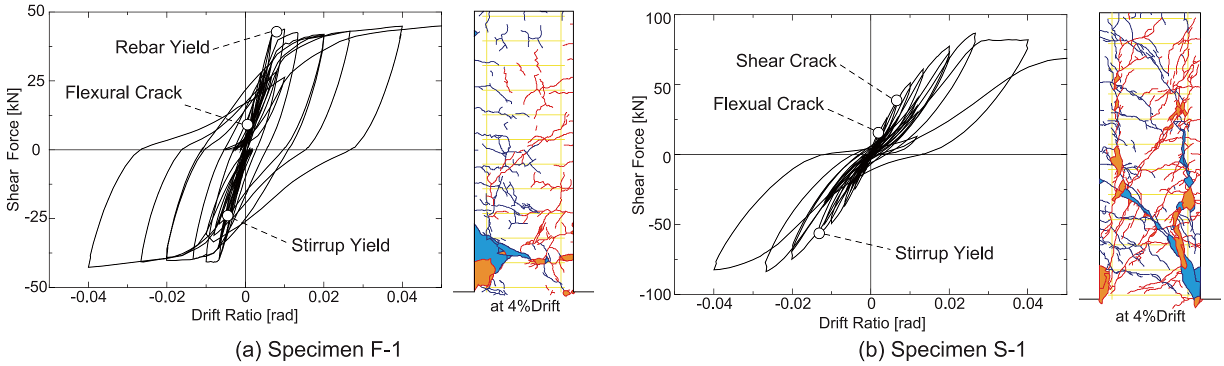


Figure 4. Shear Force versus Drift Ratio Response, and Cracking Pattern.

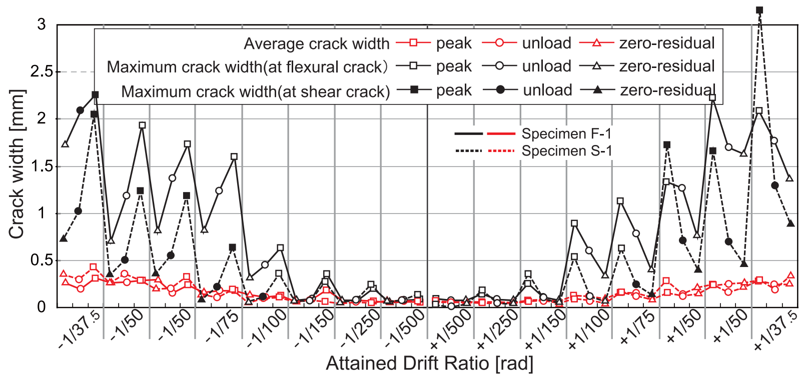


Figure 5. Crack Width for Attained Drift Ratio.

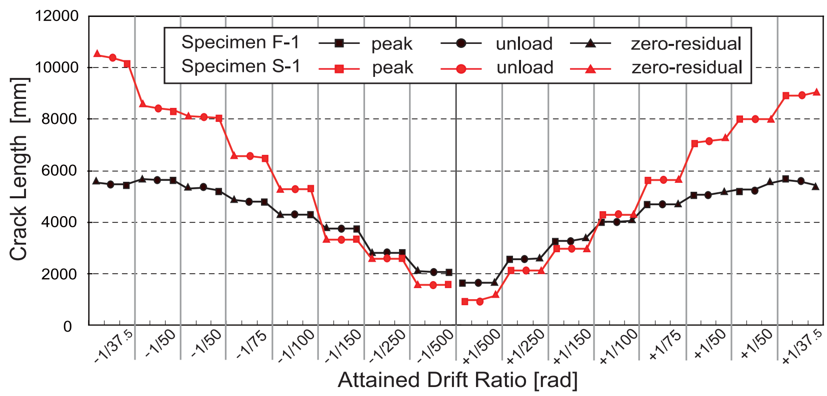


Figure 6. Crack Length for Attained Drift Ratio.

Proposed Models for Damage Quantification

Geometrical Damage Estimation Model

Architectural Institute of Japan (AIJ, 2004) proposed geometrical macro model of relation between crack width and drift ratio shown in Fig. 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 Fig. 8. Crack length at stabilized crack pattern due to Fig. 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.

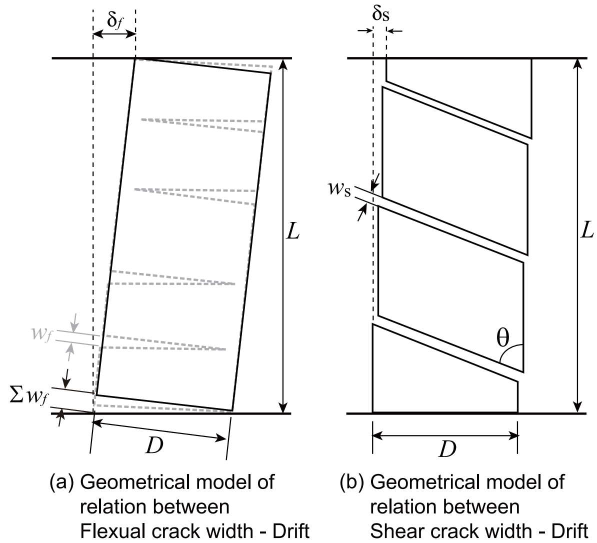
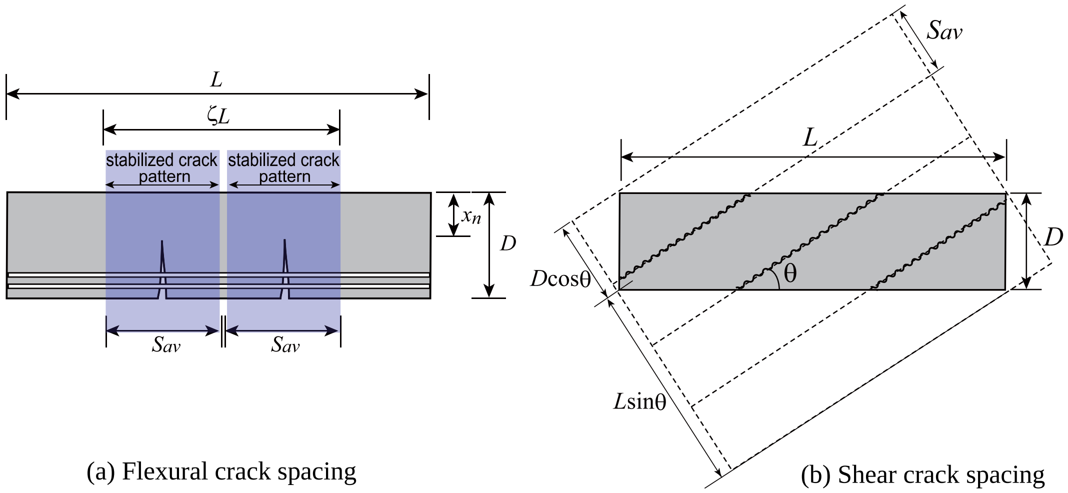


Figure 7. Geometrical Model between Crack Width and Drift.



(a) Flexural crack spacing (b) Shear crack spacing

Figure 8. Crack Spacing.

Verification and Revision of the Damage Estimation Model

Estimation results of crack width of specimen F-1 and S-1 due to this geometrical model are shown in Figs. 9 and 10, respectively. It is assumed that the crack width can be calculated from the residual drift after excitation with the geometrical model. 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 Fig. 7 matches up with the unloaded drift condition.

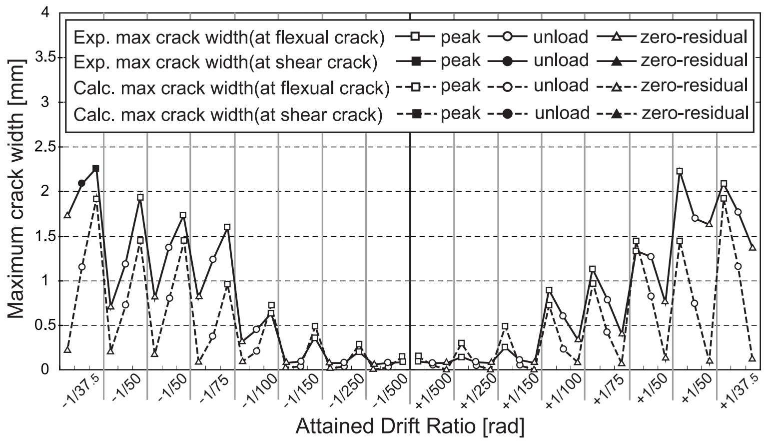


Figure 9. Crack Width Estimation of Specimen F-1.

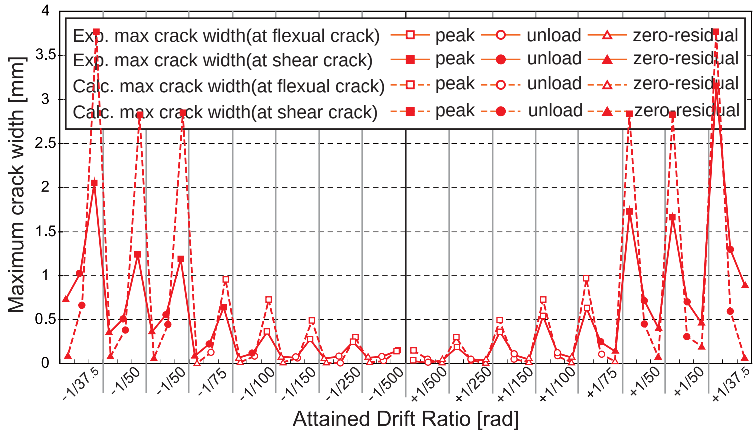


Figure 10. Crack Width Estimation of Specimen S-1.

Estimation results of crack length of specimen F-1 and S-1 due to the geometrical model are shown in Fig. 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 Fig. 11, a revised crack length propagation model is proposed in Fig. 12. In Fig. 12, β means the ratio of flexural drift to total drift. It is assumed that the clack length can be calculated from the attained maximum drift with the geometrical model.

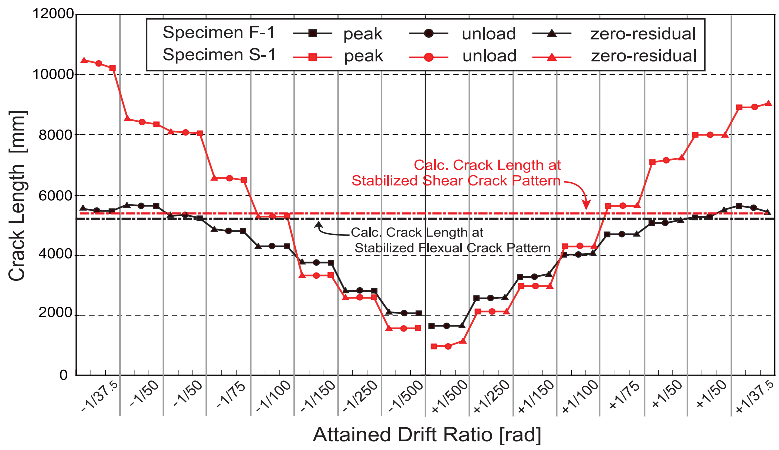


Figure 11. Crack Length Estimation.

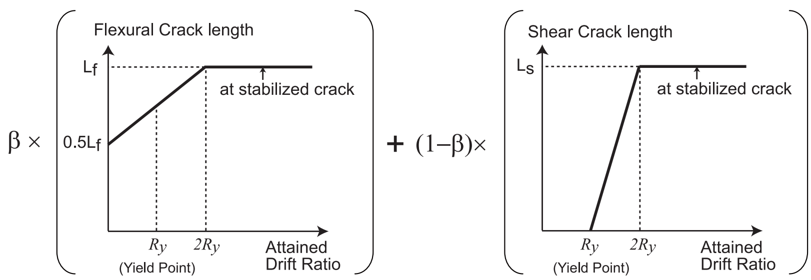


Figure 12. Crack Length Model.

Probabilistic Model between Crack Width and Length

A 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. Fig. 14 and 15 show the crack length distribution histograms at the drift of 0.002, 0.004, 0.01, 0.02 rad., respectively. As concern with the standard deviation, the experimental results are shown in Table 2. The obtained values of σ from the experimental tests are around 0.61~1.40 when a natural logarithm are used as a random variable of log-normal distribution. The average value of σ is 0.92. But the dispersed values (σ = 0.22~1.49) were observed by other researchers (Takimoto et al., 2004 and Igarashi et al., 2009), it implies that the standard deviation of crack length distribution would be unstable.

Using the crack widths estimated by the geometrical model and the standard deviation σ obtained from the experimental tests, the crack length distribution histograms at the attained drift ratio of 0.002, 0.004, 0.01, 0.02 rad. are calculated. The calculated results are overwritten in Fig. 13 and 14.

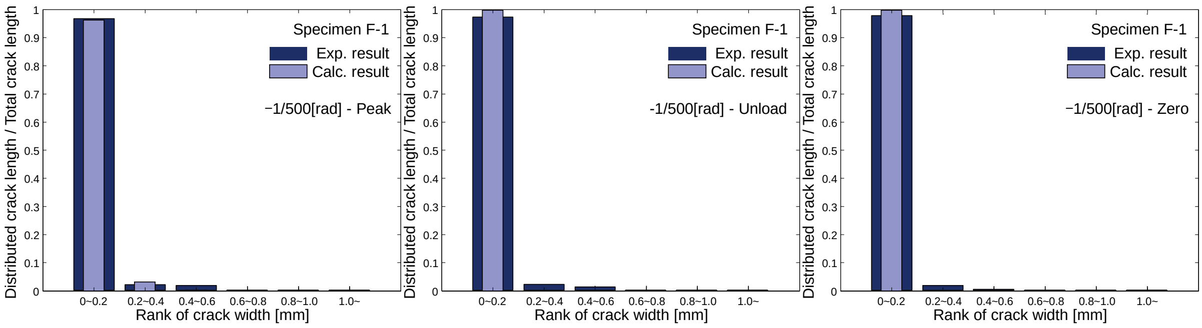
The calculated crack length distribution histograms of specimen F-1 approximately simulate the experimental results at small drift stage. But the trends for underestimating the crack length of a smaller crack width at the peak drift stage and overestimating the crack length of a smaller crack width at the zero-residual drift stage are shown in Fig. 13 according to the increase of attained drift.

The calculated crack length distribution histograms of specimen S-1 approximately simulate the experimental results at small drift stage. Also the trends for underestimating the crack length of a smaller crack width at the peak drift stage and overestimating the crack length of a smaller crack width at the zero-residual drift stage are shown in Fig. 14 according to the increase of attained drift.

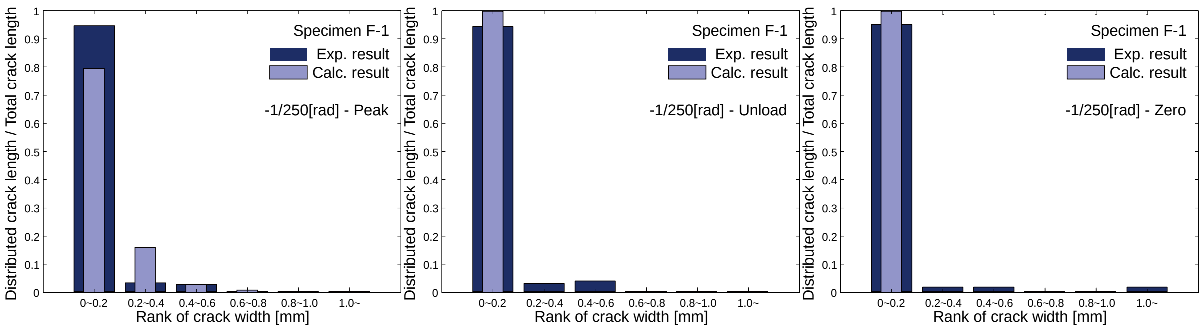
It is caused by the lack of accuracy for estimated crack widths with the geometrical model in large drift ratio.

Table 2. Standard Deviation of Crack Length Distribution Obtained from Experimental Tests.

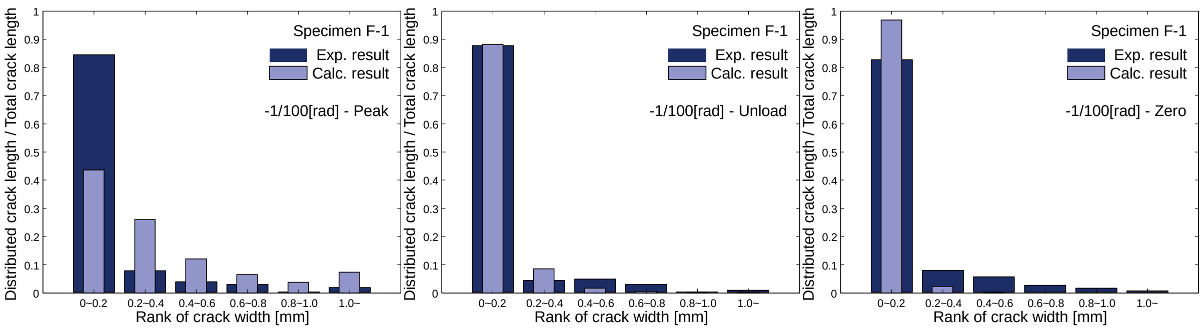
Specimen	**Attained drift 0.002[rad.]**			**Attained drift 0.004[rad.]**			**Attained drift 0.01[rad.]**			**Attained drift 0.02[rad.]**		
	peak	unloaded	zero-residual	peak	unloaded	zero-residual	peak	unloaded	zero-residual	peak	unloaded	zero-residual
F-1	0.70	0.70	0.65	0.75	0.79	0.80	1.01	0.97	1.05	1.34	1.35	1.26
S-1	0.83	0.83	0.84	0.62	0.70	0.61	0.90	0.94	0.65	1.31	1.40	1.30



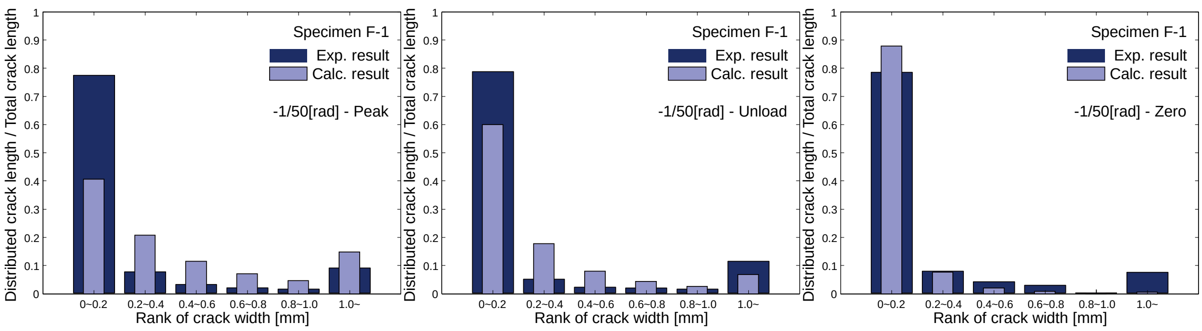
(a) At the attained drift ratio = 0.002 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)



(b) At the attained drift ratio = 0.004 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)

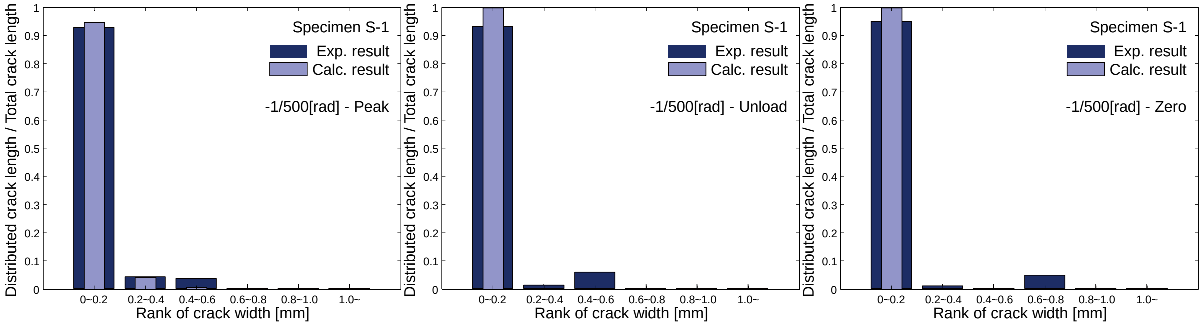


(c) At the attained drift ratio = 0.01 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)

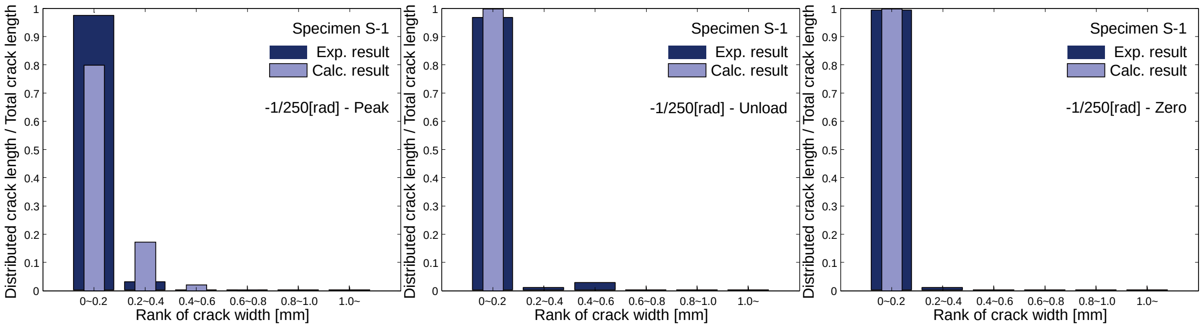


(d) At the attained drift ratio = 0.02 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)

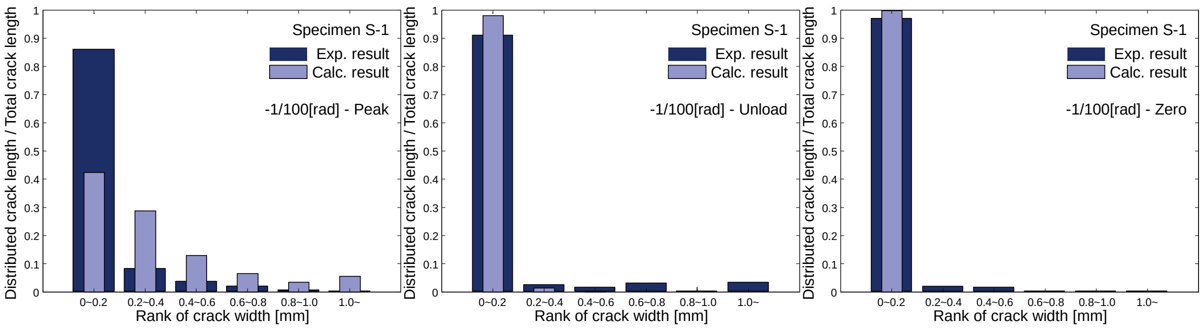
Figure 13. Crack Length Distribution to Crack Width (Specimen F-1).



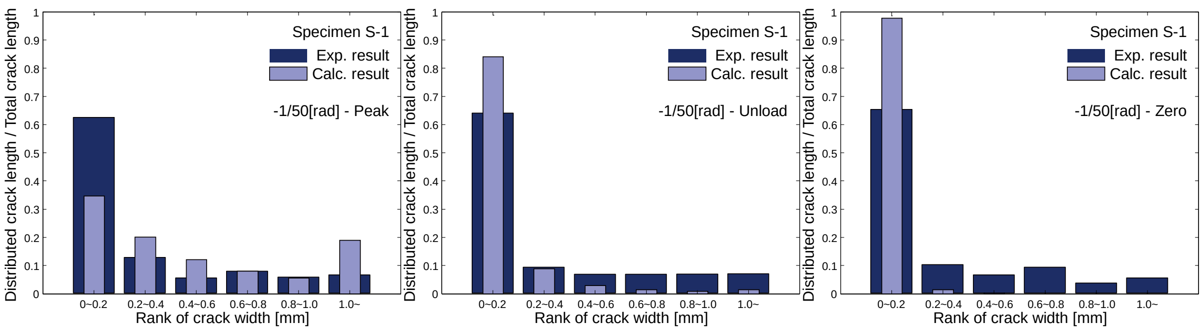
(a) At the attained drift ratio = 0.002 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)



(b) At the attained drift ratio = 0.004 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)



(c) At the attained drift ratio = 0.01 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)



(d) At the attained drift ratio = 0.02 rad. (Peak, Unloaded, Zero-residual drift stage, respectively)

Figure 14. Crack Length Distribution to Crack Width (Specimen S-1).

Concluding Remarks

To evaluate visible damage of R/C members such as crack width and length, cyclic load tests of one third scaled R/C members were carried out. And the damage estimation model, which consists of a geometrical model between crack widths and drift ratio and a probabilistic model between crack widths and lengths, was proposed. The proposed model shows that flexure crack widths successfully approximate the measured crack widths, but shear crack widths overestimate the measured crack widths at peak load stages and underestimate them at zero-residual drift stages. And the calculated crack length distribution histograms approximately simulate the experimental results when the attained drift ratio is smaller than 0.01 rad. But according to the increase of attained drift, the calculated results overestimate the crack length of a smaller crack width. It is caused by the lack of accuracy for estimated crack widths with the geometrical model in large drift ratio. Future studies will focus on the accuracy for estimated shear crack widths and the consistency of the geometrical model with the stress diagram.

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