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SIMPLIFIED METHOD OF SEISMIC DAMAGE PREDICTION AND VISUALIZATION FOR R/C BUILDING STRUCTURES

N. Takahashi[1]

ABSTRACT

To evaluate visible seismic damage of reinforced concrete (R/C) members such as crack width and length, three predictive models are proposed to quantify each crack width and corresponding length. These models are intended to apply to the earthquake response employing the simple and well-known analytical model such as one component model or fiber model in order to design the reparability performance of building structures.

The first model estimates the propagation of crack length. This model enhanced the mechanical model proposed in CEB-FIP code 1978. The second model estimates the propagation of crack width due to drift ratio. It consists primarily of a geometrical model considering the relationship between the sum of crack widths and drift ratio.

These proposed models are verified employing various test results. Crack length can be schematically estimated the crack conditions. In particular to the shear crack, the estimated crack length tends to underestimate the measured crack length due to its fractal dimension. On the other hand, crack widths can be approximately estimated corresponding to the residual drift through the geometrical model. In particular to the flexural crack, the estimated crack width successfully approximate the measured crack width. But the estimated shear crack widths occasionally disagree with test results. It implies that the estimated shear drift corresponding to each crack width in the geometrical model could be different from the actual shear drift.

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ABSTRACT

To evaluate visible seismic damage of reinforced concrete (R/C) members such as crack width and length, predictive models are proposed to quantify each crack width and corresponding length. These models are intended to apply to the earthquake response employing the simple and well-known analytical model such as one component model or fiber model in order to design the reparability performance of building structures. The proposed models are verified employing various test results. Crack length can be schematically estimated the crack pattern. On the other hand, crack widths can be approximately estimated corresponding to the residual drift through the geometrical model.

Introduction

To evaluate visible damage of reinforced concrete (R/C) members such as crack width and length, cyclic load tests of 1/3 scaled R/C members (load test series 2008) and monotonic load tests of 1/2 (load test series 2011) and were carried out. Then damage propagation process represented by crack width and length was observed in these tests.

Firstly, based on the 1/2 scaled R/C members tests named “load test series 2011,” a predictive model is proposed to quantify the propagation of crack length. This model enhanced the mechanical model which was proposed in CEB-FIP code 1978 [1]. The CEB-FIP code considered the crack propagation under a service load level. The proposed model in this paper considers the crack propagation under not only a service load but a seismic load level. Secondly, based on the 1/3 scaled R/C members tests named “load test series 2008,” a predictive model is proposed to quantify the propagation of crack width. The model consists primarily of a geometrical model considering the relationship between the sum of crack widths and drift ratio. It can take account of the crack propagation process due to the current drift ratio; crack widths can be estimated corresponding to the residual drift through the geometrical model. It can also take account of the difference in crack widths at peak load stages and those at unloaded stages. Finally, proposed models are verified. And a blind-analysis is carried out employing the above-mentioned model to estimate the combination of crack width and length. It show that the crack length schematically approximate the crack pattern but the crack widths can be approximately estimated.

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Experimental Program

Load Test Series 2011

Test Specimens, Setup and Instrumentation

Three R/C beam specimens proportioned to approximately 1/2 of full scale were tested under monotonic loading. The design parameters are given in Table 1. The dimension for the test specimens and test setup are shown in Fig. 1, 2 and 3. Crack lengths were measured by image processing of sketched cracking pattern. Crack widths were measured due to Fig. 4.

Table 1. Description of test specimens about load test series 2011

Specimen	Concrete Strength [N/mm^2]	Rebar/ Ratio to the section	Yield strength of rebar [N/mm^2]	Lateral reinforcement/ Ratio to the section	Yield strength of reinforcement [N/mm^2]	Failure mode
F-60	30.5	8-D13 / 0.0067	413 (SD295)	D6@60 / 0.0049	418 (SD295)	Flexure
F-90	32.0			D6@90 / 0.0033	387 (SD345)	Flexure
FS-90	32.5	8-D16 / 0.0104	569 (SD490)	ϕ9@90 / 0.0066	358 (SR235)	Flexure -Shear

D: diameter of deformed bar

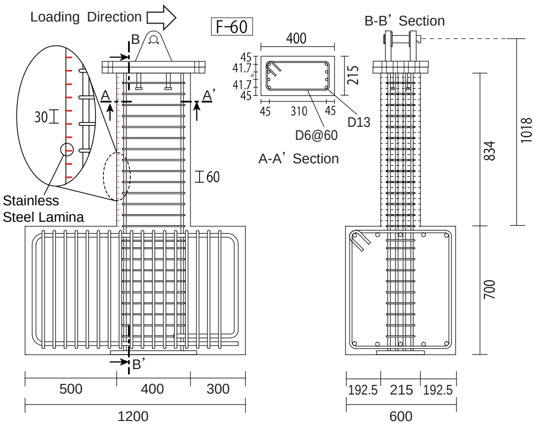


Figure 1. Dimension of specimen F-60

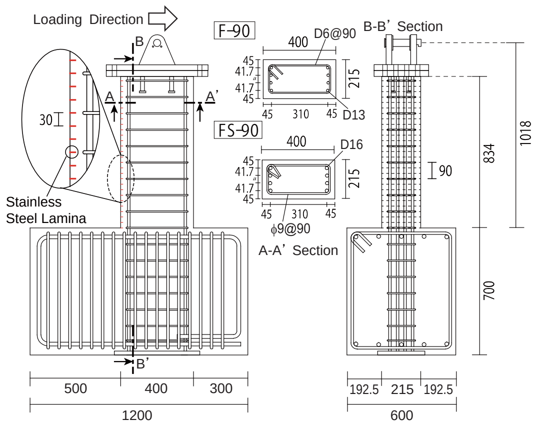


Figure 2. Dimension of specimen F-90/FS-90

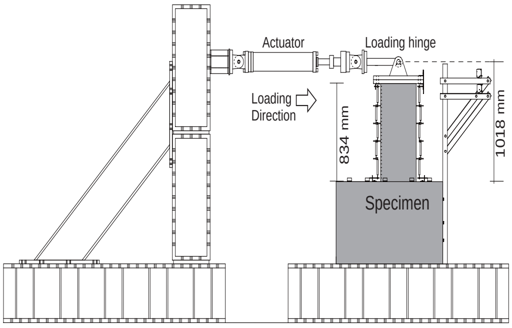


Figure 3. Test setup

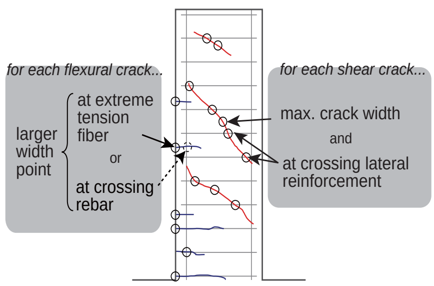


Figure 4. Crack measurement point

Test Results

Fig. 5 shows the shear force versus drift response for each specimen and the cracking pattern at 4.0% drift. Measured crack lengths are shown in Fig. 6. Specimen F-60 and F-90 designed to fail in flexure generated shear cracks after yielding and their length were the same as their flexural crack length. Specimen FS-90 designed to fail in flexural-shear generated shear cracks after yielding and its length was twice as long as its flexural crack length.

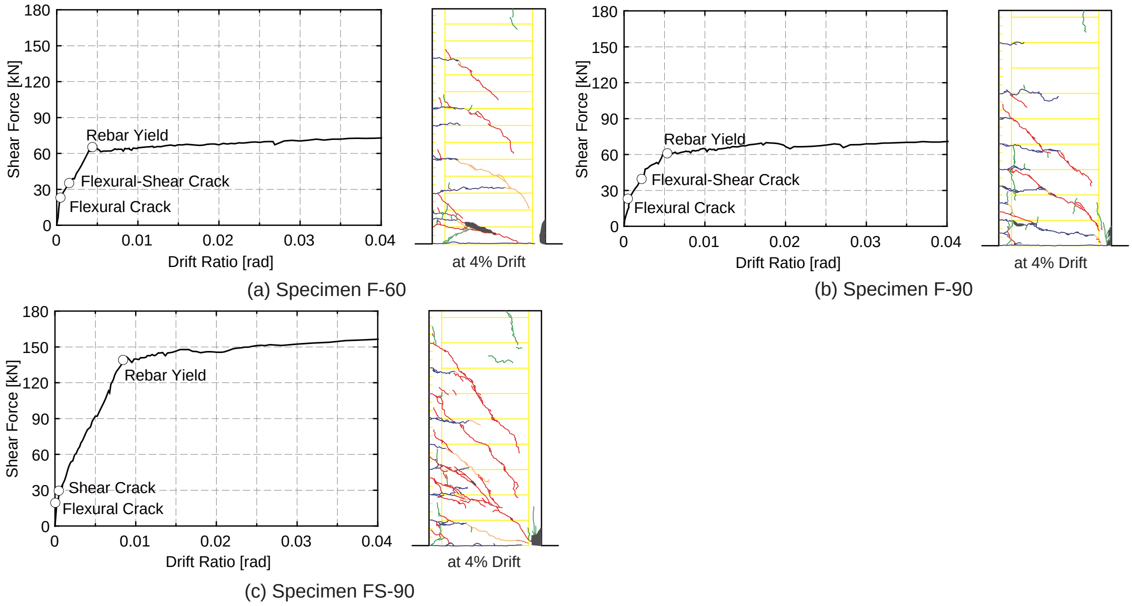


Figure 5. Shear force versus drift ratio response, and cracking pattern

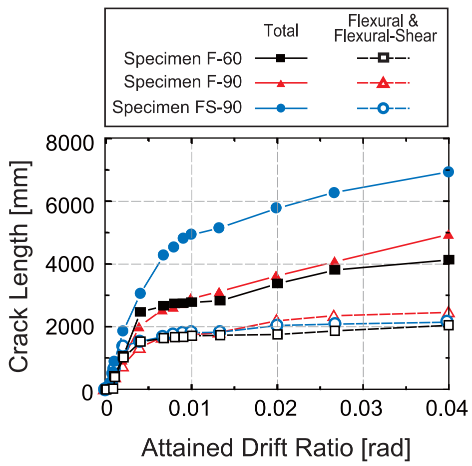


Figure 6. Crack length for attained drift ratio

Load Test Series 2008

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 2. The dimension for the test specimens and test setup are shown in Fig. 7 and 8. To obtain the propagation of crack width and length corresponding to attained and present drift ratio, crack widths were measured at peak, unload, and zero-residual drift point. Crack lengths were measured by image processing of sketched cracking pattern.

Table 2. Description of test specimens about load test series 2008

Specimen	Concrete Strength [N/mm^2]	Rebar/ Ratio to the section	Yield strength of rebar [N/mm^2]	Lateral reinforcement/ Ratio to the section	Yield strength of reinforcement (N/mm^2)	Failure mode
F-1	35.4	8-D13 / 0.0121	351 (SD295)	D4@60 / 0.0022	385 (SD295)	Flexure
S-1	25.9		902 (KSS785)		385 (SD295)	Shear

D: diameter of deformed bar

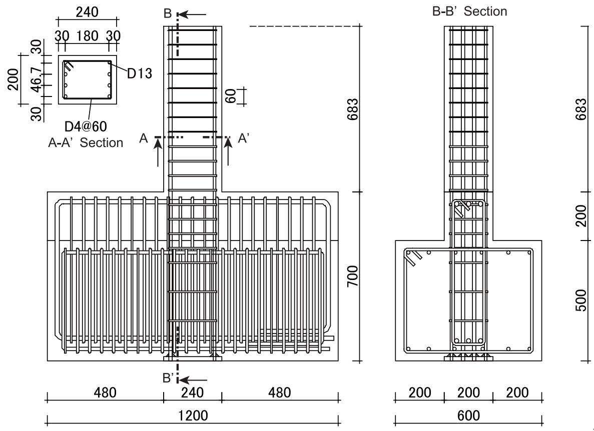


Figure 7. Dimension of beam specimen

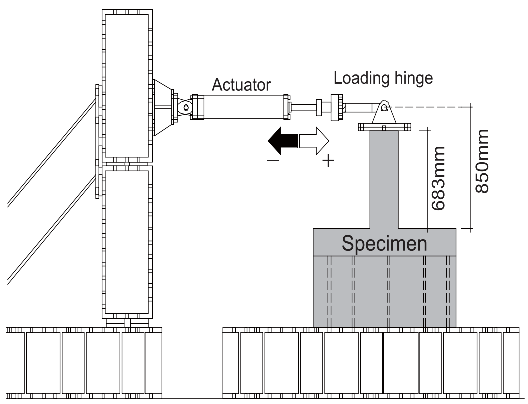


Figure 8. Test setup

Test Results

Fig. 9 shows the shear force versus drift response for each specimen and the cracking pattern at 4.0% drift. Measured maximum crack widths are shown in Fig. 10. Specimen F-1 designed to fail in flexure opened existing cracks due to increase in drift ratio instead of generating new cracks after yielding. On the other hand, Specimen S-1 designed to fail in shear generated new cracks due to the increase in drift ratio after yielding. Then crack width of specimen F-1 increased rather than specimen S-1.

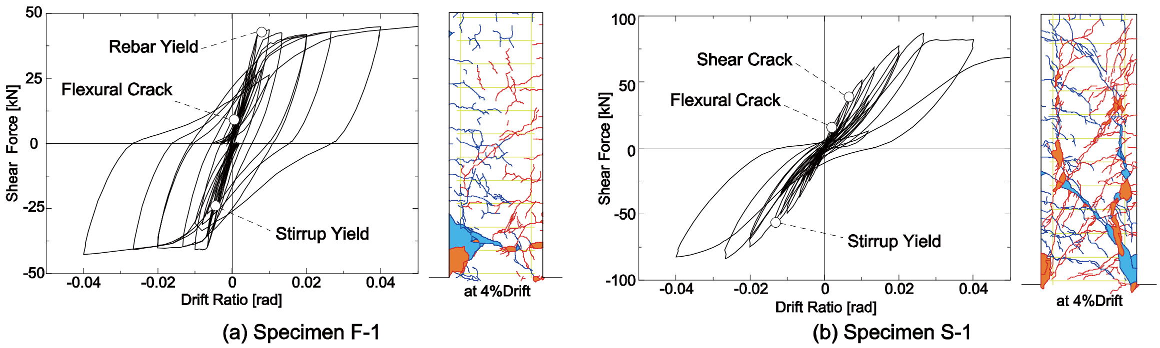


Figure 9. Shear force versus drift ratio response, and cracking pattern

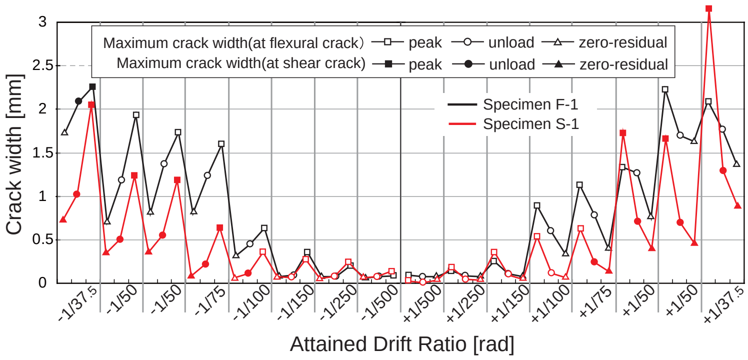


Figure 10. Crack width for attained drift ratio

Damage Estimation

Crack Length Eastimation Model

In this paper, flexural-shear cracks are modelled as bilinear according to the crack growth angle as shown in Fig. 11. Flexural and flexural-shear cracks are estimated based on a fiber model analysis. Kent & Park model [2], Okamura & Maekawa model [3], and bilinear model are employed to the compressive concrete, the tensile concrete, and the reinforcing bar model, respectively. On the other hand, shear cracks are estimated from a stabilized crack pattern after shear cracking strength, where doesn't consider the propagation of shear crack length. The following paragraphs show the detailed process and the example of crack length estimation.

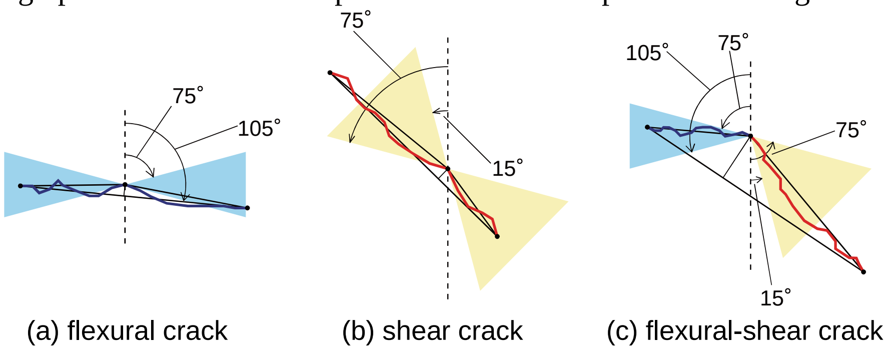


Figure 11. Crack type definition due to its angle growth

Propagation of Flexural Crack

Flexural cracks generate at the extreme tension fiber where the moment M is larger than flexural cracking moment M_c. This cracking zone, which length is defined as l_{cr}, is expressed as Eq. 1.

$$l_{cr} = (1 - \frac{M_c}{M})H \tag{1}$$

where, H: shear span. The number of flexural cracks is also expressed as Eq. 2.

$$n = \frac{l_{cr}}{S_{av}} + 1 \tag{2}$$

where, S_{av}: Average flexural cracking space [4]. The length of flexural crack is defined as the distance from the extreme tension fibre to the point of concrete tensile strength estimated from a fiber model analysis.

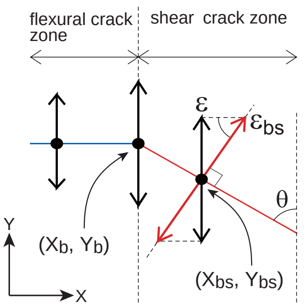
Propagation of Flexural-Shear Crack after the Inflection Point

To estimate the propagation of flexural-shear cracks after the flexural cracks extending, the inflection points (X_b, Y_b) of flexural-shear cracks are defined shown in Fig. 12. At the inflection point, the angle of principal stress to the axis of the beam calculated from Mohr's stress circle comes under 75 degrees. The crack over the inflection point will propagate to the targets shown in Fig. 13 according to their inflection point coordinates. When an inflection point is included in plastic hinge area, the crack is oriented to the stirrup at critical section in compressive zone. When an inflection point is included in the area adjoining a plastic hinge area where is expressed as Eq. 3, the crack is propagate with a constant degrees ϕ to the axis of the beam.

$$Y_{bs} \leqq (j_e \cot\phi + S_{m\theta}) - X_{bs} / \tan\phi) \tag{3}$$

where, j_e: the distance of stirrup in loading direction, $S_{m\theta}$: average shear cracking space [5], respectively. The length of flexural-shear crack is defined as the sum of the distance from the extreme tension fiber to the inflection point and the distance from the inflection point to the point of converted concrete tensile strength estimated from a fiber model analysis. That is the point where the converted strain ε_{bs}, which is expressed as Eq. 4, is larger than the strain of concrete tensile strength ε_{ct}.

$$\varepsilon_{bs} = \varepsilon / \sin\theta \tag{4}$$



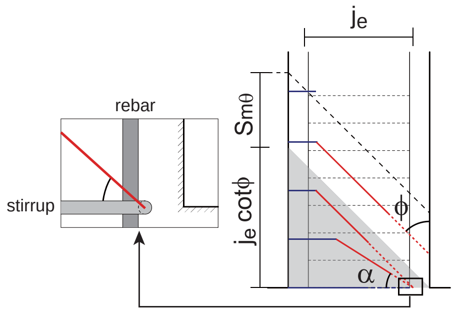


Figure 12. Inflection point and converted strain ε_{bs} **Figure 13.** Orientation of crack propagation

Shear Crack Length Model

When the shear force is larger than shear cracking strength, shear cracks are generated in the area without the plastic hinge area and the area adjoining the plastic hinge area where is expressed as Eq. 3. These shear cracks have an average shear crack space $S_{m\theta}$ and keep stable. Therefore shear crack length is constant in this paper.

Estimation Results for Crack Length

Fig. 14 shows the crack length obtained from experimental results and analytical results for the specimens of the load test series 2011. Estimated the sum of flexural-shear crack length is approximate the experimental results, but the estimated crack length divided in flexural zone part and shear zone part are not approximate the experimental results for each specimen. Estimated shear crack lengths of specimen F-60 and F-90 are approximate the experimental results, but that of specimen FS-90 is underestimated the experimental result.

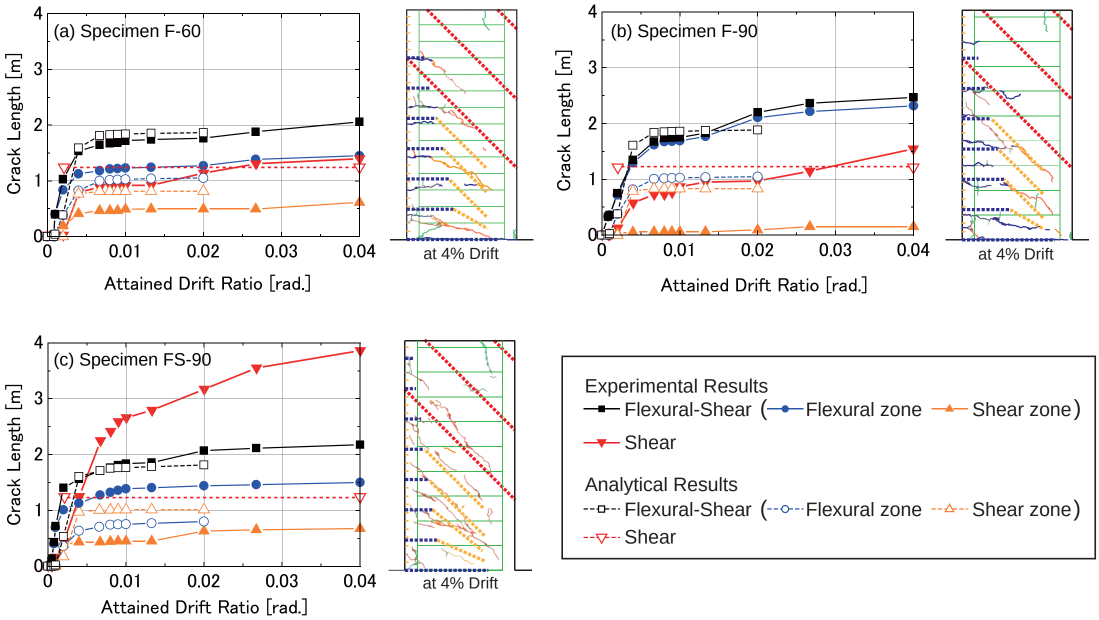
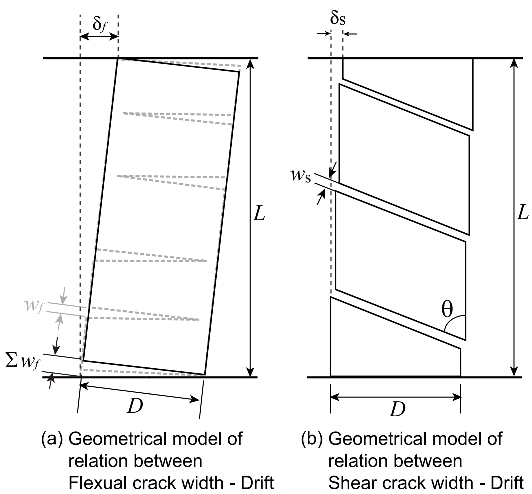


Figure 14. Comparison between the estimated crack length and experimental results

Crack Width Estimation Model

Geometrical Model of Crack Width and Drift

In this paper, geometrical macro model [5] of relation between crack width and drift ratio shown in Fig. 15 is applied to estimating the residual crack width after excitation.



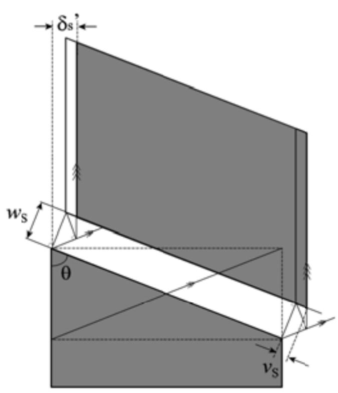


Figure 15. Geometrical model of crack width and drift **Figure 16.** Shear crack width and drift

The relation between crack width and drift ratio is expressed as

$$R = R_f + R_s = \frac{\sum w_f}{D - x_n} + \frac{2\sum w_s \cdot \cos\theta}{L} \quad (5)$$

where, R_f: current flexural drift ratio, R_s: current shear drift ratio, w_f: flexural crack width, w_s: shear crack width, D: depth, x_n: distance from extreme compression fibre to neutral axis, and L: clear span, respectively. Eq. 5 considers the experimental result of shear crack width and shear drift shown in Fig. 16, which is proposed by Sugi, et al. [6].

Estimation Results for Crack Width

Estimation results of the maximum crack width for the specimens of the load test series 2008, which is selected from larger one of the maximum flexural crack width and the maximum shear crack width, are shown in Fig. 17.

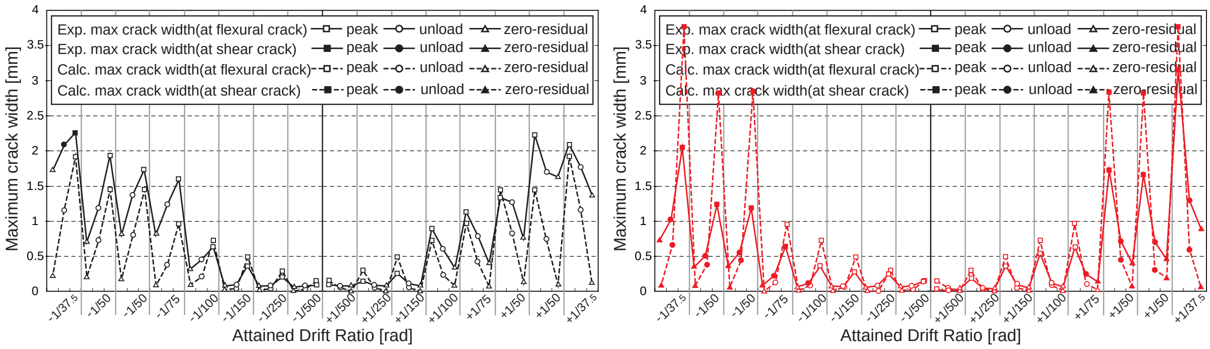


Figure 17. Crack width estimation of specimen F-1(left) and S-1(right)

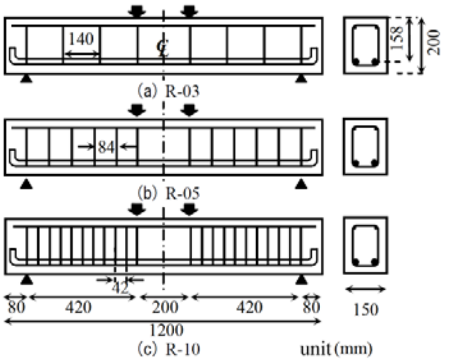
The estimated crack widths of specimen F-1 can approximately simulate the experimental result. On the contrary, that of specimen S-1 can approximately simulate the experimental result only at the unloaded drift, and it overestimates at the peak drift and underestimates at the zero-residual drift. It implies that the geometrical model shown in Fig. 15 matches up with the unloaded drift condition.

Comparison of the Estimation Methods for Combination of Crack Width and Length

Several analyses are carried out [7] to estimate the combination of crack width and length for R/C beam loading tests [8]. Fig. 18 shows the dimension of target beam specimens and the design parameters and corresponding values are given in Table 3. Fig. 19 shows the test results of crack propagation.

Analysis results employed 3D-RBSM as the most detailed model are shown in Fig. 20. Cracking pattern can be schematically simulated, but crack length tends to be overestimated due to a size of the voronoi diagram. The maximum crack widths are calculated around 0.5 mm.

Analysis results employed the proposed model as the simplest model are shown in Fig. 21. Cracking pattern can be schematically simulated. The maximum crack widths are calculated around 0.5 mm. This result is not far from the detailed method in spite of the fact that it needs only a quite-limited calculating time.



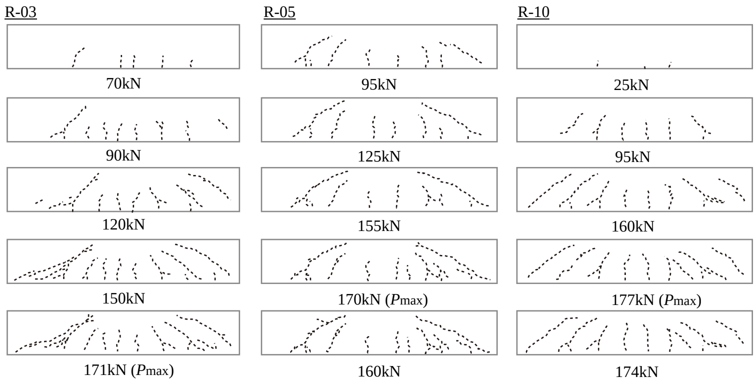


Figure 18. Dimension of specimens **Figure 19.** Crack Propagation of beam specimens

Table 3. Description of test specimens

Specimen	Concrete Strength [N/mm^2]	Rebar/ Ratio to the section	Yield strength of rebar [N/mm^2]	Lateral reinforcement/ Ratio to the section	Yield strength of reinforcement (N/mm^2)	Failure mode
R-03	34.4	2-D22/ 0.0327	357 (SD295)	D6@140 / 0.003	347 (SD295)	Shear
R-05	34.4			D6@84 / 0.005	347 (SD295)	Flexure-Shear
R-10	32.4			D6@42 / 0.010	347 (SD295)	Flexure

D: diameter of deformed bar

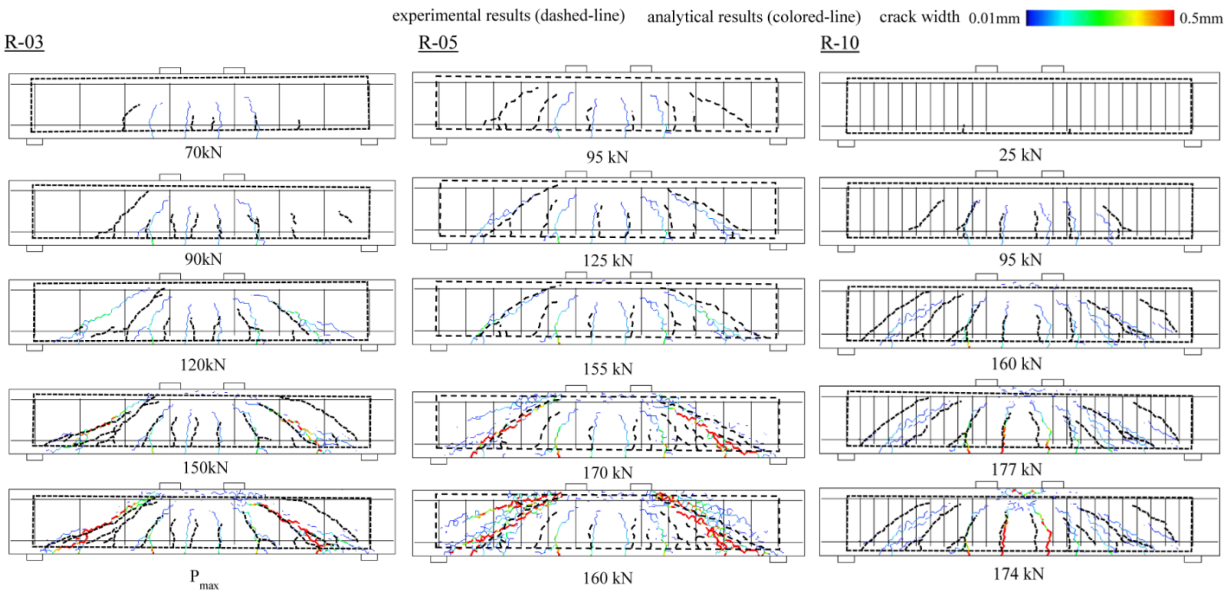


Figure 20. Analytical results of 3D-RBSM (detailed) model for crack propagation [7]

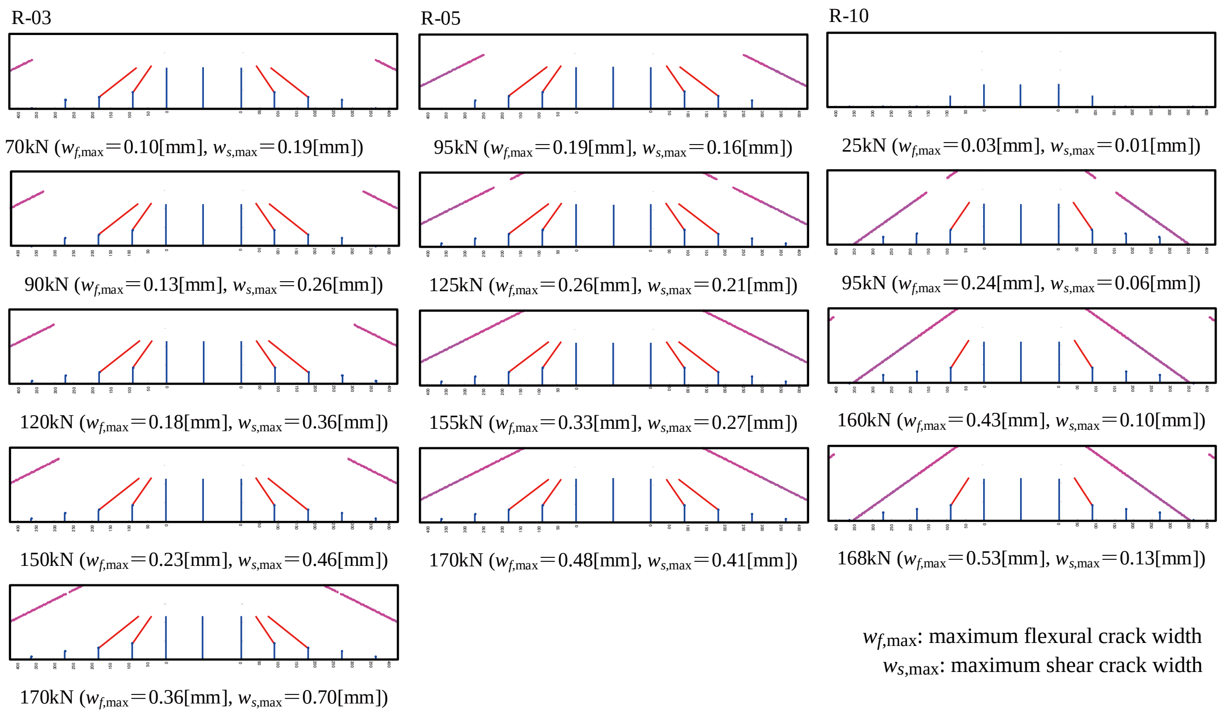


Figure 21. Analytical results of the proposed (simplified) model for crack propagation

Conclusions

The proposed model shows that the estimated flexure and flexural-shear crack widths and length approximate the measured crack widths and length, but the estimated shear crack widths and length occasionally disagree with test results. To revise the model, shear crack and drift mechanism in seismic excitation needs to be more investigated.

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