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CRACK INDICES OF REINFORCED CONCRETE SHEAR WALLS FOR SEISMIC DAMAGE EVALUATION

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SUMMARY

To investigate the correlation between seismic damage and inelastic behavior of shear walls in reinforced concrete buildings, model tests of shear walls were conducted. Two types of wall specimens with different failure mode were subjected to cyclic reversed loading. The quantity of cracks such as crack width, the number of cracks and the crack length were measured in detail at various levels of loading history. The crack width, the crack width ratio and the crack area ratio are used as crack indices. The relationships between the crack indices and the level of deformation of the specimens are investigated.

INTRODUCTION

For severe earthquakes, it is not practical to design structural elements so as to remain elastic. Therefore, the plastic design concept has been applied to the seismic design of reinforced concrete buildings. Consequently, structural elements inevitably show an inelastic behavior during severe earthquake, such as cracking and crashing of concrete and yielding of reinforcing bars.

It is important to evaluate the extent of structural damage for buildings which suffered damage due to a sever earthquake. The visual inspection of the structural elements of the damaged buildings will be the only practical way to evaluate the structural damage states. It is necessary to study the relationship between the state of damage observed after the earthquake and the actual response behavior of structures in the inelastic range during the earthquake (Ref. 1). The object of this paper is to provide information through experiments on the evaluation of damage to shear walls with emphasis on the crack indices.

EXPERIMENTAL PROGRAM OF SHEAR WALLS

Test Specimens Nominal dimensions and layout of reinforcements of test specimens are shown in Fig. 1. Two types of wall specimens with different failure mode were designed. One was designed for flexural-shear failure mode and was approximately one-fourth scaled two-story isolated shear wall with shear span ratio of 1.0. The shear span ratio (a/D) was the ratio of clear span to total depth of a wall. The other was designed for flexural failure mode and was approximately one-fifth scaled three-story isolated shear wall with shear span ratio of 1.5. The each wall specimen corresponds to the lower part of low/medium and high rise buildings, respectively. The failure modes of the wall specimens were determined the following procedures in Reference (2). One face of the two-story specimens with flexural-shear mode was covered with finishing mortar so that the cracks could be measured in the real situation. The finishing mortar was 8 mm thick.

Materials Physical properties of concrete and steel reinforcements used in the wall specimens are listed in Tables 1 and 2. River sand was used as aggregate. The maximum size of the aggregate was 5 mm for all the wall specimens. The deformed bars (D10) were used for the main reinforcements of columns and beams parts of the wall specimen. The annealed wires (4Ø) were used for hoops, stirrup ties and wall reinforcements.

Test Procedures Both columns parts of the wall specimen were subjected to constant axial load (Fc/6, Fc=compressive strength of concrete) through the test. Cyclic lateral load was applied on the top beam of the specimen. Loading program for each specimen is shown in Fig. 2. The loading was controlled by the horizontal deformation angle at the first story. In case of the two-story specimens with flexural-shear failure mode, three wall specimens were subjected to different deflection history corresponding to severe damage, medium damage and slight damage, respectively. After these loading tests they were repaired by epoxy injection to cracks and epoxy-mortar for crashed and exfoliated portions of concrete. After the repair works all the wall specimens were retested for the medium damage. In case of the three-story specimens with flexural failure mode, two wall specimens were tested for the severe damage and were not repaired.

Measurement of Cracks The widths of cracks formed on the wall specimens were measured in each loading cycle at both the time when the first story deformation was at the maximum and when the lateral load was removed. The crack width were measured with transparent plastics thin crack scale. The number of cracks and the lengths of cracks were only measured at the time when the load was removed.

DEFORMATION CHARACTERISTIC

Q-d Diagrams Typical load versus deformation curves at the first story for both failure modes are shown in Fig. 3. The curve of the two-story specimen with flexural-shear failure mode contains the original loading data (before repair) and those after repair. Behaviors of original specimen which suffered severe damage and those after repair agreed well. This indicates the epoxy repair is effective for resuming stiffness, strength and ductility of reinforced concrete shear walls.

Limit Deformation Limit deformations for specimen with different failure modes are defined by the deformation at flexural ultimate point which indicate the maximum strength after yielding of main reinforcing bars in column. The limit deformation angle ($_tR_1$) for the two-story specimen with flexural-shear failure mode was 11/1000 rad. in the first story at which sudden drop of strength was observed , and that for the three-story specimen with flexural failure mode was 20/1000 rad. at which the sudden increase of vertical compressive deformation was observed in compressive column of the first story.

QUANTITY OF CRACKS

Crack Width The mean width of cracks crossing the reference line, the number of cracks crossing that and the approximate crack length obtained by grid-line-method are used to express the quantity of shear cracks formed in wall panels. The reference line which is the horizontal line at the middle height of a wall panel is shown in Fig. 4. The comparison between the mean crack width crossing the reference line at the middle height of the wall panel and those crossing the different reference lines located both at the 12 cm of distance from the top and the bottom of the wall panel in the first story is shown in Fig. 5. The comparison indicates that the mean crack width crossing the reference line at the middle height of the wall panel is the mean crack width of cracks formed in the whole wall panel. Thus, the mean crack width ($s\bar{W}$) crossing the reference line at the middle height of the wall panel is used to express the quantity of the shear crack width.

Crack Length The approximate shear crack length are calculated by the grid-line-method as shown in Fig. 6. The following equation (1) is used to calculate the approximate shear crack length ($_sL$).

$$_sL = (N_g + N_b / 2) a / \sqrt{2} \qquad (1)$$

where N_g is the number of intersections of each grid line and the shear cracks, N_b is the number of intersections of boundary lines of the wall panel and the shear cracks, and a is the unit length between each grid. The comparison of the shear crack length between the approximate value obtained by the grid-line-method and exact value obtained by digitizer is shown in Fig. 7. A regression line and a coefficient of correlation are also shown in this figure. The grid lines dividing the height and depth of the wall panel into five and ten parts are used for both two-story and three-story specimens. The approximate value of the shear crack length is from 90 % to 110 % of the exact value obtained by digitizer and is very close to actual value. This approximate shear crack length is adopted to express the quantity of the shear crack length.

CRACK INDICES VS. DEFORMATION RATIO RELATIONSHIPS

Deformation Ratio To make clear the relationship between the quantity of deformation and cracks, the deformation ratio ($_tR_p/_tR_l$) is introduced, which is obtained by normalizing deformation by the limit deformation in each specimen with different failure mode.

Crack Indices The mean crack width, the crack width ratio and the crack area ratio are used for the shear crack indices. The relationships between the above three crack indices and the deformation ratio are investigated both at the peak deformation and at the load removal under each loading cycle . Three shear crack indices are defined as listed in Table 3. The shear crack width ratio ($s\bar{W}p$ x sN / Ds) is defined as the ratio of the product of the crack width and the number of cracks to the depth of a wall panel and means the elongation rate of the wall panel due to cracking. The shear crack area ratio ($s\bar{W}p$ x sL / As) is defined as the ratio of the product of the crack width and the crack length to the area of the wall panel (Ds x H) and means the extension rate of area of the wall panel due to cracking.

Table 3 Shear Crack Indices for Shear Walls

Shear Crack Indices	Measured State	
	at the Peak Deformation	at the Load Removal
Crack Width (mm)	$s\bar{W}p$	$s\bar{W}r$
Crack Width Ratio (%)	$s\bar{W}p$ x sN / Ds	$s\bar{W}r$ x sN / Ds
Crack Area Ratio (%)	$s\bar{W}p$ x sL / As	$s\bar{W}r$ x sL / As

$s\bar{W}p$ and $s\bar{W}r$ = The mean crack width at the peak deformation and at the load removal, respectively.
sN = The number of cracks crossing the reference line.
sL = The total crack length (approximate value).
Ds and As = The depth and the area of the wall panel (Ds x H, H is the height of wall panel), respectively.

Crack Width The relationships between the shear crack width and the deformation ratio are shown in Fig. 8. A total of 30 crack data were used. For the two-story specimens with the flexural-shear failure mode, data from both original tests and repaired tests were used. For three-story specimens with flexural failure mode, data from only original tests were available. The data of specimens with the different failure modes are plotted in the same figures. The relationship between them at the peak deformation are approximately linear and that at the load removal are nonlinear.

Crack Width Ratio The relationships between the crack width ratio and the deformation ratio are shown in Fig. 9. The relationships are the same tendency as the crack width for both at the peak deformation and at the load removal. And the coefficient of correlation are higher than the case of the crack width.

Crack Area Ratio The relationships between the crack area ratio and the deformation ratio are shown in Fig. 10. The relationships for both at the peak deformation and at the load removal are the same tendency as the relationships of two other crack indices. The relationship at the peak deformation is able to be approximated by a linear line up to the 100 % of the deformation ratio corresponding to the limit deformation. The relationship at the load removal is able to be approximated by a nonlinear curve up to the 100 % of the limit deformation. The coefficient of correlation for both at the peak deformation and at the load removal are higher than those of two other crack indices.

CONCLUSIONS

From the discussion of the relationships between three crack indices and the deformation ratio, the maximum experienced deformation of shear walls in damaged reinforced concrete buildings during sever earthquake is able to be evaluated by using the crack indices, i.e. the crack width, the crack width ratio and the crack area ratio. The evaluation using the crack area ratio will be most effective among three crack indices.

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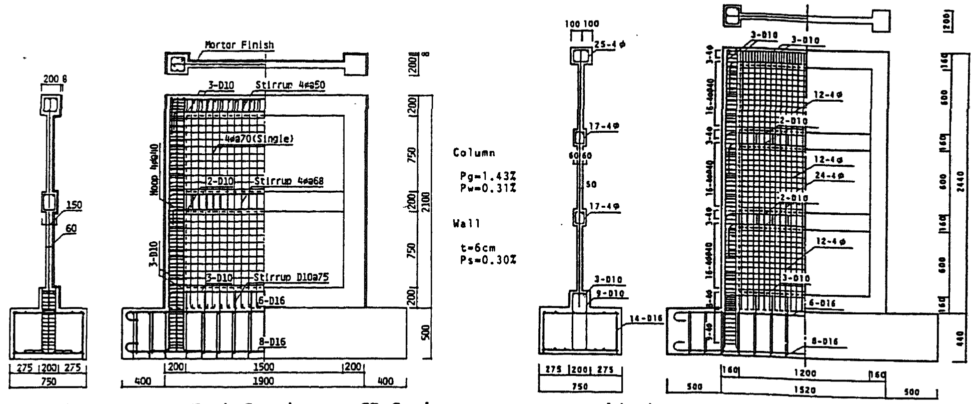


a) Two-Story Test Specimens, SP Series (Flexural-Shear Failure Type, a/D=1.0)

b) Three-Story Test Specimens, SM Series (Flexural Failure Type, a/D=1.5)

Fig.1 Dimensions and Details of Test Specimens

Table 1 Physical Properties of Concrete

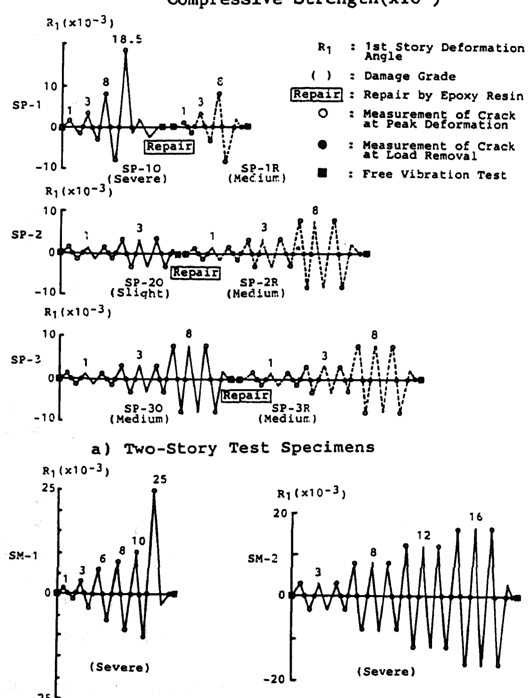
Specimen	Fc (kg/cm²)	Fsp (kg/cm²)	E (kg/cm²)
SP-1	189	14.8	--
SP-2	201	14.9	1.96
SP-3	196	16.4	2.01
SM-1	230	23.0	1.78
SM-2	221	23.0	2.03

Fc : Compressive Strength
Fsp : Splitting Strength
E : Secant Modulus at one-third Compressive Strength($\times 10^5$)

Table 2 Physical Properties of Steel

Specimen Series	Type	σ_y (kg/cm²)	σ_{max} (kg/cm²)	Elongation(%)
S P	D10	3747	5408	26.4
	4φ	1976	3104	45.3
S M	D10	3685	5375	28.2
	4φ	1976	3104	45.3

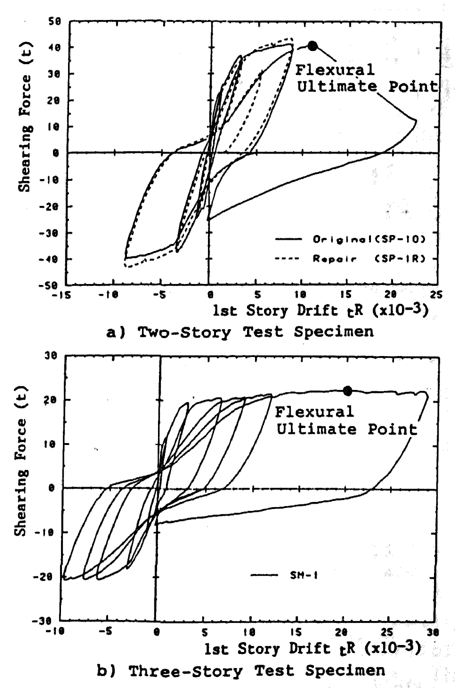
D10 : Standard of Reinforcing Bar SD30
Sectional Area is 0.71 cm²
4φ : Annealing Steel Bar
Sectional Area is 0.31 cm²



a) Two-Story Test Specimens

b) Three-Story Test Specimens

Fig.2 Loading Program



a) Two-Story Test Specimen

b) Three-Story Test Specimen

Fig.3 Load-1st Story Deformation Curves

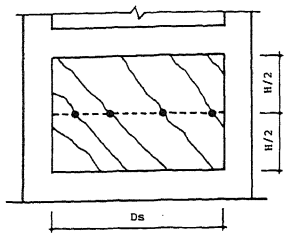
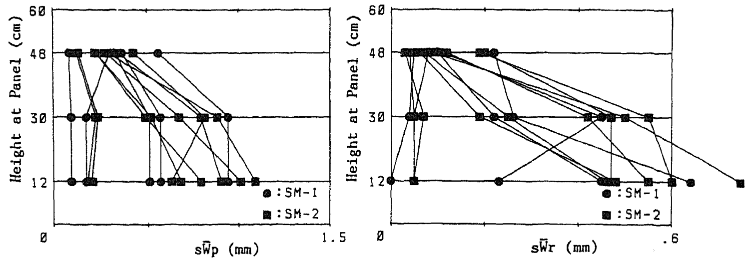


Fig.4 Reference Line for Measurement of Crack Widths and the Number of Cracks



a) at the Peak Deformation b) at the Load Removal

Fig.5 Comparison of Crack Width on Reference Lines for Different Heights of Wall Panel

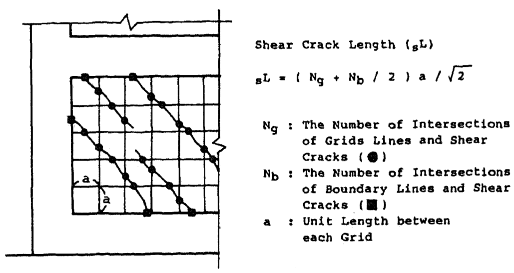


Fig.6 Approximate Calculation of Crack Length (Grid-Line-Method)

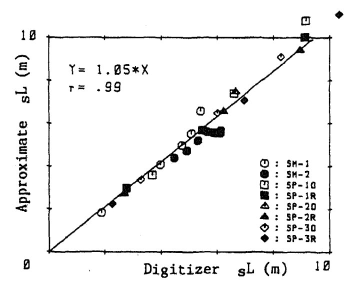
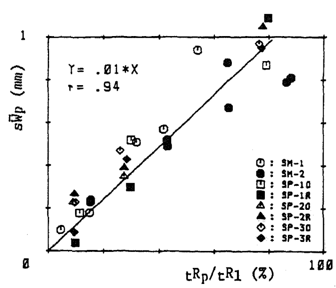
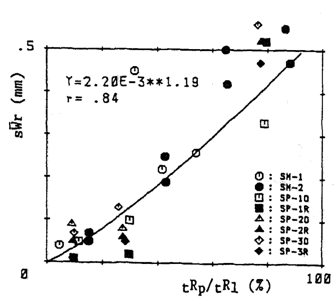


Fig.7 Comparison of Crack Length by Approximate and Exact Calculation

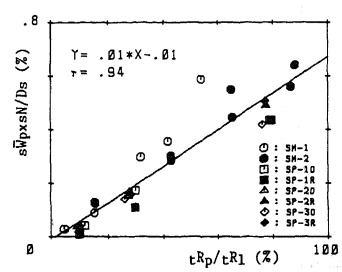


a) at the Peak Deformation

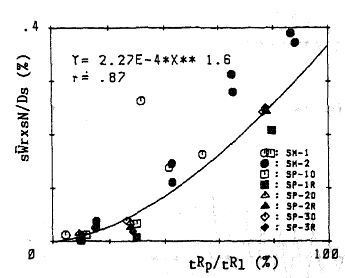


b) at the Load Removal

Fig.8 Shear Crack Width vs. Deformation Ratio

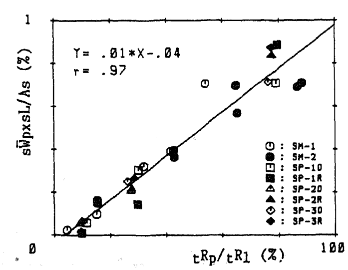


a) at the Peak Deformation

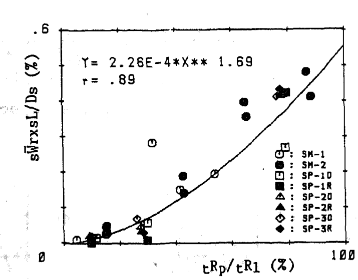


b) at the Load Removal

Fig.9 Shear Crack Width Ratio vs. Deformation Ratio



a) at the Peak Deformation



b) at the Load Removal

Fig.10 Shear Crack Area Ratio vs. Deformation Ratio