R / C 전단벽의 지진이력 거동에 관한 연구

Identification of Seismic Hysteretic Behavior of R / C Shear Walls

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요 약

축력과 횡력을 받는 전단벽의 휨과 전단 거동을 분리 산정 하기 위하여 R /C 전단벽에 관한 실험 결과에 대해 System Identification을 행한다. 이를 토대로, 전단벽의 강도 저하 계수 'R'과 극한 회전능력을 구하는 실험식을 제안한다.

R /C 뼈대구조－전단벽에 대한 비탄성 해석 유한요소 컴퓨터 프로그램(IDARC)을 이용하여 전단벽의 지진 이력 거동을 재현한다. Identification 결과를 Digitize한 실험 결과와의 비교에 의해 검증하고, 총변형으로 부터 휨과 전단에 의한 변형요소를 해석적으로 분리 함으로서 비탄성 전단 거동과 강도 저하 계수 'R'의 산정이 가능해진다. 또한 실험 결과에 대한 회귀 분석을 통하여 전단벽의 극한 회전 능력에 대한 실험식이 얻어진다.

Abstract

The system identification is carried out to evaluate the flexural and the shear behavior of shear wall by separating the flexure and shear contributions from the total lateral deformation which is caused by the lateral and axial loadings. In addition, strength deterioration parameter 'R', and the ultimate rotational capacity of walls are determined through the identification. The experiments identified involve reinforced concrete shear walls subjected to axial and lateral loadings.

A finite element program for inelastic damage analysis of R /C frame-shear wall structure, 'IDARC', is used to identify the seismic hysteretic behavior of shear walls. The results of identification are verified with the digitized test data, and the inelastic shear behavior and the

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strength deterioration parameter 'R' are evaluated statistically after the shear and flexure components of deformation are separated analytically. An empirical relation for the ultimate rotational capacity of shear walls is obtained by direct regression analysis of the experimental data.

Keywords : system identification, seismic hysteretic behavior, shear wall, flexure, shear, strength deterioration, ultimate roational capacity, regression analysis, finite element, earthquake.

1. Introduction

Shear walls are deep, relatively thin, vertically cantilevered reinforced concrete beams, and they are commonly used in structures to resist the effects of gravity loads and story shears due to wind or earthquake forces.

Shear walls can provide structures under service loading with sufficient stiffness, minimizing deformations and damages to nonstructural elements. Under severe seismic excitations, they can provide sufficient strength, energy absorption, and dissipation capacities to prevent collapse and loss of life. Despite considerable progress in earthquake engineering in the last few decades, the determination of the inelastic shear behavior is still difficult due to the unpredictable shear cracking mechanism.

Diagonal cracking under high shear conditions causes a redistribution of stresses that affects the curvature distribution along the wall. This generally causes an increase in the flexural deformations with respect to those obtained in a similar specimen subjected to the same flexural moment, but much lower shear stresses.

In the case of flexural structural elements subjected to high shear, when the load is reversed there is a temporary reduction in the moment of inertia. This leads to a decrease in stiffness and a pinching effect is observed. This effect starts to disappear when, after increasing the load, the cracks gradually close. Shear slippage in the direction parallel to the crack plane causes the irregular crack surfaces to contact. This in turn causes an increase in the flexural stiffness over that predicted by certain analytical models that have attempted to include the effect of crack opening in predicting the observed reduced stiffness. Opening of flexural cracks causes a significant drop in the contribution of concrete to shear stiffness and strength. Because of the large number of flexural cracks and the jaggedness of the crack surfaces, this effect is hard to quantify analytically. The interaction of flexural and shear mechanisms, the effect of bond on cracking, aggregate interlocking and dowel actions, and the effect of reversals must all be considered in a complete model.

In this paper, the system identification on hysteretic behavior of shear wall subjected to axial and lateral loadings due to gravity loads and earthquake forces is first presented. Then, the strength deterioration parameter and the ultimate rotational capacity of shear walls are determined by direct regression analysis of the experimental data.

2. Theoretical Background and System Identification

The system identification is performed to evaluate the inelastic behavior of shear walls using the three-parameter model. This identification model combines three different hysteretic properties, i. e., stiffness degradation, strength deterioration and pinching behavior.

2.1 Three-Parameter Model

The shear wall behavior is simulated analytically using IDARC[1] to reproduce the experimental results. For the inelastic analysis, a proper selection of hysteretic model is one of the critical factors. The three-parameter model has been developed for use in finite element computer program, IDARC, and this hysteretic model is used in the analysis of shear walls. The model combines a variety of hysteretic properties which are obtained through the combination of the trilinear skeleton curve and the three parameters 'α', 'β' and 'γ'. The values of these parameters determine the properties of stiffness degradation, strength deterioration and pinching behavior, respectivley. Fig. 1 illustrates the effects of the three parameters.

2.2 System Identification

The inelastic deformation can be regarded as composed of the flexural component, δ_f, the deformation due to bond-slippage of the reinforcing bar from its anchorage, δ_b, inelastic shear deformation, δ_{is}, and the elastic shear deformation, δ_{es}; i. e. ,

$$\delta_{total}=\delta_f+\delta_b+\delta_{is}+\delta_{es} \qquad (1)$$

'δ_{es}' is evaluated by the conventional elastic beam theory. However, a more accurate approximation is required for the remaining

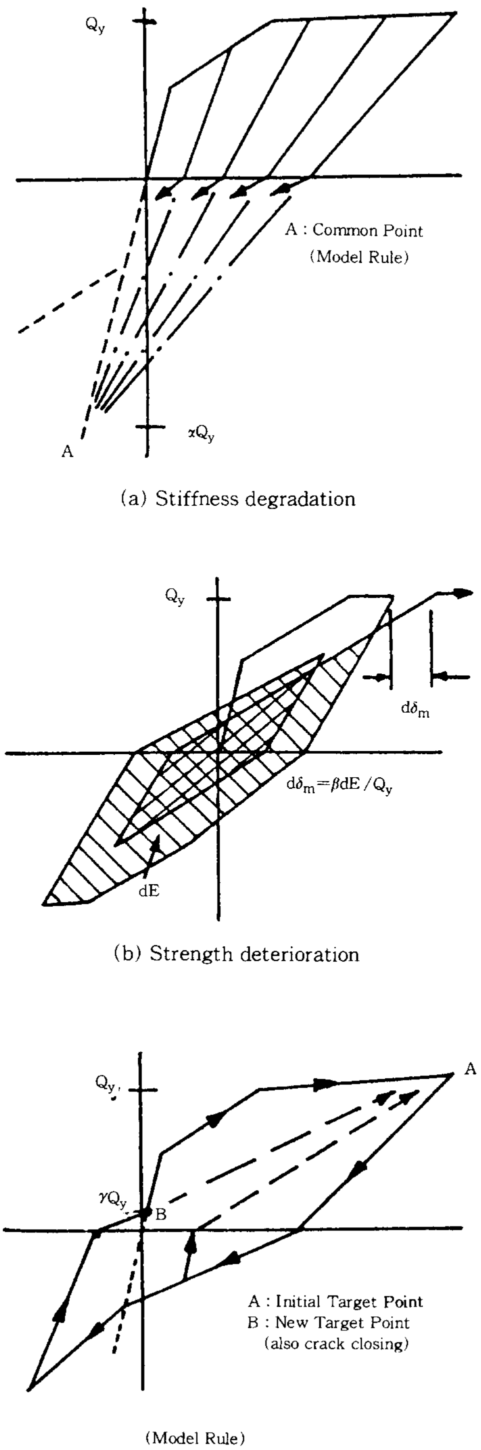

Fig. 1 Three-parameter model

parameters.

The strength-deformation parameters for shear wall arise from the following: ① Flexural behavior (δ_f) and ② Shear behavior ($\delta_s=\delta_b+\delta_{is}+\delta_{es}$). The flexural deformation characteristics of shear walls having different cross-sections may be estimated using the traditional fiber-model analysis[2]. The shear behavior of shear walls is evaluated by substracting the flexural deformation from the total deformation obtained directly from experimental results.

The process of evaluating the flexural and shear behavior of shear walls involves the following steps:

1) Selecting the hysteretic model and determination of its unknown parameters (α, β, γ).

2) Identification of the inelastic hysteretic behavior of experimental results. The total capacity of shear walls is assumed to be composed of primarily flexural and shear behavior.

$$\delta_{total}=\delta_f+\delta_s \tag{2}$$

3) Determination of the strength-deformation parameters due to the flexural component contribution. The flexural deformation characteristics are determined using the fiber-model.

4) Determination of the shear deformation characteristics which includes the deformation due to bond-slippage, the inelastic shear deformation and elastic shear deformation. From Step 2) and 3), the total deformation and flexural component are evaluated. The shear deformation, δ_s, can be obtained by subtracting the flexural deformation, δ_f from the total deformation, δ_{total}.

$$\delta_s=\delta_{total}-\delta_f \tag{3}$$

5) A regression analysis is carried out on the identified shear deformation, as a function of section properties.

2.3 Strength Deterioration Parameter 'R'

In the three-parameter model, the parameter 'β' specifies the rate of strength degradation. The same parameter 'β' can be found in the definition of the damage index, D[1, 3]

$$D=\frac{\delta_m}{\delta_u}+\frac{\beta\int dE}{\delta_u Q_y} \tag{4}$$

where, D=damage index scaling the structural damage from zero to one, δ_m=maximum response deformation under an earthquake, δ_u=ultimate deformation under monotonic loading, Q_y=yield strength, and dE=incremental dissipated hysteretic energy.

Using Eq. (4), the strength-deformation curve for each test is traced up to the failure point. Then, at the point of failure, with D=1.0, the corresponding value of β is evaluated. But a modified damage model by Reinhorn, et al.[4] is used herein and 'β' is replaced by 'R' as a strength deterioration parameter:

$$D=\frac{R(\int dE-E_p)}{Q_u\delta_u}=\frac{\Delta Q}{Q_u} \tag{5}$$

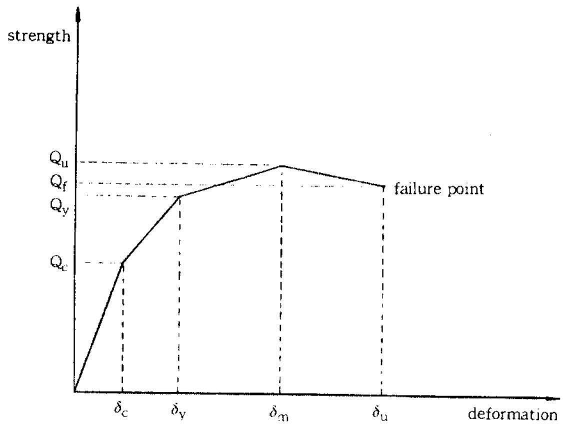

Fig. 2 Strength-deformation envelope curve

where, Q_u=maximum strength, E_p=potential energy stored (resulting from the maximum deformation of the component), $\triangle Q = Q_u - Q_f$, and Q_f=remaining strength at failure.

From Eq. (5) and the strength-deformation envelope curve, Fig. 2, new strength deterioration parameter 'R' is expressed as a function of the response δ_u and dE, that are dependent on the loading history, and the parameter Q_u, Q_f and E_p, that specify the structural capacity.

$$R = \frac{\delta_u (Q_u - Q_f)}{(\int dE - E_p)} \qquad (6)$$

The minimum-variance values of 'R' for Eq. (5) are determined in such a way that the covariance of Q_f is minimized and the mean value of D is close to unity.

$$Q_f = Q_u - \frac{R(\int dE - E_p)}{\delta_u} \qquad (7)$$

$$C.O.V = \sqrt{\Sigma[\frac{Q_f(CAL.) - Q_f(EXP.)}{Q_f(CAL.)}]^2 / (N-1)} \qquad (8)$$

where, $Q_f(CAL.)$=calculated Q_f value, Q_f (EXP.)=experimental Q_f value, C.O.V=covariance value, and N=number of specimens.

3. Shear Wall Test Data and Structural Type

An extensive test data is needed for the analysis of shear wall behavior. The experimental data which have been extensively used here for identification was obtained from Ref. 5. In this reference, the author, Hirosawa collected and listed up the test results on several critical strengths and deformations, load-deformation relationships and cracking patterns of the 179 specimens out of the past experimental results on reinforced concrete shear walls under combined loads of moment, shear force and axial load, carried out in Japan.

The experimental data used in identification were carefully selected from a large set of above test results; only those in which an abrupt failure is clearly observed or gradual failure can be identified on the envelope curve were included. These data were first digitized on a SPD-Series Graphic Tablet and an IBM/PC.

Shear wall test specimens are categorized into five structural types:

① Type A : Shear Wall without Edge Columns, ② Type B : Shear Wall with Edge Columns, 1-story, ③ Type C : Shear Wall with Edge Columns, 2-story, ④ Type D : Shear Wall-Frame with Edge Columns, 1-story, ⑤ Type E : Shear Wall-Frame with Edge Columns, 2-story.

4. Results

With the results of system identification, the comparison of the experimental and analytical results can be available and the shear behavior of shear walls is identified by the proposed formulas. A regression anaysis is carried out to express the ultimate rotational capacity and the strength deterioration parameter as a function of section properties.

4.1 Contribution of Flexure and Shear Behavior

The strength-deformation relations for the total hysteretic behavior and the flexure only were obtained through the identifiction procedure using IDARC. The parameter used in the identification were first calculated, and then modified for the better fittings to the experimental results by an iterative procedure.

The results of system identification are verified by reproducing experimental load-deformation curves and separating the flexural and shear behavior of R/C shear walls. As an illustrative case, Figure 3 shows a one-story cantilever-typed shear wall subjected to axial and lateral loadings, which is representing Type A in the above five shear wall types. Its experimental conditions are listed in Table 1, and in this case, test specimen experienced more than five cyclic lateral loadings under constant axial loading.

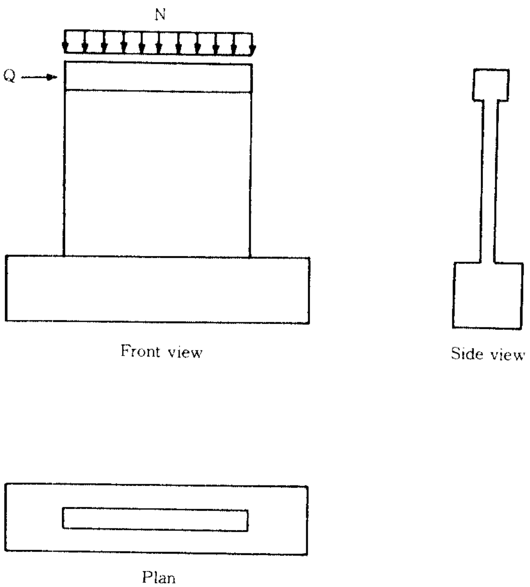

Fig. 3 Test shear wall specimen, Type A

Table 1 List of experimental conditions of test specimen, illustrative case (Ref. 5)

Concrete type	Normal concrete
Concrete strength	150kg/cm²
Shear span length	170cm
Shear span ratio	1.111
Column cross section	16cm×17cm
Web dimension (thickness×length×height)	16cm×136cm×160cm
Web thickness	16cm
Column reinforcement	2-D19, 2-ϕ9
Hoop reinforcement of column	ϕ9 @ 6.6, ϕ13 @ 6.6
Vertical web reinforcement	2-ϕ9 @ 13.3
Horizontal web reinforcement	2-ϕ9 @ 6.6, 2-ϕ13 @ 6.6
Constant axial load	54400kg

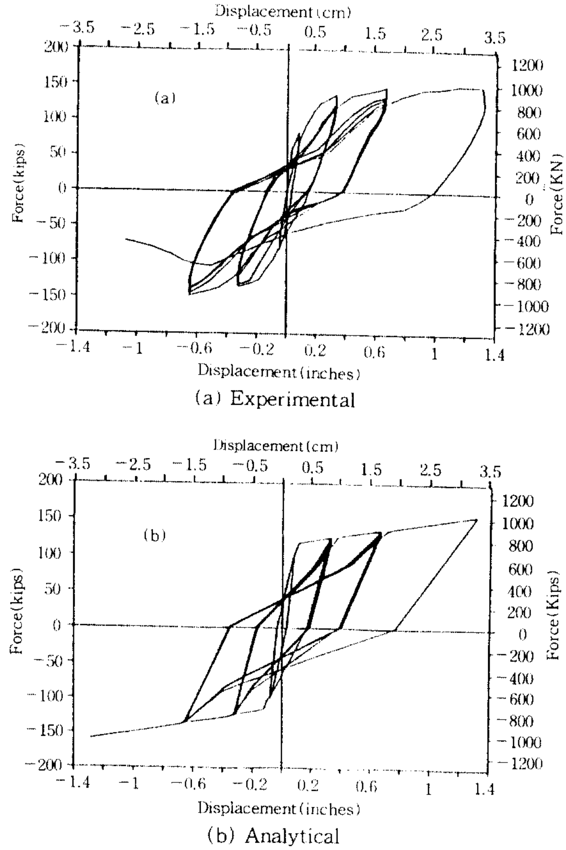

Fig. 4 Force-displacement relation

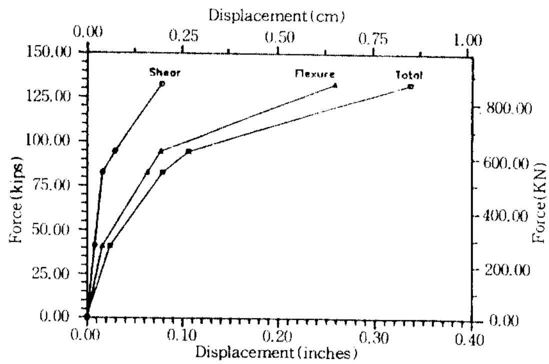

Fig. 5 Envelopes of hysteretic behavior

Table 2 Deformation distribution at different load level

Specimen Number & Type		Deformation (in & %)					
		Flexural Cracking		Shear Cracking		Yielding	
		Flexural	Shear	Flexural	Shear	Flexural	Shear
W068	A	0.018(64)	0.010(36)	0.045(60)	0.031(40)	0.222(68)	0.101(32)
W070		0.010(56)	0.008(46)	0.072(53)	0.063(47)	0.213(69)	0.094(31)
W072		0.018(68)	0.008(32)	0.080(69)	0.037(31)	0.260(75)	0.086(25)
W080		0.028(74)	0.010(26)	0.073(74)	0.025(26)	0.111(65)	0.061(35)
W081		0.028(74)	0.010(26)	0.071(74)	0.025(26)	0.269(83)	0.052(17)
W083		0.044(78)	0.012(22)	0.100(70)	0.044(30)	0.283(83)	0.054(17)
W150		0.004(57)	0.003(43)	0.010(71)	0.004(29)	0.061(83)	0.012(17)
W155		0.003(60)	0.002(40)	0.018(75)	0.006(25)	0.032(56)	0.025(44)
W156		0.005(64)	0.003(36)	0.017(71)	0.007(29)	0.035(53)	0.031(47)
W163		0.002(40)	0.003(60)	0.003(38)	0.005(62)	0.050(79)	0.013(21)
W006	B	0.050(66)	0.026(34)	0.021(68)	0.010(32)	0.021(68)	0.010(32)
W007		0.038(56)	0.030(42)	0.009(47)	0.010(53)	0.022(52)	0.020(48)
W008		0.022(38)	0.036(62)	0.006(35)	0.011(65)	0.042(38)	0.070(62)
W011		0.035(71)	0.014(29)	0.050(67)	0.025(33)	0.013(52)	0.012(48)

* Unit conversion : 1 inch=2.54cm

The graphical comparison of the experimental and analytical results for the total shear wall behavior is illustrated in Figure 4. According to the analytical results, the contributions of flexure and shear behavior can be determined separately, and the envelope curve of hysteretic behavior is drawn by taking the several critical load points, as shown in Figure 5. Actual values and percentages of the flexural and shear components in the total lateral displacement are listed in Table 2. The amount of displacement componets depends on the slenderness of the specimens. Accordingly, the more slender the specimen, the more significant the flexural displacement is. After yielding, the flexural deformation component becomes more significant.

4.2 Identified Shear Behavior

The contributions of flexure and shear behavior were evaluated for forty three test specimens. Based on regression anlysis of observed test data and contribution of shear behavior, the inelastic shear behavior of shear walls is evaluated. The following relations are proposed for the cracking and yield shear strength, 'Q_c' and 'Q_y' as a result of analysis;

$$Q_c = \frac{0.002\sqrt{b_e \cdot d}}{(a/d+2.5)} \cdot f'_c \tag{9}$$

$$Q_y = 0.1\left[\frac{\sqrt{\rho_v \cdot f_c'}}{(a/d+4.5)} + \sqrt{\rho_h} + N_o\right] \cdot \sqrt{b_e \cdot d} \tag{10}$$

where, a/d=shear span ratio, ρ_v=vertical reinforcement(%), ρ_h=transverse reinforcement(%), N_o=normalized axial stress, b_e=equivalent web thickness(inch), d=distance between edge columns(inch), and f'_c=concrete strength(psi). (Unit conversion : 1 psi = 6.89x 10^3Pa)

The yield shear deformation can be determined from the secant stiffness 'k_y' as follows, and the relation of strength and stiffness is shown in Fig. 6. The relation was obtained from the parametric analysis of test data[5] and was found to be the most suitable for defining the shear properties of walls.

$$k_y = \beta_s \cdot k_e \quad (11)$$

$$\beta_s = 0.4(a/d)^{1.1} \quad (12)$$

where, k_e=elastic shear stiffness.

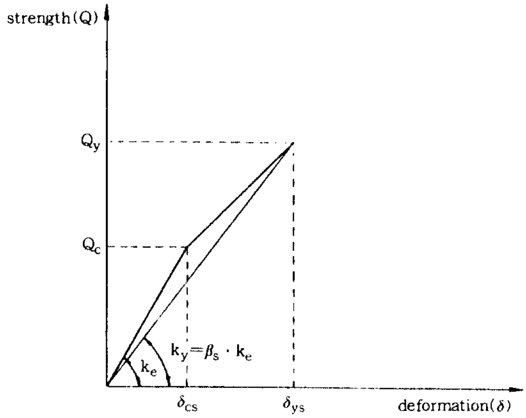

Fig. 6 Relation of strength and stiffness

4.3 Ultimate Rotational Capacity

The ultimate rotational capacity can be expressed as a function of several parameters : shear span ratio, normalized axial stress, reinforcement ratios and concrete strength.

By the regression analysis, the minimum-variance solution is obtained with C. O. V=24% for forty three specimens. The correlation between the experimental and analytical rotations is illustrated in Fig. 7.

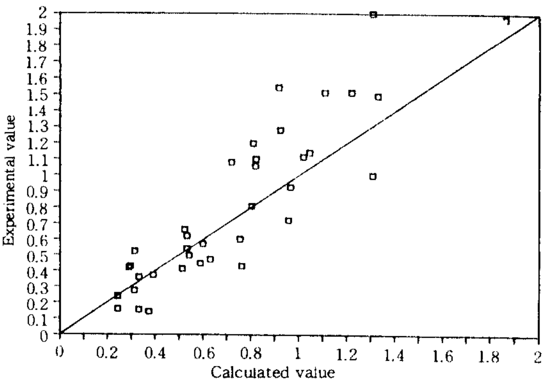

Fig. 7 Correlation of ultimate rotational capacity, θ_u

Ultimate rotational capacity, $\theta_u(\%)$;

$$\theta_u = 0.19(a/d)^{1.3}(N_o)^{0.01}(\rho_h)^{0.8}(\rho_c)^{0.1} (\rho_v)^{-1.1} (f'_c)^{2.5} \quad (13)$$

where, ρ_c=edge column reinforcement ratio (%).

4.4 Strength Deterioration Parameter

The effect of cyclic loadings on structural damage is represented by the parameter 'R' in Eq. (5). The absorbed hysteretic energy (excluding potential energy) is integrated up to the failure point for cyclic test data of shear walls. At the point of failure, with D=1.0, the corresponding value of R is evaluated. The results yielded the following relation:

$$R = 0.015(a/d)^{0.8}(N_o)^{-0.15}(\rho_h)^{0.37} (\rho_c)^{-1.4}(f'_c)^{1.4} \quad (14)$$

A large scatter can be observed between the calculated and experimental results of R value, as shown in Fig.8.

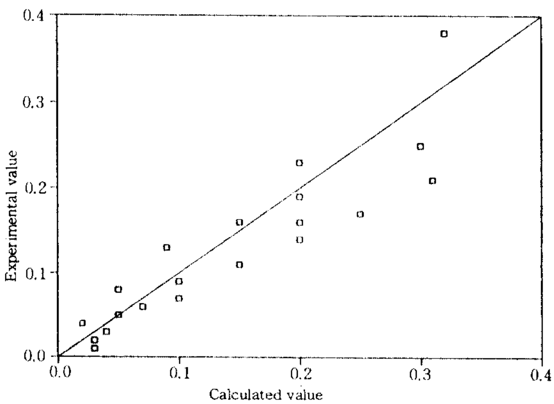

Fig. 8 Correlation of strength deterioration parameter, R

5. Conclusions

The system identification was performed to evaluate the inelastic shear behavior of shear walls under seismic loading conditions and the results of identification were verified with th digitized test data.

The flexural and the shear behavior contributions were separated from the total lateral deformation caused by the lateral and axial loadings, then two empirical equations are proposed to evaluate the cracking shear strength, Q_c, and the yield shear strength, Q_y. Covariance value, which specifies the correlation between the experimental and calculated values, was 20% and 18%, respectively. Also the ultimate rotational capacity of shear wall is expressed as Eq.(13).

The parameters, α, β, γ and post-yielding stiffness, used for three-parameter model affected greatly on force-displacement relation of hysteretic behavior, therefore, these parameters should be handled very carefully for the good results. Strength deterioration parameter, R, was calculated according to the modified damage model, Eq.(5).

Generally the graphic results show being successful in identifying the hysteretic behavior of test data with suitable selection of parameters, then the flexural and shear behavior of specimens were taken separately. Accordingly it was possible to evaluate the cracking and yielding shear strength, Q_c and Q_y, by each equation.

The components contributed from the two sources of lateral displacements, shear and flexure, are almost equally dominant, with a slight predominance of flexure over shear, in the elastic range. After yielding, the components contributed from flexure are more significant.

However, the different characteristics according to each five structural types of shear walls were not clarified in this project and this work remains for future study. Also an analysis on more extensive test data is suggested.

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